Final Report for BSEE/NOAA Project:

ANSWERING THE CHALLENGE OF ARCTIC CONDITIONS TO OIL SPILL INCIDENTS

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Executive Summary

The original proposal included the primary goal of the project:

The Emergency Response Division (ERD) of NOAA's Office of Response and Restoration is proposing to upgrade their existing fate and transport models to address the extreme conditions of a well blowout or other spill in the Arctic and other cold regions.

The project beginning was hampered by contracting difficulties, ultimately resulting an extension of the performance period. Nevertheless, the goals of the project have been achieved.

NOAA has added algorithms to the General NOAA Operational Modeling Environment (NOAA ERD's core oil spill response model) so that it can ingest data from coupled ocean-ice forecast models and use the ice information to better model the fate and transport of oil in arctic conditions and ice-infested waters. This has greatly enhanced NOAA's ability to provide full trajectory and fate analysis to the FOSC in the case of spill in the arctic.

Dr. Scott Socolofsky of Texas A&M University extended the Texas A&M Oil Spill Calculator (TAMOC) (An oil well blowout plume model) to better handle cross-flow currents and the relatively shallow waters of the Arctic region. NOAA has coupled the new version of the model with GNOME, so that it can be initialized with data from the GNOME model, and act as a source for further modeling the fate and transport of oil during response or planning. This has enhanced NOAA's ability to support the FOSC in the event of a well blowout under arctic conditions, as well as in other regions.

Both the TAMOC and GNOME models are open-source, and made available to the public via gitHub[1,2], including the broader academic, response, and oil spill planning communities. There are a number of users outside TAMU and NOAA that have begun to make use of both the GNOME and TAMOC code

[1] https://github.com/NOAA-ORR-ERD/PyGnome
[2] https://github.com/socolofs/tamoc
[3] http://www7320.nrlssc.navy.mil/hycomARC/

Work Accomplished

TAMOC Plume Model

Improvements

Improvements to the Texas A&M Oil Calculator (TAMOC) blowout plume model supported by this project include:

- New plume simulation module for blowouts in crossflow built and validated
- Developed a new entrainment algorithm for plumes in cross flow
- Upgraded and validated the oil equations of state to give more accurate simulations
- Developed a natural gas hydrates module to simulate hydrate skin -- Arctic releases are shallower, but this work has helped understand the relevant mass transfer coefficients for dissolving gas bubbles, which is critical to predict the gas mass flux to the ocean surface from any depth.
- Updated the model to allow for interaction with a rigid free surface (i.e. ice cover) and tested the algorithms for deep and shallow blowouts typical for the Chukchi and Beaufort Seas.

Detail of these developments can be found in the following publications:

Presentations and Publications supported by this project

Dissanayake, A.L., Rezvani, M., Socolofsky, S. A., Bierlein, K. A., & Little, J. C., (2016). Integral model for bubble plumes from line-source geometry, International Symposium on outfalls systems, 2016, Ottawa, Canada.

Socolofsky, S. A., Dissanayake, A., Jun, I., Gros, J., Arey, J. S., and Reddy, C. M. (2016). *Texas A&M Oilspill Calculator: Modeling suite for subsea spills*. Proc., 38th Arctic and Marine Oil-spill Program (AMOP) Technical Seminar on Environmental Contamination and Response.

Dissanayake A. L., Jun, I., Socolofsky, S. A., Gros, J., and Arey, J. M., (2016). *Importance of physical, chemical, and hydrodynamic processes in the near field plume of oil and gas blowout models*. 2016 Gulf of Mexico Oil Spill & Ecosystem Science Conference, Tampa, Florida.

Dissanayake A. L., Jun, I., Socolofsky, S., (2015). *Numerical models to simulate oil and gas blowout plumes and associated chemical and physical processes of hydrocarbons*. E-proceedings of the 36th IAHR World Congress 28 June – 3 July, 2015, The Hague, the Netherlands.

Dissanayake A. L., Jun, I, and Socolofsky, S. A., (2015). *Integral Models to Simulate Oil and Gas Blowout Plumes and Associated Chemical and Physical Process of Hydrocarbons*. Near Field Modeling Workshop, 2015 Gulf of Mexico Oil Spill & Ecosystem Science Conference, Houston, Texas.

Jun, I., Socolofsky, S. A., Dissanayake A. L., (2015). *Effect of gas hydrates on the fate of rising hydrocarbon bubbles from natural seeps and accidental releases in the deep ocean*. 2015 Gulf of Mexico Oil Spill & Ecosystem Science Conference, Houston, Texas.

Oil-ice fate and transport Algorithms

Oil-ice interactions are very complex, and while there has been a lot of research in recent years to better understand the interactions, there are still very limited methods available to model oil behavior in these complex environments. Another limitation is that a response model can only take advantage of information that Is available from remote sensing and forecasts. The available ice forecast models provide very limited information about ice conditions so the best that can be done in a oil spill forecast model are fairly simple scaling approaches.

The available operational ice forecast models provide the following parameters:

- Fractional Ice coverage
- Ice Thickness (sometimes)
- Ice age (sometimes)
- Ice drift velocity

The algorithms in the GNOME model need to be able to work with only those parameters. In the future, we may be able to use ice age and ice thickness as a proxy for other parameters that may matter, such as under-ice roughness, but methods are not yet available for making such estimations. There is ongoing work at the Arctic Domain Awareness Center (ADAC) on spreading of oil under ice that may be useful for this in the future.

However, there is some understanding of what the behavior of oil in ice might be with full ice coverage, as much of the oil is “locked in” to the ice. And modeling approaches for oil in open water are well established. With this limited information, the goal is to use algorithms that behave properly with full ice coverage and open water, and provide continuous results in-between. An Industry standard approach can be called the “80-20 rule”, similar to the approach applied by Sintef in the OSCAR model, and in RPS/ASA’s OilMap model.

The rule can be summarized as follows:

- If there is 20% or less ice coverage, the oil behaves as it would with no ice present.

- If there is 80% or less ice coverage, the oil behaves as it would with full ice coverage.
- If the coverage is in between 20% and 80%, then the process is linearly interpolated between those values.

In some cases the application of this rule is straightforward, in other cases there is more complexity. The individual algorithms are summarized below.

Transport

The transport algorithms are relatively straightforward. Oil on the water surface moves with the surface ocean currents, and is pushed by the wind, as well as spread out by diffusive processes not included in oceanographic models.

Currents

For 20% or less ice coverage, the oil moves with the currents, as it would in open water.

For 80% or more ice coverage, the oil moves with the ice.

To accomplish this, the currents are scaled down according to the ice coverage and the 80-20 rule. And the ice movement is scaled down also according to the rule, but in the opposite direction.

Net result is that with 50% ice coverage, the oil moves at the average of the ice and current velocity.

Wind Drift

The oil drifts with the wind as usual for low ice, and does not drift with the wind at all with full ice coverage. This is accomplished with an “ice modified wind”: the velocity of the wind at a given location scaled by the ice coverage according to the 80-20 rule. The wind is then applied to move the oil in the usual way.

Diffusion

Diffusion with no ice is as set by the user. With ice, we expect the oil to be “locked in”, and diffusion to be very small or zero. Diffusion is simulated with a random walk algorithm – at each time step, each element is moved a random amount, computed from the time step and the Diffusion coefficient. In the case of ice, the 80-20 rule is implemented by scaling the net movement in each random walk step by the amount of ice coverage.

Weathering Processes

Weathering processes are computed separately for each Lagrangian element (particle) in the model. It is assumed that with full (or nearly full) ice coverage, the oil is locked in and does not weather. And in partial ice coverage, weathering is suppressed. This required substantial changes in the code because each element is in a different location, and may be in different regions of ice coverage.

The previous code was written assuming that the entire slick was experiencing similar conditions, such as temperature, wind speed, etc.

Spreading

Spreading is really a physical rather than a chemical process, but it is a standard of practice to consider it as part of the weathering processes, as the exposed surface areas is a critical factor in weathering. As such, while the physical process is spreading, what this component of the model provides is actually a prediction of the area of the slick exposed to weathering processes – notably evaporation.

Until better approaches are developed, the assumption is made that that no spreading occurs when the oil is “locked in” to the ice. This is a reasonable assumption in the case where the oil has already had a chance to spread before encountering ice. Spreading is the same as open water conditions with little ice present. In between, the spreading rate can be modified by the percent coverage according to the 80/20 rule. So for a given time step, and increase in area is computed, and that increase is modified by the ice cover.

However, there is an additional effect. In practice, the spreading is terminated at an empirical “terminal thickness”. But if the ice coverage goes up, then the area exposed to the atmosphere may go down – i.e. the exposed area should be about 50% of the full area with 50% ice coverage.

This is accomplished with an ice-modified area – the area used by the other algorithms is adjusted according to the ice coverage at the location of the element and the 80-20 rule.

In reality oil under the ice can get caught up in the pockets since oceanic ice is generally not smooth. This might further inhibit spreading. If a characterization of the under ice roughness becomes available, this approach can be extended.

Evaporation

Evaporation is driven by temperature, wind speed and exposed area (and oil properties). Temperature is generally available from oceanographic models. The oil is exposed to the same wind when there is partial ice. But the ice-modified exposed area is used to compute the evaporation, resulting in an ice-modified evaporation. The ice-modified area should be zero with full ice coverage, and thus zero evaporation, and the full area with little ice, thus the same evaporation rate as in open water.

Dispersion

Dispersion is the process of oil being broken up into tiny droplets that remain suspended under the water surface by oceanic turbulence. It is driven by wave climate – we expect no waves in full ice cover, and less wave energy in partial ice cover. So the dispersion algorithm is not modified, but rather the wave algorithm is modified to provide an ice-modified wave field.

In the future there may be a way to estimate the turbulent energy under ice. If the currents under the ice are substantially different than the ice movement, there may be enough turbulence to drive dispersion.

Wave Field
If wave parameters are available from field measurements or a wave model, those parameters will be used. An appropriate wave model would have already taken the ice into account.

However, operationally, we often need to estimate the wave field from the wind field alone. The ice-modulated wind field is used with the same wave estimation algorithms currently used. This required modifying the code to work with a time and spatially varying wind field, providing a time and spatially varying wave climate.

A future extension may be to build a more sophisticated wave model into GNOME. The wave module could use the wind direction and location, and look upwind to see how far it is to either ice or land, and use that fetch to compute the waves. This would help our non-ice models as well.

Dissolution and Sedimentation
The surface dispersion process drives dissolution and sedimentation. If the dispersion process is scaled down, then these will simply follow.

Biodegradation
Biodegradation also takes place when the oil is in droplet form in the water column – so it will get scaled down with the decreased dispersion also.

Emulsification
The literature suggests that emulsification is much less likely to occur in ice conditions due to the very effective damping of wind waves by a broken ice field. So the ice-modulated wind and waves are used to compute emulsification. This results in low emulsification when the ice concentration is high.

Details of all the algorithms in GNOME will be published as a peer-reviewed NOAA Technical Report, currently in development.

GNOME Code Modifications
Adding ice coverage and ice velocity to the model required significant modifications to the code. In the previous version, eacy process was tied to a particular environmental input – a wind field, a current field, etc. But for each process that is influenced by ice, the processes require data about both the ice and the core environmental variable they are driven by: winds or currents, etc. And many separate processes need information about the physical environment, such as water temperature. The fate algorithms in particular needed substantial adaptation, as they were originally written with smaller-scale scenarios in mind,

where the environment did not vary significantly over the range of the slick – one temperature, one wave height, etc.

To accommodate these needs, the code was refactored so that each process that needs information about the environment is connected to an “environment” object that can be queried for the value of a particular parameter at any place in space and time. Simple versions of such objects can always return the same value regardless of location, keeping the simple fate code working the same way. More complex versions can query full gridded model results to return a value.

With this system, the code for each process is written in only one way, and whether it is ice-aware or not becomes a matter of matter of whether it is connected to an “ice-modified” version of the process, the raw one.

These code changes have no only allowed the addition of the ice algorithms, but have also provided a more powerful and flexible framework for response modeling and future improvements.

Coupling of GNOME and TAMOC

A major effort in the development work was to couple the GNOME and TAMOC models. TAMOC is a “near field” plume model. It models the behavior of the buoyant plume generated when and oil and gas are released under the ocean. Oil, and particularly oil and gas mixtures, are less dense than the surrounding seawater, and thus rise quickly to form a plume. The rising oil entrains water, which causes the mixture’s density to rise toward the density of the surrounding water. TAMOC models this process, as well as the interaction of oil, gas, and seawater within the plume.

Once the oil “leaves” the plume, it is transported by the surrounding currents and winds, often many miles from the original source. GNOME is designed to handle this “far field” transport, whereas TAMOC only models the behavior of the plume itself. To handle the far field transport, GNOME must know the locations and properties of the oil as it leaves the plume.

In the code, GNOME derives the environmental properties required by TAMOC (water temperature, salinity and currents in the region of the release) from its environment objects (usually a 3D oceanographic model). TAMOC is then initialized with the oil properties and release conditions of the scenario and the environmental properties, and run. TAMOC produces a set of “sources” used to initialize individual elements in gnome with properties provided by TAMOC: location, droplet diameter, chemical composition, and mass flux of that class of particles.

GNOME then “takes over” and moves the elements with the environmental drivers.

TAMOC is a steady-state model – it predicts the plume that would develop under constant flow rate and environmental conditions. If these conditions change enough to affect the plume dynamics, then the model must re-run. GNOME is designed to re-run the TAMOC model at a user-specified interval, so that its results can reflect the changing environmental conditions in the event of a long release.

Operational Response Modeling

In the event of a spill in the arctic, NOAA will need a source of winds, currents, and ice conditions for the forecast period. In the US, the only operational coupled ocean-ice forecast model for the arctic is the US Navy Arctic Cap Nowcast / Forecast system[3] (ACNFS):

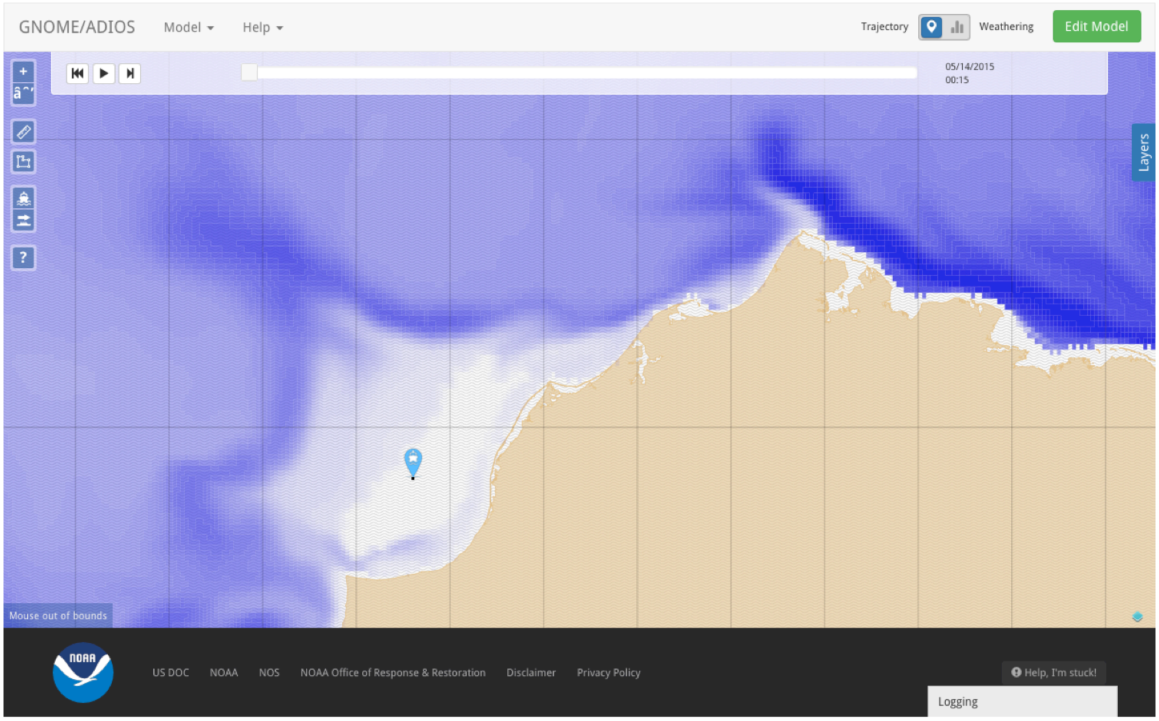
- It is a real-time model, releasing new results daily
- 1/12° resolution (3.5 km near the North Pole and 6.5 km near 40°N)
- HYCOM Circulation model
- Community Ice CodE (CICE) ice model
- NCODA Nowcast/Forecast System
- Naval Operational Global Atmospheric Prediction System (NOGAPS) atmospheric forcing
- Navy Coupled Ocean Data Assimilation (NCODA) system. Assimilates available satellite altimeter observations, satellite ice concentration, satellite and in situ SST

The GNOME code has been adapted to read the results from this model, including:

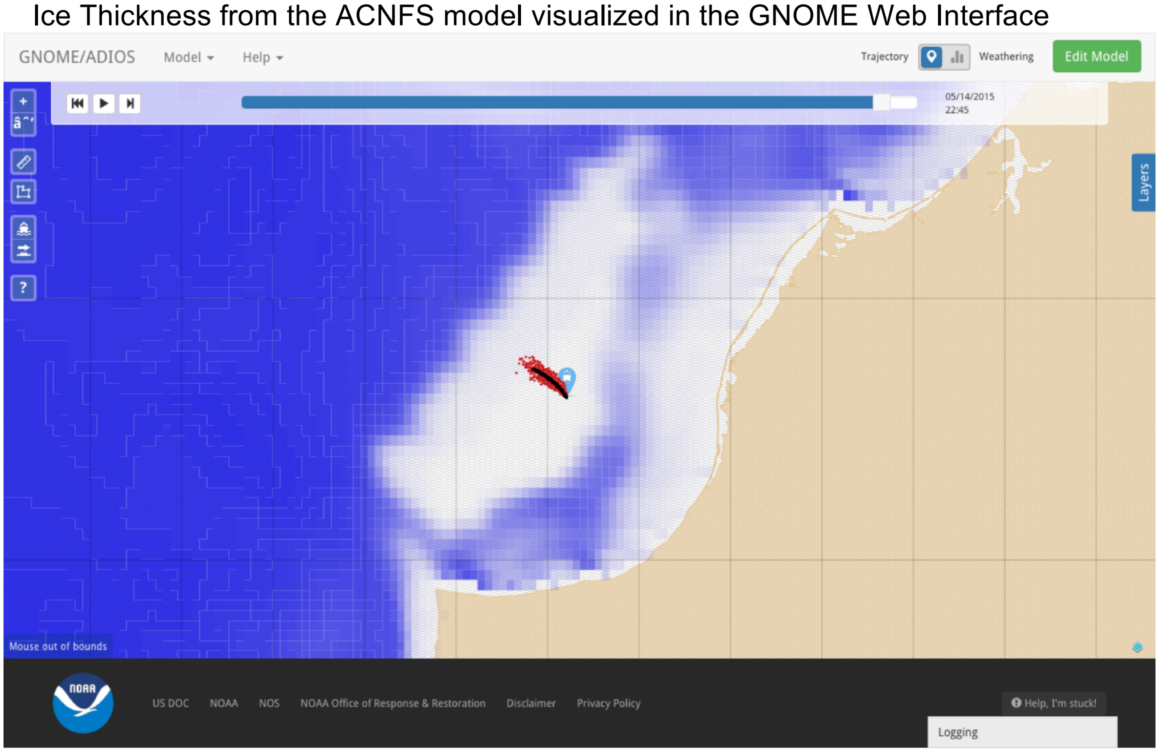
- Ocean currents
- Ice concentration
- Ice drift velocities

This model is to be included in the NOAA GOODS[4] system for easy access during a response. In addition, NOAA is working to be able access the EU-run TOPAZ arctic ocean-ice model. In particular, we are hoping to be able to use the new viscoelastic model (developed under a OGP JIP project) if/when it is made operational.

[3] https://www7320.nrlssc.navy.mil/hycomARC/
[4] https://gnome.orr.noaa.gov/goods



Ice Thickness from the ACNFS model visualized in the GNOME Web Interface



Trajectory and Ice Concentration from the ACNFS model visualized in the GNOME Web Interface

Ice Analysis

The US National Weather Service provides an Arctic Ice Analysis based on satellite, aircraft and vessel observations. This analysis provides ice concentration and stage (type). It does not, however, provide ice movement or a forecast. Nevertheless, in a real event, NOAA will use this analysis to augment the model results in providing trajectory analysis to the FOSC.

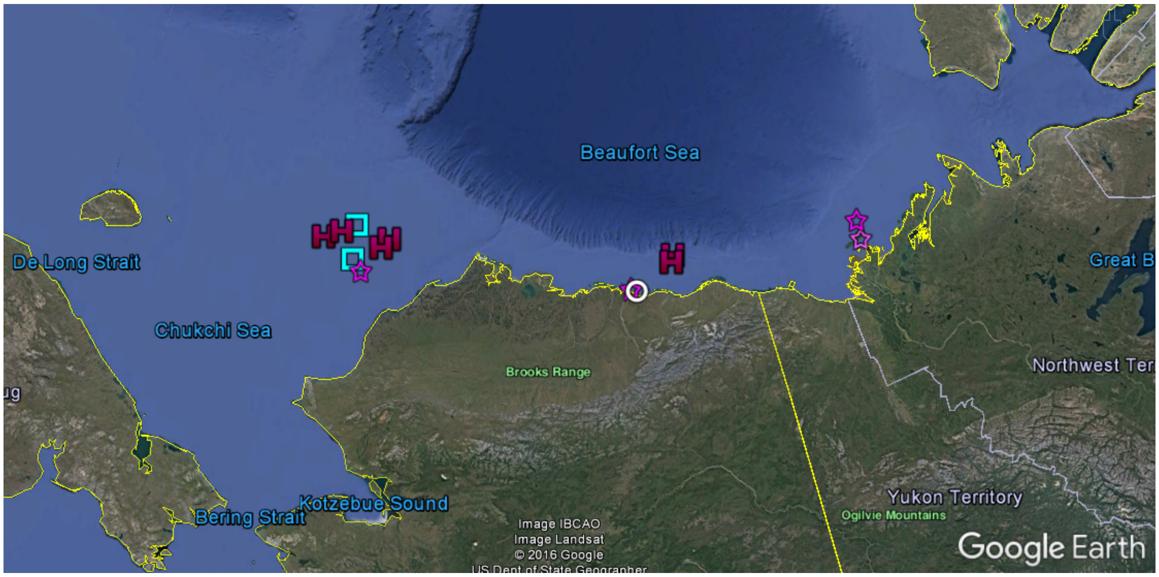
Example Simulations

These are a few example simulations that demonstrate the new capabilities developed under this project.

Well Blowout in the arctic

With global pressures on oil development, and reduced ice in the arctic, it is likely that there will be increased development in US arctic regions in the near future. With development comes risk of an accident resulting in a well blowout. NOAA needs to be prepared to provide support to the FOSC if there is incident involving a well failure.

All of the current, and most of the potential, drilling sites in the arctic are in fairly shallow water: The Chukchi Sea has a maximum depth of about 50 meters, and the shelf in the Beaufort extends to at least 50 miles offshore, with no current plans to develop farther out. In such shallow water, a blowout plume will rise fairly directly to the surface, resulting in essentially a point source as far as long-term transport is concerned. These are the scenarios used in the Arctic TAP project, discussed in a later section.



Potential drilling sites identified for the Arctic TAP project. The “H”s are proposed wells, the blue squares are possible platforms, and the Stars existing wells.

However, there are other questions that might arise in an arctic blowout scenario that a plume model can help answer. TAMOC has been updated to properly handle the recirculation when a plume encounters the surface: either open water or a rigid surface such as ice cover. This allows the model to predict the in-plume dissolution of both the oil and gas. This information can provide a more accurate characterization of the oil as it leaves the plume for further fate and effects modeling, and most importantly, predict the explosive gas flux at the surface – a serious health and safety concern.

When ambient currents are small, density stratification dominates the flow, and several subsurface intrusion layers may form. TAMOC includes the Stratified Plume Model (SPM) to handle these conditions. In stronger currents, the blowout plume bends over in the downstream direction, and gas bubbles and larger oil droplets may rise out of the upstream edge of the plume. TAMOC includes the Bent Plume Model (BPM) to handle these conditions. The TAMOC model has been run for a variety of depths and scenarios under arctic conditions with both of these models. Full results are presented in Appendix A.

The currents in the arctic tend to be small, particularly under ice cover, so the following example is using the Stratified Plume Model. This is a scenario that might result from a blowout in an exploratory well in the Chukchi Sea. Detailed composition data was not available for Chukchi Sea fields, so a Light Sweet Crude similar to what Shell Oil expected to find it its recent explorations was used in these simulations.

Release Parameters:

Release Depth	50 m
Orifice Diameter	0.3 m
Flow Rate	20000 bbl per day
Release Temperature	150C
Oil Type	Light Sweet Crude

The simulated plume reaches the surface without an under surface intrusion layer.

Parameters of the plume once it has reached the surface:

Surfacing Area	88.19 m2
Density of Fluid	975 kg/m^3
Fluid temperature	-1.47C
Liquid Flow Rate	24.28 kg/s (13,531 bbl/day)
Gas Flow Rate	12.25 kg/s

Implications of the results

The results of the plume model have some implications for response.

Temperature

There has been some concern in the response community that a blowout under ice cover might result in substantial melting of the ice due to the high temperature of the released fluid. In this case, the release fluid temperature is 150°C, but the plume rapidly entrains the cold ambient water resulting in exponential dissipation of heat. The resulting temperature of the surfacing plume is close to the ambient water temperature, and near the freezing point in seawater. We do not anticipate from these results that substantial melting would take place. This would be re-evaluated in the case of an actual spill.

Gas Flow Rate

In a deep release, much of the gas released dissolves as it rises through the water column, resulting in little gas released at the surface. However in a shallow release, much of the gas remains to be released at the surface. This can create a significant health and safety issue. In this case, the flow rate of natural gas at the surface is predicted to about 12 kg/s. If that flow rate is used as a source in the NOAA Aloha Air Hazard Model[5], we can obtain an estimate of the hazard zone from the gas release.

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[5] http://response.restoration.noaa.gov/aloha

Flammable Threat Zone **ALOHA® 5.4.6**

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Time: September 30, 2016  1357 hours ADT (using computer's clock)

Chemical Name: METHANE

Wind: 5 miles/hour from S at 10 meters

THREAT ZONE:
  Threat Modeled: Flammable Area of Vapor Cloud
  Model Run: Gaussian
  Red   : 432 yards --- (30000 ppm = 60% LEL = Flame Pockets)
  Yellow: 1169 yards --- (5000 ppm = 10% LEL)
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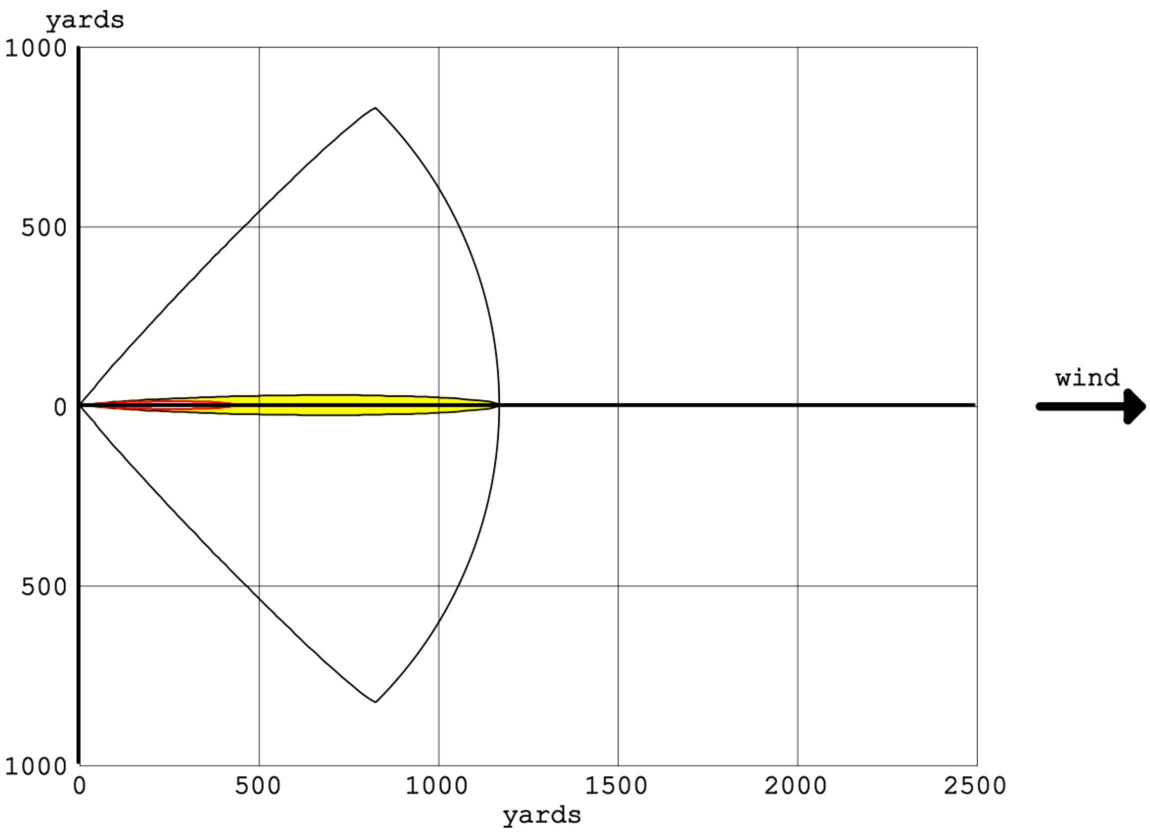


greater than 30000 ppm (60% LEL = Flame Pockets)
greater than 5000 ppm (10% LEL)
wind direction confidence lines

Results of the ALOHA model with a 5mph wind. In this case, the threat zone is about 432 yards, with a safety zone of over 1000 yards. Results will vary with wind speed and atmospheric conditions.

Ship incident in the arctic

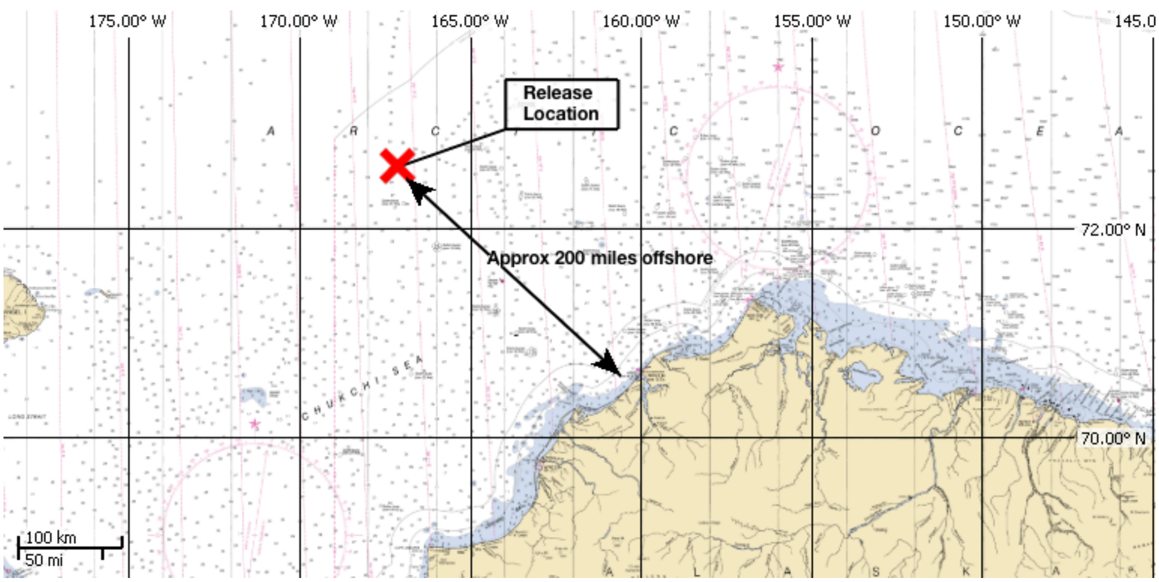
With the decrease in arctic ice with climate change, shipping has increased in arctic regions, and it is anticipated that it will continue to increase in the coming years. In other regions, shipping accidents are the most common source of spills, and we expect that this will be the case in the arctic as well. An incident like this one is the most likely scenario that NOAA is likely to have to respond to with the new capabilities developed in this proposal.

Scenario Parameters:

Location	72.55°N – 167.13°W
Release Volume	7000 bbls
Instantaneous Release	
Oil Type	Alaska North Slope Crude
Forecast Duration	Four days

Model Configuration:

Coupled Ocean-Ice Model	US Navy ACNFS
Winds	NOAA GFS

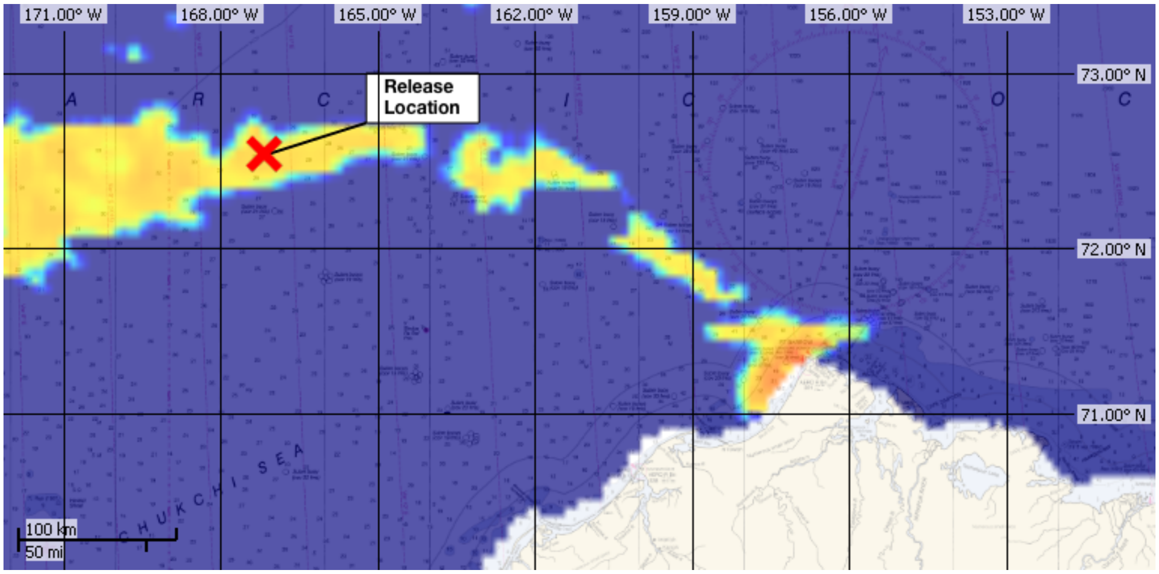


Location of the spill – approx. 200 miles off shore in the Chukchi Sea

Results

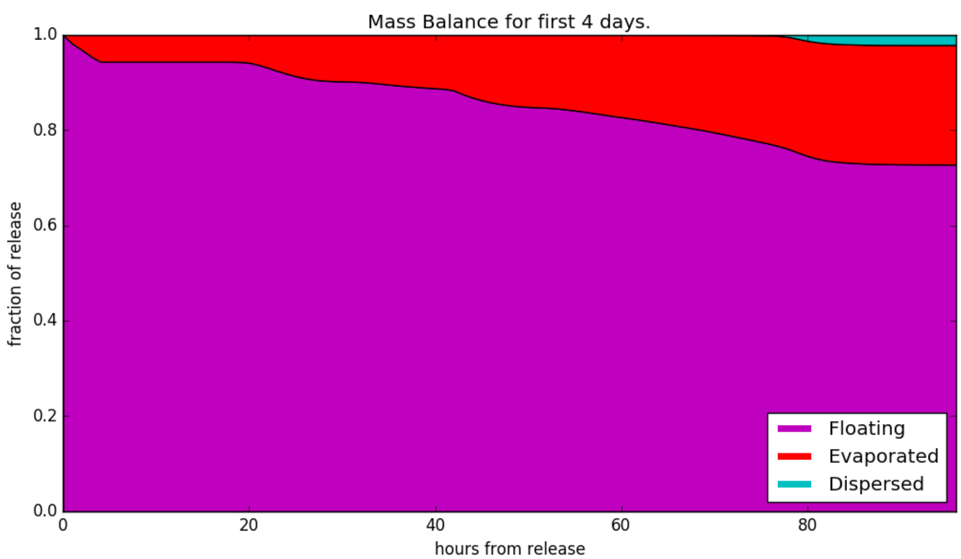
The location of this scenario is a bit unrealistic, but we wanted to use a location where the oil would encounter ice. In September, that required a location fairly far offshore. The ACNF model provides a four day forecast, so the model was run for that duration.

The initial release is in the middle of a finger of ice. The ice is not at 100% concentration throughout the spill, so the oil's movement and weathering are influenced by the changing ice concentration.



Location of ice in the ASNF model at the time of the release

Mass Balance

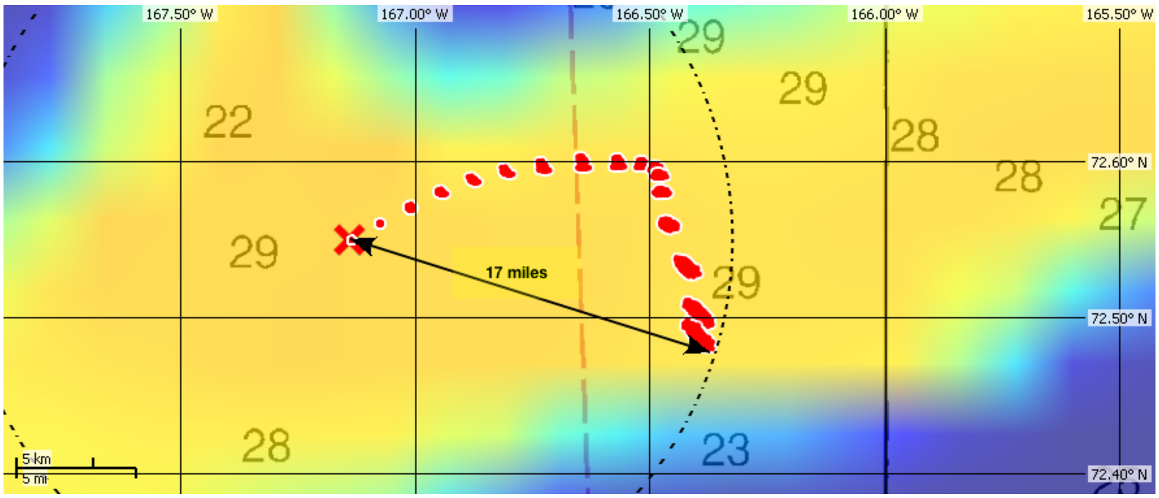


The Mass Balance for the four days of the simulation – with the low winds and ice, very little is dispersed.

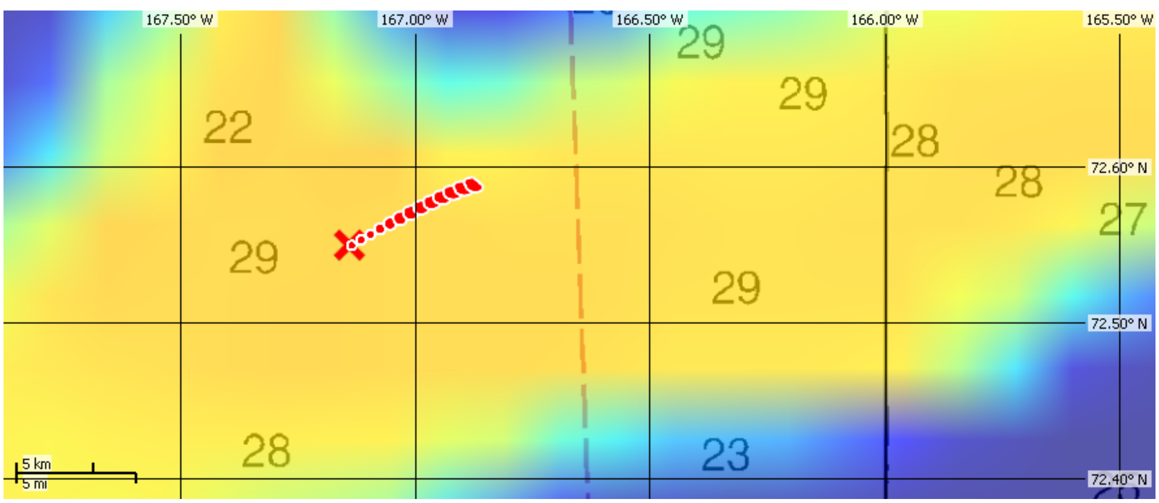
In this case, with fairly low winds and ice present, there is very little naturally dispersed. With low sediment loads, we expect little sedimentation, nor any emulsion formation. Note the kinks in the evaporation rate – the evaporation slows down considerably when the slick encountered higher concentration ice, and sped up lower concentrations. The small amount dispersed occurred in the last day, when there was in increase in wind speed, and decrease in ice concentration.

Trajectory

With the presence of ice, the overall movement of the oil was fairly small – a total of about 17 miles over the four days of the forecast.

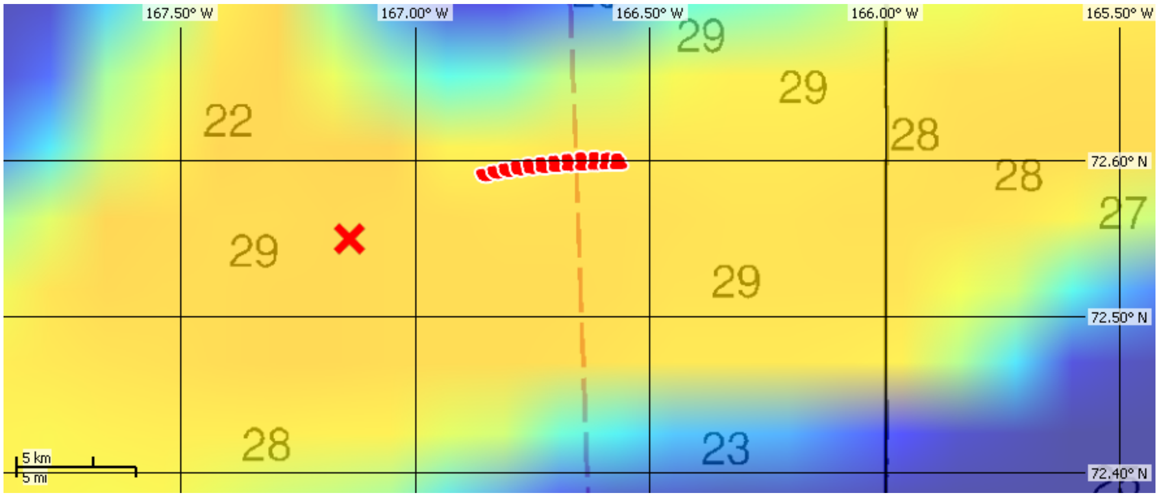


Position of the slick every 6 hours over four days.



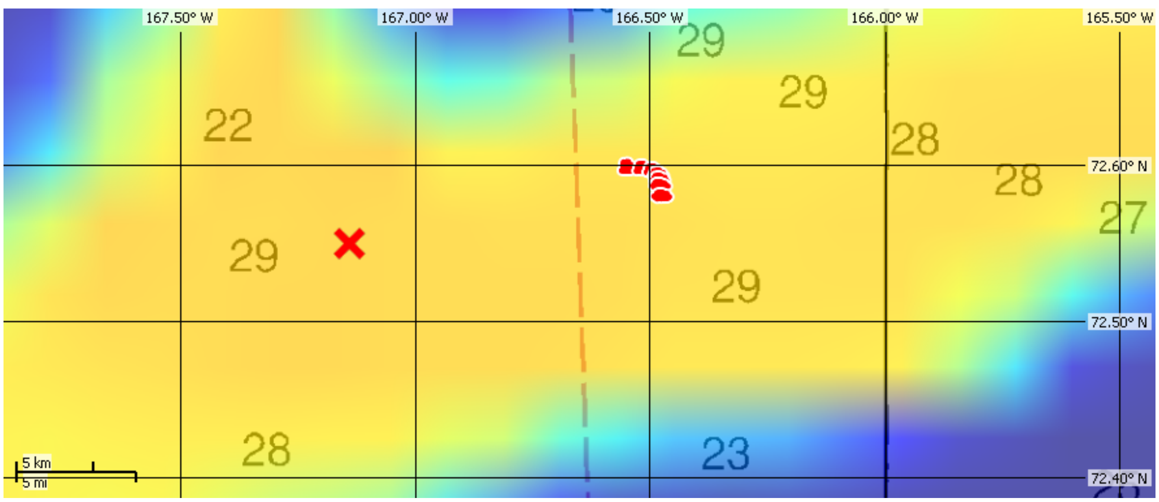
Movement of the slick on the first day.

On the first day, three was ice and current movement to the northeast.



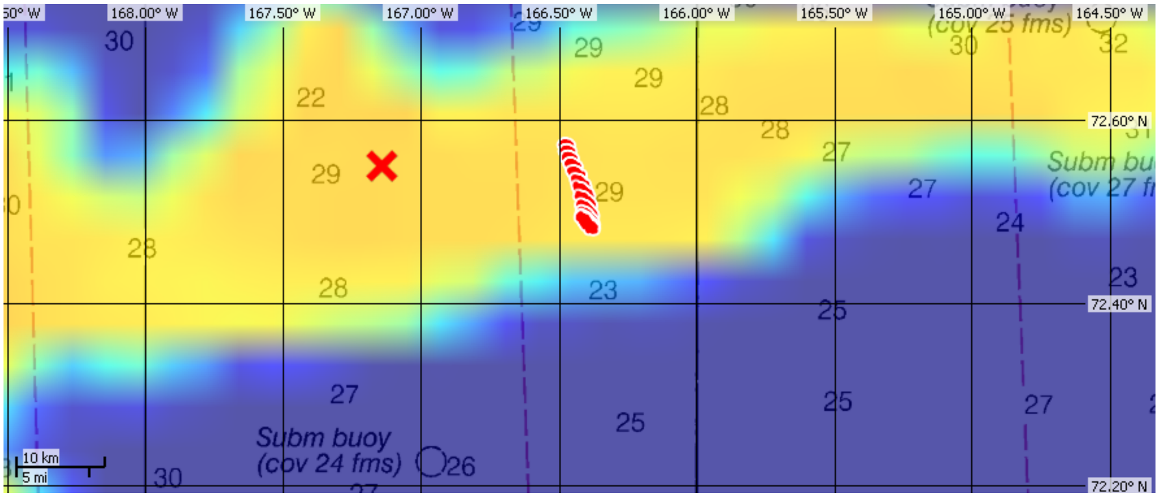
Movement of the slick on the second day.

On the second day, the movement fairly consistent.



Movement of the slick on the third day.

On day three the slick encountered thicker ice, resulting in slower movement. And then the wind shifted to be from the north.



Movement of the slick on the forth day.

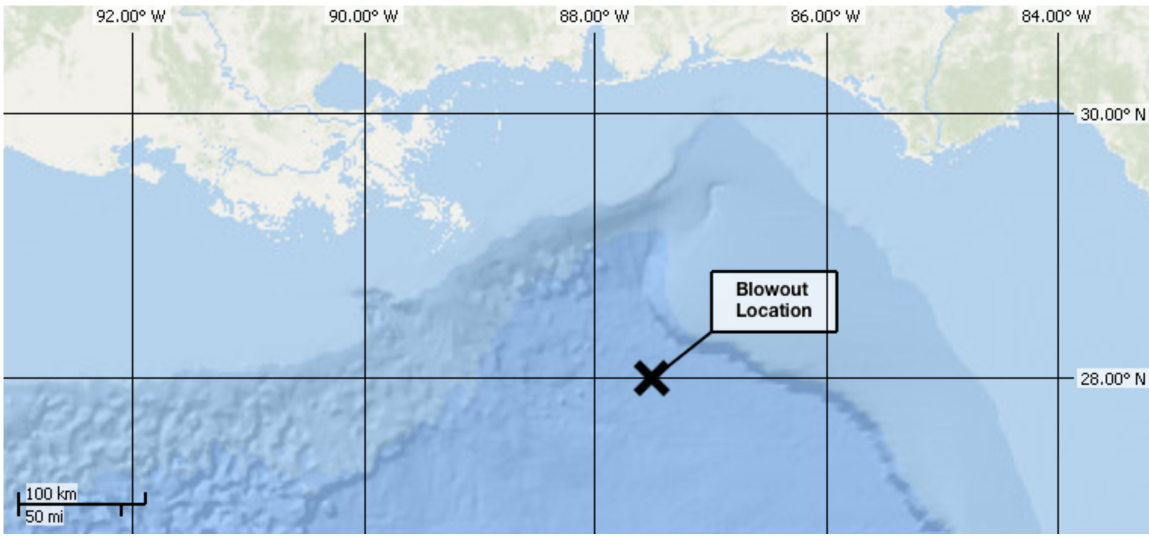
On the final day, the winds picked up from the north, as well as the ice thinning. This resulted in faster movement and bit more spreading. Note that this occurred at the same time as the dispersion event in the mass balance.

Deep water in the Gulf of Mexico

This project was focused expanding NOAA capability under arctic conditions. However, a major portion of the work was developing a coupling between the GNOME and TAMOC models. This coupling has facilitated modeling in non-arctic regions, such as the Gulf of Mexico.

Scenario Parameters:

Location	28.0°N – 87.5°W
Depth of release	2000m
Flow Rate	20,000 bbl/day
Oil Type	Louisiana Light Crude

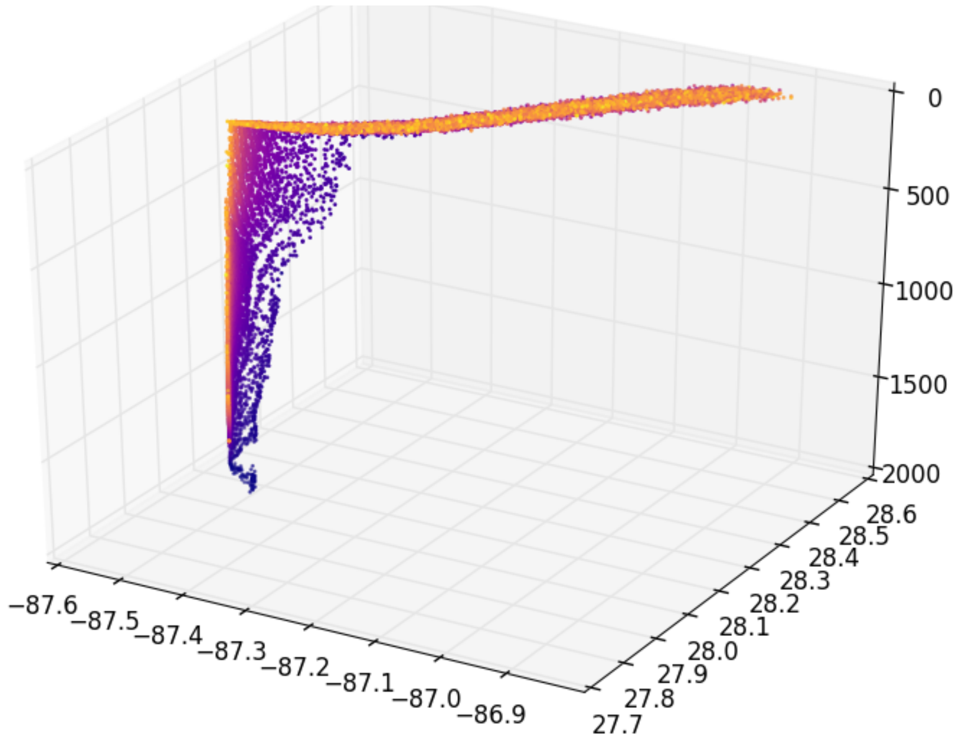


Model Configuration:

Oceanographic Circulation Model	US Navy HYCOM
Wind	NDBC Station: Station KIKT - Mississippi Canyon 474

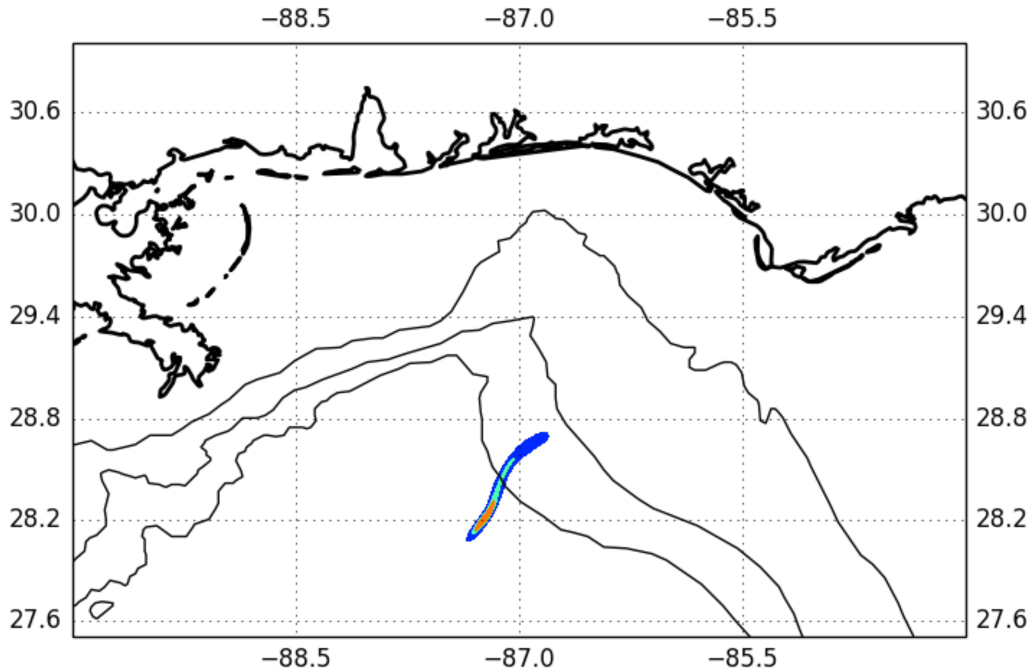
Results

With the currents at that time and depth, the plume is bent over by the currents, so the TAMOC bent plume model was used. Oil droplets are released from the plume at different locations depending on their size and density. The resulting droplets are passed to GNOME, and the GNOME model tracks them as they rise to the surface while being moved by the currents. The larger droplets rise faster, which results in a different path to the surface.



The plume rising to the surface. Elements are colored according to size. The dark purple dots are the smaller droplets, and the orange droplets are the largest droplets.

Once the droplets reach the surface, they form a surface slick, which is tracked by GNOME as it is moved by the wind and currents. Note that most of the surface slick is formed by the larger droplets.



Surface Trajectory three days after the start of the release. The orange contour is the highest concentration of oil, where the plume is rising to the surface.

Arctic TAP

The TAP (Trajectory Analysis Planner[6]) tool is designed to provide understanding about the likely distribution of oil from a spill at some unknown time in the future. Where oil goes after a spill is highly dependent on the wind and current conditions at the moment of the release. When planning for a possible spill in the future, there is no way to know what those conditions might be. TAP addresses this issue by running the GNOME spill model thousands of times, driven by historical conditions as provided by in-situ measurements and model hind casts. The result is a database of possible spill behavior that can be analyzed for statistics of spill behavior.

With Shell Oil about to get approval to do some exploratory drilling in the Arctic and with the increase in shipping traffic due to receding ice coverage there was a need to improve planning for oil spills in the arctic. The NOAA Restoration Center approached ERD with the idea of doing an Arctic TAP project. A proposal was submitted to National Fish and Wildlife Foundation (NFWF) in FY15, and funding was acquired for FY16.

NOAA has been developing TAP datasets for various locations for many years. With the new oil-in ice capability developed as part of this project, it was now possible to apply the TAP methodology to the arctic, including both summer and

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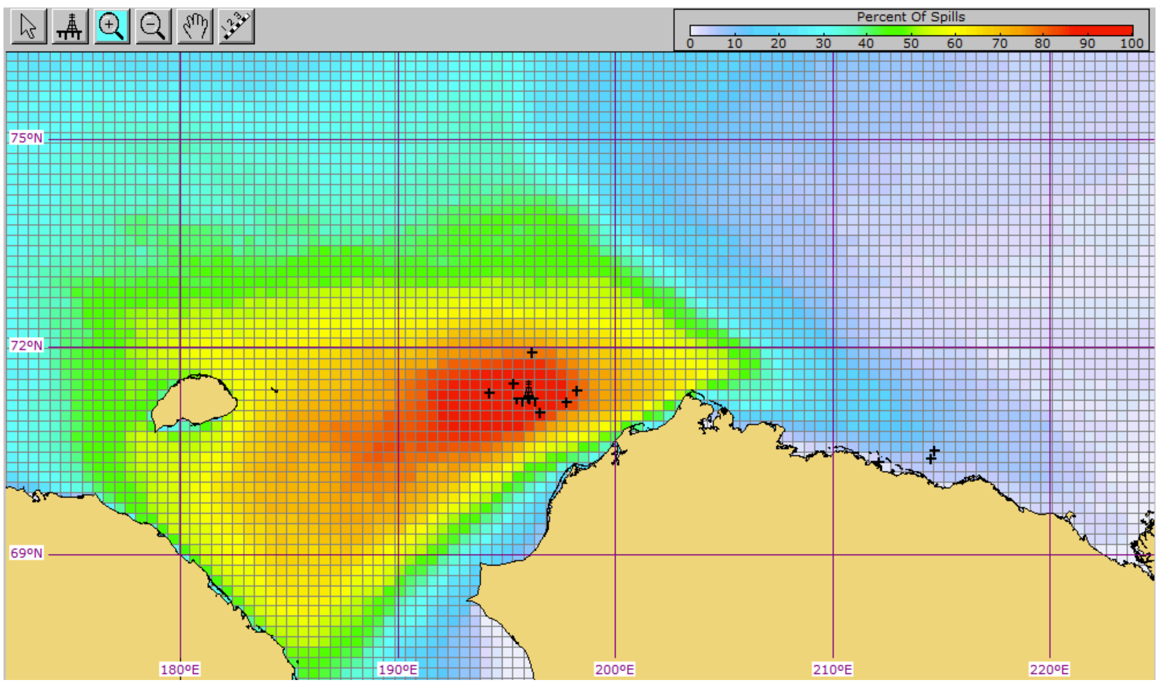
[6] http://response.restoration.noaa.gov/tap

winter conditions. The project has resulted in ERD successfully utilizing the new oil in ice enhancements implemented for GNOME for this project.

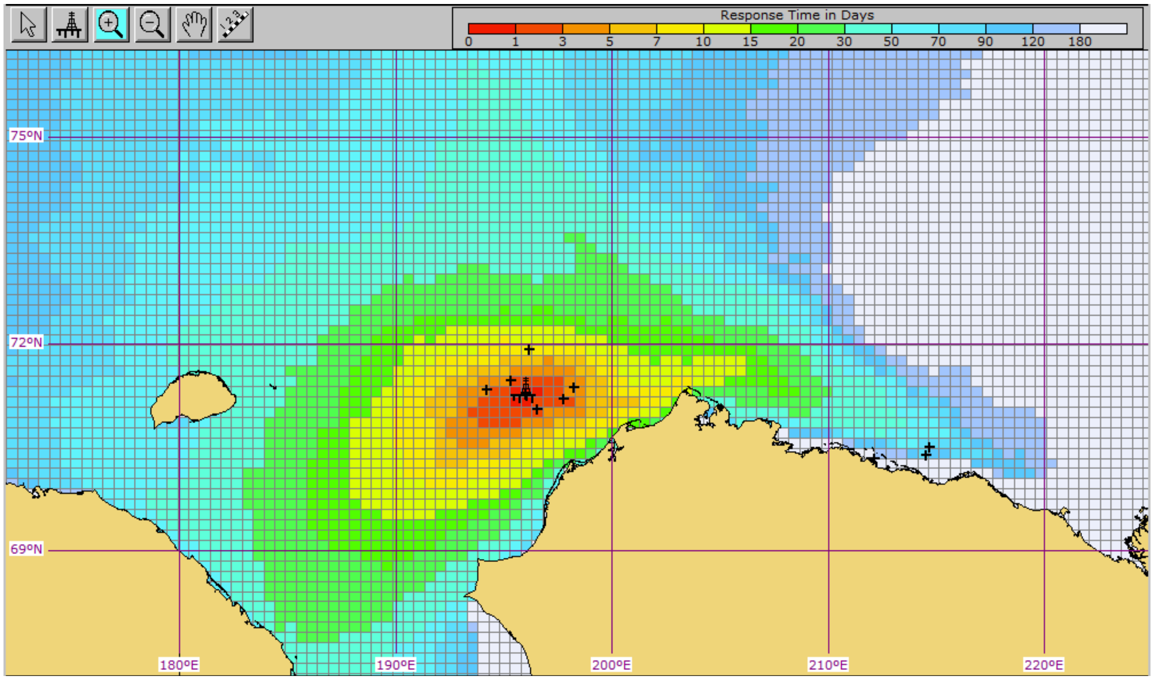
For Arctic TAP, possible well blowouts are simulated at current and likely oil platform sites in the Chukchi and Beaufort Seas. For each site, 500 instances of the GNOME model are run, each with a set of environmental conditions drawn from the historical record. Each GNOME run simulates a spill of 30 days duration, and the oil is tracked for a total of 180 days, often spanning the freeze-up or melting of the sea ice.

The GNOME model was run using water and ice velocities from a coupled ocean/sea ice Regional Ocean Modeling System (ROMS)[7] model of the Arctic developed for BOEM. The model has resolution of 4-5 kilometers in the Beaufort and Chukchi Seas and larger grid spacing for the rest of the Arctic Ocean. The algorithms outlined above were applied in GNOME, using the ice concentration and movement data from the ROMS model.



TAP Impact Analysis results for a 10,000bbl release. The colors correspond to the probability of oil reaching each location in the grid.

[7] https://www.myroms.org/



TAP Response Time Analysis results for a 10,000bbl release. The colors correspond to the amount of time likely to be available to mount a response. The red areas correspond to 0-3 days, the green corresponds to 15-20 days before the oil will reach that location.

Future Work

NOAA will continue to develop its modeling capability. The GNOME model is under active development, both in improving algorithms and improving usability for operational response. In particular we are keeping an eye on various Joint Industry Projects (JIP) from the API and OGP that seek to better understand the behavior of oil in ice and response options. When new understanding becomes available, NOAA will include updated algorithms it its modeling suite.

Dr. Socolofsky continues to improve the TAMOC model. In particular, he is working with the University of Alaska at Anchorage on a project funded by the DHS Arctic Domain Awareness Center (ADAC)[8]. This project (http://adac.uaa.alaska.edu/home/project_3_oil_spill) is focused on predicting the spread of the oil under the ice when the ice is not smooth. No one has tried this before because it is so difficult to characterize the under ice roughness. In order to test the approach, they will be coupling TAMOC with an under-ice spreading code. If the approach works well, then NOAA will work with ADAC to bring the method into the GNOME model. As part of this work, Dr. Socolofsky expects to improve the translation methods for swapping oil composition data between

[8] http://adac.uaa.alaska.edu/home/project_3_oil_spill

TAMOC and GNOME (TAMOC and GNOME currently use different approaches for describing oil composition).

Of significant interest also is the OGP's Arctic Response Technology program, particularly the Oil Spill Trajectory Modeling in Ice project[9]. In the early days of the project, it was decided that a primary limiting factor in the ability to model oil in ice was the quality of the ice models themselves. So the first phase of the project was to develop better ice forecast models. If and when these new models becomes operational, NOAA will adapt GNOME to be able to ingest the model results. In addition, if the final phase of the project results in any new algorithms for modeling the oil transport in ice, NOAA will consider adding those methods to the GNOME system.

[9] http://www.arcticresponsetechnology.org/research-projects/oil-spill-trajectory-modelling-in-ice

Appendix A: Oil and Gas Blowout Simulations in the arctic with TAMOC Stratified Plume Model

Input parameters used for the simulations

Simulations are carried out with the Stratified Plume Model and the Bent Plume Model in the Texas A&M Oil Spill Calculator (TAMOC). The input ambient salinity and temperature are extracted from Profile Ice Tethered Profiler-21 in the Beaufort sea in August 2008 and February 2009. They are shown in **Figure. 1**. They are obtained from the http://www.whoi.edu/itp. The other release parameters are shown in the Table. 1. The simulations are repeated for the depths shown in the table for the two scenarios of ambient salinity and temperature conditions mentioned above with the Stratified Plume Model. The Bent Plume Model simulations are done for the two scenarios but only for the 350 m depth with uniform currents of 0.07 m/s and 0.02 m/s in x and y horizontal directions which are perpendicular to each other. The release fluid composition used in the simulations is shown in the **Table. 2**.

Table. 1: Input data used for the simulation

Parameter	Value
Release depths (m)	350, 100, 50, 25, 10 350, 100, 50, 25, 10
Orifice Diameter (m)	0.3
Release Flowrate (bpd)	20000
Release Temperature (°C)	150

Table. 2: Release fluid composition

Compound	Mass Fraction GOR = 2000
carbon_dioxide	0.000529539
nitrogen	0.001251952
methane	0.17017256
ethane	0.033079719
propane	0.033275299
isobutane	0.009591083
n-butane	0.021979566
isopentane	0.0124018
n-pentane	0.015006179
n-hexane	0.031255196
C7+	0.671457107

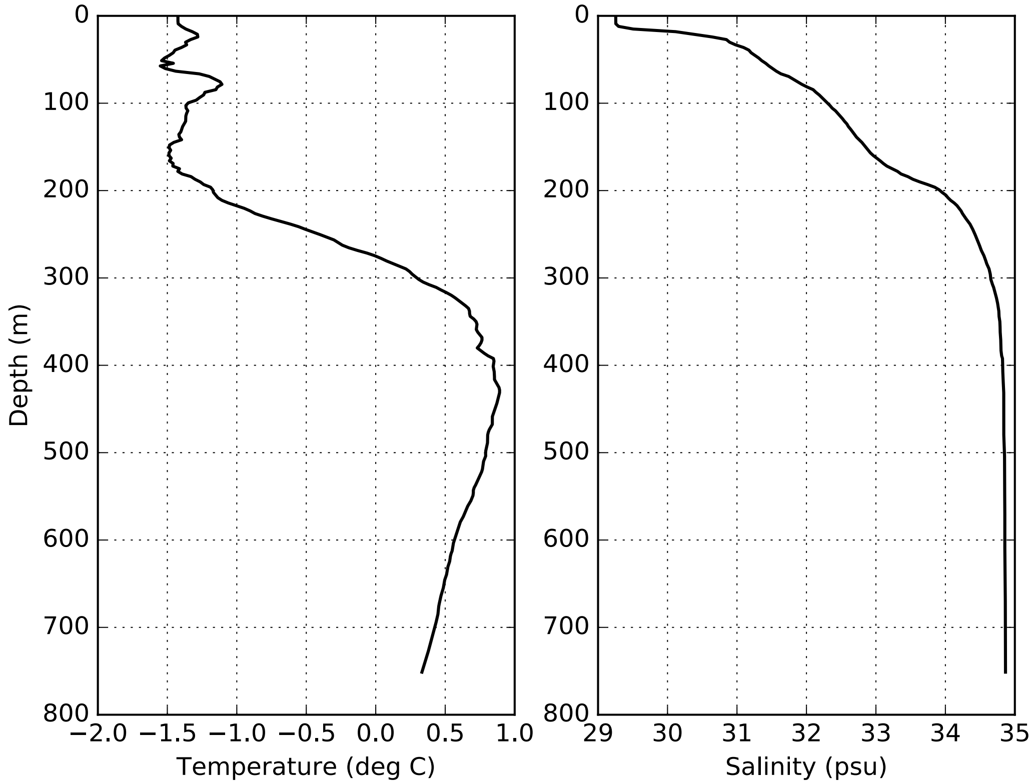


Figure. 1: Salinity and Temperature Profile extracted from Ice Tethered Profiler - 21 for August 2008- Scenario 1

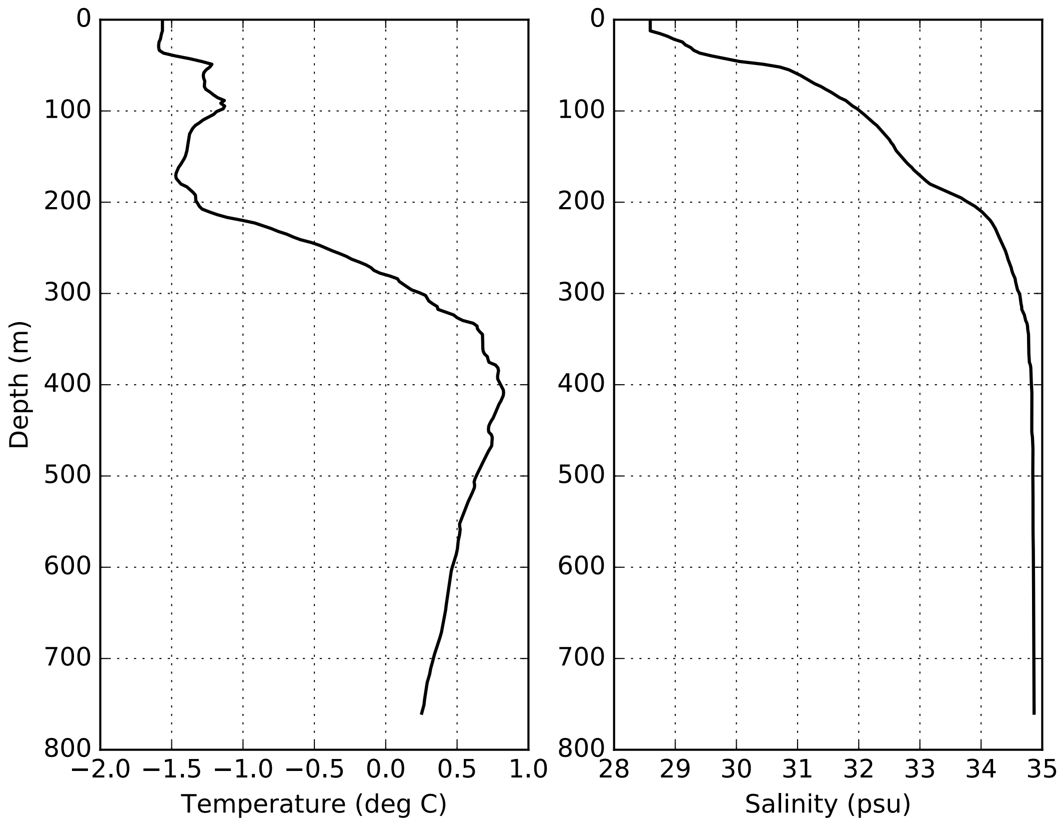


Figure. 2: Salinity and Temperature Profile Ice Tethered Profiler -21 for February 2009- Scenario-2

Variation of release fluid parameters

The variation of simulation release fluid parameters for the two scenarios, are shown explained in this section.

Scenario -1

When the simulations are carried out releasing live oil at different depths. Based on the release fluid equilibrium calculations at different release depths, the release flowrates of gas and liquid phases differ. They are shown in Figure. 3. As the depth reduces the mass fraction of gas phase increases while liquid phase decreases even though the total mass flux is the same for all the cases. The variation of gas phase and liquid phase densities at varying release depths are shown in Figure. 4. When the release depth is reduced the density of gas phase reduces while the density of liquid phase increases. This variation in gas and liquid phase mass fractions and the densities of released fluid at different depth cause the total release volume rates to increase with reducing depth and it is shown in the bottom subplot of Figure. 5. The top subplot of Figure. 5 shows that the plume release velocity increases with reducing release depth and it can be explained when looking at the variation in release volumes of the plumes.

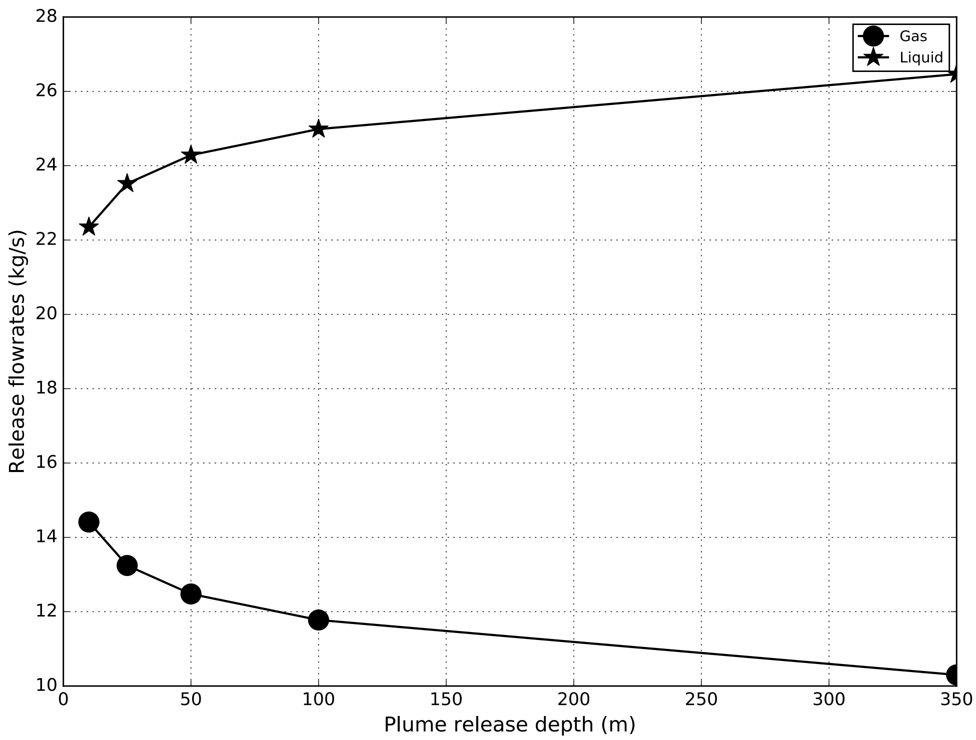


Figure. 3: Variation of release fluid flowrates with release depth- scenario -1

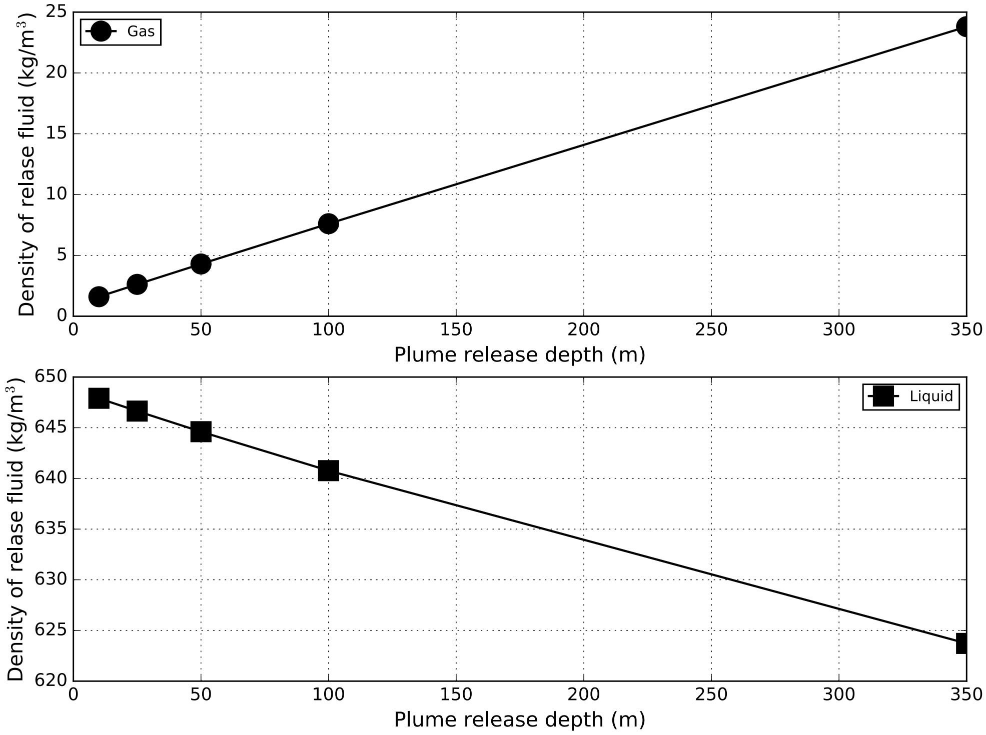


Figure. 4: Variation of plume release fluid densities with release depth - scenario -1

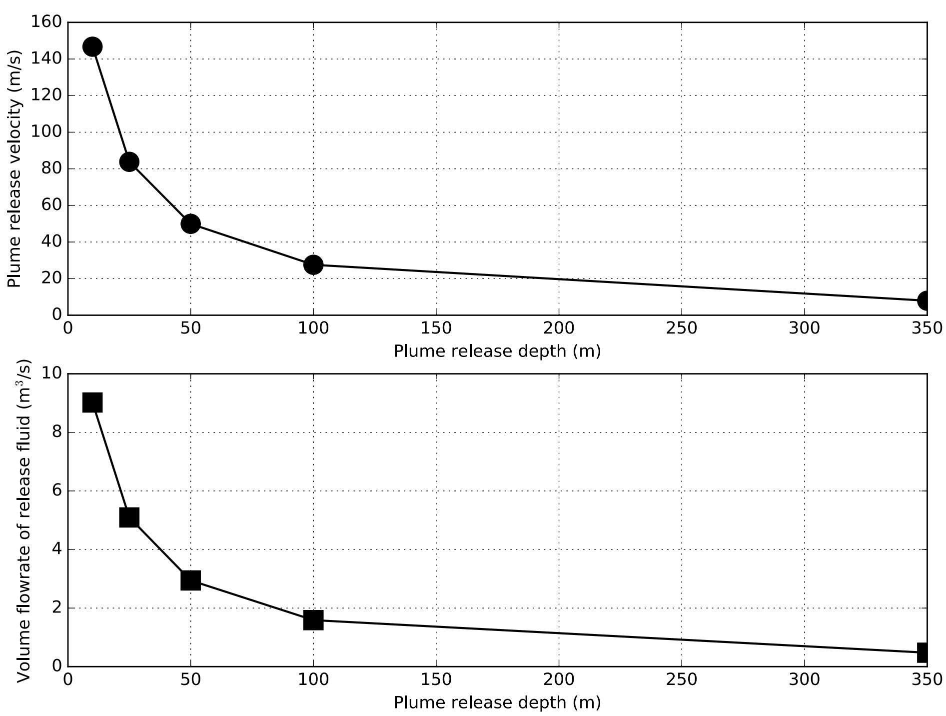


Figure. 5: Variation of plume release velocity and release volume with release depth - scenario -1

Scenario -2

A similar behavior to scenaio-1 is seen in the plume the release fluid parameters in the case of scenario -2 and they are shown in the following Figures from Figure. 6 to Figure. 8.

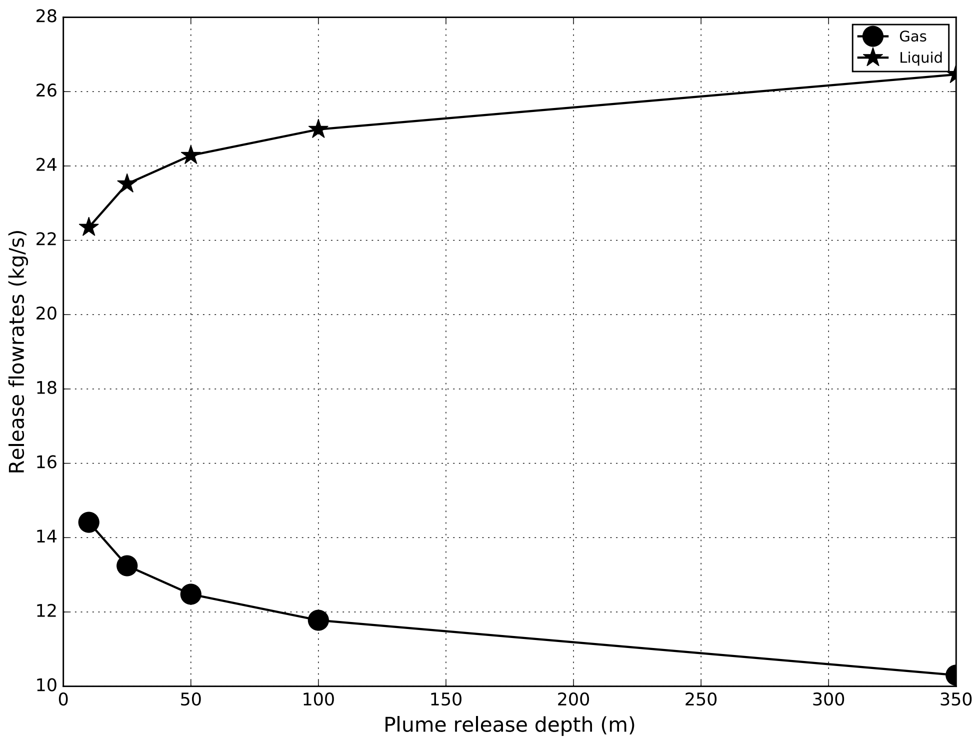


Figure. 6: Variation of release fluid flowrate with release depth - scenario -2

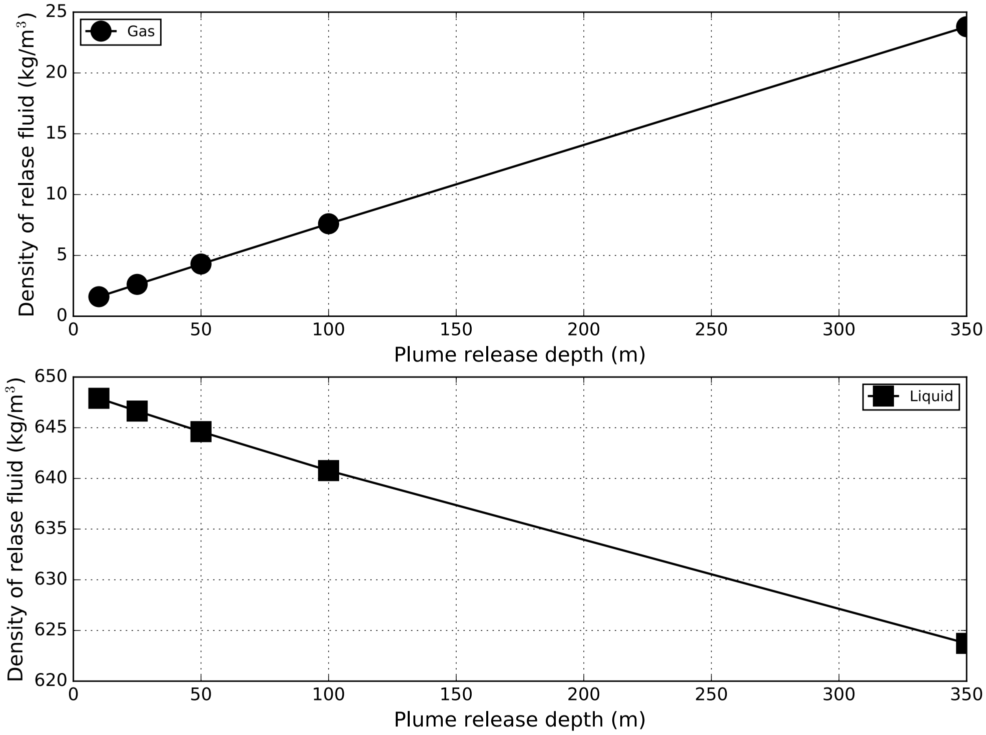


Figure. 7: Variation of plume release fluid densities with release depth - scenario -2

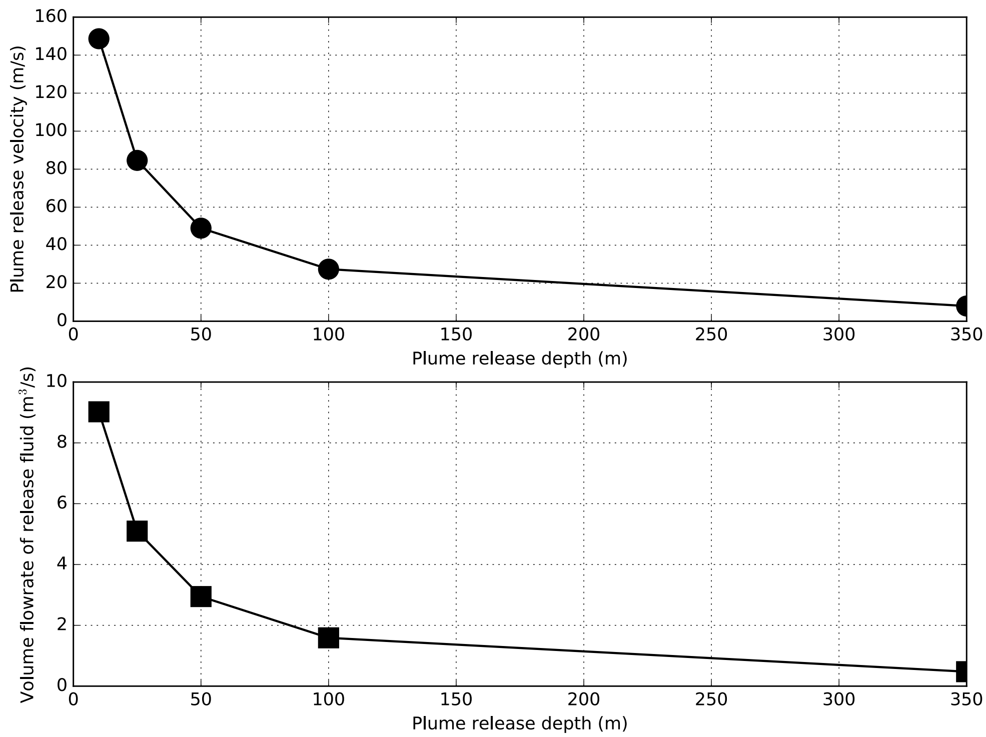


Figure. 8: Variation of plume release velocity and release volume with release depth - scenario -2

Results and Discussion

In contingency planning of oil and gas blowouts it is important to look at the variation of surface conditions formed by different plumes. The variation of plume surface parameters namely the plume fluid temperature, total surfacing area of the plume, variation of gas and liquid fluxes, the mix density of the plume, and the plume rise time are investigated in the simulations presented here for the two scenarios considered in the simulations.
All the plume simulations with Stratified Plume Model predicts the plume to reach the surface

Stratified Plume Model - Scenario -1

The model results for the scenario 1 are presented and discussed in this section.

The variation surface plume temperature is shown in Figure. 9. Even though the release fluid temperature is 150 °C due to the entrainment of cold ambient water causes the dissipation of heat exponentially, therefore the surfacing plume does not vary a lot compared with the ambient water temperature. Figure. 10 shows the surfacing plume area and it is getting reduced for different plumes when the release depth is reduced. In the simulations presented, only the plume released at 350 m depth detrains the plume fluid before reaching the surface as shown in Figure. 11. All the other plumes reach the surface without creating any deepwater intrusions. Figure. 13 , demonstrate this for the plumes released at 100, 50, 25 and 10 m depth respectively. Surfacing gas and liquid phase flowrates for different cases are shown in Figure. 16. For the shallow cases the surfacing gas fluxes are higher when compared with deeper cases and it is the opposite for the surfacing liquid fluxes. This can be explained when comparing with the release fluxes of the two phases as shown in Figure. 3. For the shallow and high volume flowrate releases the initial plume velocities are much higher compared with the deeper cases and it is shown in Figure. 5. As expected these high release velocities and shallow release depths makes the plumes released at shallower depths to reach the surface much faster compared to the plume release at deeper levels in the water column and this variation of plume surfacing time is shown in Figure. 17. In the areas where the bubble and droplet plumes are surfaced in water bodies, the mix density of surfacing plume water may vary compared with the surrounding water. The ships and other floating structures rely on the buoyancy from the water for their stability. Therefore, it is important to investigate the change in this density caused by the bubble or droplet plumes. Figure. 18 shows the mix density variation of the surfacing plumes. The plumes released at shallow depths have the lowest mix density in the surfacing waters because the volume of dispersed phases (bubbles and droplets) are highest in these plumes.

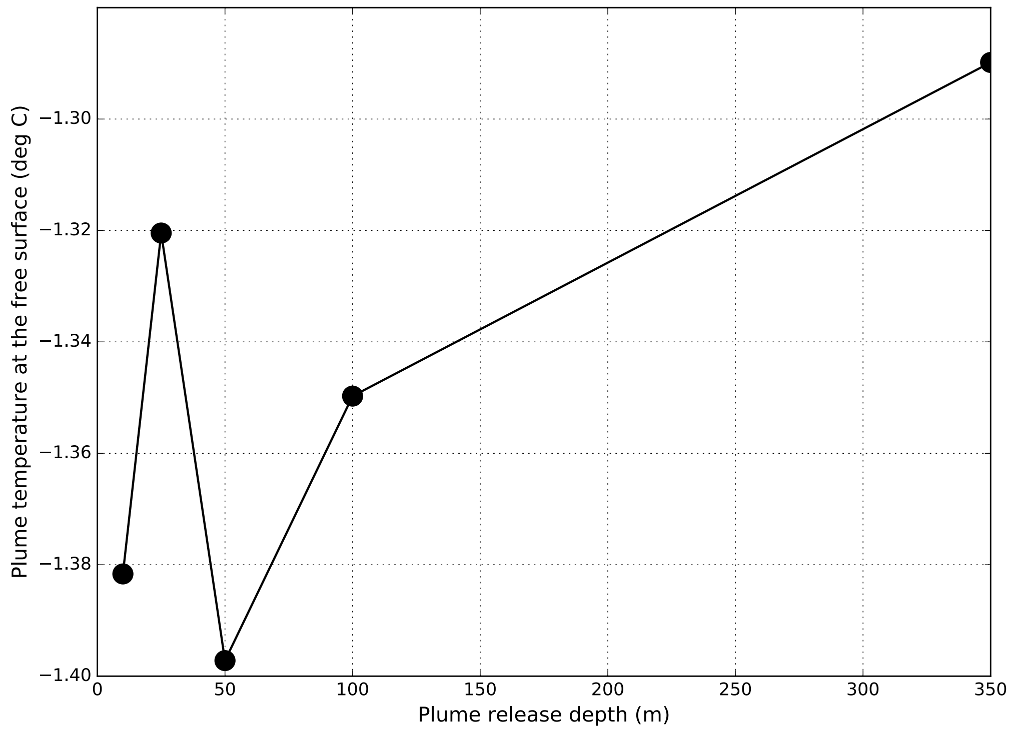


Figure. 9: Plume temperature variation at the surface for plumes released at different depths - scenario -1

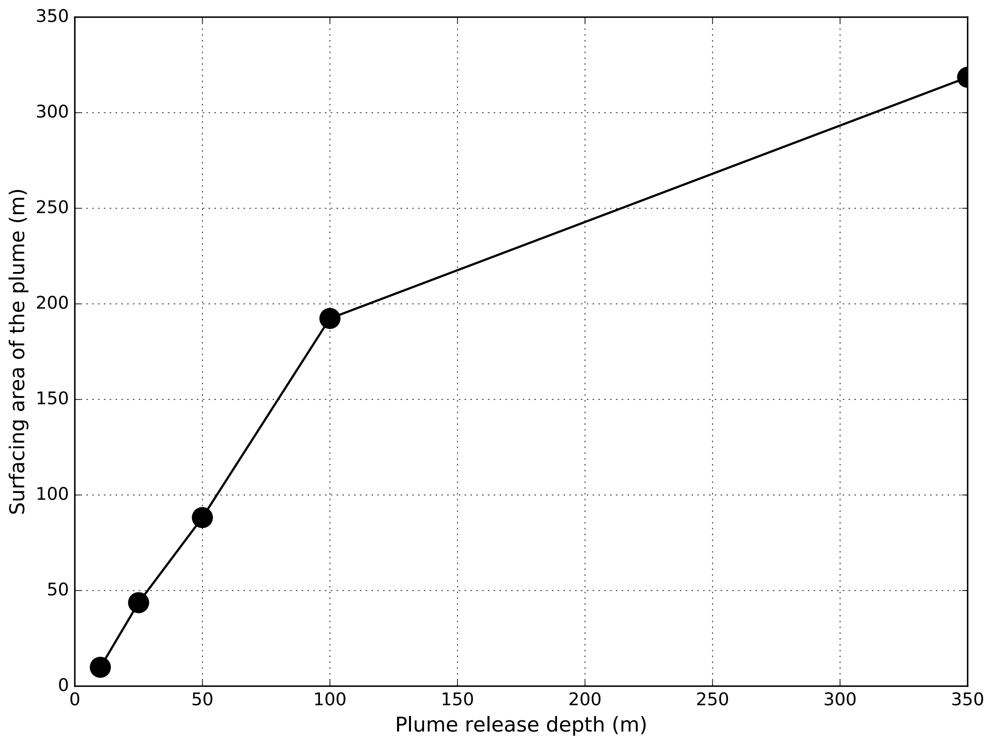


Figure. 10: Plume surface area variation for plumes released at different depths - scenario -1

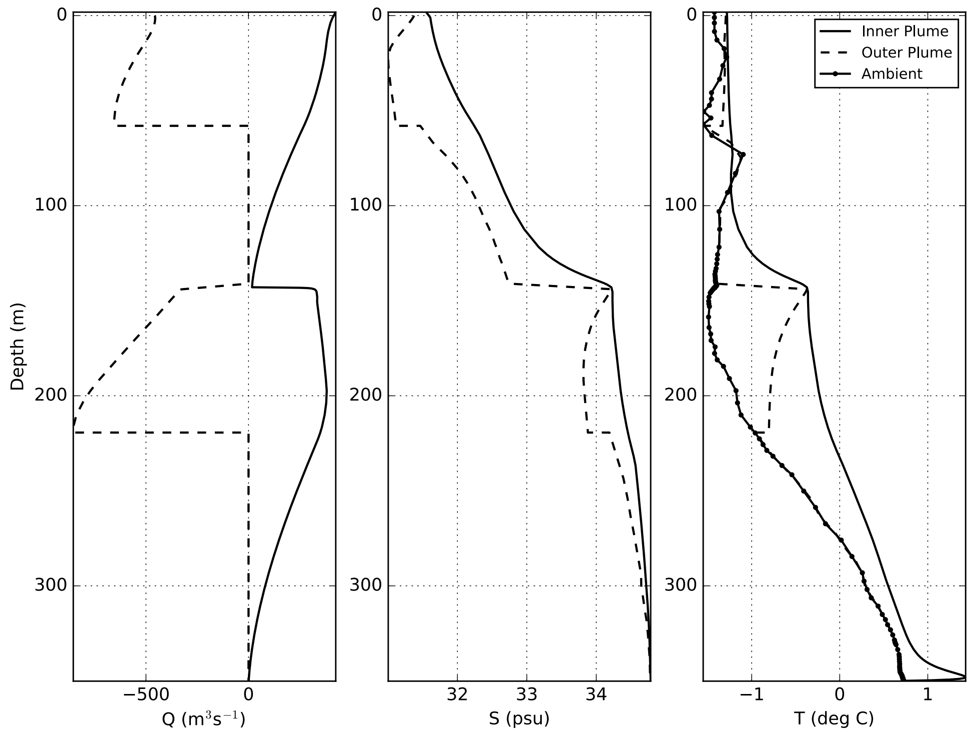


Figure. 11: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 350 m depth - scenario -1

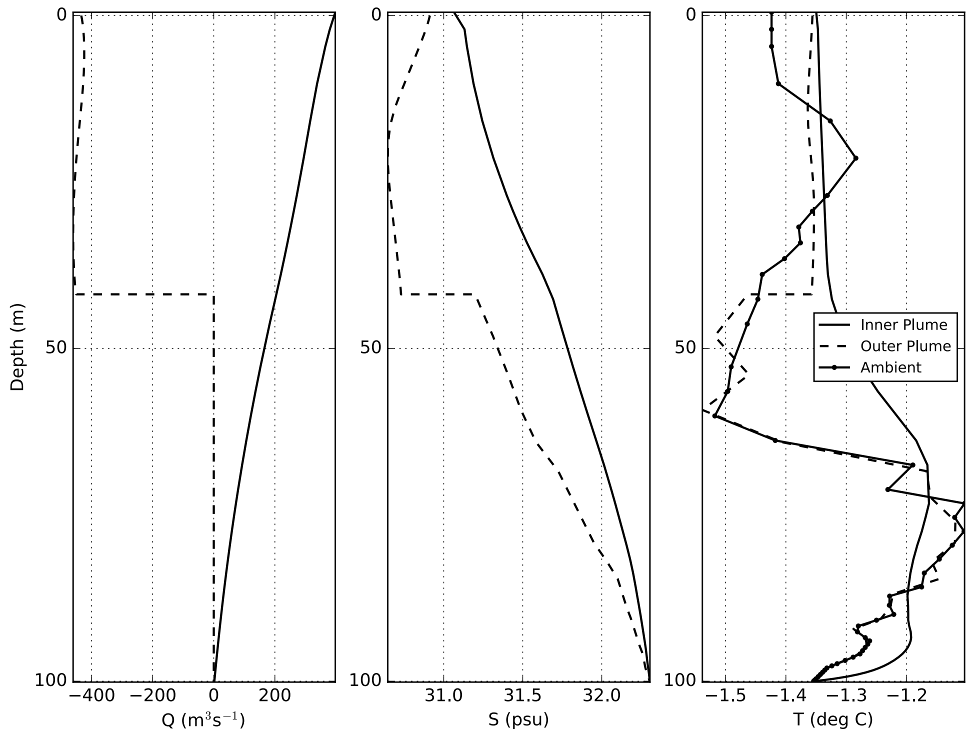


Figure. 12: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 100 m depth - scenario -1

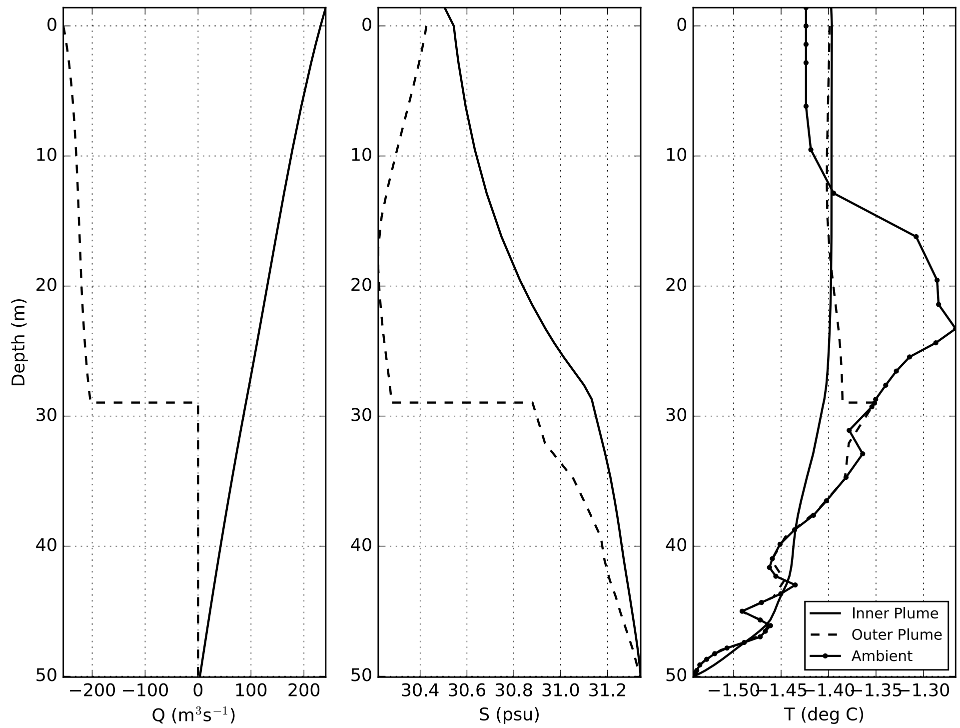


Figure. 13: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 50 m depth - scenario -1

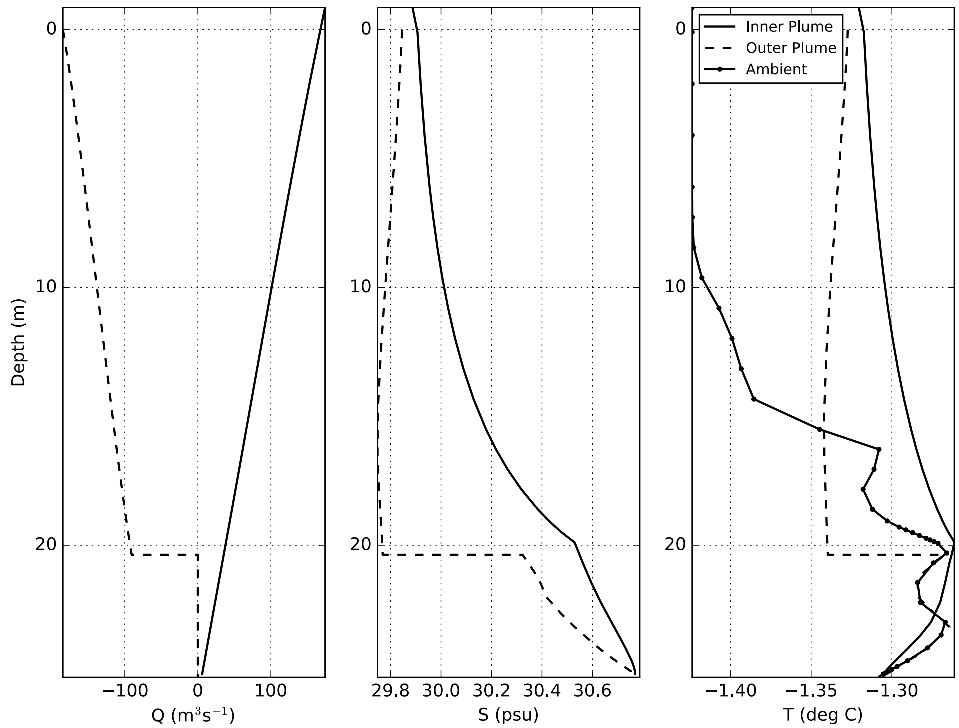


Figure. 14: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 25 m depth - scenario -1

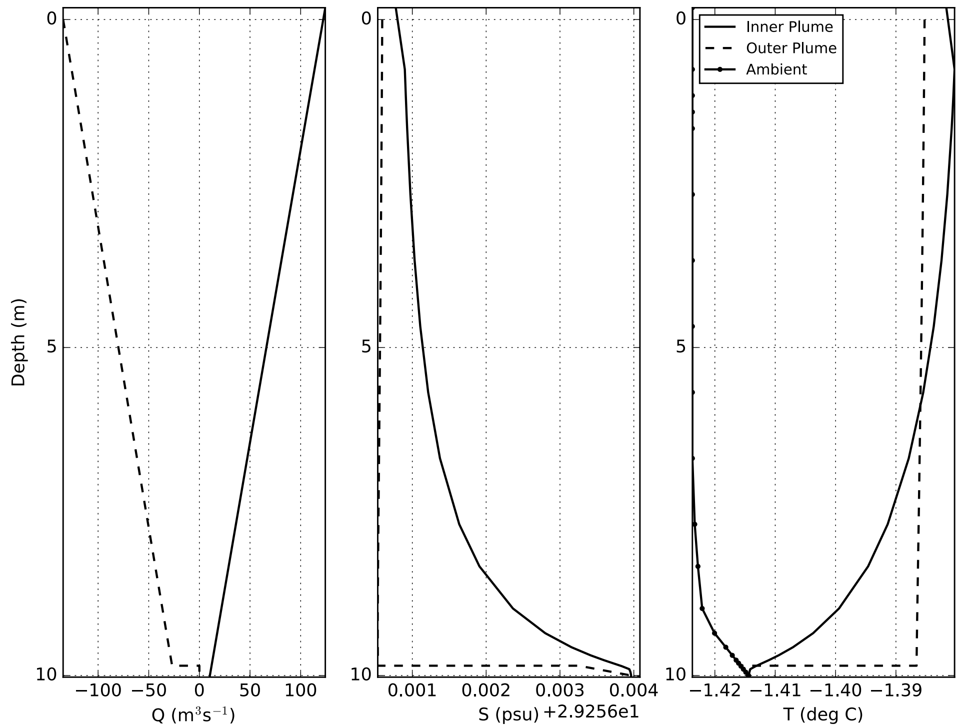


Figure. 15: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 10 m depth - scenario -1

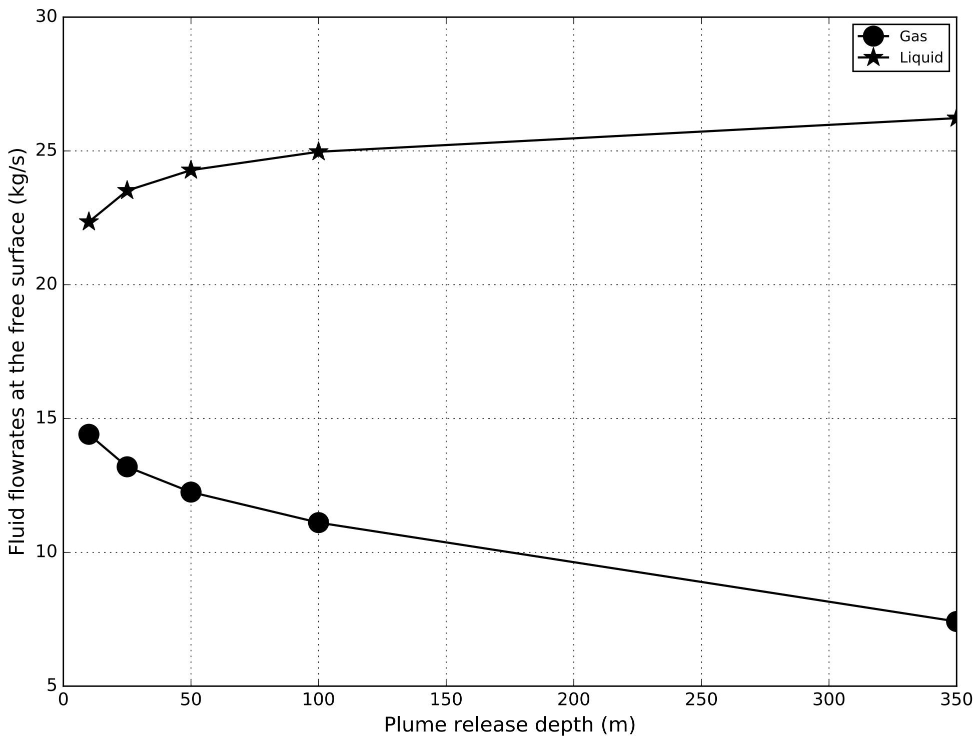


Figure. 16: Gas and liquid flowrate variation at the surface for plumes released at different depths - scenario -1

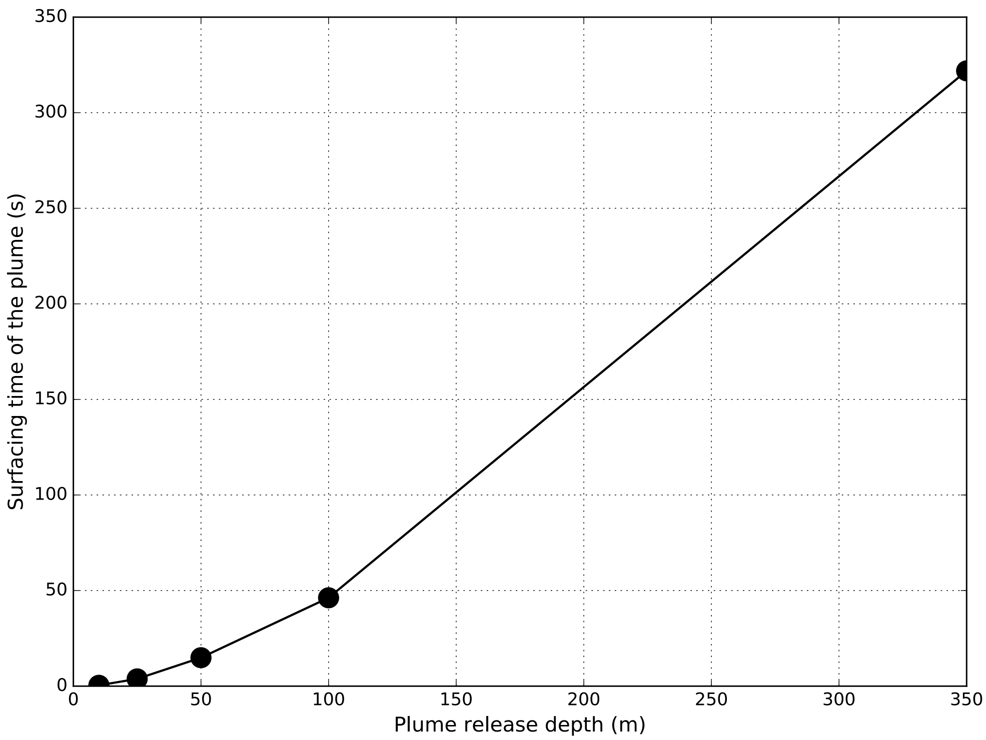


Figure. 17: Gas surfacing time variation for plumes released at different depths - scenario -1

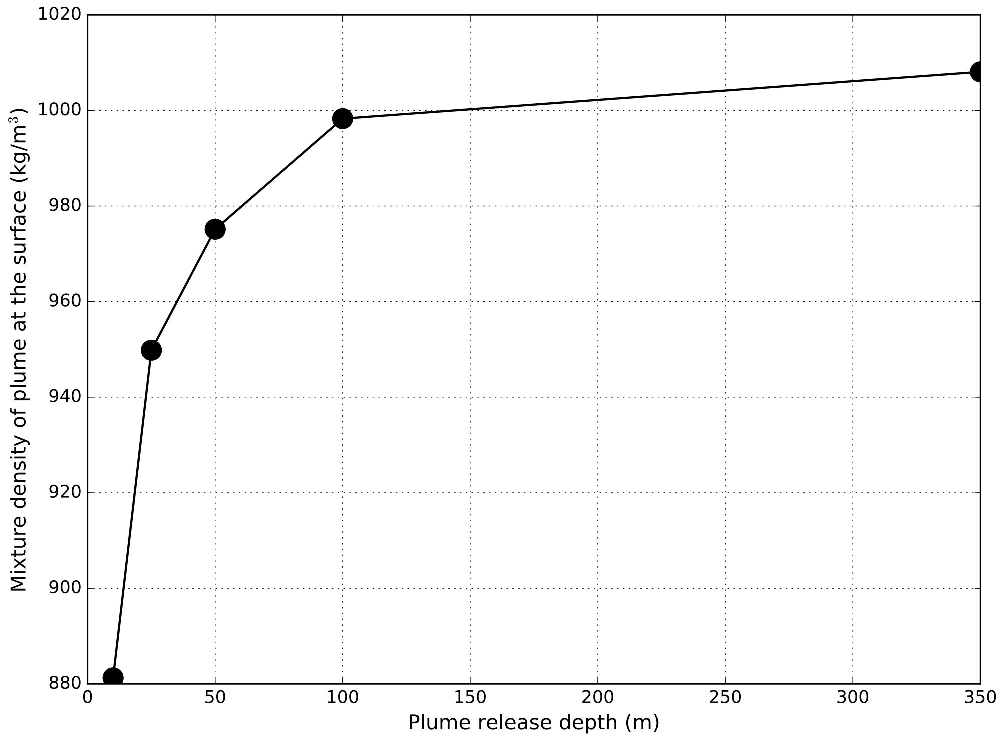


Figure. 18: Variation of mix density of plume fluid at the surface for plumes released at different depths - scenario -1

Stratified Plume Model - Scenario -2

The model results for the scenario 2 are presented in this section and the behaviors of model parameters are similar to the scenario 1 because the two ambient profiles used for the two scenarios (**Figure. 1** and **Figure. 2**) do not differ significantly.

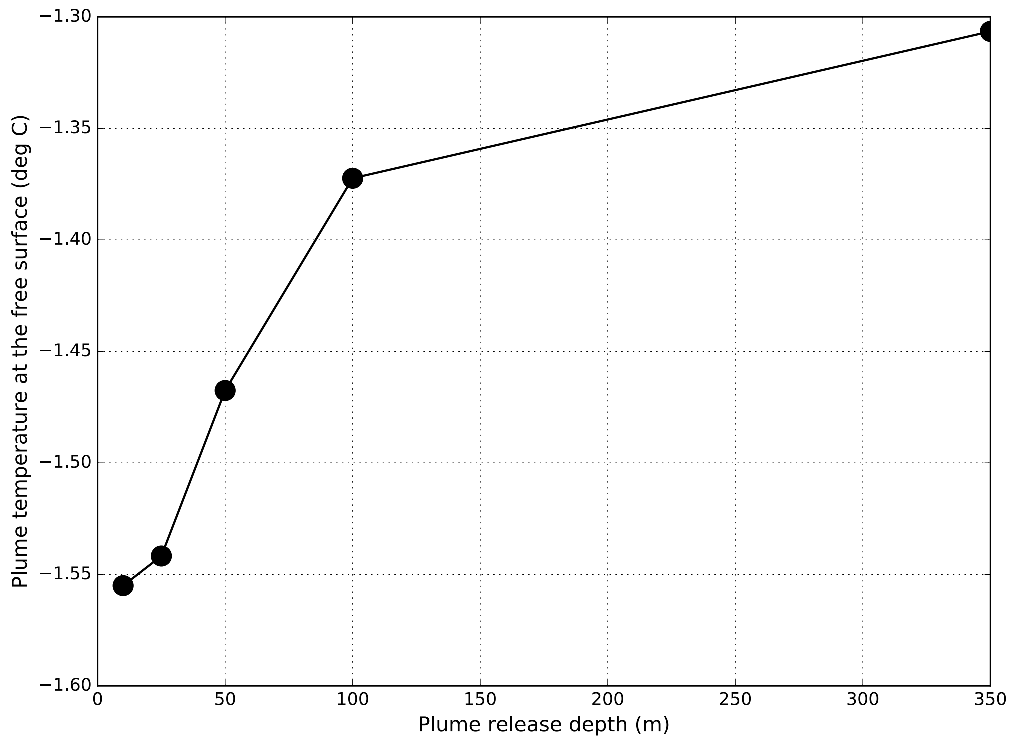


Figure. 19: Plume temperature variation at the surface for plumes released at different depths - scenario -2

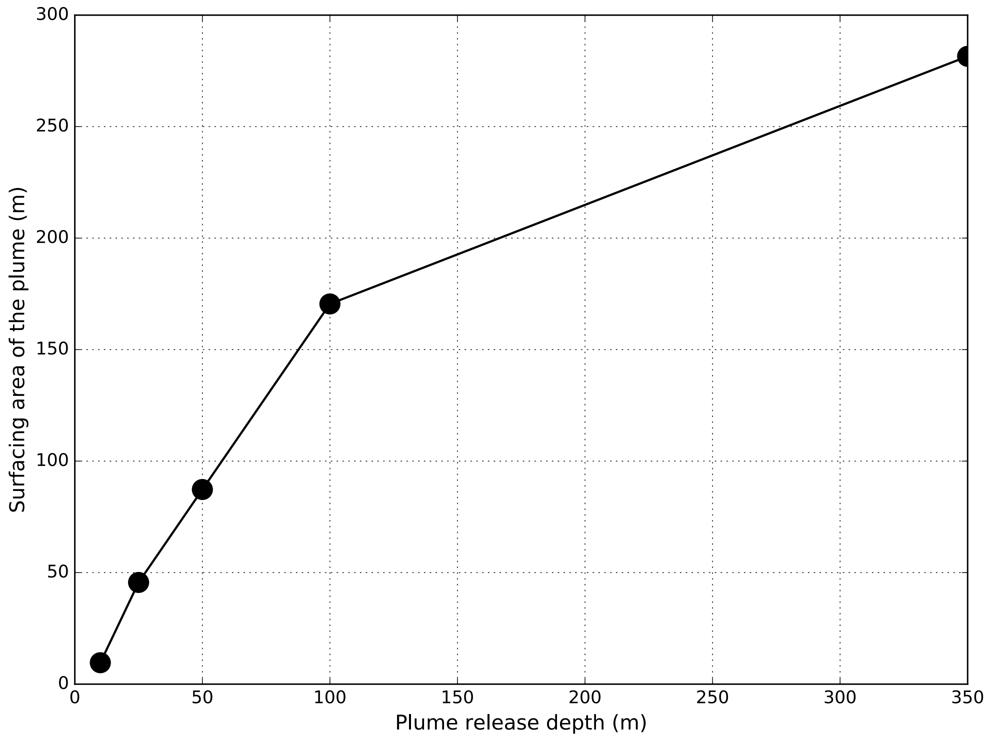


Figure. 20: Plume surface area variation for plumes released at different depths - scenario -2

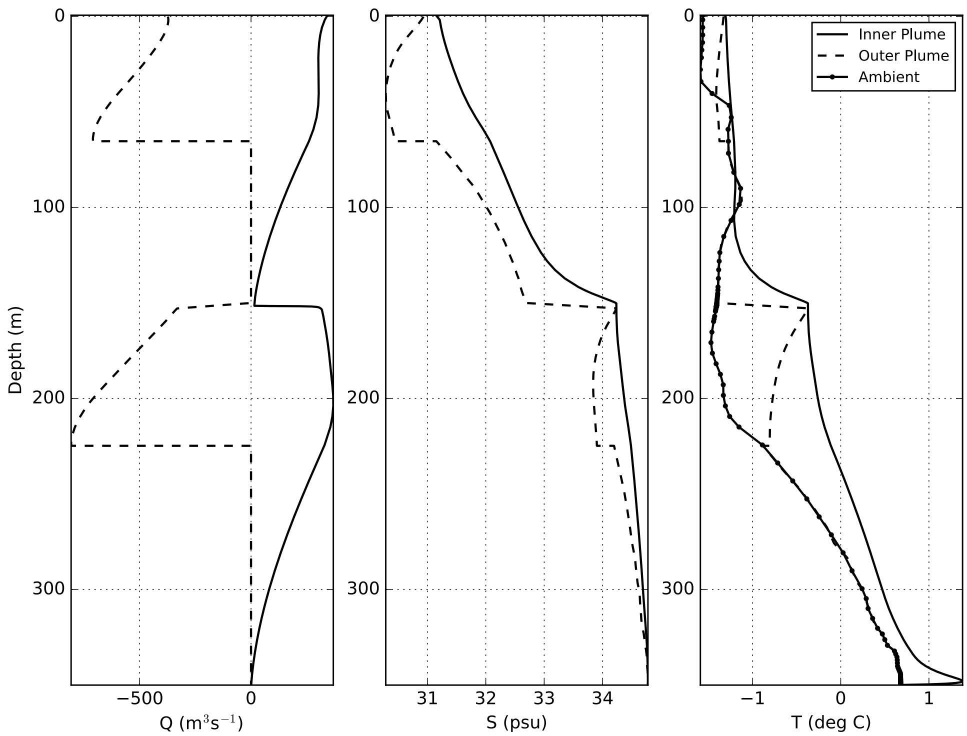


Figure. 21: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 350 m depth - scenario -2

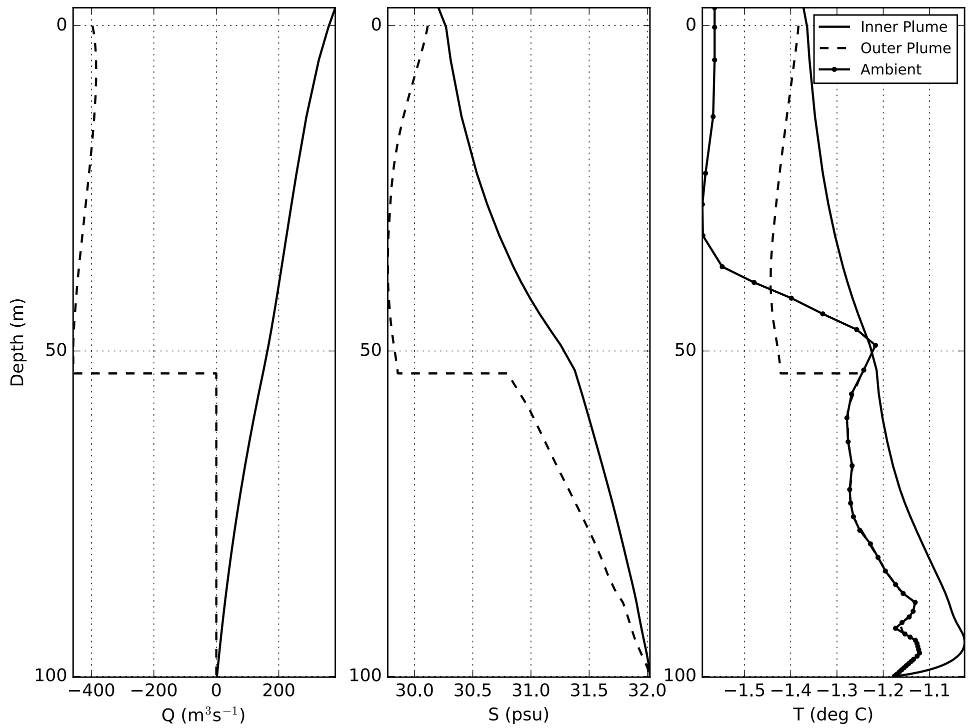


Figure. 22: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 100 m depth - scenario -2

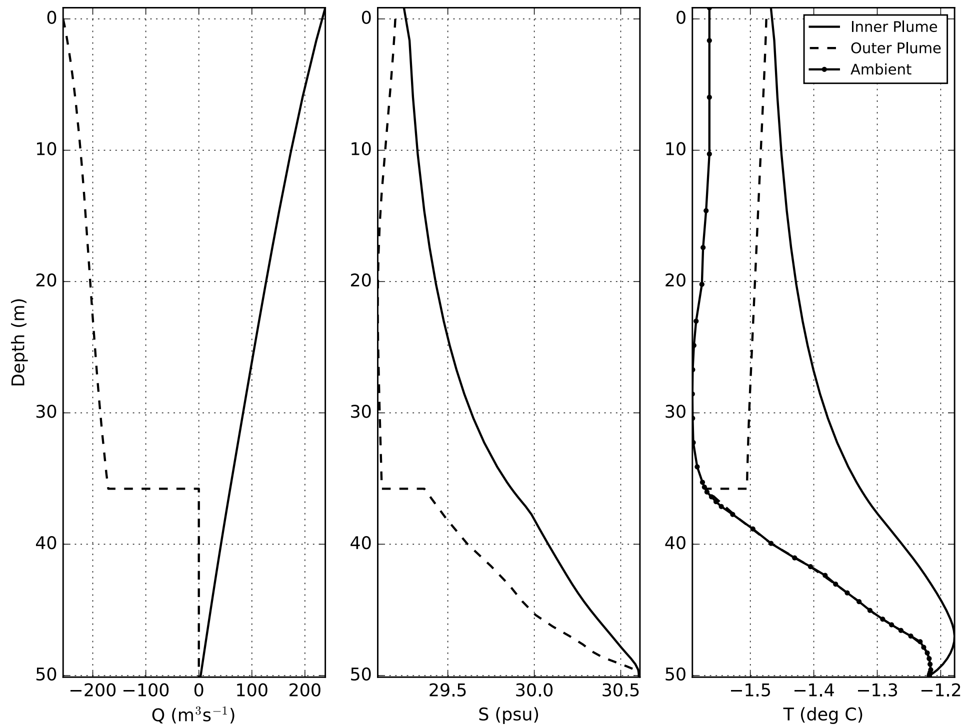


Figure. 23: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 50 m depth - scenario -2

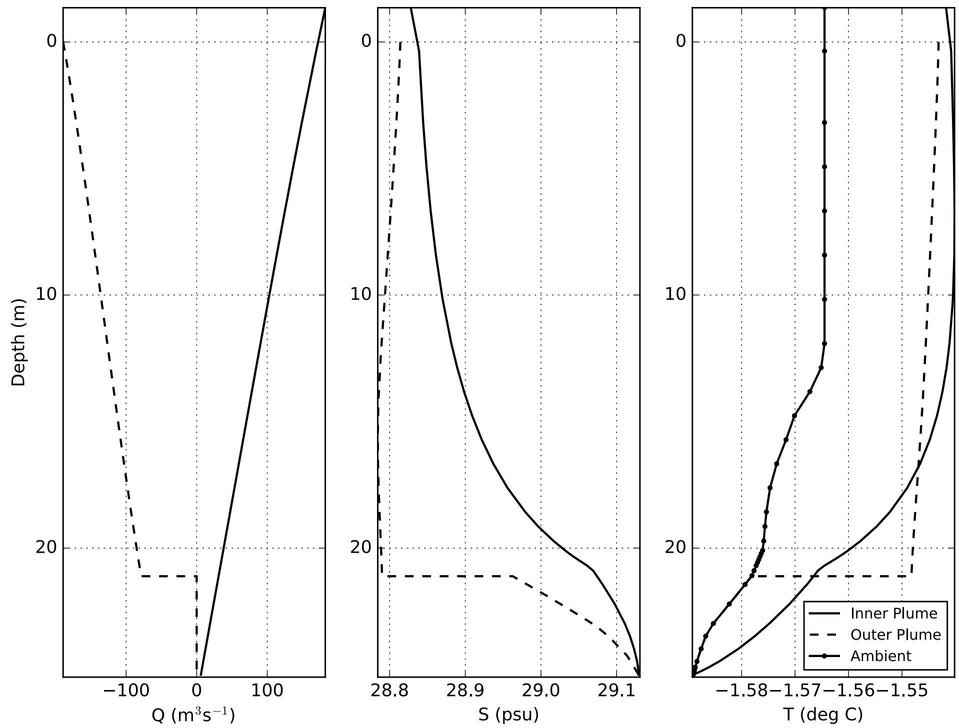


Figure. 24: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 25 m depth - scenario -2

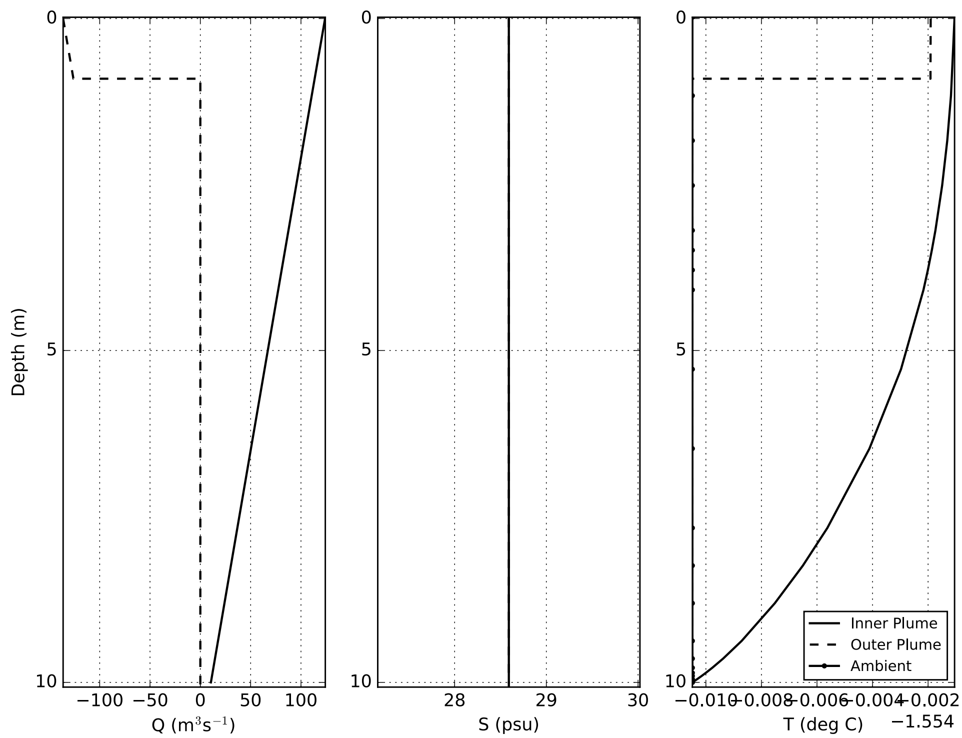


Figure. 25: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with depths for the plume released at 10 m depth - scenario -2

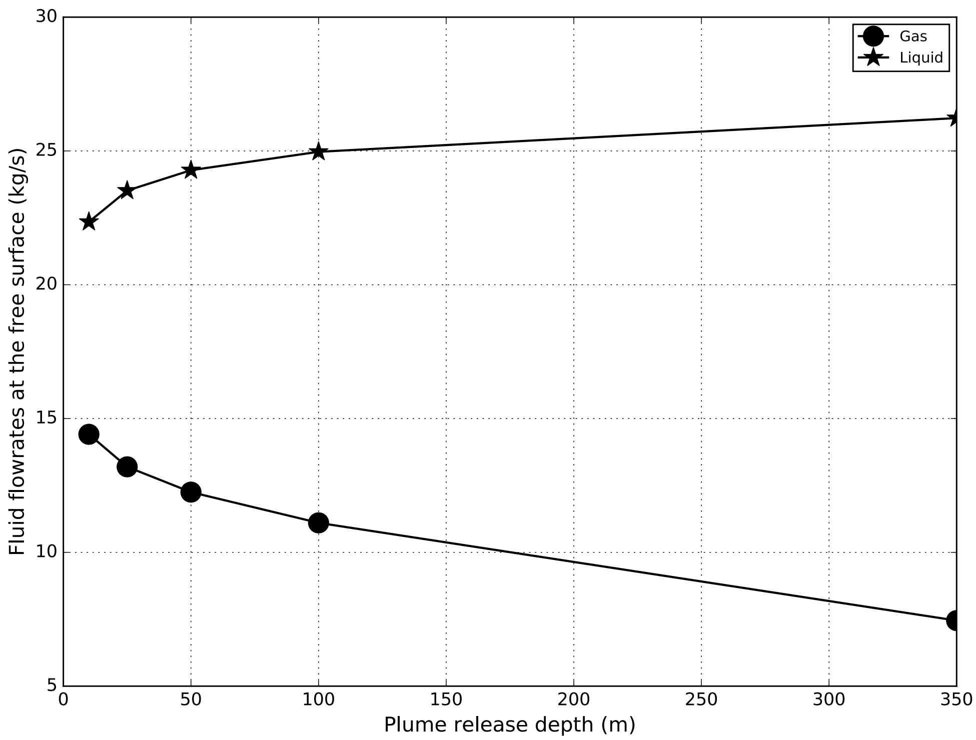


Figure. 26: Gas and liquid flowrate variation at the surface for plumes released at different depths scenario -2

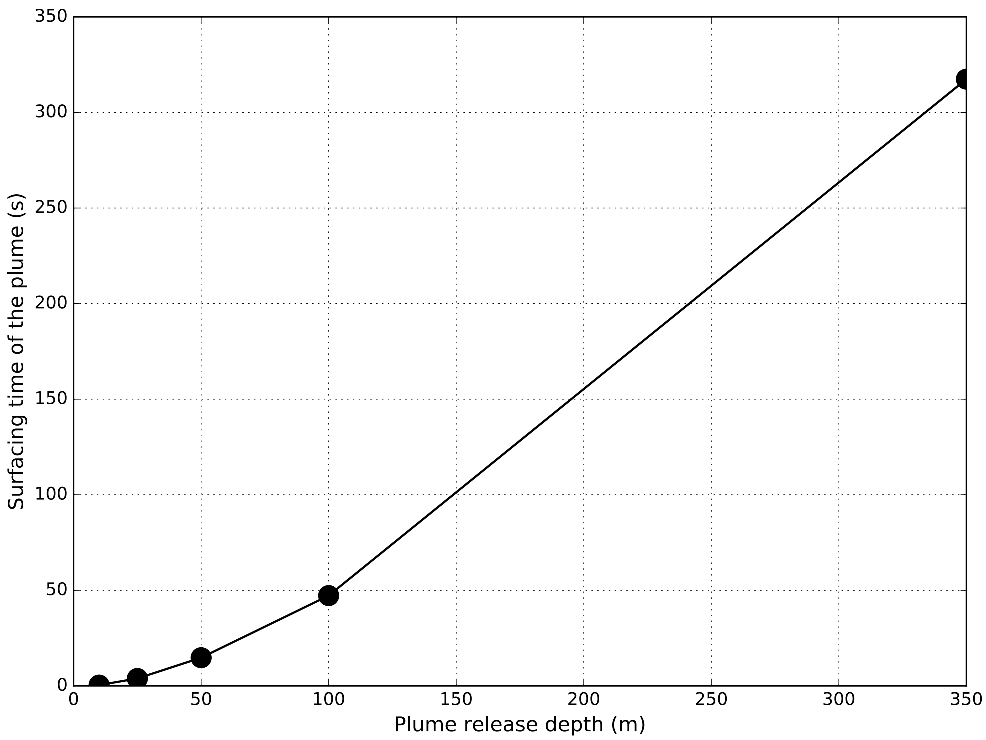


Figure. 27: Gas surfacing time variation at the surface for plumes released at different depths - scenario -2

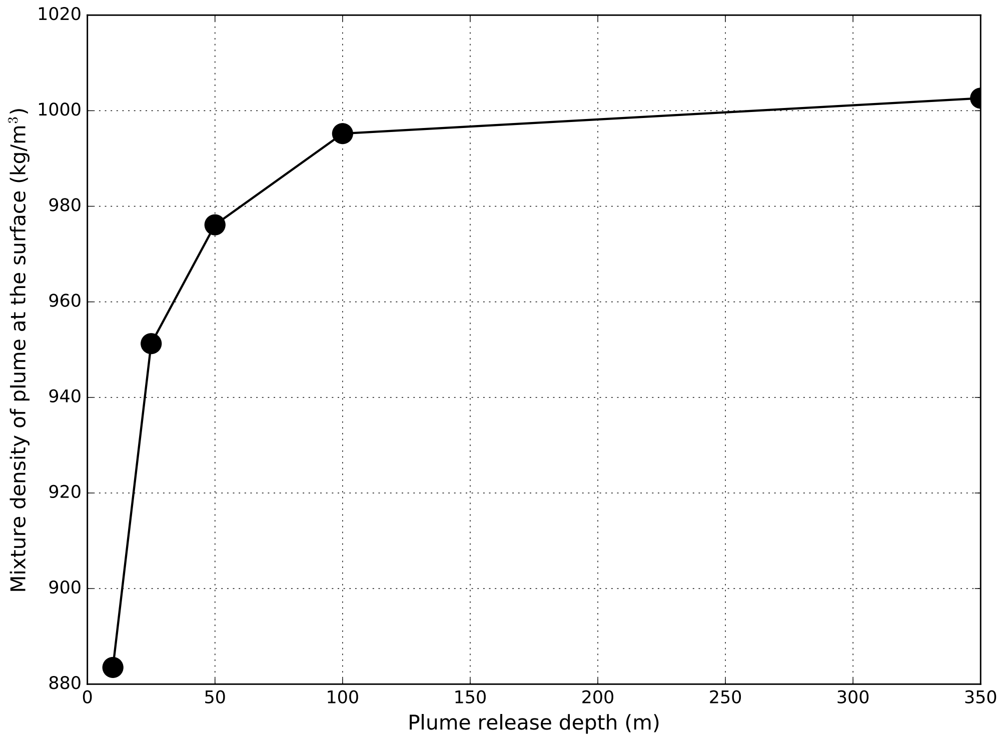


Figure. 28: Variation of mix density of plume fluid at the surface for plumes released at different depths - scenario -2

Bent Plume Model - Scenario -1

The bent plume model simulations do not predict the plume to reach the surface when released at 350 m depth. Instead the plumes make an intrusions about 150 m below the surface. Therefore, only the variation of plume flowrate, temperature, and the salinity of plume fluid are presented in the Figure. 29 and the plume centerline variation with depth are shown in Figure. 30.

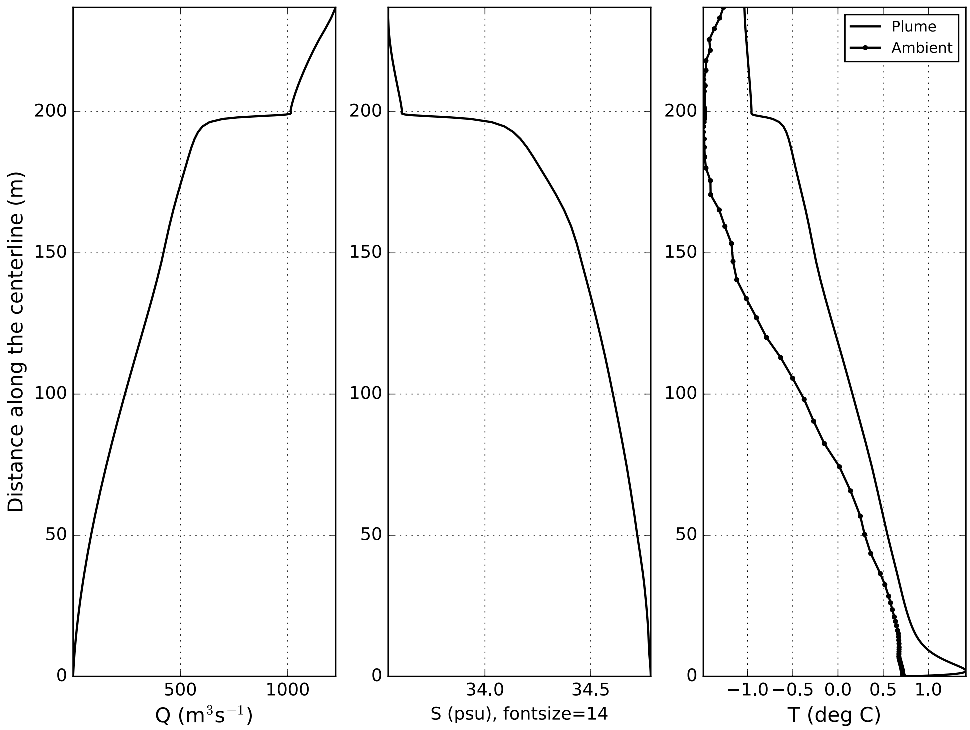


Figure. 29: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with the plume progression distance along the centerline for the plume released at 350 m depth - scenario -1

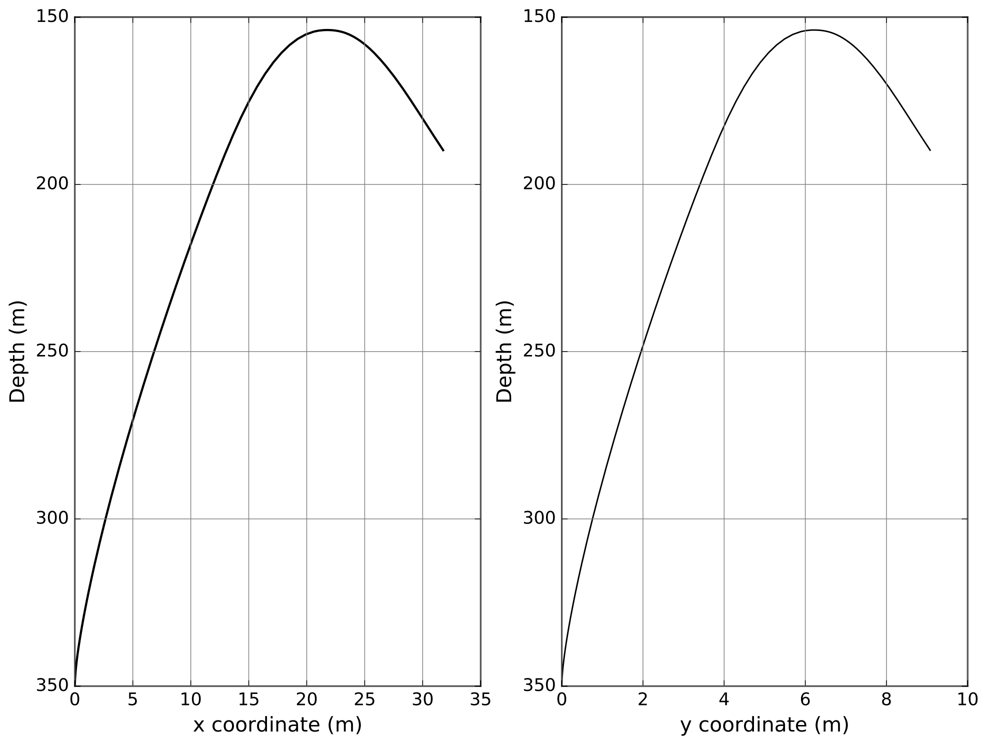


Figure. 30: Variation of the plume centerline with depth for the plume released at 350 m depth - scenario -1

Bent Plume Model - Scenario -2

Similar to the simulations with Stratified Plume Model, the overall results between the scenario 1 and 2 of the Bent Plume Model simulations are not very different because the two scenarios have slightly varying ambient salinity and temperature profiles and the same ambient current profiles used in the calculations. The variation of plume flowrate, temperature, and the salinity of plume fluid are presented in the Figure. 31 and the plume centerline variation with depth are shown in Figure. 32, for scenario 2 simulations with the Bent Plume Model.

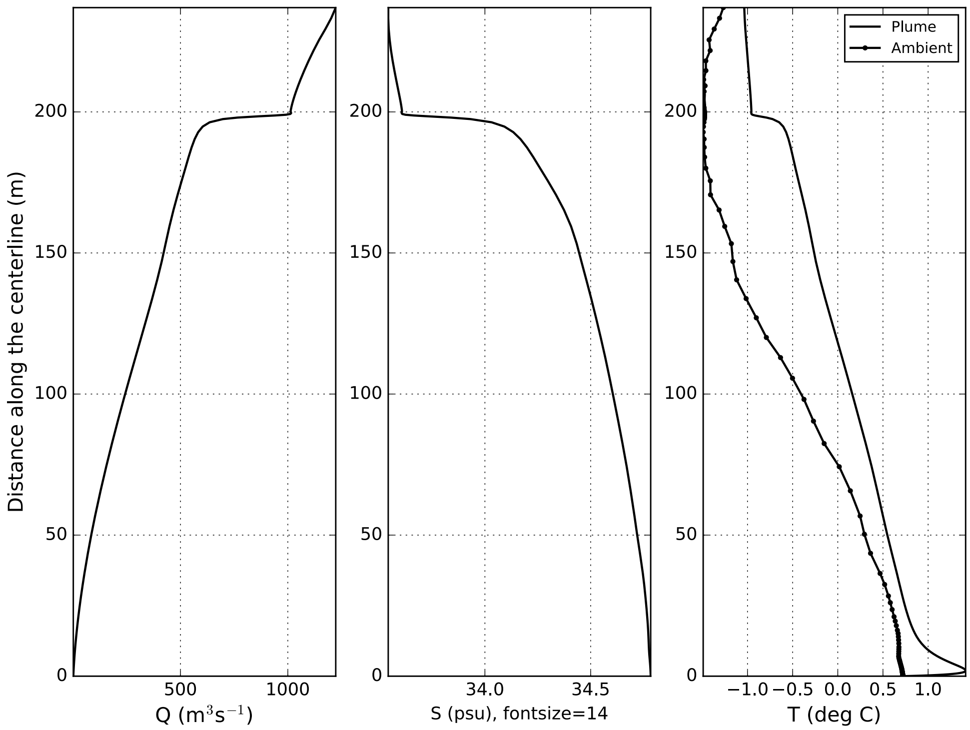


Figure. 31: Variation of the plume flowrate (Q), salinity (S) and the temperature (T) with the plume progression distance along the centerline for the plume released at 350 m depth - scenario -2

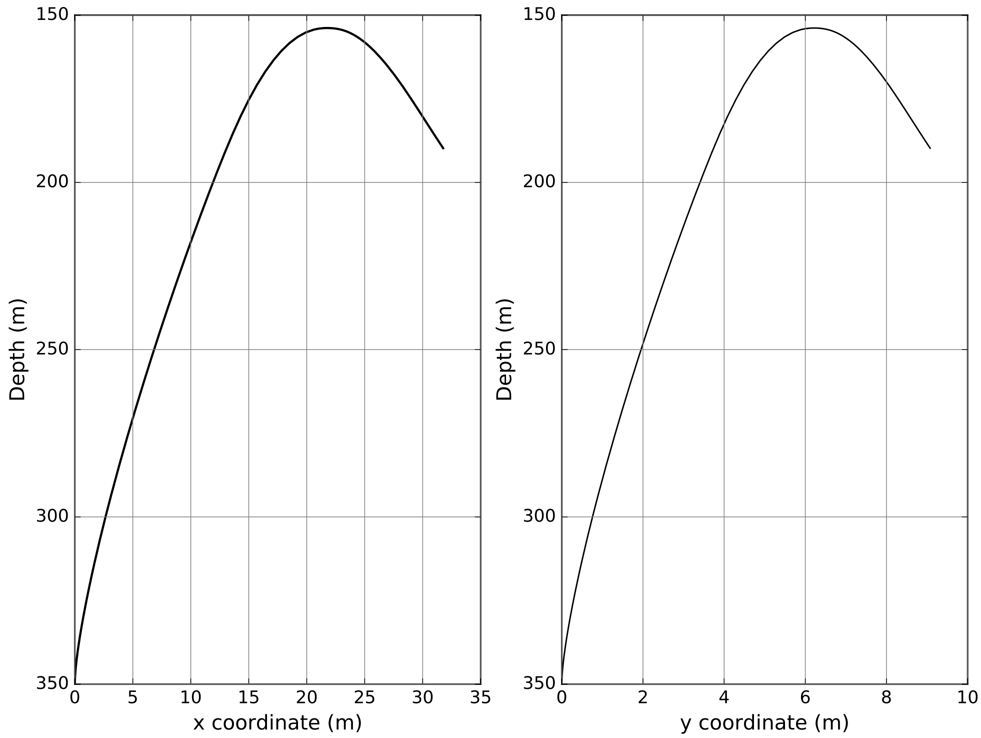


Figure. 32: Variation of the plume centerline with depth for the plume released at 350 m depth - scenario -2