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Report

Virtual Proof of Concept

Can large scale bubble curtains lower the surface temperature ocean waters

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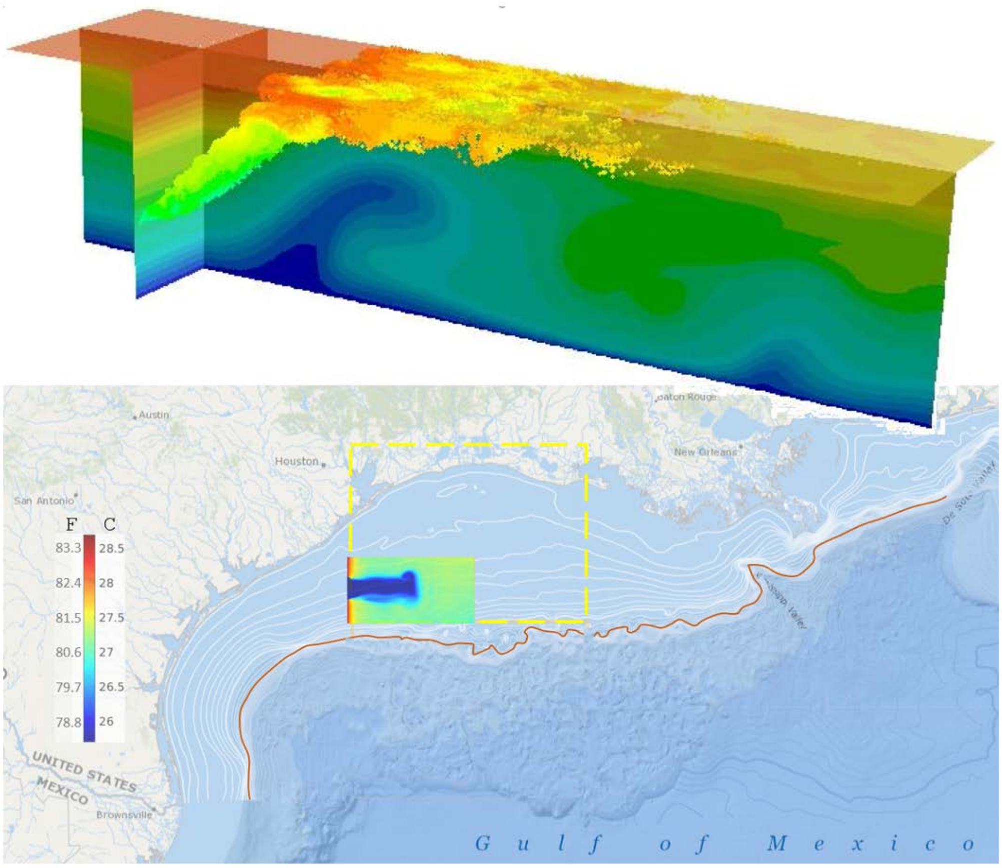

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ABSTRACT

Computer simulations were used to investigate the potential of large-scale bubble curtains for lowering the sea surface temperature locally and regionally.

Large scale simulations of this type have not been reported in the literature to our knowledge nor does large scale validation data exist. It is partly due to the latter and the cost involved in generating such validation data that a "Virtual Proof of Concept" was chosen to build confidence in the science behind the technological concept of using bubble curtains to lower sea surface temperatures over large areas.

With the assumptions inherent in the use-case definition we find that the technology has potential to reduce sea surface temperatures (SST) both locally and on a regional basis. The merits and assumptions are discussed in the report.

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Document history

VERSION	DATE	VERSION DESCRIPTION
1	2021-11-05	First draft version with both local and regional results.
2	2021-11-26	Second draft version. As requested by client the report is shortened for clarity. The present version can be classified as open.
3	2021-12-08	Final report. Some details moved from Appendix to a Project Memo.

Table of contents

APPENDICES

A.1 Evolution of curtain dynamics and temperature profiles at surface and vertical cut plane

1 Introduction

OceanTherm has proposed a novel concept for combating the destructive power of hurricanes. The concept focuses on reducing the energy available for the hurricane to maintain or grow in intensity. One of the key energy sources responsible for maintaining or intensifying a hurricane is the latent heat of condensation released when warm moist air rises in the "eye of the storm". The hurricane system can briefly be described as a low-pressure area drawing in air over the ocean to its centre where the warm and moist surface air ascends at its centre. As this warm and moist air rises it cools and water vapor begins to condense. Heat is released as the water condenses (condensation is the opposite of evaporation which consumes heat). This heat is transferred to the air surrounding the condensed water droplets (which start forming clouds). The heating of this air enables it to continue ascending and thus draw in even more air at the centre of the low-pressure area. Under the right conditions this becomes a self-amplifying process, i.e. if the sea surface temperature is above 26.5 C / 80 F (Emanuel et-al. 2008).

Thus, high sea surface temperatures (SST) are a pre-requisite for hurricanes to form, maintain and amplify their intensity (energy).

The properties of sea water are a complex subject. In the present context it can be said to have a temperature and a composition (dissolved salts, organic compounds, and dissolved gases). The concentration of dissolved salts strongly influences the density of sea water as does its temperature. Generally, in the Gulf of Mexico, the temperature of sea water decreases with depth while the salinity increases. The seawater density increases with depth. At the sea surface the ocean couples to the atmospheric and earth system through wind and radiative heat balances. This interaction results in what is known as the mixed (surface) layer where salinity and temperature vary little with depth. Below this mixed (surface) layer we find what is either called the pycnocline or thermocline depending on whether salinity or temperature is the parameter mainly responsible for the density change of water. In shallow waters the mixed layer can extends all the way to the ocean bottom.

The concept proposed by OceanTherm is to use bubble curtains to transport water from below the mixed layer to the sea surface to reduce the sea surface temperature (SST). The goal can either be to reduce the SST below the critical cut off for self-amplification of the hurricane (~26.5 C / ~80 F / ~300 K), or to reduce the amount of energy available to the hurricanes for self-amplification by bringing the SST down as much as possible. In the ocean, cold water is denser than warm water the challenge is to create a stable mixed layer locally and regionally with a lower SST.

In one embodiment of the concept a long bubble curtain is deployed/installed which is aligned such that the surface current would carry the water with reduced SST downstream and with time blanket a substantial area over which the storm system is predicted to pass.

As full-scale tests are prohibitively expensive and time consuming and given that no large-scale tests for this specific purpose has ever been successfully performed or documented, computer simulations offer an interesting alternative to build confidence in the science behind the technological concept of using bubble curtains to lower sea surface temperatures. The main questions that need to be answered are:

i. can a bubble curtain create a mixed layer with reduced SST?
ii. when carried off with the ambient current, will the mixed layer remain stable or will mixing due to ocean processes, atmospheric forcing and solar heating re-heat / erode the mixed layer?

2 Use case description

Several hurricanes that have hit the Gulf of Mexico states have intensified as they near the coastline of these states. A use case was selected that was consistent with this possibility.

The selected area was between 92 to 95 degrees west and 28 to 30 degrees north as indicated by the dashed yellow rectangle in Figure 1. Data was retrieved from the World Ocean Atlas (WOA) provided by NOAA's National Centers for Environmental Information. This resulted in most of the sampled profiles of salinity and temperature data originating from depths down to 70 m with only a few reaching a depth of 150 m. As can be seen the area borders on the continental slope which falls off to the south.

The surface current in the area selected was set to 0.5 m/s (1 knot) which is advantageous for demonstrating the potential of the technology.

The oceanographic data was taken as climatological averages for the period 2005 through 2017 for the month of October. The resulting temperature and salinity profiles are shown in Figure 2.

Atmospheric forcing, solar and thermal radiation typical for late August (23rd through 25th of August 2017) was taken from ECMWF’s ERA5 data set (Hersbach et al. 2020).

The design basis explored was that of a bubble curtain in a uniform ambient current of 0.5 m/s located at a depth of 100 m (328 ft) in waters 150 m (492 ft) deep. The target gas injection rate and nozzle spacing was supplied by OceanTherm.

As the present study constitutes a virtual proof of concept it is of interest to examine how the length of the bubble curtain affects its regional influence. Thus, two curtain lengths were investigated: 1500 meters (5000 ft) and 30 kilometres (18.64 mi). An outline of the simulation methodology is given in the next section.

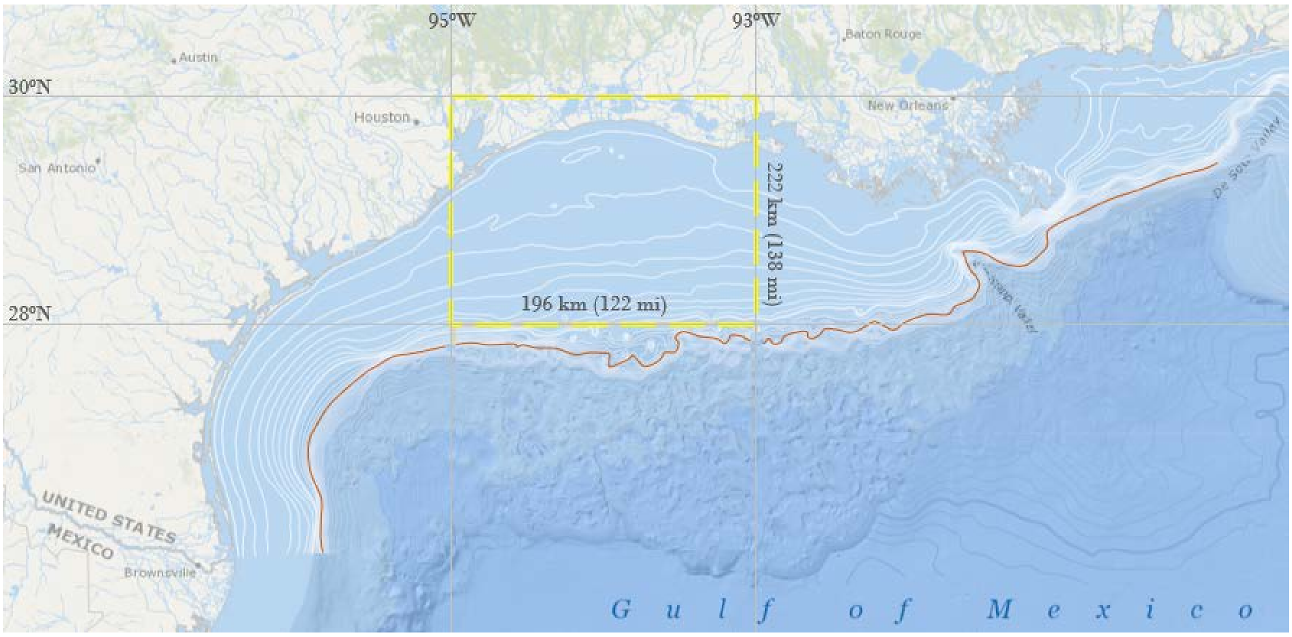

Figure 1: Illustration of the bathymetry in the suggested study area. The dashed yellow rectangle illustrates the region where salinity and temperature data were sampled. The bathymetry in the region goes down to 3000 meters (9842 ft). The dark red line follows the 150 m (492 ft) contour.

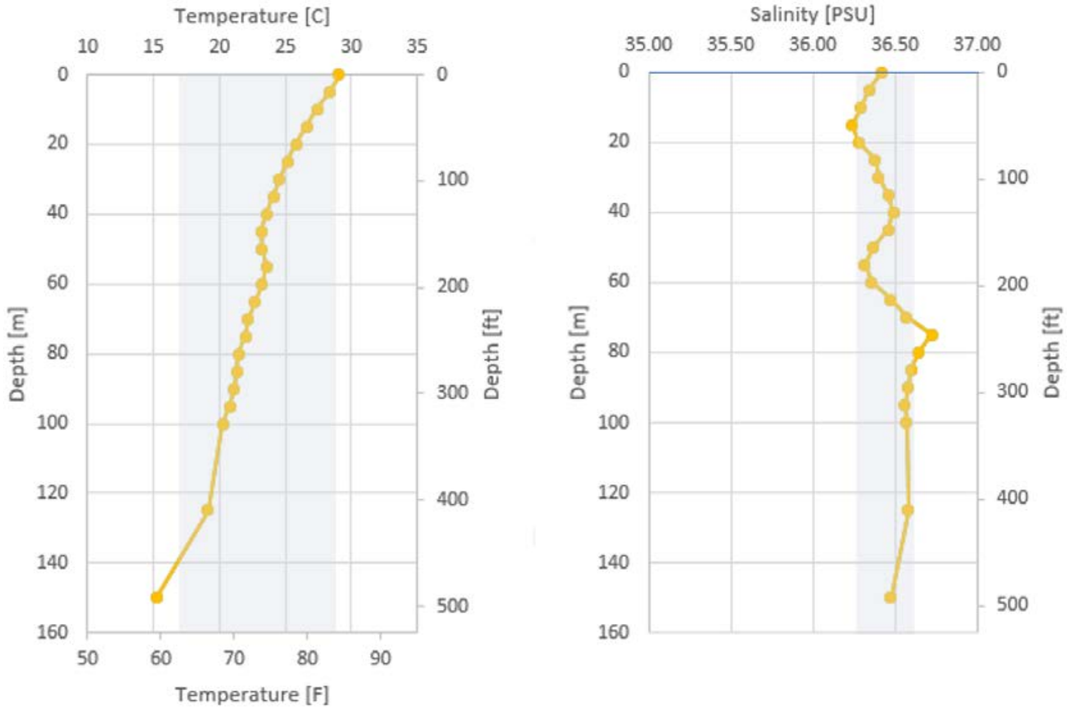

Figure 2: Depth averaged temperature and salinity profiles used in the test simulations. The initial sea surface temperature was 29.1 C (84.3 F). The light grey regions show the temperature and salinity ranges used in **Figure 7** for reference.

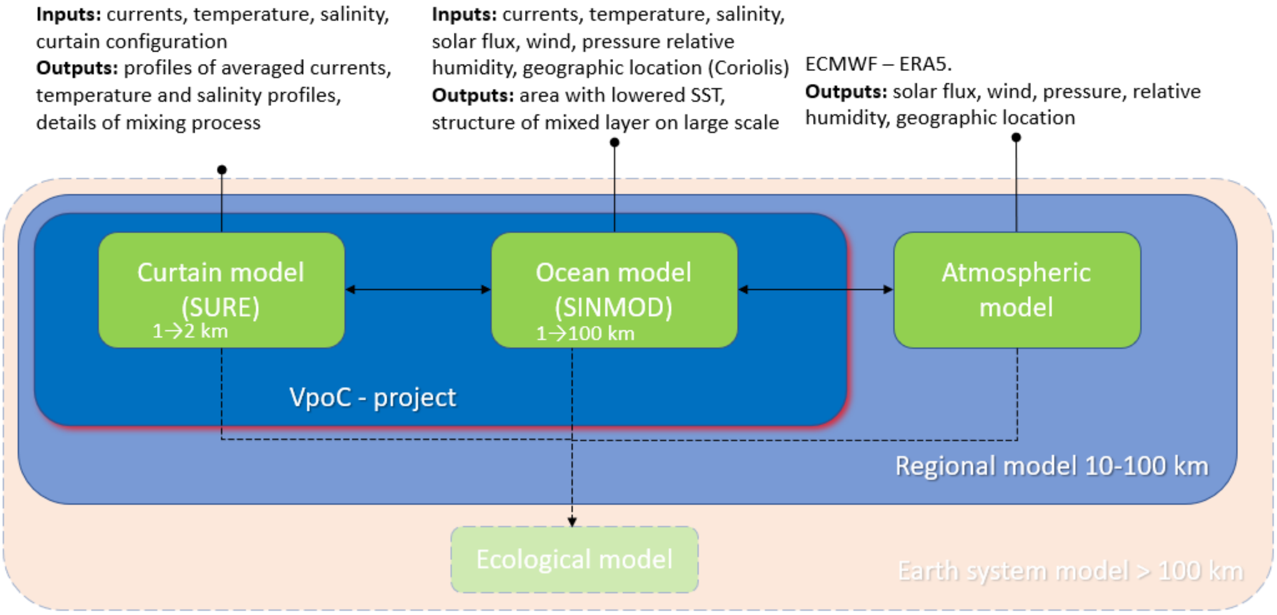

Figure 3: Nesting of models capturing phenomena and dynamics at different time and length scales. This study encompasses the curtain model, the ocean model and input from an atmospheric model. The figure also outlines how these models could be coupled to ecological models for environmental impact assessments.

3 Methodology

The problem contains a wide range of time and length scales. At the lower end bubble dynamics play out on scales of millimetres and fractions of a second. The lifting and mixing of seawater occurs on length scales of ~1-100 meters and time scales of minutes to an hour, finally large-scale advection, mixing and interaction with the earth system occurs on length scales of many kilometres/miles and time scales of hours and days. This nesting of phenomena, scales and models are illustrated schematically in Figure 3.

To resolve all these phenomena is beyond the reach of a single model. Instead, a hierarchy of models is used. Building on experimental observations and simulations of the dynamics of single as well as clusters of bubbles, models for bubble drag, size and mass transfer have been developed. These models are then implemented into a multiphase flow model to calculate the dynamic behavior of bubble curtains. These two levels of modelling are combined into what we refer to as a "curtain model". The focus of the curtain model is to represent as accurately as possible the process of lifting of cold dens water towards the sea surface, the mixing within the curtain during upwelling and as it spreads at the surface. Downstream of the surfacing region it is assumed that a quasi-steady state flow develops. This flow is then used as input to the regional ocean model. This model makes use of inputs from meteorological models and geographic location. The latter is used to include solar radiation and Coriolis forces.

The high-resolution curtain model (SURE, Olsen and Skjetne 2020) takes its oceanographic input either from observations, forecast models or climatological databases. In the present case climatological data was retrieved and used (Boyer et.al 2018). The high-resolution curtain model cannot be run for the entire length of the bubble curtain. Instead the model is run for what is assumed to be an "internal" section / longitudinal slice of the bubble curtain (cf. Figure 4). The width of this slice is set such that it will not confine the turbulent length scales produced by the curtain. The downstream flow is then averaged (both in space and time) and exported as vertical profiles of velocity, temperature, and salinity (cf. dashed red boxes/planes in Figure 4). As can be seen the high-resolution curtain model extends well upstream of the curtain to capture the diversion and mixing of incoming current with the upwelling produced by the bubble curtain. It also extends well downstream of the curtain to capture the complex mixing that takes place downstream of the upwelling. In the present study the domain extended five curtain depths downstream the curtain location. The averages used as boundary condition profiles for the ocean model were sampled half a curtain depth upstream the end of the domain. A modified version of the SURE model (Olsen and Skjetne 2020) was used to simulate the curtain dynamics where bubble size was held constant and mass transfer to the ocean was turned off.

In the SINMOD (Slagstad and McClimans 2005) setup we used a canal with a vertical structure of temperature (T) and salinity (S) shown in Figure 2. There are no horizontal variations in the T and S. The initial velocity is 0.5 m/s (1 knot) along the canal and the sea surface elevation is calculated from the geostrophic equation. These conditions are also applied at the boundaries except in the section where the bobble curtain was placed. Here the stationary boundary condition obtained from the curtain model was gradually turned on, increasing from zero to full value using a time constant of 300 s. The lower left corner of the model domain has a position equal to 26 ^{o}N, 95 ^{o}W

The high-resolution version of SINMOD (20 m) was used to study the upper layer dynamics as the input from the bobble curtain model was advected into the model domain. No atmospheric or wave input was applied. To evaluate the effect of horizontal resolution models running with 50 and 100 m horizontal resolution were also implemented. The setup using 100 m resolution was also used for the 30 km bubble curtain with atmospheric forcing and wave induced mixing. The atmospheric forcing was taken from ECMWF’s ERA5 data set (Hersbach et al. 2020). The vertical mixing in SINMOD is calculated as a function of the Richardson number (Sundfjord et a. 2008). The model calculates horizontal diffusivity of momentum using biharmonic friction while horizontal diffusion of scalars applies diffusion coefficients as in Smagorinsky (1963).

We simplify the problem to that of a "canal" with a constant depth of 150 meters (no bathymetry included). The length and width of this "canal" depended on the width of the bubble curtain under investigation.

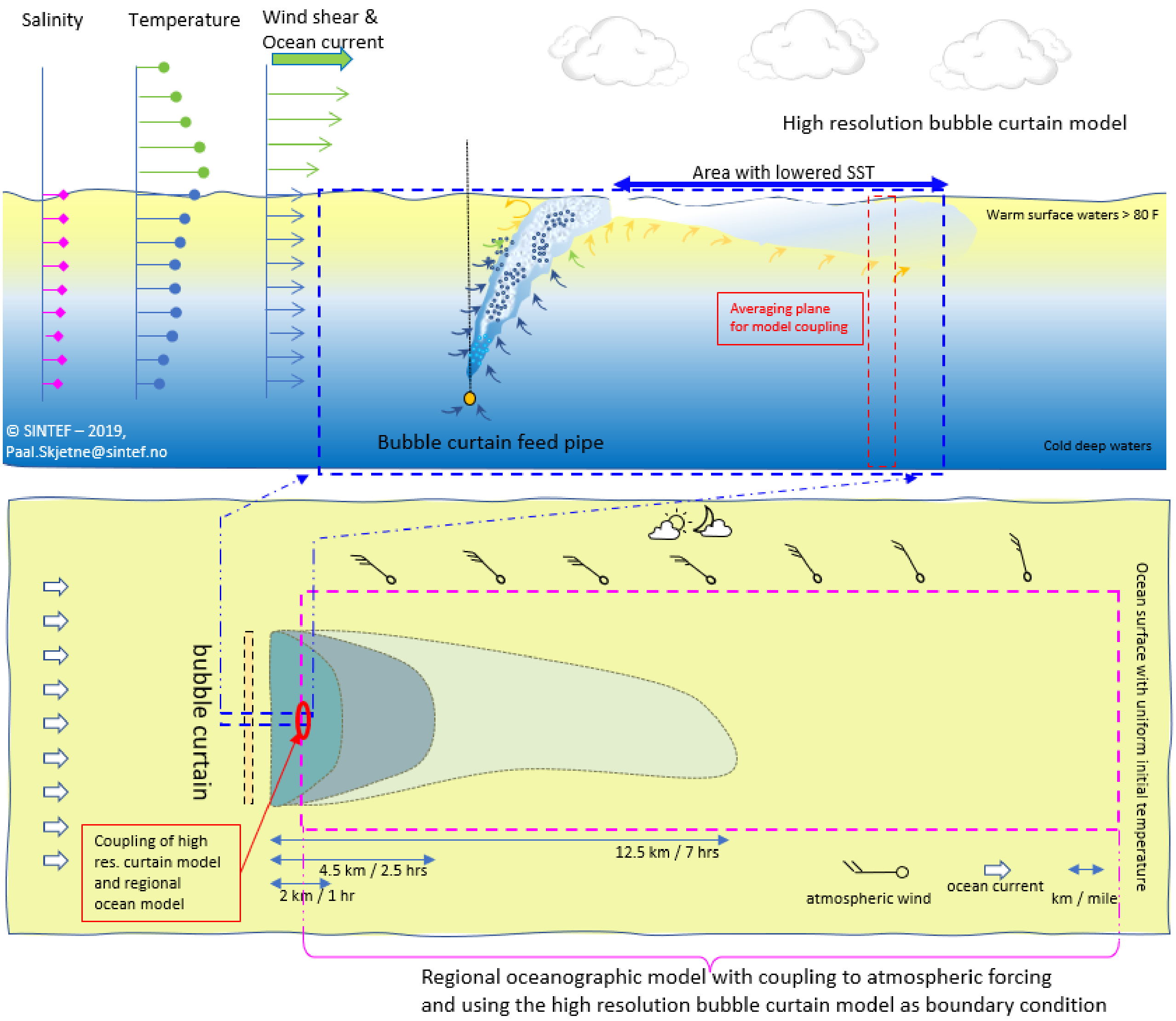

Figure 4: *Top:* Schematic of the working principle of the bubble curtain and the domain of the high-resolution multiphase curtain model. The curtain is seen from the side. The red area indicates the area where the boundary condition for the regional ocean model is sampled. To the far left in the top figure the wind, current, temperature and salinity profiles are indicated. *Bottom:* Schematic showing a bird's eye view of the regional spread of cold surface waters, indicating typical length and time scales. It also indicates how the high-resolution curtain model relates to the regional ocean model in extent and in where the coupling information is gathered.

4 Results

4.1 Curtain model

4.1.1 150 m bubble curtain with SURE model in a domain 150x600 m

The rise time of the gas was approximately 140 seconds. The surfacing position was evolved with time, with the location gradually moving downstream after first gas. This is illustrated in Figure 5 for the time when gas is first surfacing (140 seconds) and at quasi steady state (40 minutes). Another feature to notice in this figure are the turbulent surfacing "boils" of gas. They give a visible manifestation of the large-scale turbulence produced by the curtain. For the present configuration boils up to 40-50 m in diameter were observed. The curtain consists of individual bubble jets that start coalescing with each other as they ascend to the ocean surface. The turbulence created is responsible for entraining and mixing water during ascent. As the ascending water reaches the surface further mixing results both due to turbulence and the upstream part of the flow colliding with the incoming ocean current.

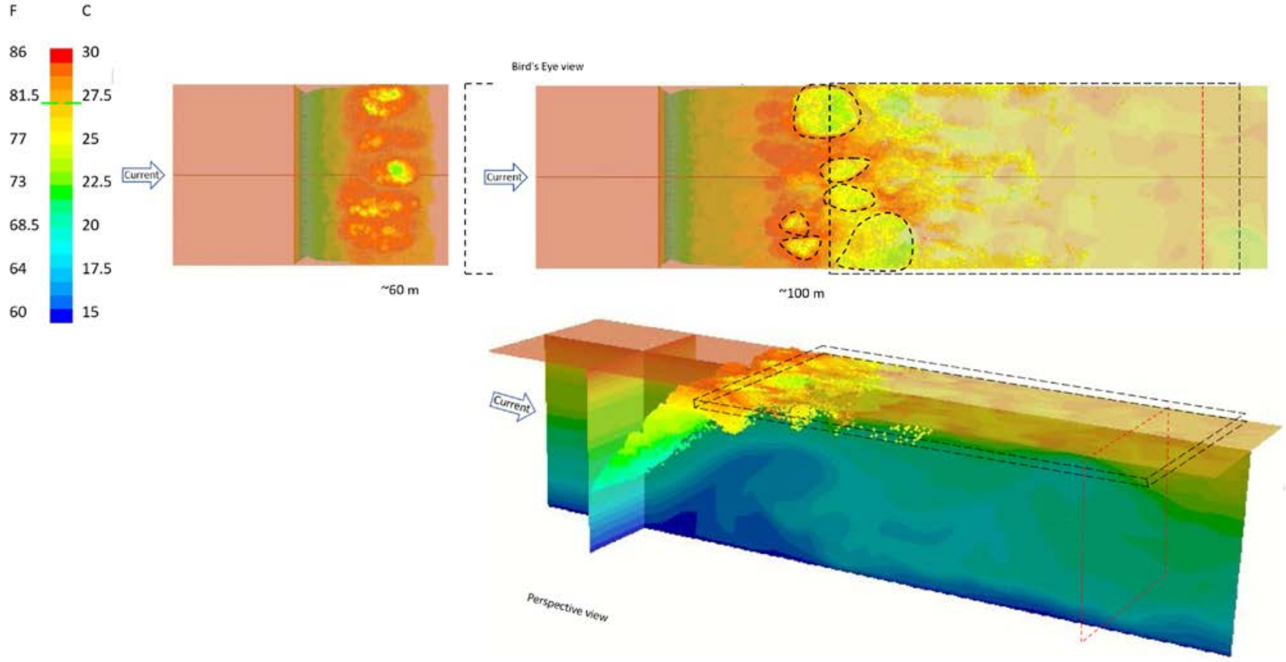

Figure 5: First gas at surface after ~ 2 minutes (left) and after 40 minutes (right). The images are in perspective, so it is hard to judge distances directly from the images. Numerical averages are indicated on the margins. First gas surfaces roughly 60 m downstream the curtain. At quasi steady state (40 minutes) the average surfacing distance has increased and migrated downstream to roughly 100 m. Averaging volume for sea surface temperature SST (dashed black outline) and averaging plane for the time averaged depth profiles of temperature, salinity and current exported to the regional ocean model (dashed red outline).

The sea surface temperature (SST) was monitored as a volume average of the top 5 meters of the seawater in a region starting 150 m downstream the curtain and ending 25 m upstream of the end of the domain as indicated by the dashed black box in the lower part of Figure 5. The averaged SST is reported in Figure 6. It is important to keep in mind that the reported SST is the average for the upper 5 meters (18 ft) of the ocean column.

As can be seen the volume averaged SST for the upper 5 m of the ocean column falls below the critical 26.5 C (79.7 F). The time trace of SST shows a steady drop until 1000 seconds (~ 17 minutes) after turning the bubble curtain on. This corresponds to the oceanic advection time from the bubble curtain to the exit of the computational domain when the ocean current is 0.5 m/s (1.64 ft/s / 1 knot). The undershoot of the temperature is probably due to a phenomenon associated with starting bubble plumes. A "cap" forms at the front of the curtain as it accelerates the water in front of it from a state with little vertical transport. This cap swells to contain a larger amount of gas (and therefore more buoyancy / accelerating force per volume). This allows the curtain to store and lift a larger amount of cold water to the surface during this time. As the curtain reaches quasi-steady state gas residence time approaches a statistical average and so does the buoyancy (gas) per volume available to lift and entrain water.

For the selected use case the method proposed by OceanTherm can reduce the SST by 2.5 C (4.5 F).

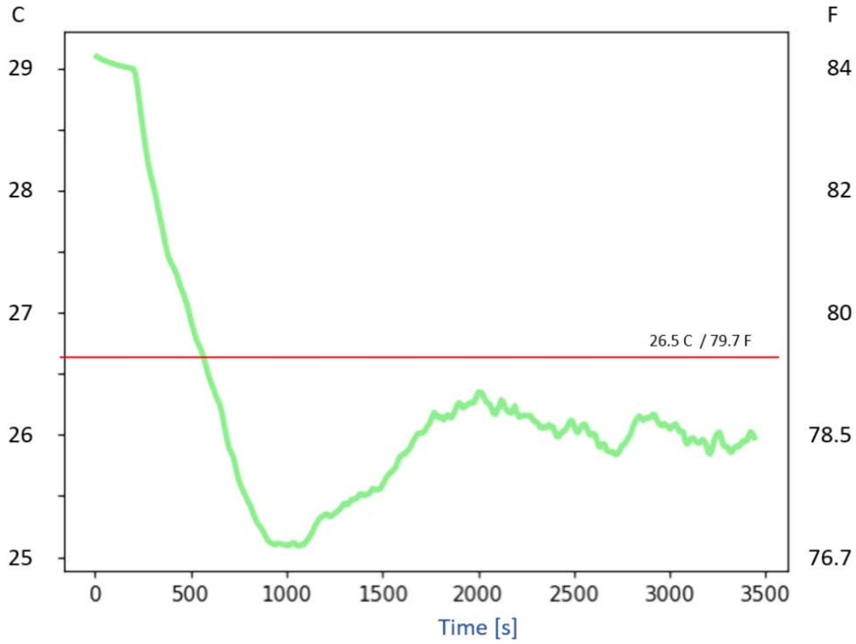

Figure 6: The temperature trace is for the averaging volume indicated in **Figure 5**.

The high-resolution curtain model is coupled to the regional ocean model through a time averaged depth profile obtained at a plane 450 meters (1475 ft / ~ ¼ mile) downstream of the curtain (cf. Figure 5). The profiles are obtained by area averaging in the spanwise direction at 5-meter depth intervals down to 100 meters and then for every 25 meters. This spacing in depth was chosen to be consistent with the WOA input data used.

It was decided that the last 1000 seconds made up the most realistic representation of the quasi-steady state. The resulting profiles used as boundary conditions in the regional ocean model are plotted in yellow in Figure 7.

To illustrate the variability of the profiles as time progressed, profiles were sampled every 50 seconds, and all these profiles are show in the plot. The middle plot shows temperature profiles, for this plot profiles with a surface temperature above 26.5 C are colored red all others blue. This was not done for velocity in the streamwise direction or salinity. The bold red line lines indicate starting profiles, green profiles indicate the profile at the end of the simulation and yellow profiles give the profile averaged over the last 1000 seconds of the simulation.

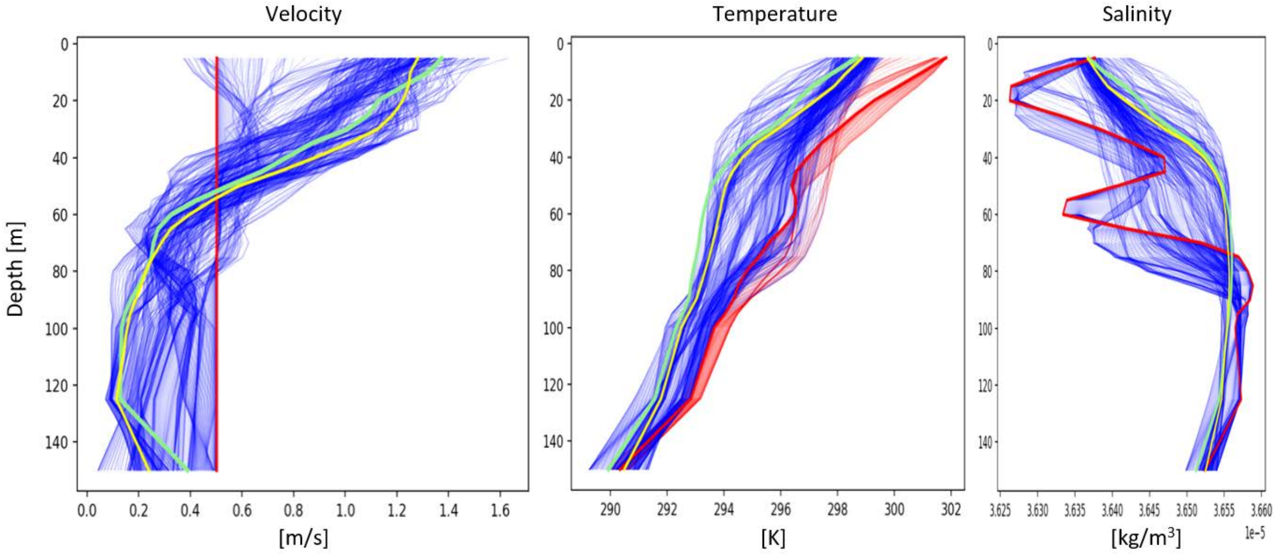

Figure 7: Velocity (left), temperature (middle) and salinity (right) profiles sampled close to the end of the simulation domain. Bold red profile gives the initial condition. The green profile gives the final profile at the end of the simulation, and the yellow profiles gives profiles time average over 1000 seconds ~17 minutes.

The velocity profile deserves some mention. Upstream of the bubble curtain the velocity field is uniform and set to 0.5 m/s. As can be seen from the plot in Figure 7 the velocity develops a distinct profile. For depths below ~50 meters it drops below the ambient 0.5 m/s and for depths above this it increases to 1.2 – 1.3 m/s at the surface.

Further detail of the flow field development can be seen in the accompanying PowerPoint with video animations and in Figure 11 in the Appendix.

4.2 Regional ocean model

A few sensitivity tests of horizontal model resolutions and curtain lengths are shown in Appendix A2.

4.2.1 30-km bubble curtain with 100m horizontal resolution and 100x160 km extent

Her we present results from runs with a 30-kilometre bubble curtain in a horizontal domain of 100 x 160 km and a horizontal resolution of 100 m and with atmospheric forcing and heat radiation included, and the importance is clearly seen in Figure 8. Vertical resolution was 1 m down to a depth of 50 meters, from 50-100 m depth the resolution was 2 m and from 100-150 m depth the resolution was 5 m. With atmospheric forcing applied the wind mixing and cooling during the night the surface temperature is reduced in the whole model domain (lower left). The wind effect cause upwelling at the lower (southern) canal wall and thereby overestimate the area covered by SST less than 27 C.

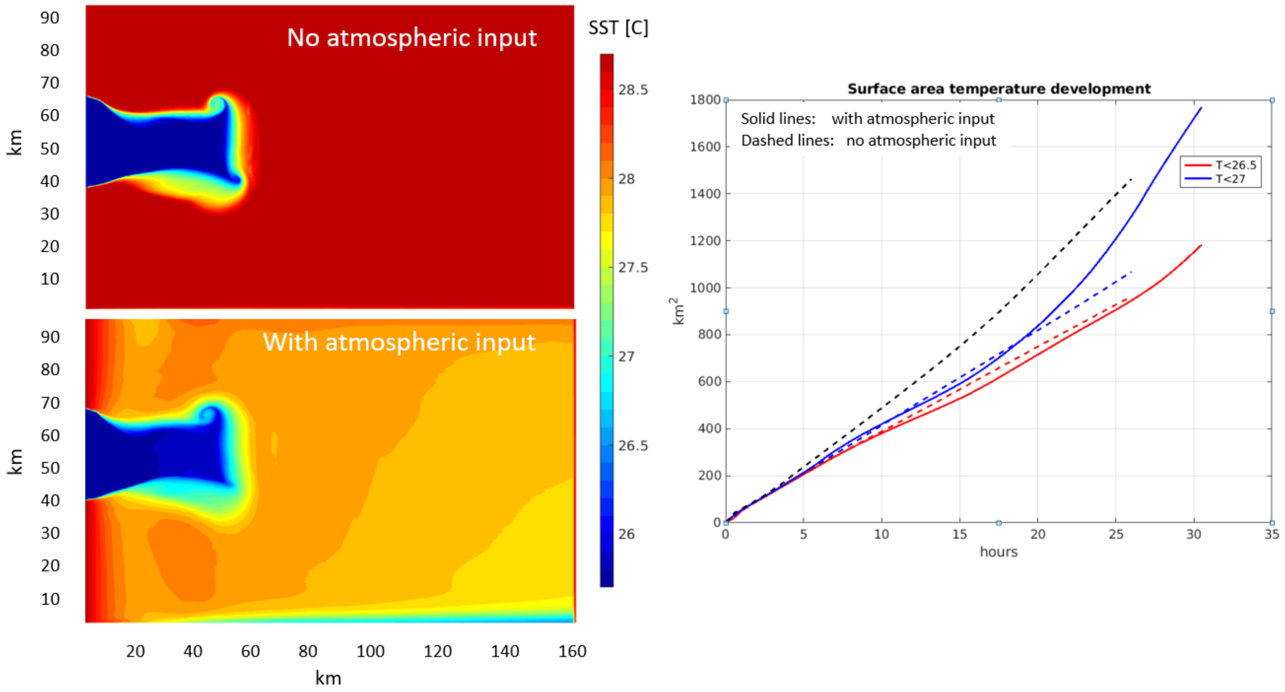

Figure 8: 30 km bubble curtain with and without atmospheric input after 26 hours. Temperature scale is in Celsius. In the right plot the solid lines are with atmospheric forcing and the dashed lines without atmospheric forcing.

When the wind velocity increases after about 40 hours of simulation (Figure 9, right panel), surface mixing brings up colder water in the whole model domain. This effect depends strongly on the vertical temperature structure. In this case the plume from the bubble curtain keeps its structure although there is some erosion from the plume boundaries. During the first night, the temperature drops around 0.7 C due to surface cooling and vertical mixing but increases again the following day. The plume hits the location of the point for time series at around 20 hours leading to a sharp drop in surface temperature which continues through the simulation.

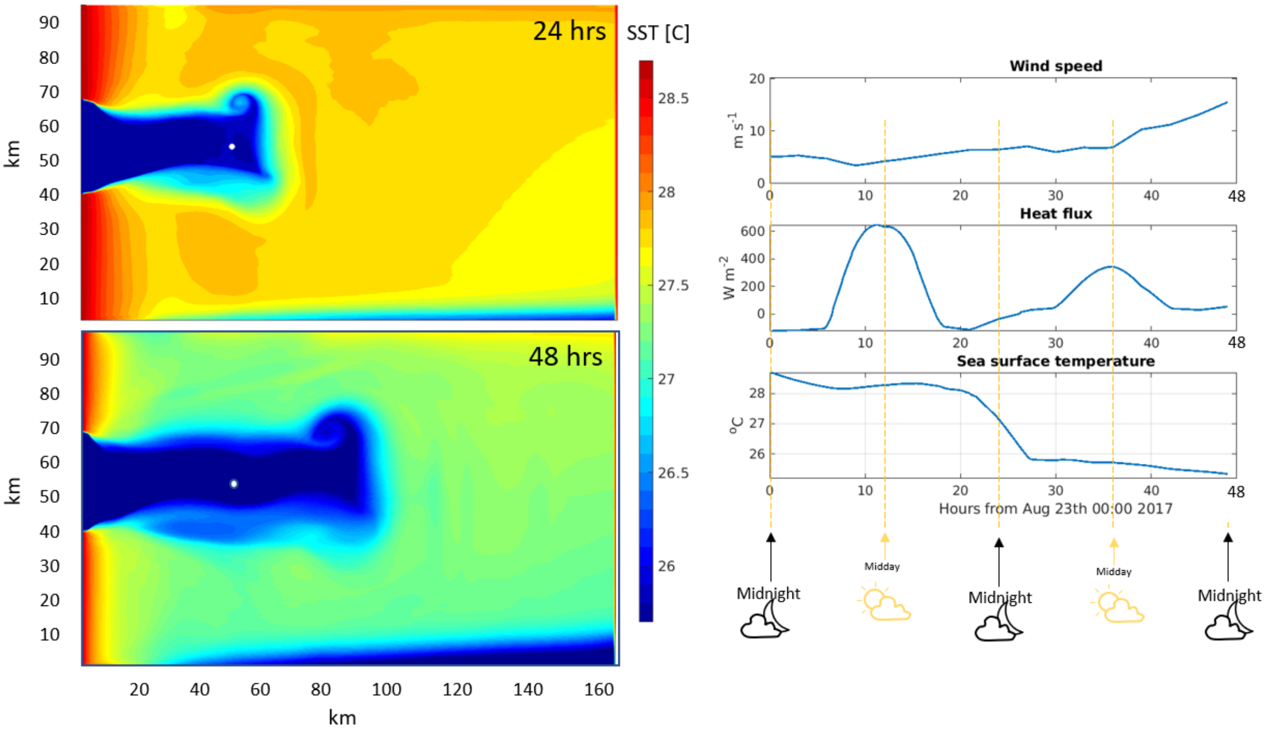

Figure 9: SST for the 30-kilometre bubble curtain after one and two days. The atmospheric forcing induces mixing of the ocean column reducing the overall SST through evaporative cooling, radiative heat transfer and wave mixing. The right panel shows a timeseries of wind speed, heat flux and sea surface temperature from the centre of the plume (indicated by a white dot).

5 Summary

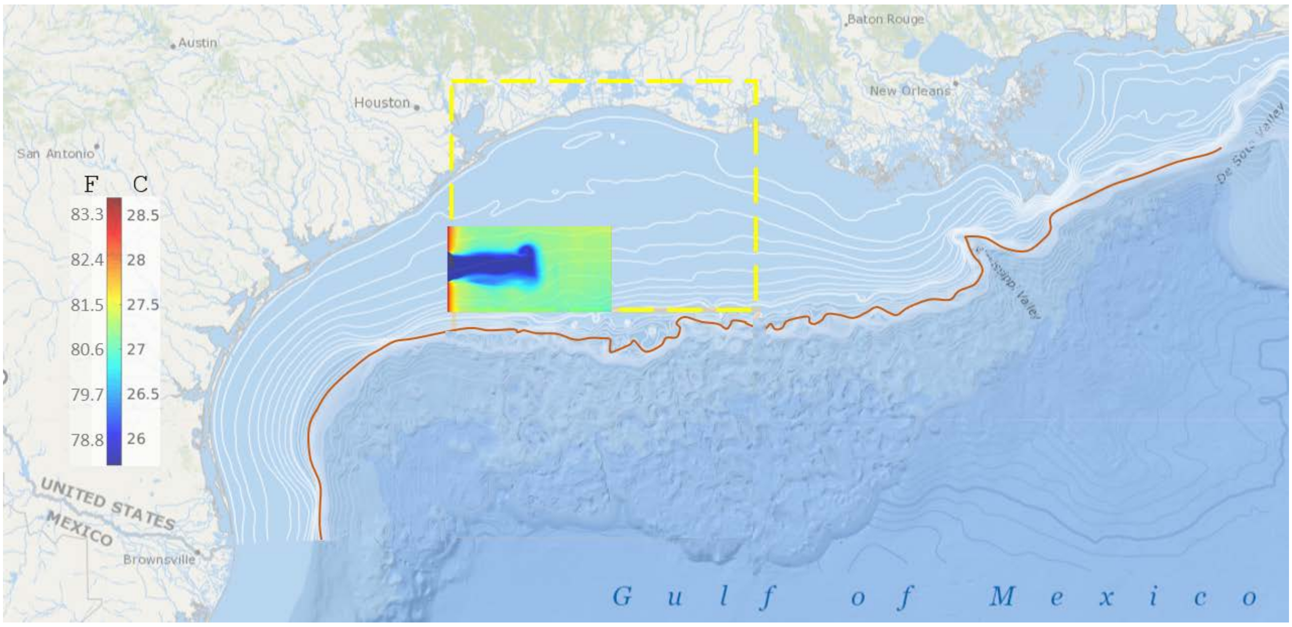

Figure 10: Simulation embedded on the regional map from which the intended use case is defined. The extent of the cold region is that achieved 48 hrs after the curtain was turned on.

(i) The high-resolution curtain model shows the concept can produce a stable mixed layer with reduced sea surface temperature for the given use case. The volume averaged sea surface temperature in the uppermost 5 meters of the ocean column from 150- to 450-meters downstream the bubble curtain dropped by 2.7 C (4.9 F) for the given use case. The time averaged temperature drops at a distance of 450 m downstream of the bubble curtain (also for the uppermost 5 meters of the water column) was 26 C (78.8 F). Thus, the area averaged temperature and the time averaged temperature drops were equal, both producing a drop in surface temperature from 28.7 C (83.6 F) to 26 C (78.8 F), i.e. a drop of 2.7 C (4.9 F).

(ii) The regional ocean model has shown that the upwelling produced by both the 1500-meter (Appendix A.2) and 30-kilometre bubble curtain is stable both with and without atmospheric forcing. For the 30-kilometre bubble curtain the area with sea surface temperature below 26.5 C (79.8 F) was 867 square kilometres (335 square miles) after 24 hours. The corresponding area below 27 C (80.6 F) was 1128 square kilometres (435 square miles) after 24 hours. The regional extent of the cooled area is illustrated in Figure 10 where it is superimposed on a map of the region where the oceanic data was collected.

Thus, for the selected use case the numerical models predict that the technology and process configuration employed serves the intended purpose of reducing the SST over a substantial area.

To our knowledge this is the first time such calculations have been made on this scale. Several useful insights were learned, and further modelling will surely elaborate further on these findings.

6 Acknowledgements

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7 References

Kerry Emanuel, Jeff Callaghan, and Peter Otto, A Hypothesis for the Redevelopment of Warm-Core Cyclones over Northern Australia. AMS Monthly Weather Review (2008) Vol 136, Issue 10 pp 3863-3872 https://doi.org/10.1175/2008MWR2409.1

Boyer, Tim P.; Garcia, Hernan E.; Locarnini, Ricardo A.; Zweng, Melissa M.; Mishonov, Alexey V.; Reagan, James R.; Weathers, Katharine A.; Baranova, Olga K.; Seidov, Dan; Smolyar, Igor V. (2018). World Ocean Atlas 2018. [WOA18-temperature and salinit]. NOAA National Centers for Environmental Information. Dataset. https://accession.nodc.noaa.gov/NCEI-WOA18. Accessed 25.11.2021.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999-2049. https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.3803

Olsen, J.E., Skjetne, P., Summarizing an Eulerian–Lagrangian model for subsea gas release and comparing release of CO_2 with CH_4, Applied Mathematical Modelling, **79**, (2020), 672–684, https://doi.org/10.1016/j.apm.2019.10.057

Slagstad, D., & McClimans, T. A. (2005). Modeling the ecosystem dynamics of the Barents Sea including the marginal ice zone: I. Physical and chemical oceanography. Journal of Marine Systems, 58(1-2), 1-18. <Go to ISI>://000233320200001

Smagorinsky, J. (1963). General circulation experiments with the primitive equations. I. The basic experiment. Monthly Weather Review, 91, 99-164.

Sundfjord, A., Ellingsen, I., Slagstad, D., & Svendsen, H. (2008). Vertical mixing in the marginal ice zone of the northern Barents Sea--Results from numerical model experiments. Deep Sea Research Part II: Topical Studies in Oceanography, 55(20-21), 2154-2168. http://www.sciencedirect.com/science/article/B6VGC-4T24FMB-1/2/b2ba25396c5d2f84b55552daa1ef0163

A Appendix

A.1 Evolution of curtain dynamics and temperature profiles at surface and vertical cut plane

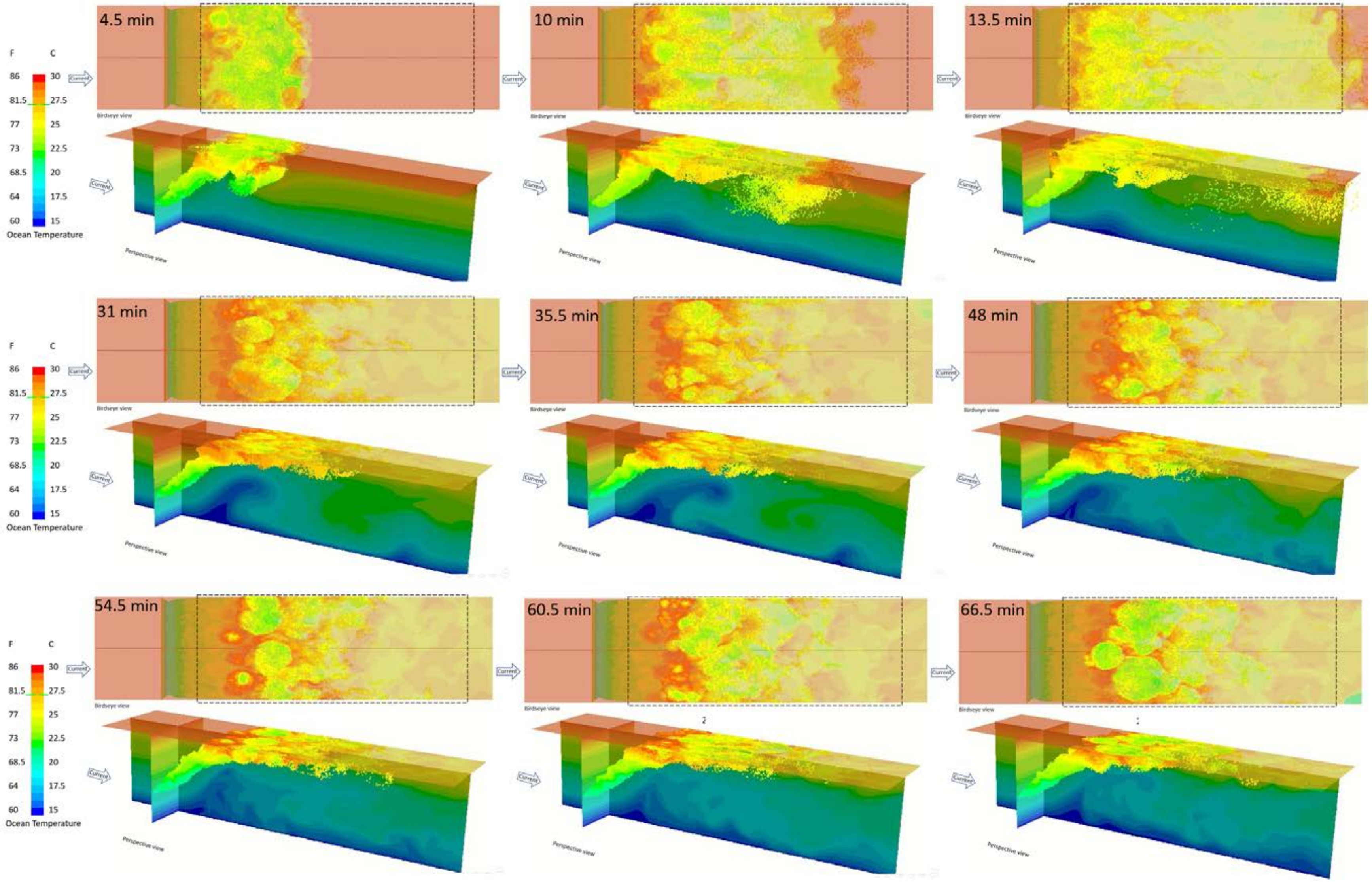

Figure 11: Temperature distribution at various times during the high-resolution curtain simulation. Points represent temperature of bubble clusters

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