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14. ABSTRACT

Hybrid finite element/finite volume based CaMEL shallow water flow solvers have been successfully extended to study wave effects on ice floes in a simplified 10 sq-km ocean domain. Our solver combines the merits of both the finite element and finite volume methods and is much more sophisticated, robust, super convergent, and is the first of its kind approach extended for studying the dynamics and dispersion of ice chunks in ocean.

Apart from studying the influence of waves on rigid, non-moving ice floes, We have also successfully implemented the automatic mesh moving techniques to study the ice kinematics. We have studied the wave-ice

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Report Title

Final Report: High Performance Computing Technologies for Modeling the Dynamics and Dispersion of Ice Chunks in the Arctic Ocean

ABSTRACT

Hybrid finite element/finite volume based CaMEL shallow water flow solvers have been successfully extended to study wave effects on ice floes in a simplified 10 sq-km ocean domain. Our solver combines the merits of both the finite element and finite volume methods and is much more sophisticated, robust, super convergent, and is the first of its kind approach extended for studying the dynamics and dispersion of ice chunks in ocean.

Apart from studying the influence of waves on rigid, non-moving ice floes, We have also successfully implemented the automatic mesh moving techniques to study the ice kinematics. We have studied the wave-ice interactions using different artificial wave forcing mechanisms impacting, movable isolated ice floes, and also uniformly placed cluster of ice floes that are free to drift.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

[1] Palle, S., and Aliabadi, S. "Direct Numerical Simulation of Ocean Ice Dynamics", 11th International Conference on Advances in Fluid Mechanics- AFM2016, September 5-7, 2016, Ancona, Italy (Abstract accepted).
[2] Palle, S., and Aliabadi, S. "Direct Numerical Simulation of Sea Ice Dynamics in a Simplified Marginal Ice Zone (MIZ), WCCM XII, Seoul, Korea, July 24-29, 2016 (Abstract submitted).
[3] Palle, S., and Aliabadi, S. "Numerical Simulation of Ocean Ice Dynamics using Hybrid FE/FV Methods", The Ninth International Conference on Advanced Engineering Computing and Applications in Sciences- ADVCOMP 2015, July 10-24, 2015, Nice France.
[4] Palle, S., and Aliabadi, S. Numerical Simulation of Ocean Ice Dynamics using Hybrid FE/FV Methods", PANACM 2015, April 27-29, 2015, Buenos Aires, Argentina.

Number of Presentations: 4.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
09/09/2015	1.00	Dr. Sridhar Palle, Dr. Shahrouz K. Aliabadi. Numerical Simulation of Ocean Ice Dynamics using Hybrid FE/FV Methods, ADVCOMP 2015 : The Ninth International Conference on Advanced Engineering Computing and Applications in Sciences. 20-JUL-15, . : ,

TOTAL: **1**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Sridhar Palle	0.60
FTE Equivalent:	**0.60**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Dr. Shahrouz Aliabadi	0.20	
FTE Equivalent:	**0.20**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Andrew Moncure	0.20
FTE Equivalent:	**0.20**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

High Performance Computing Technologies for Modeling the Dynamics and Dispersion of Ice Chunks in the Arctic Ocean

(Investigator: Shahrouz Aliabadi)

<u>Student Training:</u> Lufat Rahman - Sophomore, Computer Engineering; Daryl Jones – Junior, Electrical Engineering; and Fariba Samiei - Graduate student, Computational Engineering.

Research Assignment/Accomplishments: The students have received training relative to mesh generation software such as IcemCFD, Pointwise, flow visualization and other CFD related activities.

<u>Postdoctoral Research Associates</u>: Dr. Sridhar Palle

<u>Research Assignment:</u> To develop a robust and accurate sea ice dynamics model that can be utilized for both short term and long term forecasts in climatic simulations and ocean circulation studies. By taking advantage of our innovative hybrid finite element/finite volume based CaMEL fluid flow solvers, CaMEL structural dynamics solvers and also our sophisticated high performance computing infrastructure, the goal would be to first simulate ice dynamics in simplified oceanic conditions, and eventually extend the developed technology to more complicated and much more realistic ocean conditions. The CaMEL technologies that will be developed through this project will be based on all-parallel and scalable high-order hybrid numerical schemes, generalized hybrid unstructured mesh topologies, stabilitized coupling of multi-physics, efficient nonlinear mesh-moving methods, and sophisticated thermodynamic models to account for ice melting and freezing.

<u>Accomplishments:</u> Hybrid finite element/finite volume based CaMel shallow water flow solvers have been successfully extended to study wave effects on ice floes in a simplified 10 sq-km ocean domain. Our solver combines the merits of both the finite element and finite volume methods and is much more sophisticated, robust, super convergent, and is the first of its kind approach extended for studying the dynamics and dispersion of ice chunks in ocean.

We have also successfully implemented the automatic mesh moving techniques to study ice kinematics. We have studied the wave-ice interactions using different artificial wave forcing mechanisms impacting, movable isolated ice floes, and also multiple uniformly placed ice floes that are free to drift.

<u>Research Progress</u>

I. Rigid Non-movable Ice floes: Wave Effects on ice floes in 10 sq-km ocean domain

As a first step we have simulated a simplified 10 sq-km ocean domain with non-moving rigid ice floes. Our CaMEL hybrid FE/FV shallow water flow solver has been successfully extended for this simplistic ocean domain by first studying uniform distribution of ice floes.

<u>Uniform distribution of circular ice floes:</u>

Wave effects on circular ice floes are thoroughly analyzed for two different initial conditions. For the first case, waves are created through artificial forcing of a dam break. This case is a simplified representation of tsunami type waves impacting the ice floes and is also an extension of our dam break shallow water bench mark case [1]. Fig.1 depicts the dam break case where water height is plotted at different times. It can be seen that while depression wave travels left, the bore wave travels right towards the ice floes. While hybrid (quad/tri) mesh elements are used in the overall domain, highly refined unstructured triangular mesh elements are used near the ice floes to capture the flow features accurately.

Case 1: Tsunami type waves impacting the ice floes

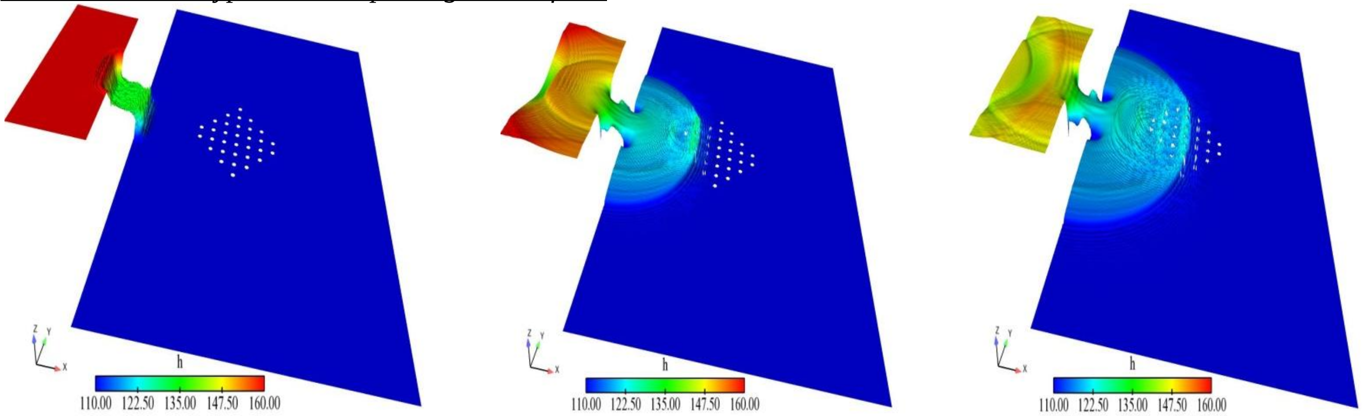


Fig.1: Waves from a dam break impacting uniformly distributed circular ice floes

For the second case, circular waves are created through artificial forcing as in the case of sudden ice melting situation as shown in Fig. 2. The flow is depicted at three different times where water height is plotted. This case was also implemented to study the impact of circular waves on the ice floes.

Case 2: Circular waves impacting the ice floes

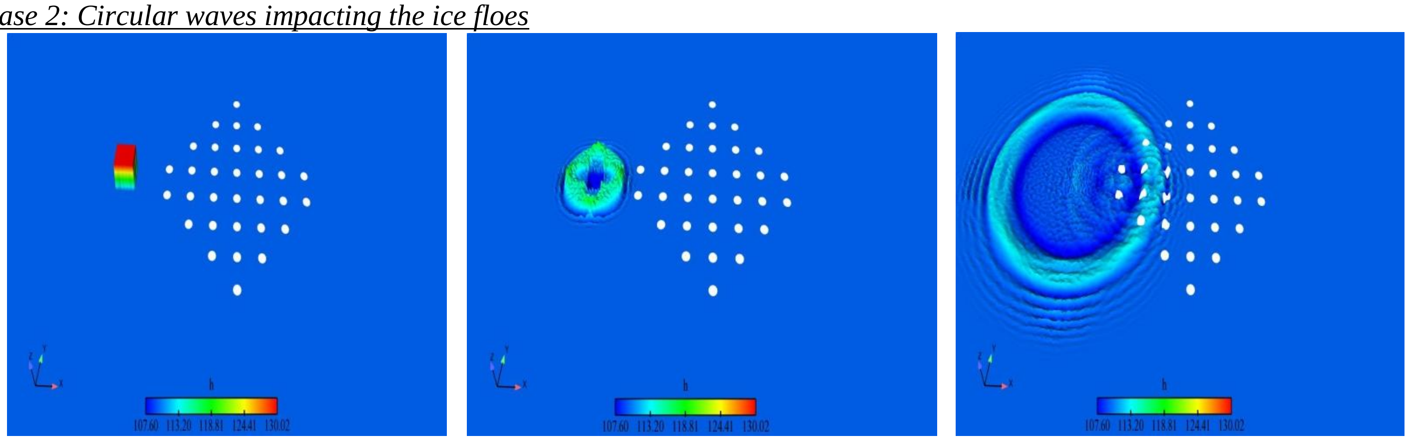


Fig.2: Circular waves impacting uniformly distributed circular ice floes

Random distribution of non-uniform ice floes:

For more realistic representation of ice-floes, 17 non-uniform ice floes randomly distributed in the 10 sq-km ocean domain are also simulated as shown in Fig. 3 and Fig. 4.

Case 1: Tsunami type waves

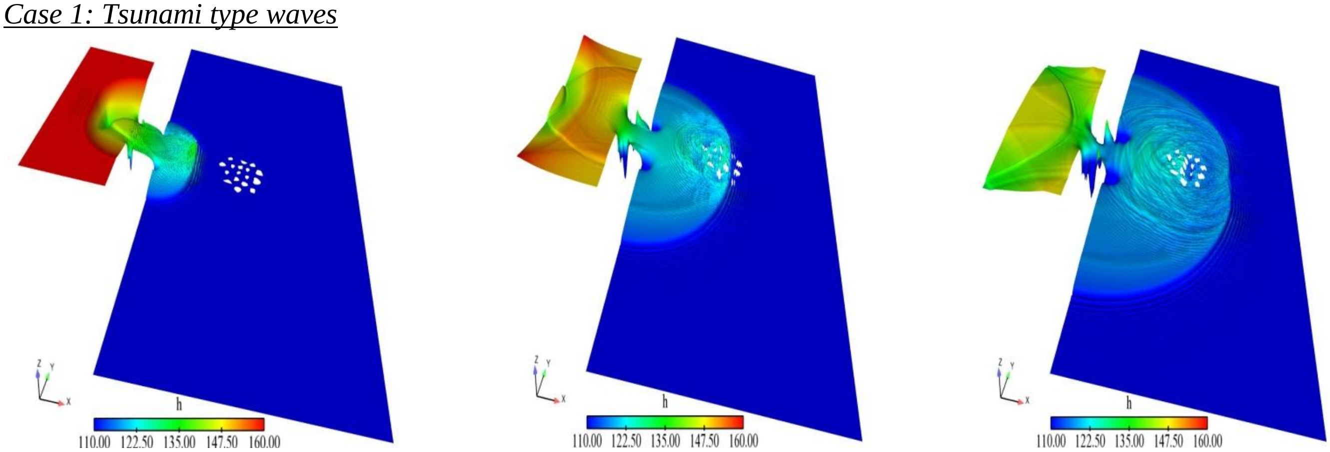


Fig.3: Waves from a dam break impacting randomly distributed non-uniform ice floes

Case 2: Circular waves as in sudden ice melting

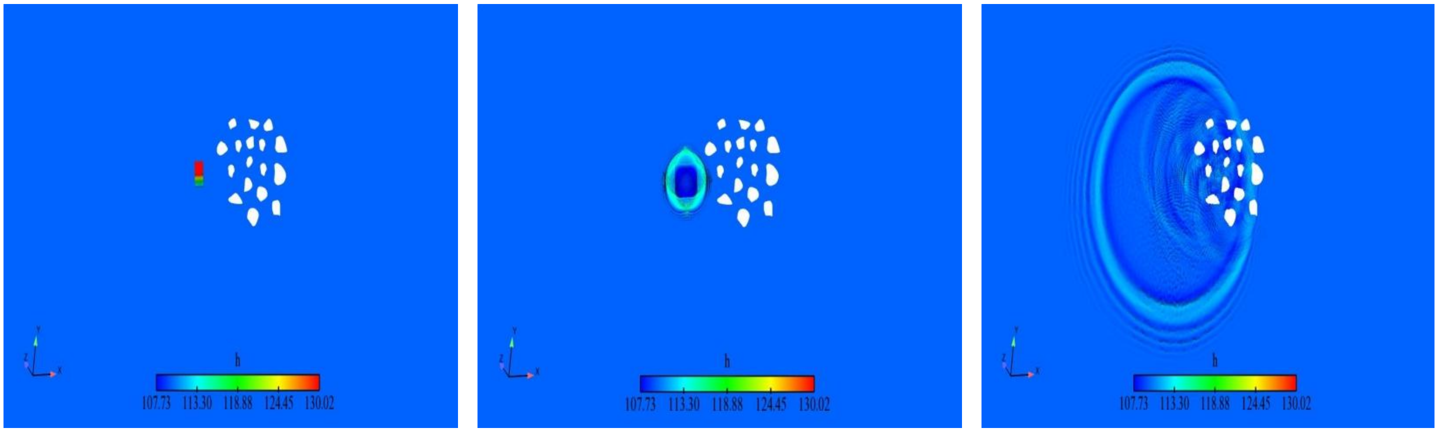


Fig.4: Circular wave's impacting randomly distributed non-uniform ice floes.

For both circular ice floes and also non-uniform randomly distributed ice floes, it can be observed that waves bounce back after impacting the ice floes.

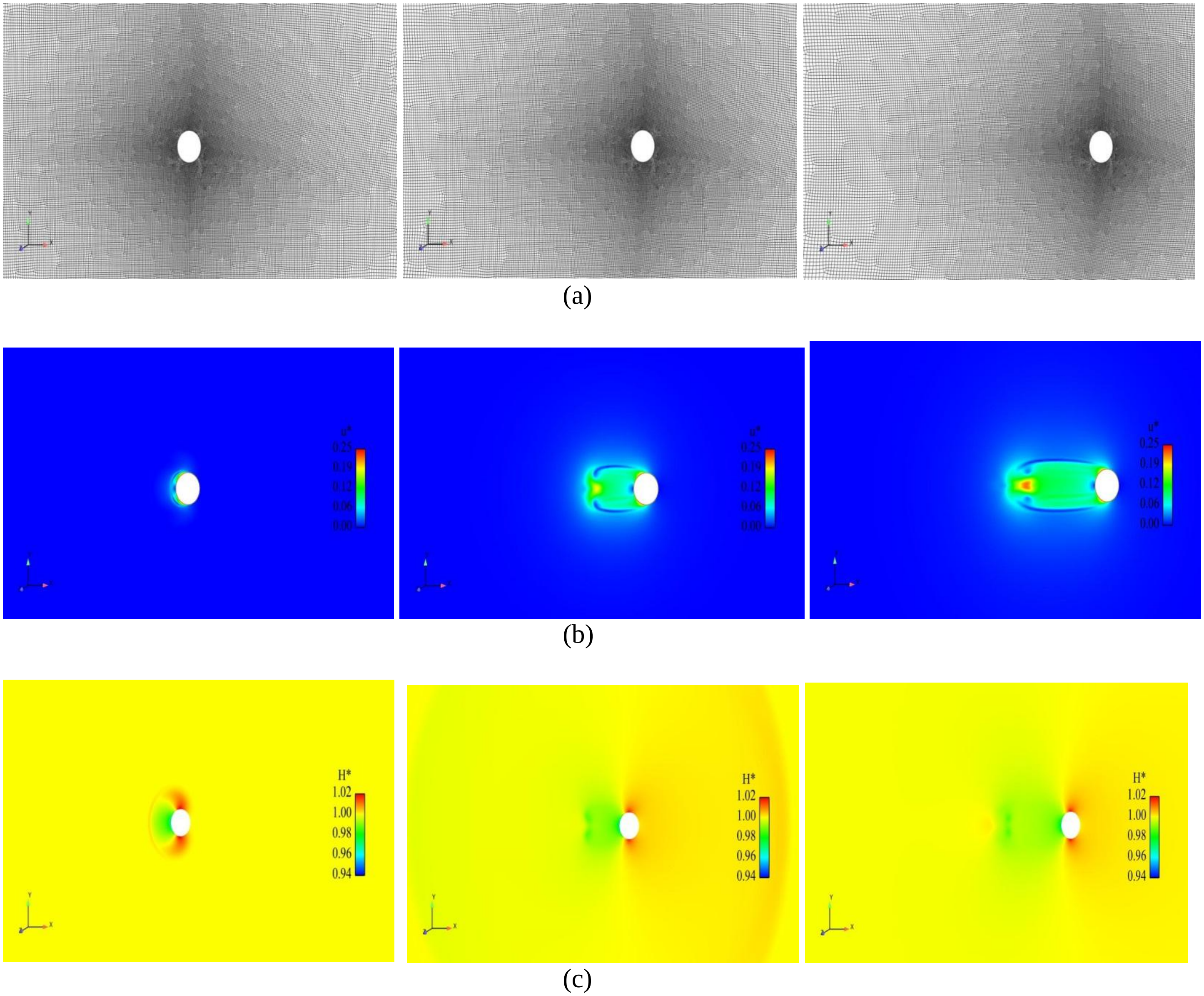
We have successfully extended our hybrid FE/FV based CaMEL shallow water flow solver for studying wave effects on both uniformly and also randomly distributed ice floes. Having tested our flow solver for simplistic initial conditions through artificial forcing, for the next steps we plan to implement more realistic, complex, and detailed ocean ice dynamics. Presently we are in the process of extending our automatic mesh moving capabilities to study the motion of ice chunks. Future research plans are summarized as listed below:

II. Automatic Mesh Movement Implementation:

We have successfully implemented the automatic mesh movement capability in our CaMEL shallow water solver to account for the motion of ice floes. We achieved this by solving linear elasticity equations coupled with shallow water equations. Momentum equation is solved using the cell-centered finite volume method (FVM) for the velocity and continuity wave equation is solved using finite element method (FEM) for the water depth. From velocity and water depth, forces acting on individual ice floes are calculated, which are then used to solve linear elasticity equations for mesh displacement using FEM. Our implementation of automatic mesh movement is thoroughly tested by first studying isolated ice floes, and eventually through multiple ice floe dynamics studies. At present, only translation motion is implemented.

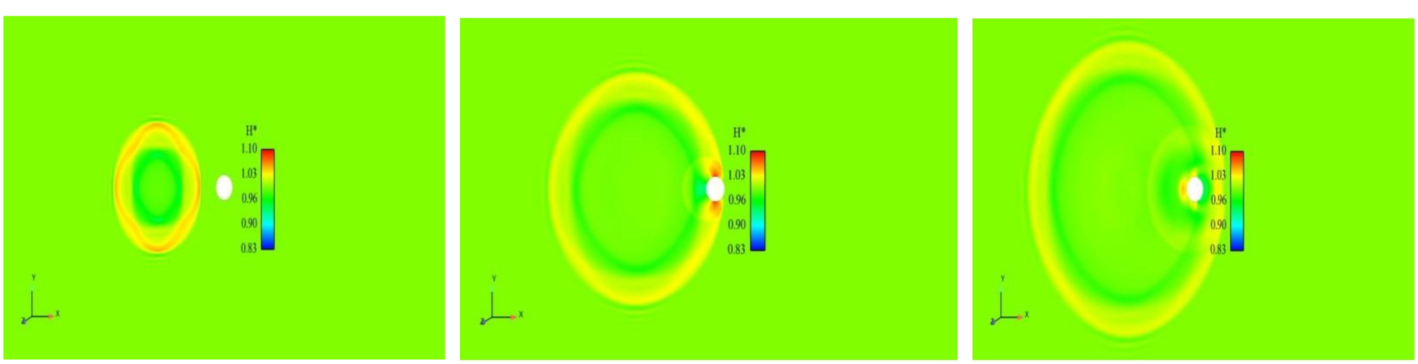
III. Isolated Movable Circular Ice Floe

Automatic mesh movement was tested by first studying the motion of an isolated circular ice floe moving with a constant velocity ($u^* = 0.25$). Fig. 5 shows the movement of an isolated ice floe through a 10 Sq-km ocean domain at different non-dimensional times. Mesh was highly refined near the ice floe to capture the boundary flow physics accurately. Fig. 5(a) shows the grid plot, from which it can be seen that mesh refinement is maintained as the floe moves through the grid. Fig.5 (b) shows the velocity plot and Fig.5(c) shows the water depth. Our implementation was also tested for grid independence using both structured and unstructured mesh elements with varied grid sizes. All the results shown are in dimensionless form. Fig. 6 depicts the case, where circular waves (such as in sudden ice burst) are shown impacting the movable ice floe with water depth plotted at different times. Ice floes are swayed back and forth as the waves pass through them. The case of dam-break type tsunami waves impacting the isolated floe is shown in Fig. 7.



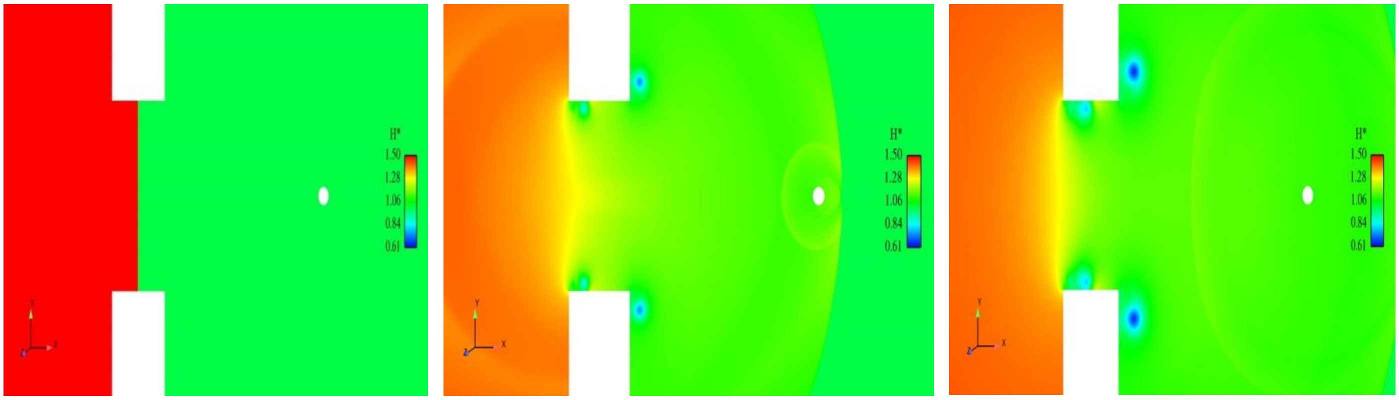
t* = 1 t* = 10 t* = 20

Fig.5: Isolated circular ice floe moving with a constant velocity.



t* = 2 t* = 4 t* = 5.5

Fig.6: Water depth plotted at different times for circular waves impacting an isolated ice floe

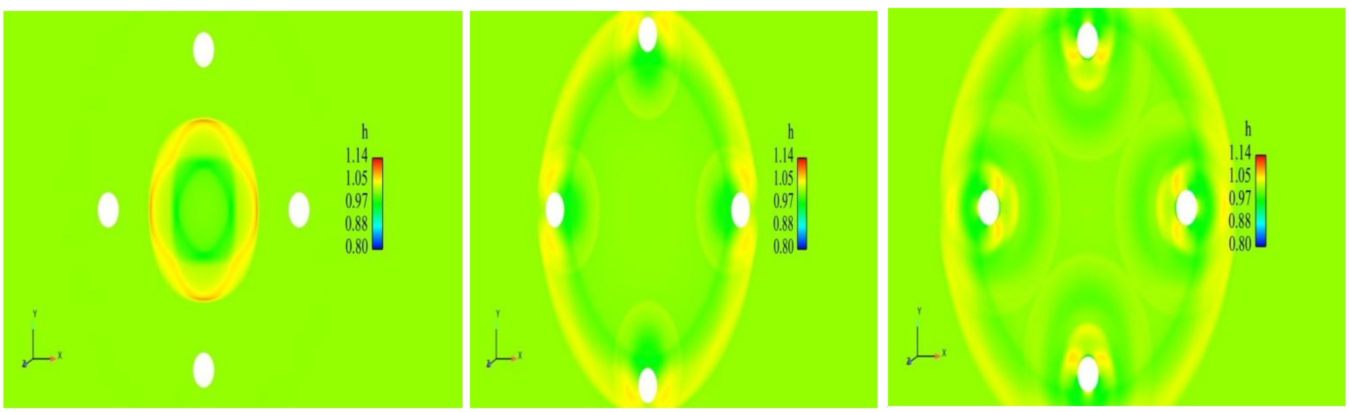


t* = 0 t* = 17.5 t* = 25.0

Fig.7: Water depth plotted at different times for dam-break tsunami waves impacting an isolated ice floe

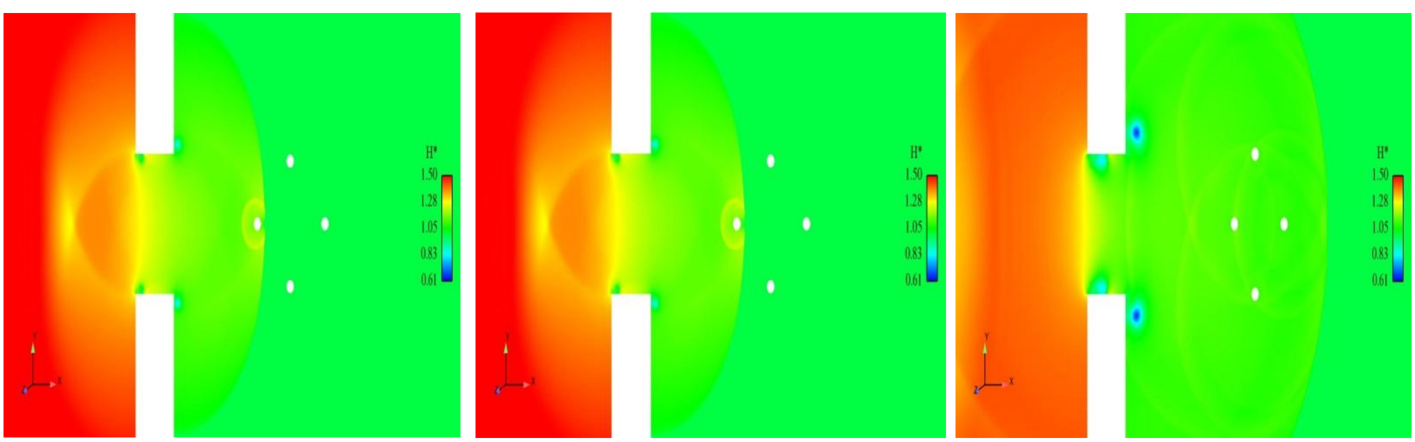
IV. Multiple Circular Ice Floes

Impact of waves on multiple circular ice floes is shown in Fig 8 and Fig. 9 for circular waves and dam-break tsunami type waves respectively. It can be observed that the simulation captures the wave features accurately, and floes are oscillated back and forth as the waves pass through them. Similarly tsunami type waves also impact the circular ice floes giving them significant momentum, as the waves impact the floes. At present, floe-floe interactions have not yet been implemented and are planned for future work.



t* = 2 t* = 5 t* = 6

Fig.8: Circular waves impacting uniformly placed circular ice floes



t* = 0 t* = 12.5 t* = 25

Fig.9: Dam-break waves impacting uniformly placed multiple circular ice floes.

Future Research Plan: Next Steps

Present hybrid FE/FV methods of implementation in studying ocean ice dynamics are the first of its kind in studying ice-wave interactions. With varying degrees of complexity we plan to make our simulations much more thorough, robust, comprehensive and realistic so that the present sea ice dynamics models can be eventually employed for a variety of applications in the arctic including navigational applications, offshore drilling, and global climate forecasting. The proposed future work planned to bring forth these goals are listed below (not necessarily in order):

- Presently, only translation motion is implemented. Rotational motion will also be implemented to account for all degrees of freedom and make the mesh movement implementation thorough and complete.
- Effect of ice floe shapes (circular, square, non-uniform) and sizes (different length scales) on the ice/wave interaction will be studied.
- Validation studies with experimental data for drift velocities of isolated ice floes and also with data on impact forces for offshore platforms will be conducted.
- Floe-floe interactions will be implemented and studied.
- Ice mobility due to wind stress, ocean current, pressure, and also tides will be investigated.
- Real ocean bathymetry will be incorporated.
- Parallelization of the flow solver will be accomplished to address the needs of significant computing power required for more realistic simulations of MIZ.
- Thermodynamics models to account for ice melting and freezing will be implemented.
- Feasibility of 3D CaMEL for more realistic simulations of ice dynamics will be explored.

References:

[1] Palle, S., and Aliabadi, S. “Direct Numerical Simulation of Ocean Ice Dynamics”, 11th International Conference on Advances in Fluid Mechanics- AFM2016, September 5-7, 2016, Ancona, Italy (Abstract accepted).

[2] Palle, S., and Aliabadi, S. “Direct Numerical Simulation of Sea Ice Dynamics in a Simplified Marginal Ice Zone (MIZ), WCCM XII, Seoul, Korea, July 24-29, 2016 (Abstract submitted).

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[4] Palle, S., and Aliabadi, S. Numerical Simulation of Ocean Ice Dynamics using Hybrid FE/FV Methods”, PANACM 2015, April 27-29, 2015, Buenos Aires, Argentina.

[5] Aliabadi, S., Akbar, M.K., Patel, R. Hybrid Finite Element / Volume Method for Shallow Water Equations. Int. J. Num. Meth. Fluids, 83 (13), 1719-1738, 2010.