# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**EFFECTS OF PROPAGATING SUBMERGED OBJECTS ON DIFFUSIVE STAIRCASES**

by

James E. Davis

June 2018

Thesis Advisor: Timour Radko
Second Reader: John E. Joseph

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With the Arctic ice pack melting, and the realization of vast economic opportunity becoming apparent, the U.S. Navy may deploy warships in the Arctic Ocean to protect American national interests. Before entering a new area of operations, a thorough study of the environment should take place in order to maintain a competitive advantage over potential adversaries. A feature of the Arctic Ocean that merits advance study is thermohaline staircases, which have been identified as one of the key processes affecting the diapycnal heat transport in the high-latitude oceans and, ultimately, the melting of the sea-ice. Thermohaline staircases are commonly occurring in the main halocline of the Arctic Ocean. This study uses numerical simulations to model an object travelling through diffusive staircases to understand the resilience of staircases, their ability to maintain the vertical heat transport, and the ability to detect the persistent hydrodynamic signatures of propagating submersibles. The results show that hydrodynamic signatures of a submerged object travelling through a staircase can be detected long after its passage. The time it takes for the thermohaline staircase to reform depends critically on both characteristics of the submersible and the environmental parameters.

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**EFFECTS OF PROPAGATING SUBMERGED OBJECTS ON DIFFUSIVE STAIRCASES**

James E. Davis
Lieutenant, United States Navy
BS, U.S. Naval Academy, 2010

Submitted in partial fulfillment of the
requirements for the degree of

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Approved by: Timour Radko
Advisor

John E. Joseph
Second Reader

Peter C. Chu
Chair, Department of Oceanography

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# ABSTRACT

With the Arctic ice pack melting, and the realization of vast economic opportunity becoming apparent, the U.S. Navy may deploy warships in the Arctic Ocean to protect American national interests. Before entering a new area of operations, a thorough study of the environment should take place in order to maintain a competitive advantage over potential adversaries. A feature of the Arctic Ocean that merits advance study is thermohaline staircases, which have been identified as one of the key processes affecting the diapycnal heat transport in the high-latitude oceans and, ultimately, the melting of the sea-ice. Thermohaline staircases are commonly occurring in the main halocline of the Arctic Ocean. This study uses numerical simulations to model an object travelling through diffusive staircases to understand the resilience of staircases, their ability to maintain the vertical heat transport, and the ability to detect the persistent hydrodynamic signatures of propagating submersibles. The results show that hydrodynamic signatures of a submerged object travelling through a staircase can be detected long after its passage. The time it takes for the thermohaline staircase to reform depends critically on both characteristics of the submersible and the environmental parameters.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AIWEX | Arctic Internal Wave Experiment |
| AW | Atlantic Water |
| ITP | Ice Tethered Profilers |
| MITgcm | Massachusetts Institute of Technology General Circulation Model |
| NPS | Naval Postgraduate School |

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# I. INTRODUCTION

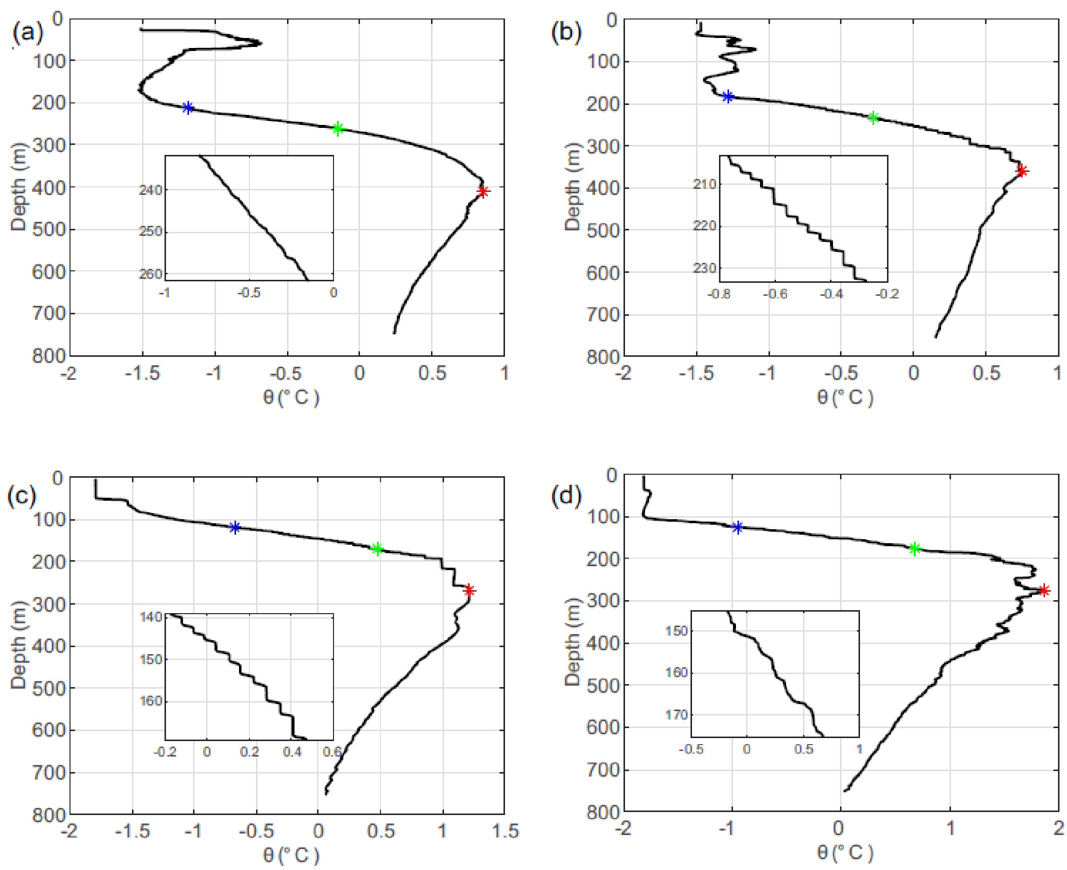
## A. BACKGROUND

In the pursuit of maintaining undersea dominance, the Navy invests a significant amount of time and resources into researching the best techniques for anti-submarine warfare operations. With the recession of the Arctic ice caps, the Navy may send more ships and submarines into the Arctic Ocean to promote national interests. Because of these potential deployments, the Navy should explore and identify any potential ways to exploit features in this environment. One such feature is a phenomenon present throughout the Arctic basin known as thermohaline staircases. Thermohaline staircases are present in over 95% of the Arctic Ocean at depths of 150 to 300 meters (Radko 2013). These depths are of interest for anti-submarine warfare operations. Due to their presence throughout the Arctic Ocean and at a depth of interest, this is an area of potential exploitation. This thesis investigates these staircases and identifies potential methods of non-acoustic detection which could result from a propagating object passing through thermohaline staircases.

Thermohaline staircases are a layered structure of temperature and salinity in a vertical water column characterized by sharp gradients in these properties in interfaces separating mixed layers. These layers are homogenous and are illustrated in Figure 1. The behavior of thermohaline staircases is governed by several key quantities, the most important of which is the density ratio, given by

$$R_\rho = \frac{\beta \Delta S}{\alpha \Delta T}. \tag{1}$$

Equation (1) represents a ratio of the stabilizing effect of salinity to the destabilizing effect of temperature. $\alpha$ and $\beta$ are the coefficients of thermal expansion and haline contraction respectively. $\Delta S$ and $\Delta T$ are the vertical differences in salt and temperature, respectively. If the destabilizing effect of temperature is less than the stabilizing effect of salt, a $R_\rho > 1$ is achieved which is a requirement for diffusive staircases. (Shibley et al. 2017). Bebieva and Timmermans (2017) propose the formation of thermohaline staircases is due to interleaving motions when the vertical density ratio is less than the critical density ratio for a particular given lateral and vertical temperature and salinity gradients. This proposal requires thermohaline intrusions below the thermohaline staircases and a lateral gradient in temperature and salinity (Bebieva and Timmermans 2017). An excellent review of thermohaline staircases and other double-diffusive phenomena, including formation theories of other double-diffusive processes is presented in Radko (2013).




Note: (a) Canadian Basin boundary staircase profile, (b) central Canadian Basin staircase profile, (c) central Eurasian basin staircase profile, (d) Fram Strait staircase profile. Blue and green stars are the bounds for the zoom-in plots and red star indicates Atlantic Water potential temperature maximum.

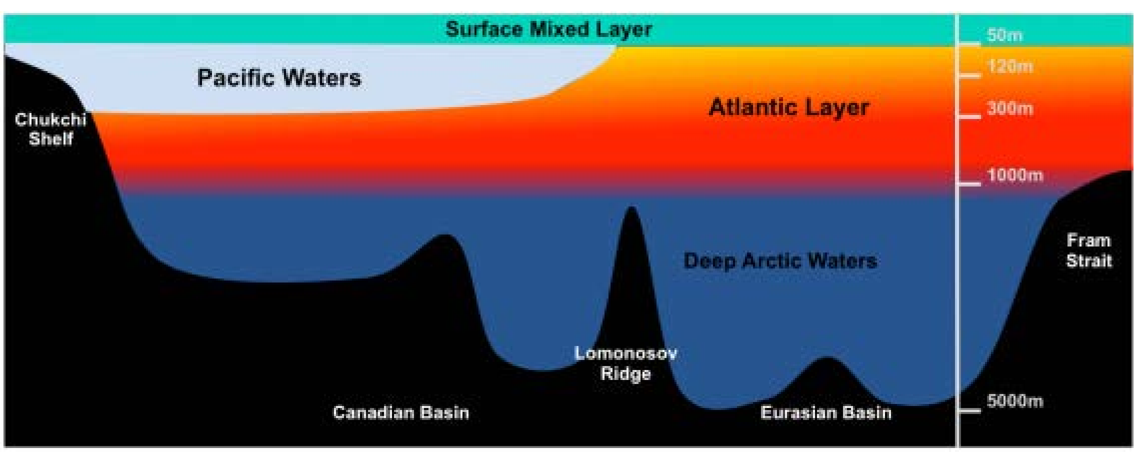
Figure 1. Typical Staircase Profiles Observed in the Arctic.
Source: Shibley et al. (2017).

These staircases are driven by the competing influences of temperature and salinity on the density of the system. In oceanography, the two main seawater properties examined are salt, S, and temperature, T, which contribute to overall density, $\rho$, approximated by the following linear equation of state:

$$\rho = \rho_0 \left[1 - \alpha (T - T_0) + \beta (S - S_0)\right], \tag{2}$$

where α and β represent the thermal expansion coefficient and the haline contraction coefficient, respectively. The diffusivity of salt is ~1% of thermal diffusivity, which drives instabilities in the fluid.

In the ocean, thermohaline staircases are seen only under specific conditions of heat and salt stratification. Diffusive staircases, the subset of thermohaline staircases that are observed in the halocline of the Arctic Ocean, occur when cool fresh water overlies warm salty water. This configuration can be seen in Figure 2, which shows an example of the various water masses that form the Arctic Ocean. Atlantic Water (AW) enters through the Fram Strait and Barents Sea where it is cooled off. This cooling effect increases the density of AW and subducts it underneath the surface layer of the Arctic Ocean (DiMaggio 2016). As AW crosses the Lomonosov Ridge, AW is confined to roughly 250 m to 800 m in depth. In this situation, warm, salty water is underneath relatively cold and freshwater, which is necessary for diffusive staircases to form.

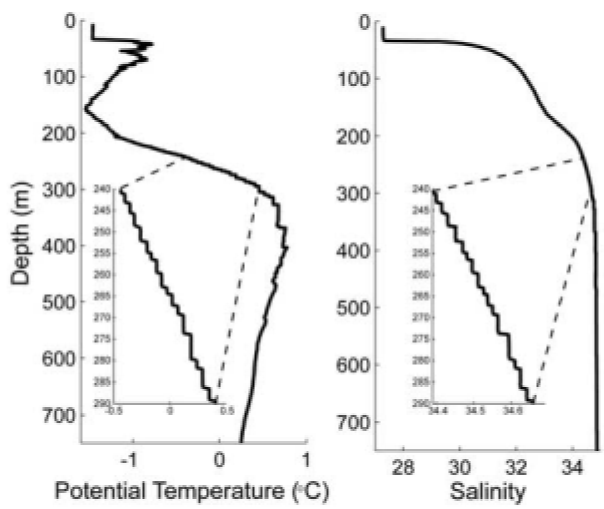



Note how AW is a layer across the entire Arctic Ocean.

Figure 2. Cross Section of Water Masses in Arctic Ocean.
Source: DiMaggio (2016).

## B. OBSERVATIONS

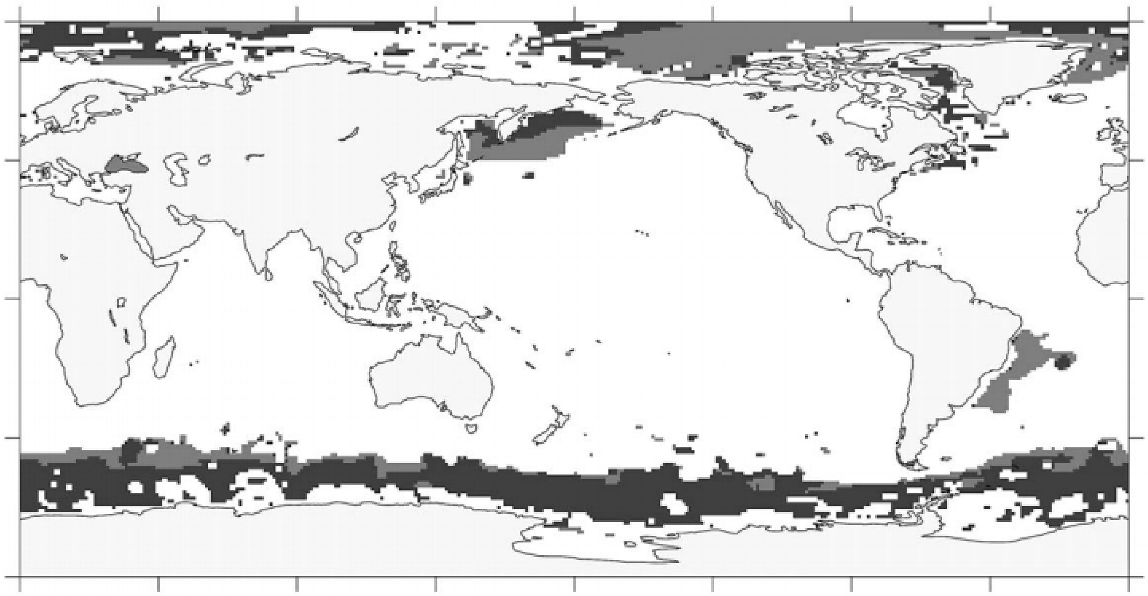
First observed in the Arctic in the late 1960s, thermohaline staircases were immediately attributed to double diffusion (Radko 2013). Following initial observations, subsequent Ice-Tethered Profilers (ITPs) in the central Arctic have shown thermohaline staircases are quite common throughout the Arctic basin. Individual ITPs are on station for over a year and can produce over 700 vertical profiles during that time period (Toole et al. 2011). From the ITPs, Timmermans et al. (2008) found that thermohaline staircases were present in 96% of their measurements across the Central Artic from about 200–300 m in depth with a step height of approximately 1–5 m. The staircases are noticeable year-round and across hundreds of kilometers spatially. Areas where thermohaline staircases were absent were located within mesoscale eddies or near basin boundaries (Radko 2013). Figure 3 shows an example of an ITP measurement in the Canada Basin.




Note the Staircase shape for *T* and *S* in main halocline.

Figure 3. ITP of Potential Temp and Salinity in Canada Basin.
Source: Timmermans et al. (2008).

These areas in the Arctic Ocean where thermohaline staircases are located have a density ratio between 1 and 10, which are prone to have diffusive convection (Kelley et al. 2003). As seen in Figure 4, density ratios less than 10 are observed in much of the Arctic Ocean and also in other oceans and seas. The density ratio less than 10 is the standard for double-diffusive staircase formation due buoyancy fluxes across layers decreasing by an order of magnitude when density ratio is increased from 1.5 to 10 (Kelley et al. 2003). The high latitude zones where thermohaline staircases are observed motivate this thesis from an oceanographic and military perspective.



Light Grey Areas correspond to Density Ratio from $3<R_\rho<10$ and Dark Grey indicates a Density Ratio from $1\leq R_\rho<3$.

Figure 4. Density Ratios across the World's Oceans.
Source: Kelley et al. (2003).

## C. MOTIVATION

The investigation into the resilience of staircases is motivated by two fundamental problems. The first one is of direct interest for general oceanography and climate science. Recent observations in the Arctic Ocean suggest a correlation may exist between heat stored in the Arctic Ocean main halocline and sea ice melt (Polyakov et al. 2010). Currently, in the Canadian Basin, the AW vertical heat fluxes are significantly less than ice-to-ocean heat flux in the summer, thus AW is unlikely to have a significant impact on the sea-ice decline; however, in the Eurasian Basin, AW vertical heat fluxes are significant and should be accounted for in sea-ice calculations (Shibley et al. 2017). The vertical heat transport between water-masses of the Atlantic and Pacific origin is, in turn, by thermohaline staircases.

Thermohaline staircases physical location in the Arctic Ocean is also changing in response to the warming AW. The staircase regime, as studied by Timmermans et al. (2008), is about 100 m shallower than earlier measurements taken during the 1985 Arctic Internal Wave Experiment (AIWEX) performed by Padman et al. (1987). The variation of temperature and salinity within the thermohaline staircases are also higher than AIWEX observations (Timmermans et al. 2008). Thermohaline staircase step sizes has also increased. The typical step size of these staircases measured in the 1985 AIWEX was in the range of 1–3 m, whereas the more recent observations by Timmermans et al. (2008) show that this has increased to 1–5 m, averaging 3 m in size. These rapid changes in depth and heat flux motivate an immediate need for greater understanding of the resiliency of thermohaline staircases and of their ability to maintain vertical heat transport in the Arctic.

Not only do thermohaline staircases have an impact on oceanographic studies, they also could have an important impact on military operations in the Arctic Ocean. The depth at which the staircase regime is located is in the Arctic Ocean main halocline, which lends itself well to anti-submarine warfare depths of concern. With more economic opportunity in the Arctic, more warships will most likely deploy to the region to protect each nation’s interests. This study investigates whether thermohaline staircases are fragile and susceptible to disruption as a submerged object passes through the staircase. Also, this study investigates whether this disruption can be observed by looking at the temperature and salinity mixing at depth. Finally, investigating the time which it takes the thermohaline staircases to regenerate could lead to whether one can quantitatively determine when an object passed through an area. Studying this topic could potentially lead to an understanding about the regeneration process of these staircases which could lead to more developments in non-acoustic anti-submarine warfare.

## D. HYPOTHESIS

A propagating submersible leaves a hydrodynamic signature in the Arctic thermohaline staircases which can be detected and measured. This has major implications for studies of the resilience of thermohaline staircases and their ability to maintain vertical heat transport in the Arctic. This mechanism gives military members a new non-acoustic detection method of submersible objects. Through numerical simulations, it will be shown that a submerged object disrupts these staircases and that they do not reform until multiple hours have elapsed. The reformation time depends on the submerged object’s size and velocity, and the size of the thermohaline staircase steps. Chapter II describes the development of a working model for these experiments. Chapter III describes the results of the experiments and offers explanations of the findings. Chapter IV presents the conclusions of this experiment and offers potential future work on this topic.

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# II. MODEL DESCRIPTION

The following experiments model an object passing through a thermohaline staircase like those commonly seen in the Arctic Ocean. Because the spatial scales considered are relatively small, several assumptions can be made regarding the governing physics of this problem. The equation of state is assumed to be linear, as shown in Equation (2). The fluid is considered to be incompressible, and no external rotation is modeled. Numerical simulations of a fluid with these assumptions were performed with the Massachusetts Institute of Technology General Circulation Model (MITgcm). MITgcm was selected because it is non-proprietary, non-hydrostatic, scalable to many CPUs, and flexible for many applications of oceanographic modeling.

The first step in formulating the model is to develop the thermohaline staircases observed in the Arctic. Figure 5 contains the model configuration for this experiment. *Lz*, *Ly*, and *Lx* are the dimensions of the model. *R* and *U* represent the radius and velocity of the object, *d* is the size of the layer and *N* represents the number of layers in the model. Table 1 summarizes the dimensions and model configurations of the experiment. Two major domain configurations are used. The first domain, 4.16 × 4.16 × 8 m, has adequate resolution to model the dissipative scale completely and the second domain (41.6 × 41.6 × 40 m) models dissipation with a raised "eddy" diffusivity. The object's size was 0.5 m for the first domain and 5 m for the second domain. The layer size, *d*, takes the baseline value of 2 m (Radko 2013), which is typical of the Arctic halocline. Larger values, 5 and 8 m, are also considered. From Timmermans et al. (2008), up to 5 m layers have been observed in the Arctic Ocean. When measuring for resiliency of the staircases, the 2 m, 5 m and 8 m layers are used for comparison. The object was introduced into the center of the computational domain in the *y*-direction, *y*=0, and halfway up in the *z*-direction. The sphere's starting position in the *x*-direction was to the right of *x*=0 to ensure the boundary did not affect the wake of the sphere propagating to the right in the model.

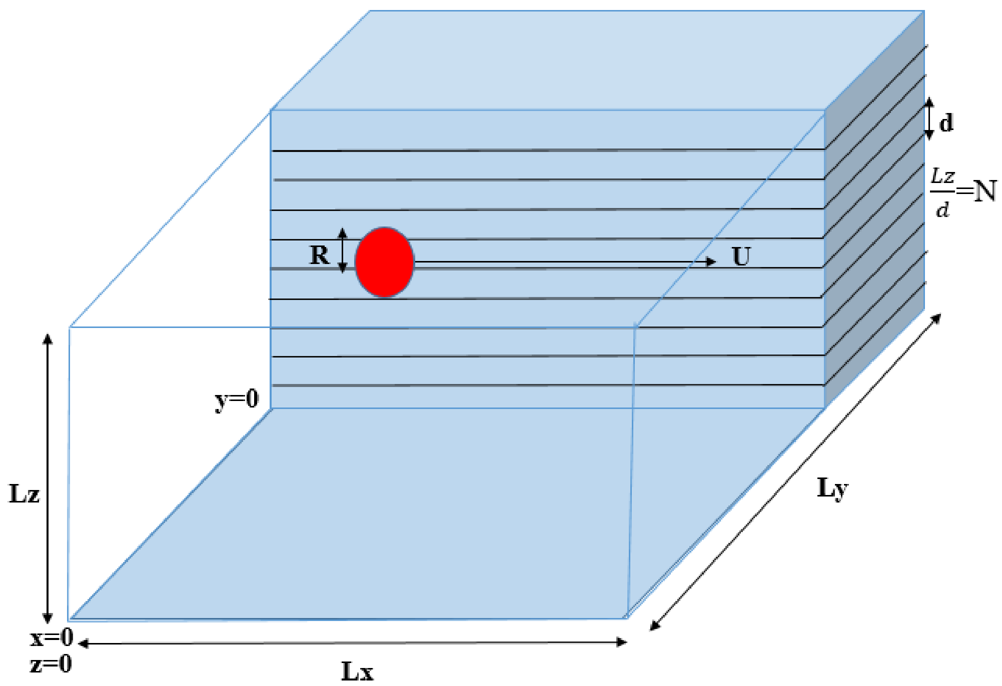


Figure 5. Model Configuration

Table 1. Dimensions and Parameters used for the Experiment

| Number of Grid Points | Resolution (m) | Lx × Ly × Lz (m) | N | d (m) | R (m) | U (m/s) |
|---|---|---|---|---|---|---|
| 512 x 512 x 256 | 0.078 × 0.078 × 0.039 | 40 × 20 × 20 | 10 | 2 | 0 | 0 |
| 416 x 416 x 1600 | 0.01 × 0.01 × 0.005 | 4.16 × 4.16 × 8 | 4 | 2 | 0.5 | 0.2 |
| 416 x 416 x 800 | 0.1 × 0.1 × 0.05 | 41.6 × 41.6 × 40 | 5, 8, or 20 | 2, 5, or 8 | 5 | 0.2 or 1 |

The *T* and *S* fields are typical of values observed in the Arctic Ocean. The difference in *T* used in the model runs was ~1˚C. The *T* difference between layers is based off a temperature variation of 0.05˚C in the Central Arctic staircase (Radko 2013). The upper value of the temperature is 1.2˚C, based off Figure 3. The salinity gradient is then calculated to ensure the desired density ratio, as given by Equation (1). In the situations where double-diffusion is resolved, the $K_T$ and $K_S$ are $1.5 \times 10^{-7}$ and $1.5 \times 10^{-9}$, respectively. Otherwise $K_T$ and $K_S$ were set equal at $1.5 \times 10^{-7}$. The boundary conditions in the model included the Dirichlet conditions in z and y, which means that the sidewalls would enforce the assumed temperature and salinity patterns, and periodic boundary conditions were in x-direction. The sidewalls were enforced using a relaxation method. This means the mask applied in MITgcm reads the current value of temperature and salinity at each cell and steps it closer to the original staircase value by the quotient of the current time step to the relaxation time set, nominally 50 seconds. The mask applied this strongest at each edge with exponentially decaying strength near the center of the model. This was used as the restoration force in the mechanical regeneration cases.

Multiple supercomputers were used throughout this experiment to run MITgcm. In particular, the Department of Defense (DoD) High Performance Computing Modernization Program SGI ICE XA System (Centennial), Cray XE6m Open Research System (Copper), Cray XC40/50 System (Onyx), and the University of Texas at Austin's Texas Advanced Computing Center Stampede2 were all used at various times for running the model. All data analysis was completed on NPS computers.

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# III. RESULTS

## A. MODELING THERMOHALINE STAIRCASES

In order to evaluate the effect of various parameters on the regeneration time of thermohaline staircases, different parameters were used over multiple model runs. The difference in model runs included changing the step size and changing the density ratio. The reason for varying layer size was to investigate whether the thickness of the layer had an impact on the resiliency. From laboratory experiments [e.g. Turner (1973), Marmorino and Caldwell (1976), Linden and Shirtcliffe (1978), and Kelley (1990)] the "4/3 flux laws,"

$$\alpha F_T = C(R_\rho)(g k_T^2 / \nu)^{1/3} (\alpha \Delta T)^{4/3}, \tag{3}$$

was developed where $\alpha$ is the coefficient of thermal expansion, $F_T$ is the vertical heat transport, $C(R_\rho)$ is the flux law coefficient which is dependent on density ratio, g is gravity, $k_T$ is molecular diffusivity of heat, and $\nu$ is viscosity. The "4/3 flux laws" places an emphasis on differences between temperature and salinity as the primary force for vertical heat transport, whereas, layer thickness has a minor role (Flanagan et al. 2013). With the layer thickness playing a secondary role in vertical heat transport, our analysis shows that is actively controls the resilience of staircases. Another parameter that is known to influence the dynamics of thermohaline staircases is the density ratio. As shown in Figure 4, density ratio suitable for diffusive staircases range from $1 < R_\rho < 10$. Varying density ratio could provide insight if density ratio has an effect on the time it takes for a staircase to reform. Table 2 illustrates the input parameters for each model run. The nominal *d* is 2 m, *Rρ* is 3, and *U* is 1 m/s. Figure 6 and Figure 7 are the initial temperature and salinity outputs for the 5 m layer case. The temperature is warmer at the bottom of the model. Likewise, salinity is higher at the bottom of the model as well. Utilizing Equation (2), the density anomaly for this model is formed and is illustrated in Figure 8.

Table 2. Parameters for Model Runs

| Model Runs | *Lx* × *Ly* × *Lz* (m) | *R* (m) | *U* (m/s) | *d* (m) | *N* | $R_\rho$ |
|---|---|---|---|---|---|---|
| 1 | 41.6 × 41.6 × 40 | 5 | 1 | 2 | 20 | 3 |
| 2 | 41.6 × 41.6 × 40 | 5 | 0.2 | 2 | 20 | 3 |
| 3 | 41.6 × 41.6 × 40 | 5 | 1 | 2 | 20 | 4 |
| 4 | 41.6 × 41.6 × 40 | 5 | 1 | 2 | 20 | 1.5 |
| 5 | 41.6 × 41.6 × 40 | 5 | 1 | 8 | 5 | 3 |
| 6 | 41.6 × 41.6 × 40 | 5 | 1 | 5 | 8 | 3 |
| 7 | 4.16 × 4.16 × 8 | 0.5 | 0.2 | 2 | 4 | 3 |
| 8 | 4.16 × 4.16 × 8 | 0.5 | 0.2 | 2 | 4 | 3 |
| 9 | 4.16 × 4.16 × 8 | 0.5 | 0.2 | 2 | 4 | 3 |

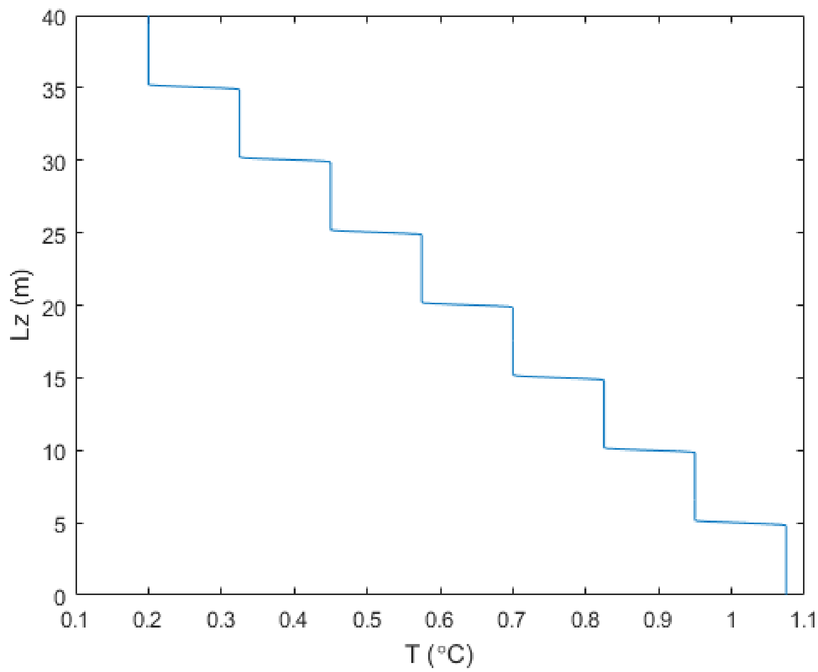



Figure 6. Temperature Profile for 5m Layer Case

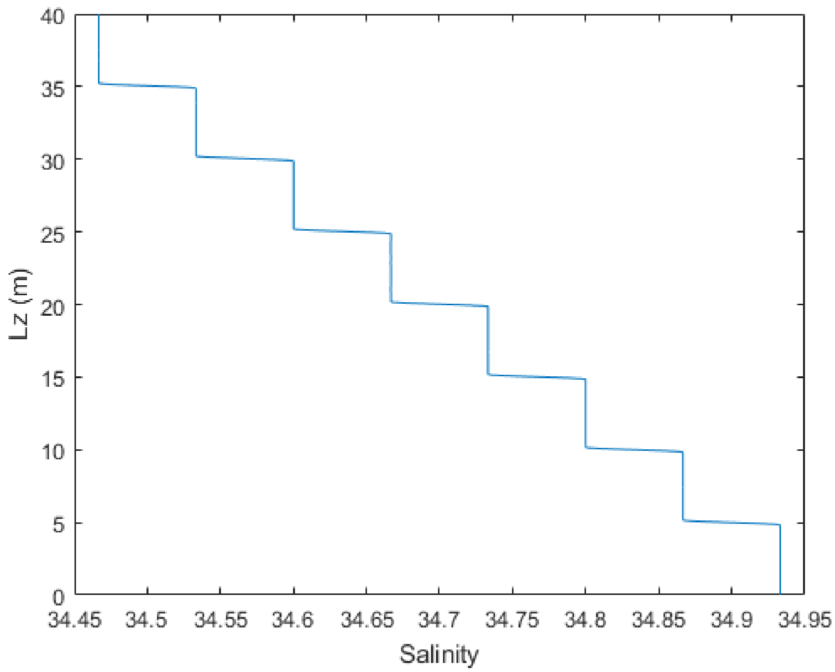



Figure 7. Salinity Profile for 5m Layer Case

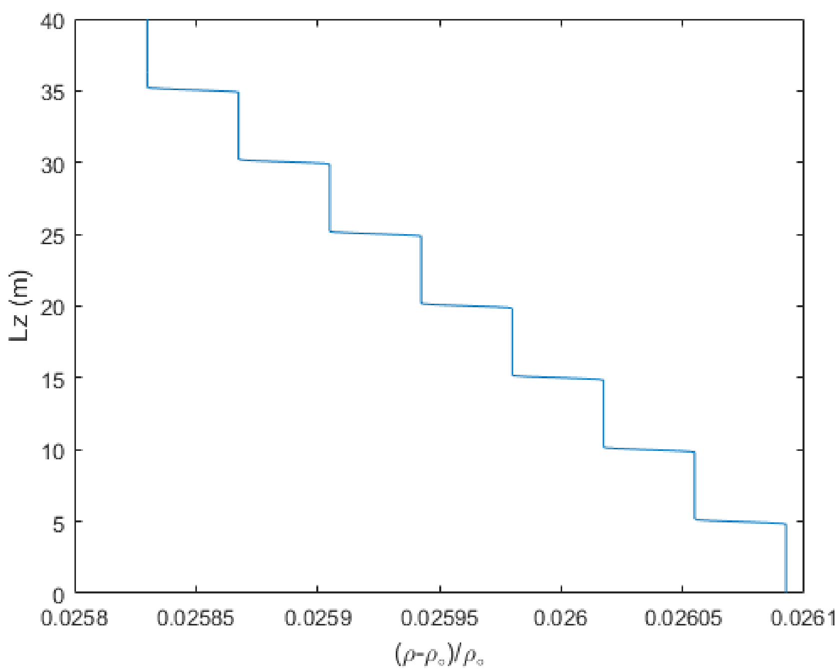



Figure 8. Density Anomaly for the 5m Layer Case

## B. RUNNING A SUBMERGED OBJECT THROUGH A STAIRCASE

The propagating object is of similar size to a submarine, except in three model runs (Expts. 7,8,9). In those model runs, listed in Table 2, the propagating object's radius is 0.5 m. Figure 9 displays a 5 m radius sphere propagating through the staircase, in terms of horizontal velocity. The sphere is propagating left to right at a nominal speed of 1 m/s. As the sphere traveled through the staircase, the sphere disrupted the temperature staircases, shown in Figure 10 and Figure 11. In both cases, a temperature slice is presented at *y*=0.

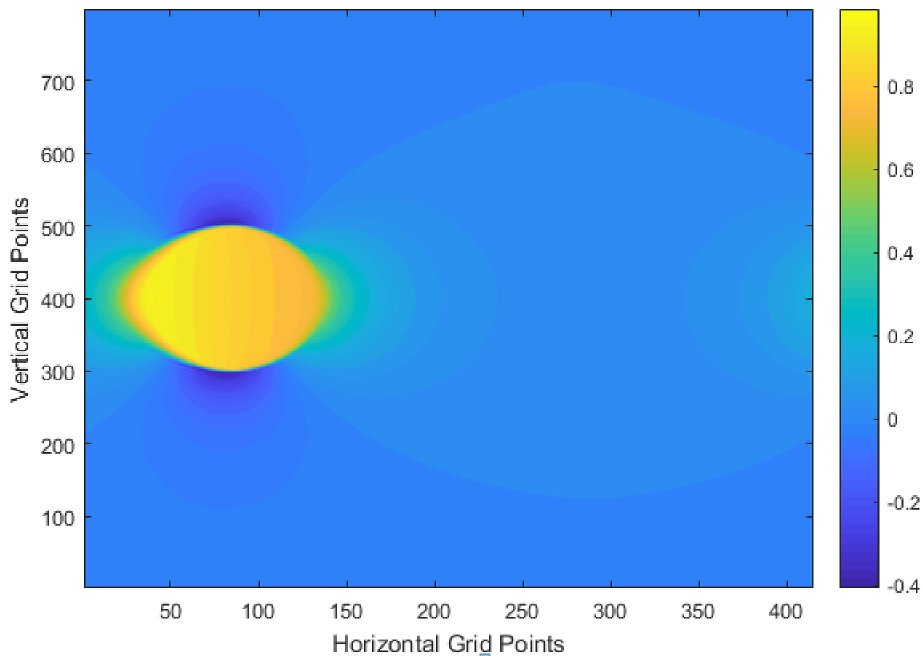



Figure 9. Horizontal Velocity of a 5 m Sphere in the Rρ=1.5 Simulation

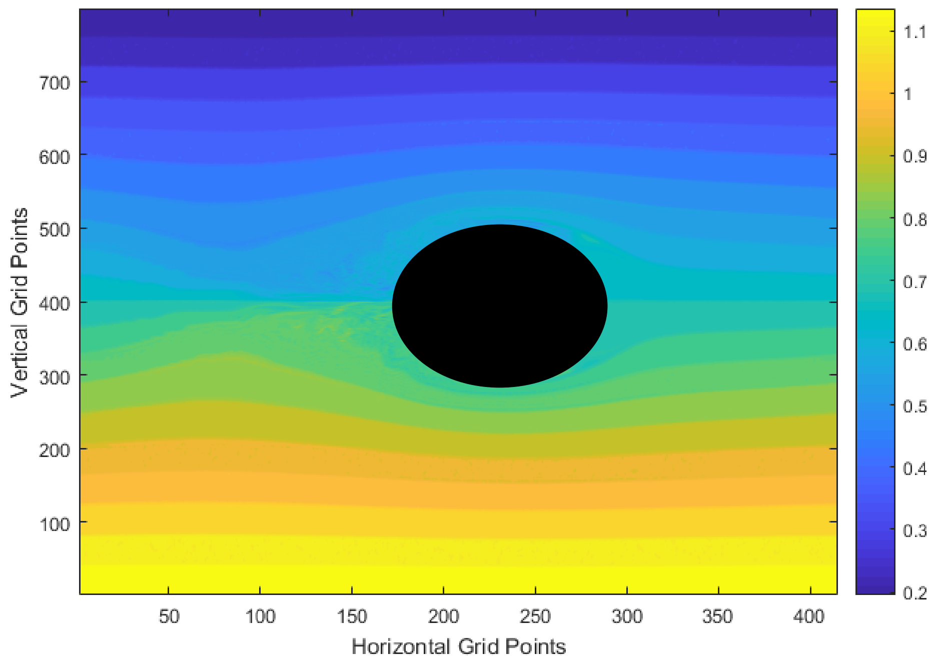



Figure 10. Temperature Perturbation for Rρ=1.5 as Object Passes through the Domain

After the sphere passed through the computational domain, mixing between the layers occurred. Figure 11 highlights mixing in the model approximately 1 hour after the object passed through. In all of the simulations, the same basic pattern was observed. First the propagating object displaced the water mass around the object, generating a laminar flow. As water departed the boundary along the sphere, the wake became increasingly turbulent. With an increase in turbulent flow, mixing in *T* and *S* of the water column occurred. The time it took for the staircases to mix was dependent on the size and speed of the propagating object, along with the size of the layers in the model.

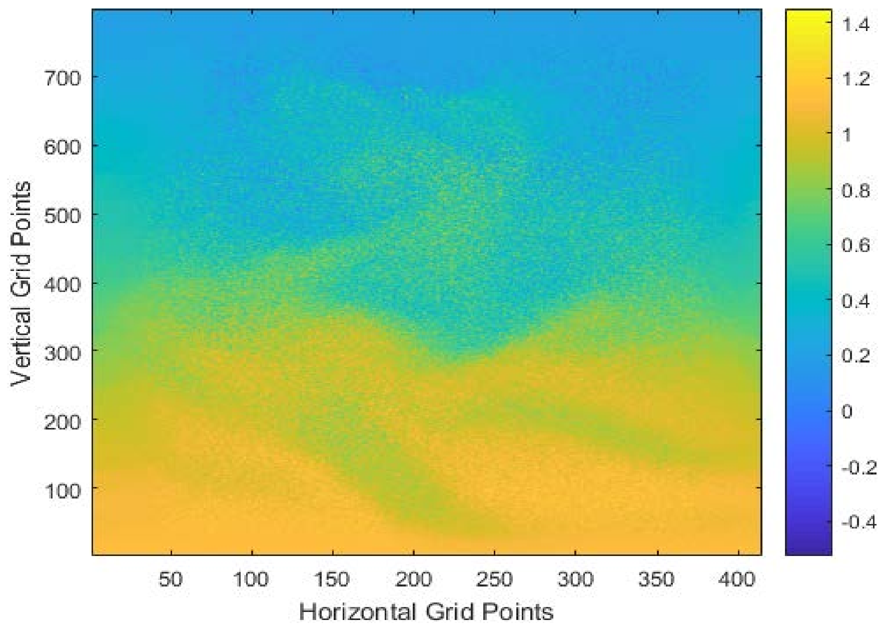



Figure 11. Mixing of Temperature Layers 1 Hour after Sphere Propagation

## C. THERMOHALINE STAIRCASE REGENERATION

### 1. Motivation

After the submerged object passed through the model, the time it took for the thermohaline staircases to reform varied from a few hours to roughly a day. Table 3 lists the regeneration time and parameters for each model run. This section and the associated subsections investigate the diagnostic algorithm created for staircase regeneration, the forcing mechanism for regeneration, and how varying model parameters affected the time of regeneration. In short, regeneration time is heavily dependent on the speed of the submerged object, the size of the object, and the size of the staircases.

The following discussion of staircase regeneration is organized as follows. Subsection 2 discusses the diagnostic algorithm created to determine when thermohaline staircases reformed after disturbance. While qualitatively comparing density graphs is an easy way of determining staircase reformation, a diagnostic algorithm should be considered because this takes away user error. One user visually comparing graphs may evaluate regeneration time different than another user. This diagnostic algorithm can reduce the subjectivity of the evaluation process, therefore, a number of military applications with undermanned vehicles could be considered in the future.

Subsection 3 investigates the primary restoration force. Model runs 7 and 8 were provided with adequate resolution such that the diffusive processes could be active and compared to model run 9 which utilized mechanical regeneration. The results indicate mechanical regeneration is the primary restoring force in the regeneration of thermohaline staircases from a disturbance from an object. From this finding, model runs 1–7 utilize mechanical regeneration as the restoring force for thermohaline staircases.

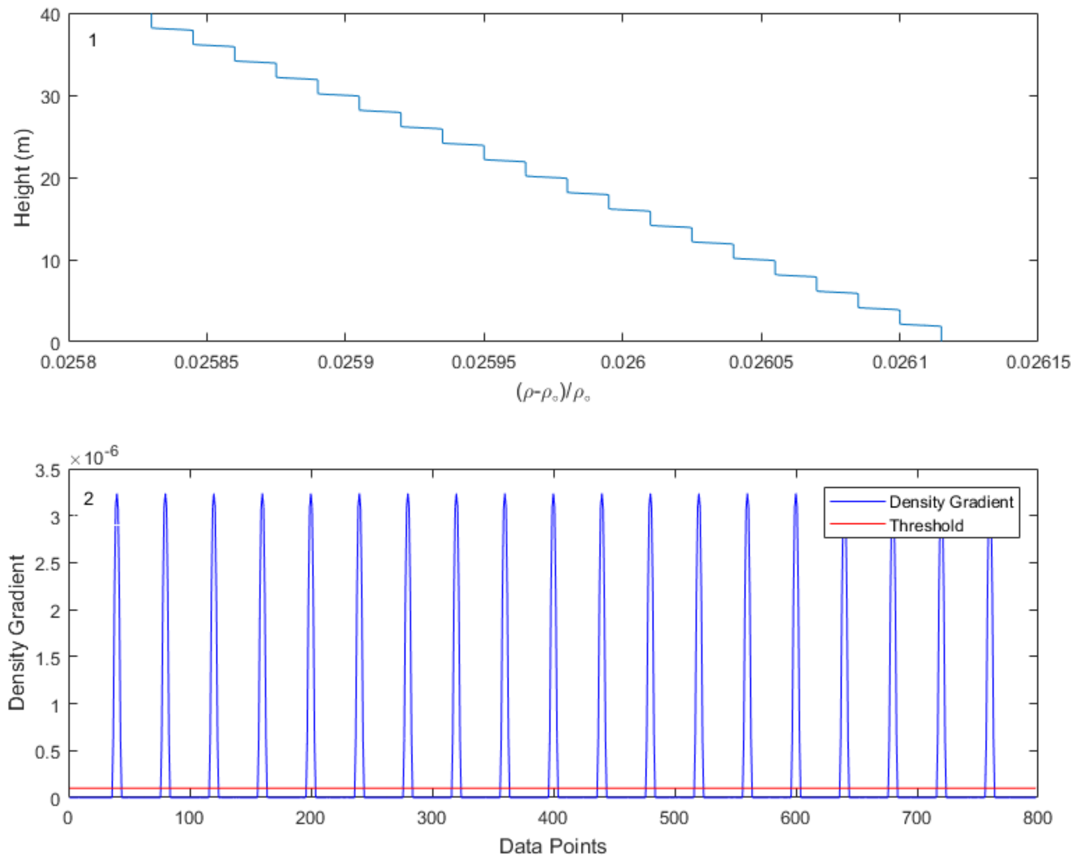
Subsections 4–7 compare different properties of the submerged object and environmental parameters in order to determine which properties have the greatest effect on restoration time. The parameters investigated are the $R_\rho$, $d$, and $U$. The speed of the propagating object had the greatest effect on thermohaline staircase regeneration time.

Table 3. Regeneration Time for Thermohaline Staircases

| Model Runs | $Lx \times Ly \times Lz$ (m) | $R$ (m) | $U$ (m/s) | $d$ (m) | $N$ | $R_\rho$ | Restoration Method | Regeneration Time (hr) |
|---|---|---|---|---|---|---|---|---|
| 1 | 41.6 x 41.6 x 40 | 5 | 1 | 2 | 20 | 3 | Mechanical | 26.0 |
| 2 | 41.6 x 41.6 x 40 | 5 | 0.2 | 2 | 20 | 3 | Mechanical | 2.3 |
| 3 | 41.6 x 41.6 x 40 | 5 | 1 | 2 | 20 | 4 | Mechanical | 29.3 |
| 4 | 41.6 x 41.6 x 40 | 5 | 1 | 2 | 20 | 1.5 | Mechanical | 25.1 |
| 5 | 41.6 x 41.6 x 40 | 5 | 1 | 8 | 5 | 3 | Mechanical | N/A |
| 6 | 41.6 x 41.6 x 40 | 5 | 1 | 5 | 8 | 3 | Mechanical | N/A |
| 7 | 4.16 x4.16 x 8 | 0.5 | 0.2 | 2 | 4 | 3 | Double Diffusion | 7.7 |
| 8 | 4.16 x4.16 x 8 | 0.5 | 0.2 | 2 | 4 | 3 | Both | 1.7 |
| 9 | 4.16 x4.16 x 8 | 0.5 | 0.2 | 2 | 4 | 3 | Mechanical | 2.2 |

### 2. Diagnostic Algorithm

A diagnostic algorithm was created to determine when thermohaline staircases were restored. The algorithm utilizes density gradients to determine when a staircase has reformed. The approach determines the number of low-gradient regions which reflect the presence of mixed layers in a staircase. To solve for this step parameter, temperature and salinity outputs for a particular time were used to calculate density anomaly, via the linear equation of state, Equation (2). The absolute value of the density gradient is compared to an empirically derived threshold number. It is assumed that the number of times which a pair of density gradient values crosses the threshold number, as seen in Figure 12, represents a number of thermohaline staircase step.




Note: Subplot 1 is the density anomaly and subplot 2 is the absolute value of the density gradient with a threshold value of $10^{-7}$.

Figure 12. Density Anomaly and Absolute Value of Density Gradient for $R_\rho$=4 at Time=0

As the submerged object passes through the model and mixing occurs, the density becomes quasi-linear and the density gradient structure breaks down. This is illustrated in Figure 13.

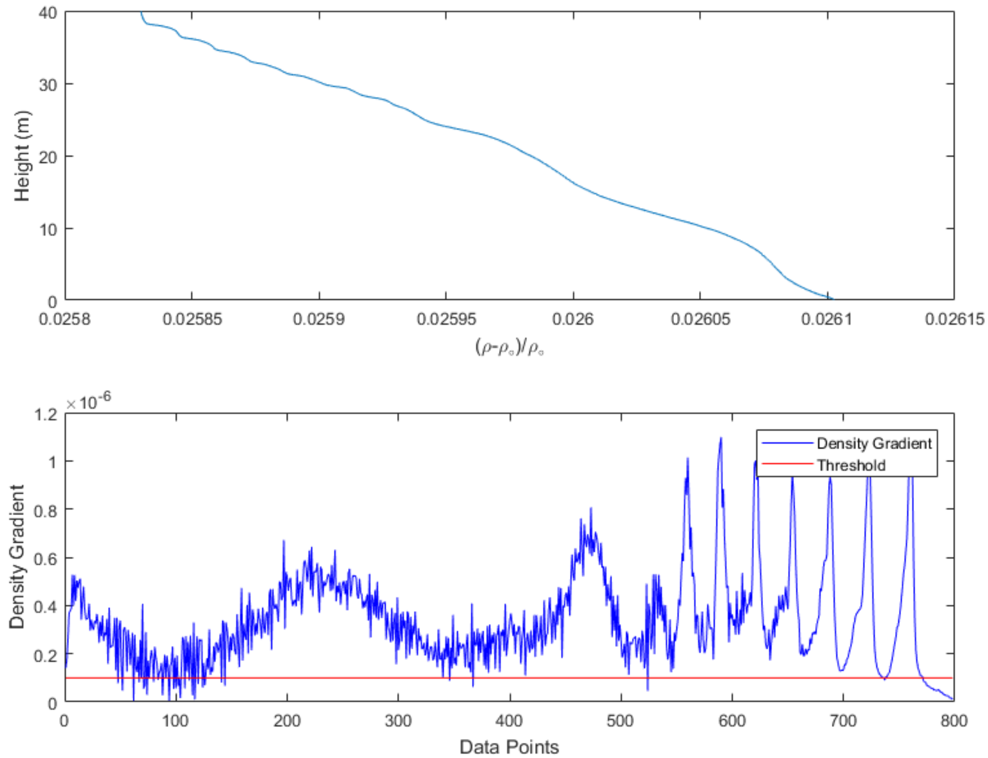



Figure 13. Density Anomaly and Absolute Value of Density Gradient for $R_\rho$=4 at Time= 7 Minutes

As time passes, the staircases start to reform, which is adequately captured with the diagnostic algorithm calculating the number of steps at a given time. As illustrated in Figure 14, the staircase is reforming to the original state which is reflected in the density anomaly and density gradient subplots. The extensive experimentation with the proposed algorithm has led to the following condition for the overall regeneration of the staircase. We assume that the staircase has largely regenerated after reappearance of at least 75%of initial steps. The choice of the threshold value is critical in determining the number of steps. If the threshold value is set too high, the diagnostic algorithm will output a higher number of steps than actually present, if comparing to the density anomaly graphs. This would result in a shorter amount of time until the diagnostic algorithm would output the staircases have reformed to the criteria.

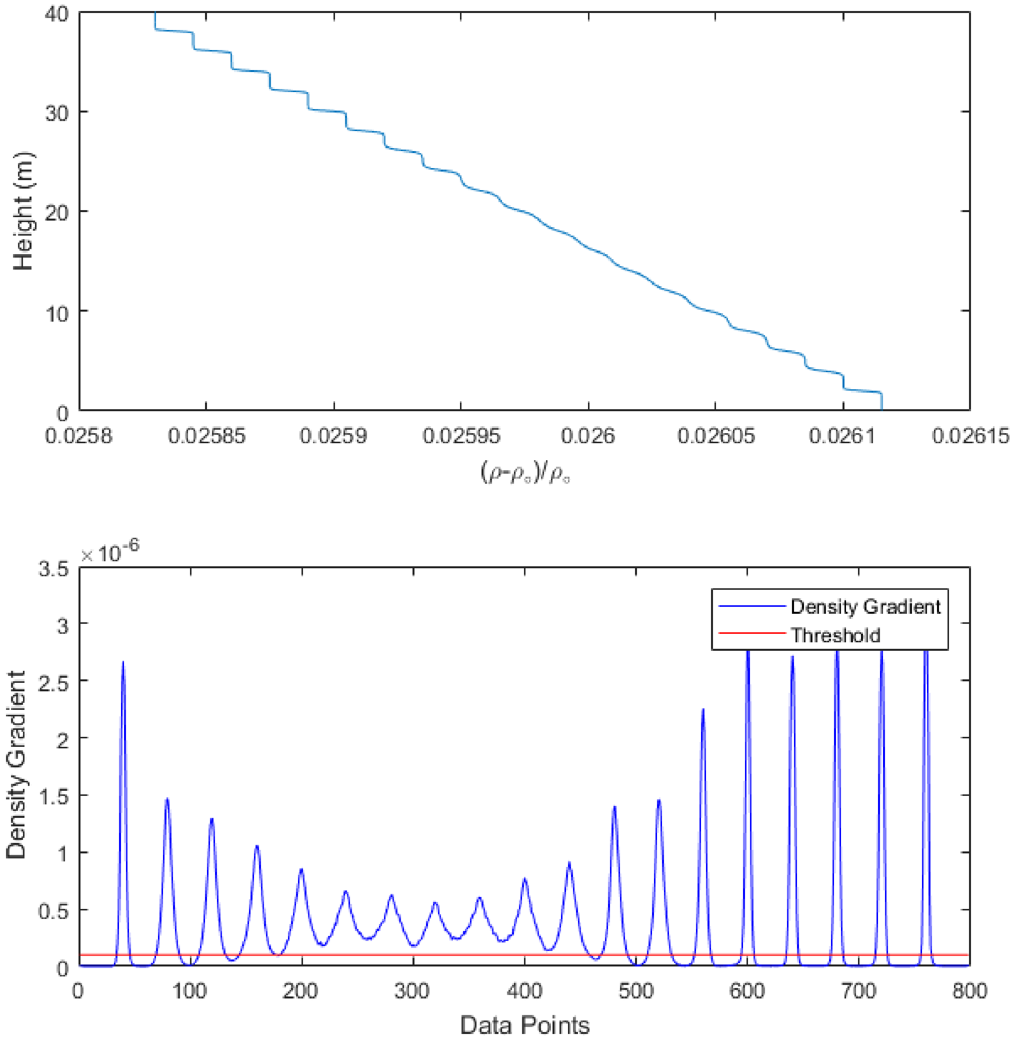



Figure 14. Density Anomaly and absolute Value of Density Gradient for $R_\rho$=4 at Time=24.5 Hours

### 3. Reformation Mechanism Comparison

The two different restoration forces this experiment investigates are mechanical regeneration and the double-diffusive process. The mechanical regeneration refers to a largely lateral process in which the distant water-masses, largely unaffected by the turbulent wake, spread into the wake interior and reform the step-like stratification, as illustrated in Figure 15. Double-diffusive regeneration is the process in which step-formation is induced by the convergence of vertical temperature and salinity fluxes – the process responsible for formation of the original staircases.   From Table 3, model runs 7–9 were utilized as comparison for these restoring forces. Each model had the same dimensions and parameters. The object size and velocity were also the same for each of the model runs. One model run utilized the double-diffusive process as restoring force only. The second model utilized mechanical regeneration only. The third model utilized both mechanical regeneration the double-diffusive process for restoration.

From Table 3, mechanical forcing regenerates the thermohaline staircases faster than the double-diffusive process. Mechanical regeneration is the dominant process in restoration. Timmermans et al. (2008) proved the staircases are basin wide and span 100s of kilometers spatially. The submerged object in this experiment is disrupting meters in the water column. In this regeneration mechanism, thermohaline staircases restore themselves by laterally creeping in from the sides. That mechanical regeneration is more effective than the fundamental double-diffusive processes is surprising considering that diffusive staircases are driven by the presence of double-diffusive fluid motion.

With mechanical regeneration as the primary restoring force, this facilitates the use of lower resolution models for the other model runs in this experiment. Double-diffusive processes require higher resolution to resolve the dissipation scale of salinity. Mechanical regeneration does not require this scale to be resolved, therefore lower resolution requirements were used for the subsequent model runs described in this thesis.

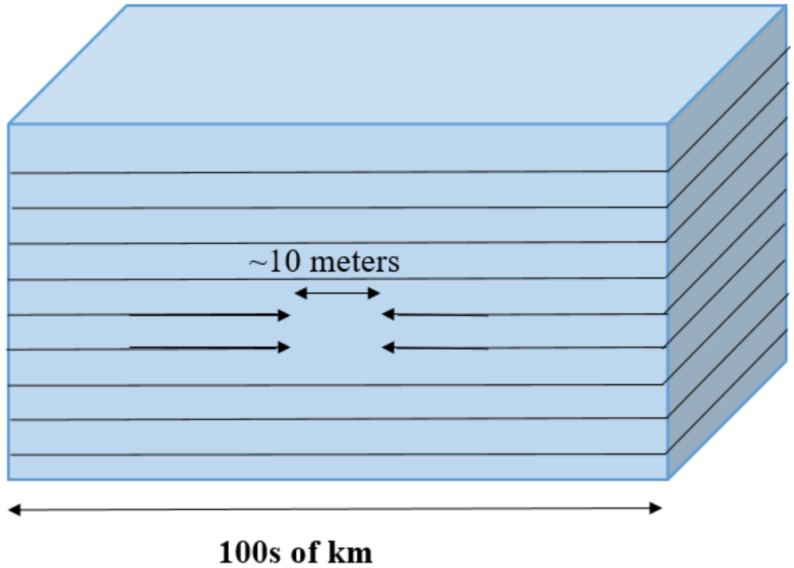


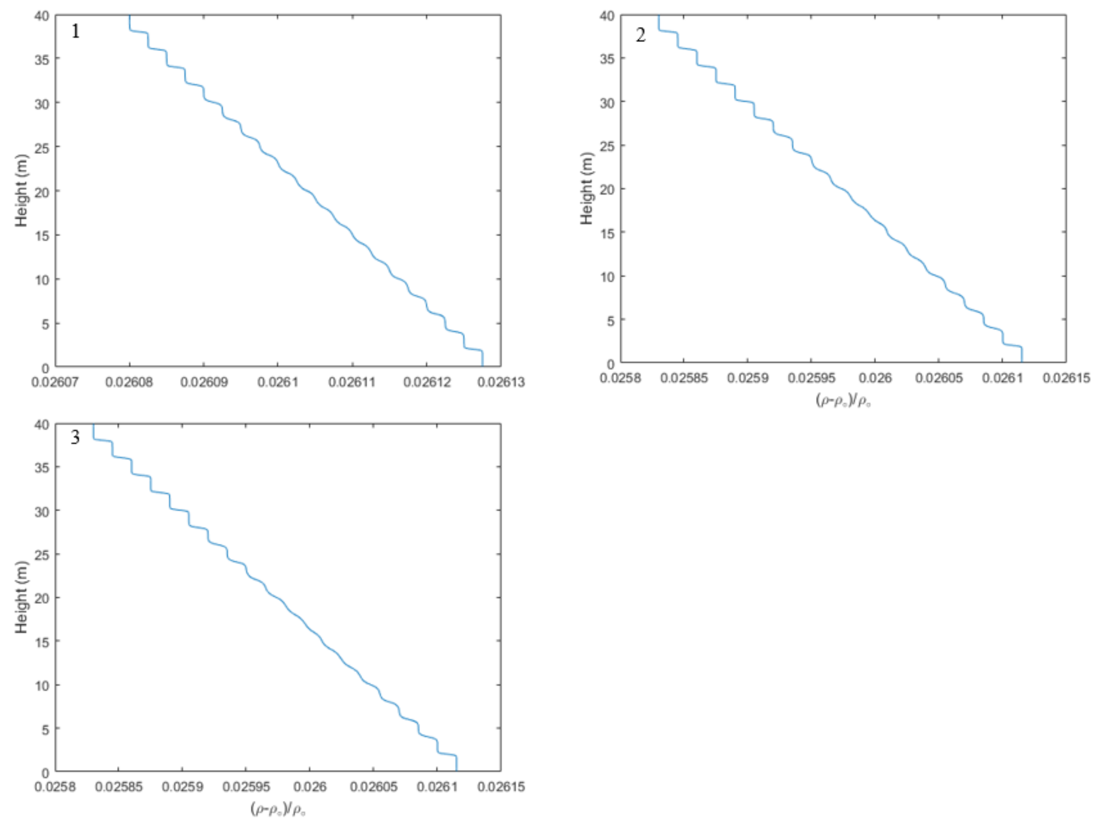

Figure 15. Illustration of the Mechanical Regeneration Mechanism

### 4. Density Ratio Effects

As can be seen in Table 4, the density ratio does not appear to play a significant role in determining the restoration time. In each case, restoration time is about 1 day. The different $R_\rho$ chosen were 1.5, 3, and 4. All of those $R_\rho$ are all within the observed quantities for the Arctic Ocean. Since the diffusivities of temperature and salinity are set equal in these model runs, the $R_\rho$ only affects the value of salinity. In the model setup, the initial temperature profile was held constant in each of the model runs. From Figure 16, the density anomalies show the higher the density ratio, the larger range of density anomaly values. After the submerged object passed through the model, the entire layer was mixed and reforming started to occur. The difference in regeneration time can most likely be attributed to a larger density range as $R_\rho$ increases.

Table 4. Parameters Utilized for Density Ratio Comparison

| Model Runs | $Lx \times Ly \times Lz$ (m) | $R$ (m) | $U$ (m/s) | $d$ (m) | $N$ | $R_\rho$ | Restoration Method | Regeneration Time (hr) |
|---|---|---|---|---|---|---|---|---|
| 1 | 41.6 x 41.6 x 40 | 5 | 1 | 2 | 20 | 3 | Mechanical | 26.0 |
| 2 | 41.6 x 41.6 x 40 | 5 | 1 | 2 | 20 | 4 | Mechanical | 29.3 |
| 3 | 41.6 x 41.6 x 40 | 5 | 1 | 2 | 20 | 1.5 | Mechanical | 25.1 |




Note: Subplot 1 is the final density anomaly for $R_\rho$=1.5, Subplot 2 is final density anomaly for $R_\rho$=3, Subplot 3 is the final density anomaly for $R_\rho$=4

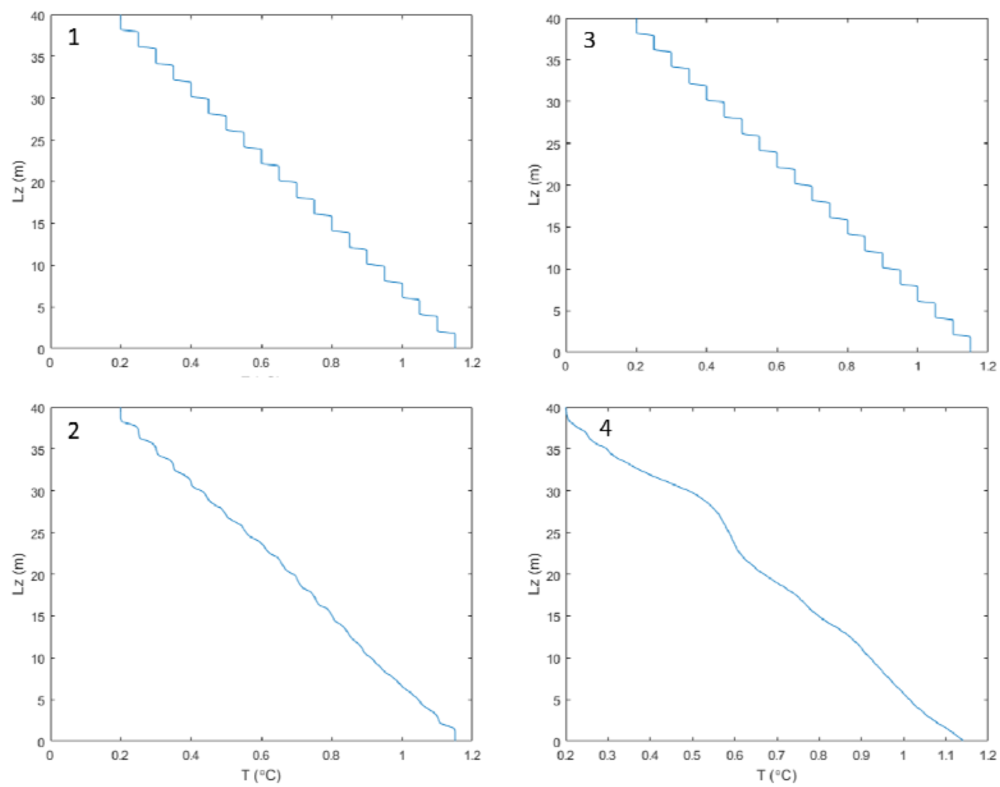
Figure 16. Density Anomalies for the Three Model Runs at Time ~1 Day

### 5. Effects of the Variation in the Speed of the Submersible

The speed of the submerged object strongly impacts the reformation time, resulting in faster bodies disrupting the staircases for longer. Table 5 shows the two models used for comparison. Five times increase in speed results in over ten times increase in regeneration time. The amount of mixing in the layer was more significant in the 1 m/s case. Figure 17 illustrates the extent of mixing in the model. In Figure 17, the amount of mixing in the in the $U$=0.2 m/s case, subplot 2, is less than the mixing in the $U$=1.0 m/s case, subplot 4. This mixing causes the thermohaline staircases to become linear and thus take longer for them to reform.

Table 5. Parameters Utilized for Speed Comparison

| Model Runs | $Lx \times Ly \times Lz$ (m) | $R$ (m) | $U$ (m/s) | $d$ (m) | $N$ | $R_\rho$ | Restoration Method | Regeneration Time (hr) |
|---|---|---|---|---|---|---|---|---|
| 1 | 41.6 x 41.6 x 40 | 5 | 1 | 2 | 20 | 3 | Mechanical | 26.0 |
| 2 | 41.6 x 41.6 x 40 | 5 | 0.2 | 2 | 20 | 3 | Mechanical | 2.3 |




Note: Subplot 1 is the initial temperature field. Subplot 2 is the temperature field 15 minutes after the submerged object ($U$=0.2 m/s) passed. Subplot 3 is the initial temperature field. Subplot 4 is the temperature field 15 minutes after the submerged object ($U$=1 m/s) passed.

Figure 17. Temperature Profiles of Model with $U$=0.2 m/s and 1 m/s at $y$=0

### 6. Effect of the Variation in Step Heights

An increase of step height impacts the resiliency of the staircases. The three step heights investigated were 2 m, 5 m and 8 m. These steps were chosen because larger size thermohaline staircases have been observed in other water masses. In the Black Sea and Mediterranean, step heights of 10m are present (Radko 2013). In a balance of computing resources and maintaining the model dimensions, 5 m and 8 m steps were chosen for observation vice 10 m. Table 3 displays the parameters utilized for comparison. The 1 m/s sphere is insufficient to completely mix all the layers in the 5m and 8m layer cases. Qualitatively, it appears the resiliency of the layers increases with the size of the step. However, further work will have to take place to prove quantitatively the resiliency of thermohaline staircases increases with an increase in layer size. The location of the submerged object and placement within the column could also be important for mixing. In the 8 m layer case, the 5 m radius submerged object was nearly completely enclosed inside one layer. This particular placement of the submerged object resulted in very little mixing between layers. In a similar situation, the sphere was inside only two layers in the 5 m step case. Inadequate mixing occurred in the layers leading to no recorded restoration time.

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# IV. DISCUSSION

## A. CONCLUSIONS

The numerical simulations of this study show that a propagating submersible leaves a hydrodynamic signature in the Arctic Ocean thermohaline staircases which can be detected and measured. The most important parameter for regeneration time is the speed of the object. The 0.2 m/s propagating object results in restoration times of roughly 2–3 hours, whereas the 1 m/s propagating object results in restoration times of roughly 1 day. This is due to more mixing within the model due to the increased speed of the submerged object. Qualitatively, increasing layer thickness increases the resiliency of the layers. A 1 m/s propagating object did not completely mix the model in the 5 m and 8 m step size cases, whereas, complete mixing occurred in the 2 m step size cases.

Another major conclusion is mechanical regeneration is the primary restoring force for thermohaline staircases, vice the double-diffusive process. This fact is surprising considering that the origin of diffusive staircases is universally attributed to double-diffusive mixing. However, when considering the area of disturbance of a propagating object is very small compared to the overall area which the thermohaline staircases exist, mechanical regeneration becomes the primary restoring force for thermohaline staircases.

## B. OPERATIONAL RELEVANCE

Thermohaline staircases can be exploited for anti-submarine warfare purposes. With the ice caps melting, more nations will explore the area. In order to promote and defend U.S. national interests, the Navy may be called upon to deploy warships in this area of operations. With the potential of more deployments in the Arctic Ocean, the Navy should look at various ways to exploit any potential advantage over an adversary. Thermohaline staircases studied in this project are a permanent feature in the Arctic Ocean and observable in over 96% of the Arctic Ocean at depths of concern (Timmermans et al. 2008). Simply put, a submerged object propagating through the main halocline in the Arctic Ocean will disturb the thermohaline staircase structure. The time it takes for the staircases to reform is dependent on parameters in the Arctic Ocean which are measurable. While future work is required to determine whether this study has the potential of developing into a non-acoustic detection method against submerged objects, this project allows our Navy to start attempting to look at and exploit the ocean environment and its properties in the Arctic.

## C. FUTURE WORK

Further work on this project could lead to advancements in oceanography and could be used for future military application. Further study in the link between resiliency of thermohaline staircases and the associated heat transport would advance oceanographic knowledge in the field. For future military application, changing the shape and the speed of the object will result in more realistic submarine wakes. A fully automated detection algorithm that could estimate the properties of a passing body would lead to a predictive model. This predictive model could potentially evaluate a broken-down thermohaline staircase that correlates the passing body to various size and speeds. Finally, experimental work in the Arctic could validate the results in this paper and future modeling work. Undoubtedly, further work on this topic and other forms of stratified wake non-acoustic detection methods should be considered to aid in the planning and execution of anti-submarine warfare.

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