Simulating a Self-propelled Submerged Body in a Coastal Ocean Hindcast Using the NRL-MIT Nonhydrostatic Model

Dr. Patrick C. Gallacher
Naval Research Laboratory, Ocean Sciences Branch
Stennis Space Center, MS 39529
phone: (228) 688-5315 fax: (228) 688-4149 e-mail: gallacher@nrlssc.navy.mil

Dr. David A. Hebert
National Research Council Postdoctoral Fellow
Naval Research Laboratory, Ocean Sciences Branch
Stennis Space Center, MS 39529

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LONG-TERM GOALS

- To enhance our ability to detect self-propelled submerged bodies (SSBs), (e.g., submarines and AUVs) at a distance. Little work has been done to improve our understanding of how we can sense changes in the environment caused by internal waves (IWs) and wakes generated by the passage of an SSB.

Simulations of self-propelled submerged bodies have been conducted in idealized environments with simple environmental geometries and stratifications. The focus of those simulations was on improving the submarine performance, including reduced drag, less vortex production, improved maneuverability and greater speed. Thus, many of the simulations focused on the near field and on complex, realistic submarine geometry. Some simulations looked at the far field but usually for simple shapes and simple background stratification.

OBJECTIVES

- To incorporate the ability to simulate a SSB into the NRL-MIT nonhydrostatic model. A SSB can be simulated as a smooth, bluff or streamlined body moving through the model domain. It can also be simulated as a point momentum source with or without swirl (to better simulate a propeller) to generate the extreme far field.

These simulations will focus on the environmental impact of a SSB to improve our understanding of the signatures that would be measured by acoustical or E+M systems. To this end we are interested in hindcasting realistic coastal ocean environments with accurate stratification, currents, ambient IW fields and bathymetry and simulating changes in this environment caused by the wake and IWs generated by the SSB's movement. In a stratified fluid the wake collapses vertically and spreads horizontally. Thus, it's signature becomes two dimensional. However, the collapse also generates IWs which propagate three dimensionally thus yielding additional potential signatures of the SSB.

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14. ABSTRACT
To enhance our ability to detect self-propelled submerged bodies (SSBs), (e.g., submarines and AUVs) at a distance. Little work has been done to improve our understanding of how we can sense changes in the environment caused by internal waves (IWs) and wakes generated by the passage of an SSB.

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APPROACH

The SSB must be self-propelled because there are significant differences between towed (drag) wakes and self-propelled (momentumless) wakes (Menuier and Spedding, 2006). The details of the geometries and relative motions of the parts of the SSB, e.g. sail, diving planes, and propeller(s) or jet, are critically important in determining the near wake. However, much of the detail is lost in the far wake particularly after wake collapse at approximately 7Nt (where N is the Brunt-Vaisala frequency). However, swirl from the propulsion system can remain a factor for many nondimensional time periods.

We plan to simulate the SSB as a smooth, self-propelled, body with and without swirl. Since we are interested in the far wake and the IW fields that are generated from the wake, particularly during wake collapse, we are not concerned about the details of the SSB's geometry. Also for larger domains and coarser resolution we can simulate the SSB using a subgrid scale (SGS) model. The SGS model includes the SSB as a point source of momentum (e.g., Sirviente and Patel, 1999).

WORK COMPLETED

A moving momentum source has been inserted into the NRL-MIT system in order to more accurately model the wake of a SSB. This has been accomplished by code modification allowing a desired momentum profile and translating velocity to be prescribed within the simulation. The code takes care of units (degrees or meters), momentum source location as simulation evolves, and the crossing of processor boundaries in parallel simulations.

Simulations of the wake generated by the moving momentum source in linearly stratified fluids have been run for comparison with wake properties published in experimental results. We find that the decay rate and vortex formation time from the simulated wake are similar to experimental values. Also, the phase of internal waves generated from the moving momentum source are in good agreement with theoretical predictions.

Finally, the moving momentum source has been inserted into a simulation with "realistic" ambient temperature, salinity and velocity in the vicinity of the Alabama Alps. This simulation includes full Alabama Alps bathymetry as well as observed temperature and salinity profiles. Interaction between the wake and ambient velocity and temperature fields are seen.

RESULTS

In the prior year the SSB wake was modeled as a stationary jet at the simulation boundary. While adequate decay laws were obtained for the jet, the objective is to model a moving SSB wake, and turbulent wake decay laws differ from turbulent jet (e.g., Pope, 2000). Thus, the major focus of the work this fiscal year has been modeling the SSB via a moving momentum source within the computational domain. This has been accomplished by modifying the code to insert a prescribed momentum profile and traversing velocity at the end of the momentum-correction step. The code is designed for the user to only enter the desired momentum profile and traversing velocity. The code works with Cartesian or lat/lon grids,. updates the location of the momentum source every timestep and handles the crossing of processor boundaries for simulations run in parallel. A sample wake from a parallel simulation of the momentum source in a linearly stratified fluid is shown in Figure 1. Here the moving momentum source moves from right to left and a vortex street forms behind the source as one would expect.

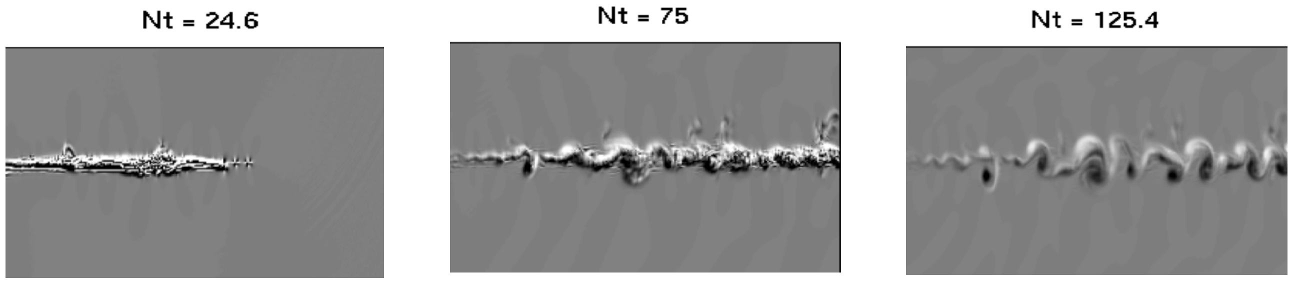

Figure 1: Representative vorticity plot of moving momentum source in a stratified fluid at different nondimensional times Nt. Momentum source moves from right to left. A vortex street forms as the simulation evolves.

Linearly Stratified Wake Properties

Simulations of the moving momentum source in linearly stratified fluids are performed to compare the properites of the resulting wake with results of experimental studies. Defining $N^2 = (g/\rho_0)\, d\rho/dz$, the momentum source velocity, U_m, and using the diameter of the momentum source, D, as a length scale, the Froude and Reynolds numbers are now defined as:

$$\mathrm{F}_D = \frac{U_m}{ND}, \qquad \mathrm{Re}_D = \frac{U_m D}{\nu}.$$

Three simluations with $\mathrm{F}_D = 0.5, 1, 2$ have been simulated. For each simulation $\mathrm{Re}_D = 4000$. The moving momentum source is specified with a diameter D=10m and traversing velocity of 0.2m/s. The mometum profile is specified as a 2D (xz) circular profile with U_m=0.2m/s. The velocity of the momentum profile and momentum source are the same in order to mimic a no slip condition of a drag wake genereated by a sphere.

The ratio of the wake centerline velocity, U_c, to the prescribed momentum velocity U_m, for each F_D are shown in Figure 2. Figure 2(a) is the velocity vs. nondimensional time. Figure 2(b) is velocity vs. nondimensional distance from the source. The dashed line in each plot is the experimentally obtained decay law for a stratified wake obtained by Spedding et al. (1996):

$$\frac{U_c}{U_m} \sim \left(F_D N t\right)^{-0.89} \tag{1}$$

$$\frac{U_c}{U_m} \sim \left(\frac{x}{D}\right)^{-0.89} \tag{2}$$

Equations (1) and (2) are shown as dotted line in Figures 2(a) and 2(b), respectively. In each case the decay of the wake is in good agreement with experimental decays laws.

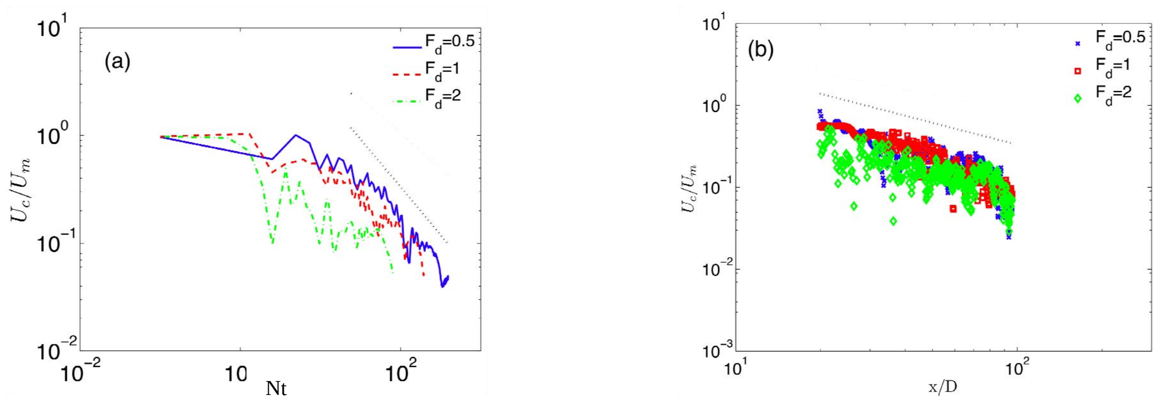

Figure 2: Normalized centerline velocity vs. (a) nondimensional time and (b) nondimensional distance from momentum source. The dotted line is experimental decay law for stratified wake found by Spedding et al. (1996).

Another interesting characteristic of the wake examined here is the time to vortex formation, τ. Figure 3 contains a plot of τ vs. F_D. Also shown in Figure 3 (dashed line) is the experimental relationship of τ vs. F_D found by Voropayev and Smirnov, (2003) and Spedding et al. (1996). From Figure 3 it is seen that τ from our simulations matche closely with experimentally obtained values.

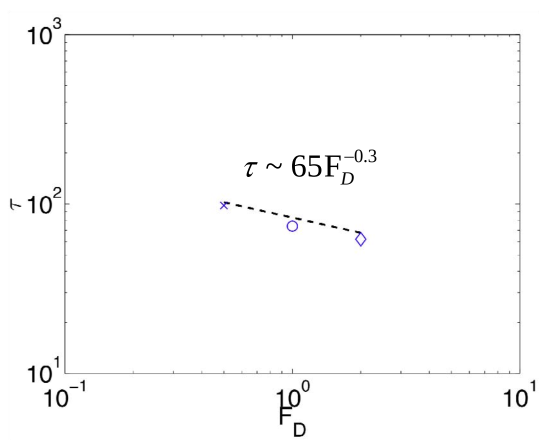

Figure 3: Vortex formation time vs. Froude number for linearly stratified simulations. Dashed line corresponds to relationship found by Voropayev and Smirnov, (2003) and Spedding et al. (1996).

Internal waves

Motion of a body in a stratified fluid is expected to generate internal waves. The left column of Figure 4 contains contours of vertical velocity for each simulation through a horizontal (*xy*) plane *z/D* = 3 above the momentum source. The right column contains phase lines predicted by internal wave theory for the corresponding Froude number (Voisin, 1994). Comparison of the two columns indicates our simulations agree closely with theoretical predictions.

In addition to the phase lines, a separate "wide" pattern of waves is seen in the left column of Figure 4. At this time the wide pattern of waves is believed to be a reflection from the domain surface. To investigate this a separate, smaller simulation was conducted with vertical size half of the original simulation. Figure 5 shows horizontal and vertical slices of vertical velocity contours at the same simulation time for the original sized simulation (left column) and the smaller simulation (right

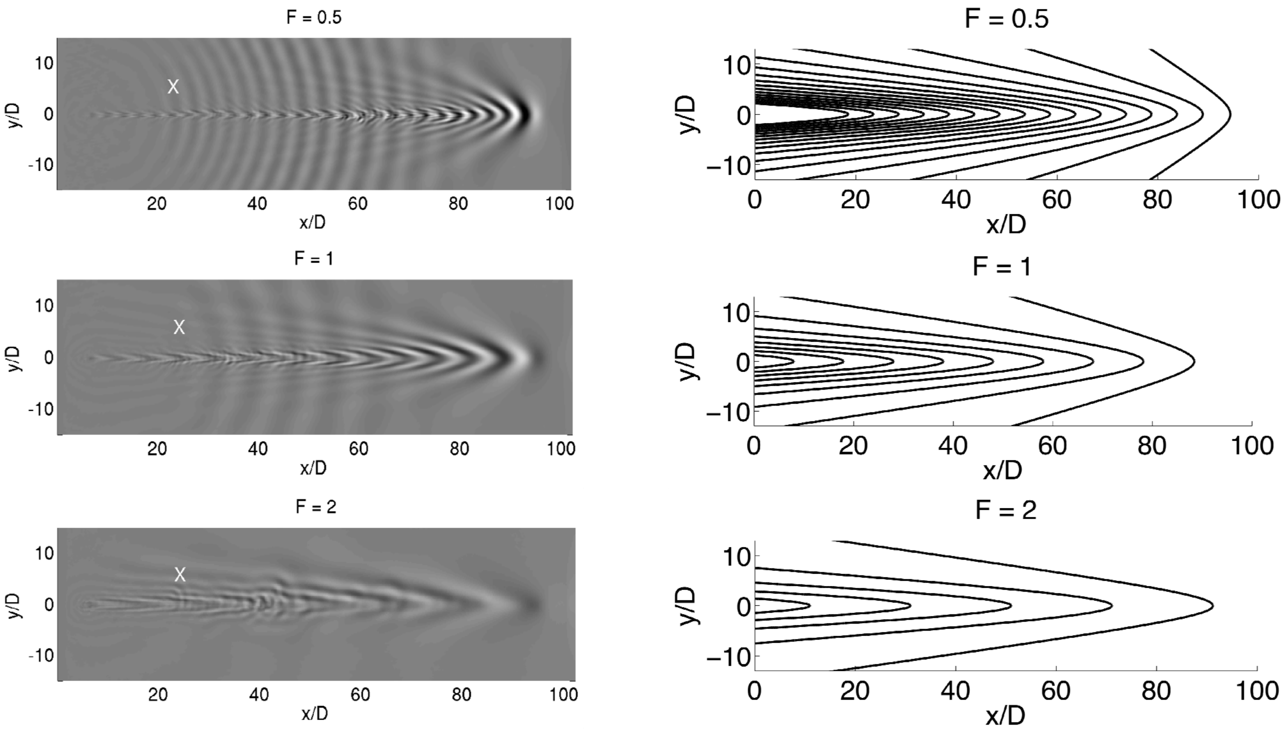

Figure 4: Contours of vertical velocity (left) on a horizontal plane z/D = 3 above the moving momentum source for each simulation. Positive and negative velocities are represented by dark and light colors, respectively. Theoretical internal wave phase lines (right) (Voisin, 1994).

column). The wide wave pattern is seen in the smaller simulation, but not the larger one, supporting the idea the waves are reflections from the surface. Reflections of internal waves have been reported in nature (e.g., Cole et al., 2009).

Moving Momentum Source in Realistic Environment

The final accomplishment this year was to simulate the moving momentum source in a realistic environment. For this simulation a moving momentum source in ambient crossflow near the Alabama Alps, a reef located in the Gulf of Mexico, is conducted. The left plots of Figure 6 contain smoothed temperature, *T*, and salinity, *S*, (and resulting density, σ, and *N*) profiles obtained from 12 CTD locations around the Alabama Alps and used for initial conditions. The right plot in Figure 6 contains the bathymetry used in this realistic simulation. The ambient crossflow U_A=5cm/s. The simulation was run for 36 model hours without the momentum source to obtain a quasi-equilibrium background state. Then the moving momentum source with diameter *D*=5m and traversing velocity 0.2m/s northward is inserted at the southern boundary to the west (left) of the Alps. The momentum source imparted a velocity U_m=0.2m/s north into the domain. The domain size is 5km x 5km x 90m, with resolutions dx=7m, dy=2m, dz=1m. The simulation is run for 6 hours allowing the momentum source to traverse the entire domain.

Figure 7 contains plots of northward velocity (*V*) and temperature (*T*) after time *t*=1.67hrs and 3.33hrs. Each cross section is taken through the center of the momentum source. In the upper plots the cross flow is shown to advect the wake to the west. After 3hrs of simulation (right column) the southern part of the wake bends due to interaction with bathymetry. The temperature plots demonstrate internal wave formation and propagation. The bottom plots show the momentum and temperature contour displacement by the momentum source as it traverses through the domain.

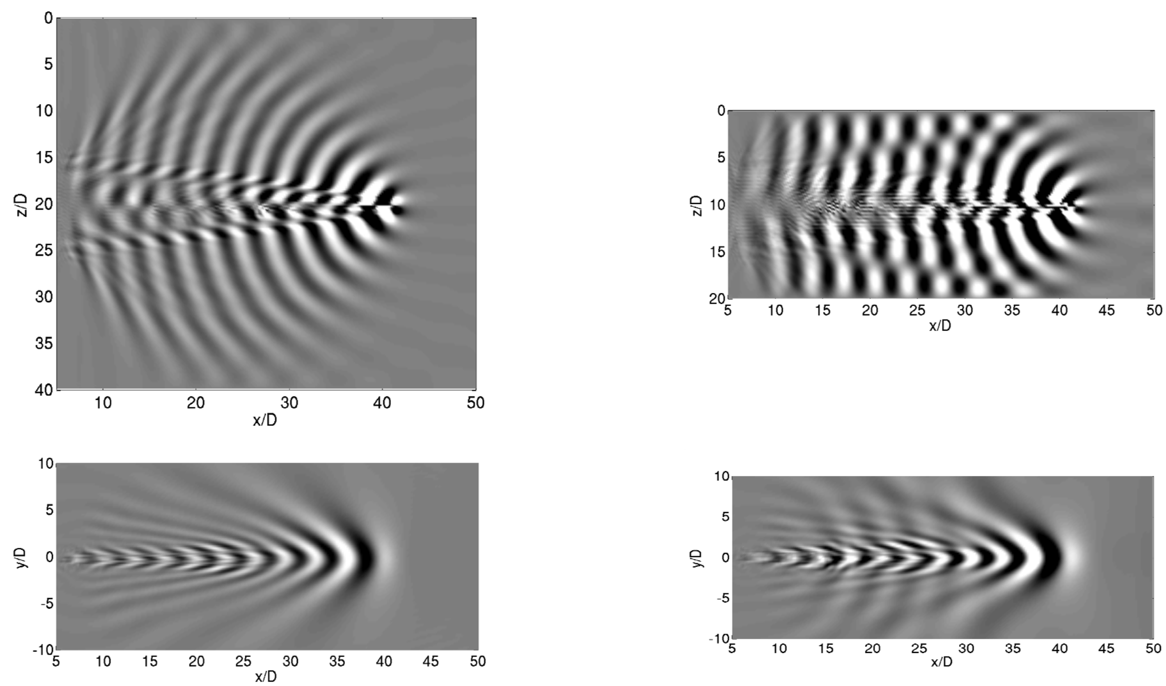

Figure 5: Original size simulation (left) and simulation with half the original height (right). Upper row is vertical slice (xz) through the center of the momentum source. Lower row is horizonal (xy) slice at z/D=3 above the momentum source. All plots are at the same simulation time. The "wide" wave pattern is seen in the shorter domain earlier than the original depth simulation.

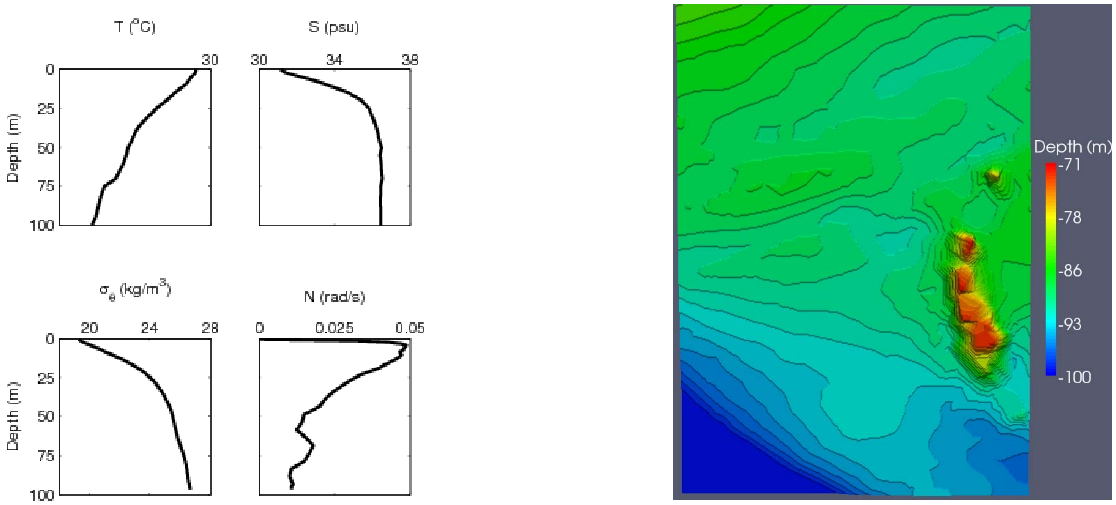

Figure 6: Initial T and S (and resulting density and N) profiles (left) and bathymetry (right) used in simulations of a moving momentum source in a realistic environment. T and S are smoothed averaged observations from 12 stations near the Alabama Alps. Bathymetry is obtained from a special USGS survey (Continental Shelf Associates, Inc and Texas A&M University, Geochemical and Environmental Research Grpup, 2001) .

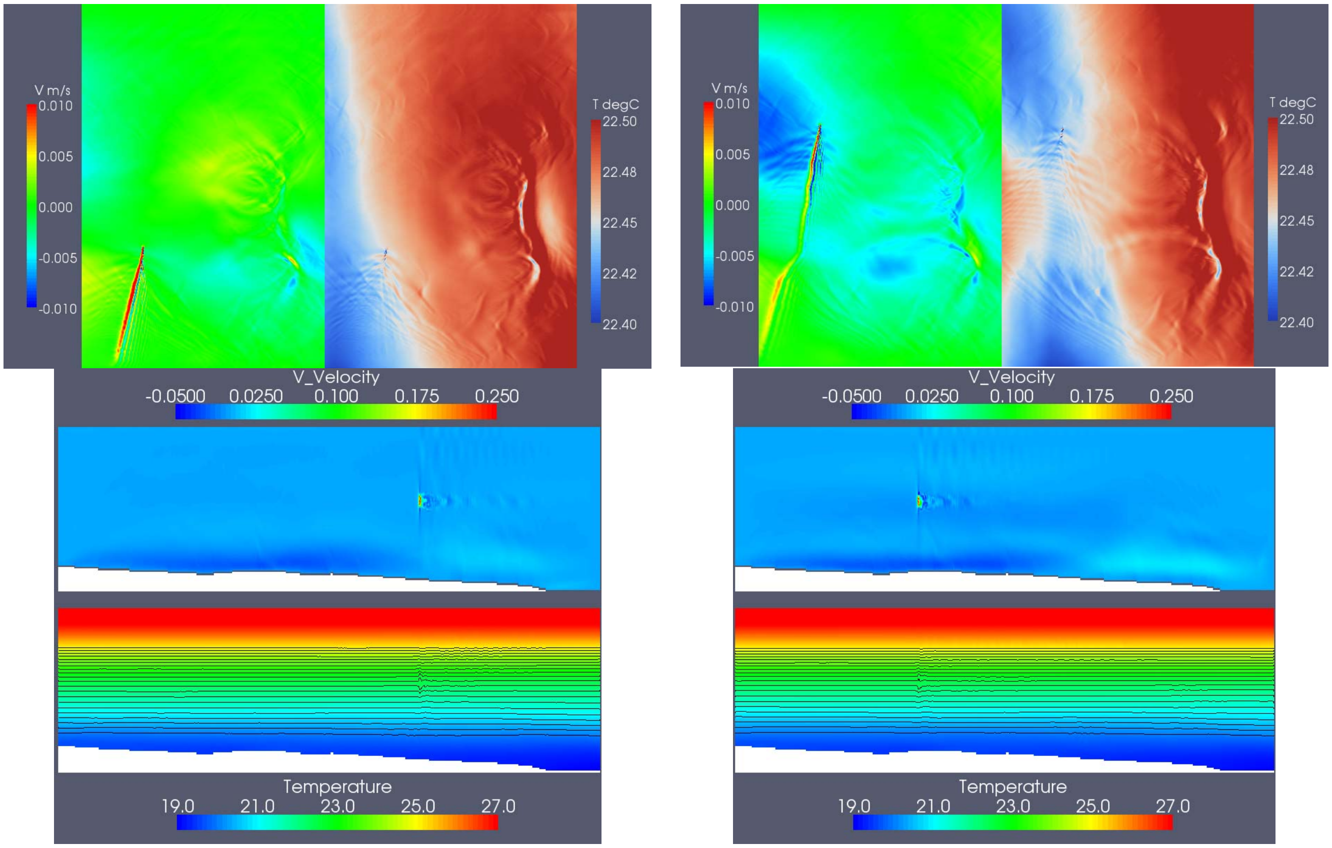

Figure 7: Top view (upper row) and side view (bottom row) of moving momentum source after (left column) t=1.67hrs and (right column) t=3.33hrs. Each plot is a slice through the center of the momentum source. Also each plot contains a contour of velocity and temperature

IMPACT/APPLICATIONS

This work will help to determine the importance of and the requirements for nonhydrostatic forecast systems for naval applications. The scales and features which will require nonhydrostatic simulation are being assessed.

RELATED PROJECTS

The NRL project Autonomous Characterization of Environmentally Induced Non-Acoustic Noise and the Adaptation of Multi-Sensor USW Networks. (6.2, Undersea Warfare) is related to this project because it involves nonhydrostatic modeling of the SW06 experimental area and time and comparison with measurements taken during SW06. Components of SW06 are funded through this ONR NLIWI DRI.

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