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TECHNICAL REPORT

SHARC Validation and Verification Study of Oil Spill Transport and Fate Algorithms Leveraging the Cosco Busan Incident

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14. ABSTRACT A verification and validation study was undertaken to assess the transport and material fate mechanisms within the System for Hazard Assessment of Released Chemicals (SHARC) to determine the degree to which this waterborne hazard modeling capability can accurately reproduce a documented oil spill in a highly dynamic coastal environment. Aerial and shoreline oiling observations from the November 2007 Cosco Busan oil spill, combined with available environmental forcing data, were used to compare model predicted plume locations, oil thickness, and shoreline stranding with these observations. SHARC showed excellent agreement based on material location, thickness, and overall extent within the first 72 hours of the incident.					
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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement^{*}

U.S. Customary Units	Multiply by Divide by[†]	International Units
Length/Area/Volume		
inch (in)	2.54 $\times 10^{-2}$	meter (m)
foot (ft)	3.048 $\times 10^{-1}$	meter (m)
yard (yd)	9.144 $\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344 $\times 10^3$	meter (m)
mile (nmi, nautical, U.S.)	1.852 $\times 10^3$	meter (m)
barn (b)	1 $\times 10^{-28}$	square meter (m ²)
gallon (gal, U.S. liquid)	3.785 412 $\times 10^{-3}$	cubic meter (m ³)
cubic foot (ft ³)	2.831 685 $\times 10^{-2}$	cubic meter (m ³)
Mass/Density		
pound (lb)	4.535 924 $\times 10^{-1}$	kilogram (kg)
atomic mass unit (AMU)	1.660 539 $\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft ⁻³)	1.601 846 $\times 10^1$	kilogram per cubic meter (kg m ⁻³)
Pound-force (lbf avoirdupois)	4.448 222	Newton (N)
Energy/Work/Power		
electronvolt (eV)	1.602 177 $\times 10^{-19}$	joule (J)
erg	1 $\times 10^{-7}$	joule (J)
kiloton (kT) (TNT equivalent)	4.184 $\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350 $\times 10^3$	joule (J)
foot-pound-force (ft lbf)	1.355 818	joule (J)
calorie (cal) (thermochemical)	4.184	joule (J)
Pressure		
atmosphere (atm)	1.013 250 $\times 10^5$	pascal (Pa)
pound force per square inch (psi)	6.984 757 $\times 10^3$	pascal (Pa)
Temperature		
degree Fahrenheit (°F)	[T(°F) – 32]/1.8	degree Celsius (°C)
degree Fahrenheit (°F)	[T(°F) + 459.67]/1.8	kelvin (K)
Radiation		
activity of radionuclides [curie (Ci)]	3.7 $\times 10^{10}$	per second (s ⁻¹ [‡])
air exposure [roentgen (R)]	2.579 760 $\times 10^{-4}$	coulomb per kilogram (C kg ⁻¹)
absorbed dose (rad)	1 $\times 10^{-2}$	joule per kilogram (J kg ⁻¹ [§])
equivalent and effective dose (rem)	1 $\times 10^{-2}$	joule per kilogram (J kg ⁻¹ ^{**})

^{*} Specific details regarding the implementation of SI units may be viewed at <http://www.bipm.org/en/si/>.

[†] Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

[‡] The special name for the SI unit of the activity of a radionuclide is the becquerel (Bq). (1 Bq = 1 s⁻¹).

[§] The special name for the SI unit of absorbed dose is the gray (Gy). (1 Gy = 1 J kg⁻¹).

^{**} The special name for the SI unit of equivalent and effective dose is the sievert (Sv). (1 Sv = 1 J kg⁻¹).

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EXECUTIVE SUMMARY

Maritime Planning Associates, Inc. (MPA) scientists performed a targeted verification and validation study to assess the transport and material fate mechanisms within the System for Hazard Assessment of Released Chemicals (SHARC) to determine the degree to which the model can accurately reproduce a documented oil spill in a highly dynamic coastal environment. On November 7, 2007, the container ship *Cosco Busan* collided with the San Francisco Oakland Bay Bridge delta tower – spilling over 53,000 gallons of Intermediate Fuel Oil-380 (IFO-380) into San Francisco Bay. MPA scientists selected this incident as a verification and validation case for several key reasons:

- Observational data was available for comparison with model-predicted transport and slick spreading kinetics.
- Poor visibility delayed initial response efforts; therefore, the remediation efforts did not impact initial observational data.
- The spill occurred in a region with dynamic environmental conditions and complex shoreline morphology, where simulating forcing conditions is challenging.
- The spilled material, IFO-380, is highly viscous, which contributes to prolonged environmental persistence.

Available observational data, in conjunction with high-resolution bathymetry, was used to generate a synthetic testing environment to best describe the environmental conditions during the *Cosco Busan* incident. High fidelity wind data was compiled from multiple observational stations across San Francisco Bay to generate meteorological forcing conditions, improving wind-driven transport compared to available meteorological model forecasts. Basin-scale hydrodynamic forecasts were combined with modeled tidal currents for San Francisco Bay to generate the fine-scale hydrodynamic forcing conditions necessary to characterize the advective transport of material within this dynamic coastal environment. MPA's scientists also leveraged observed measurements to derive environmental water quality conditions that best described the kinetic conditions during the incident for the validation study.

A parametric run matrix was developed to validate SHARC's material transport and oil kinetics. The turbulent dispersion and the slick spreading coefficients were varied to determine the impact of these two model tuning parameters on the modeled material transport and fate. Comparisons of model output to in-bay overflight observations for each simulation in the run matrix were used to assess how accurately SHARC depicted the observational data. The calculated agreement between model-predicted transport timing and slick thickness and overflight observations was used to evaluate the quality of the modeling forecast.

SHARC model output showed excellent agreement based on material location and oil thickness analyses within the first 72 hours of the incident. Model-predicted material transport agreement,

measured as the number of coincident observation stations with model-predicted oil, was 87% within a two-hour window of the overflight start and end times for overflight, less than a quarter of a complete tidal cycle. Model transport agreement was to 100% for analyses conducted against the November 10th overflight after tarball-only observations were removed from the analysis set. Increasing the search distance from the overflight observation points did not significantly improve the frequency or occurrence of agreement, nor did it reduce the absolute error between model predictions and station observations. The largest differences were observed in the highest slick spreading and turbulent dispersion coefficient simulations. These levels of agreement indicate that the hydrodynamic forcing conditions accurately captured the speed, direction, and timing of surface water current velocities within San Francisco Bay. However, the hydrodynamic simulation did not effectively capture the hydrodynamics of the coastal zone. The modeled currents moved released material more rapidly in the east-west direction within the San Francisco Bay plume while limiting transport to the north and south, making it impossible for model-forced material to be transported to the observed locations along the California coast.

Model-predicted surface oil thicknesses were within 20 microns of documented oil thickness for observed oil locations, with three observed error values: less than 1 micron, 5 microns, and 20 microns. The 20-micron absolute differences between the model predictions and observed oil thickness were found for the stations with the thickest observed oil, less than a 10% error in predicted thickness. Absolute errors of 1 and 5 microns were associated with thinner sheens of oil, where aerial oil observation becomes highly subjective. Beyond the 72-hour time window, oil observations consisted mainly of tarballs and sheens from wave-driven disintegration. SHARC, like all operational oil spill models, does not include tarball formation kinetics, which posed an obstacle to an extended model validation beyond 72 hours. Within these limitations, model-predicted surface oiling showed excellent agreement to the spatial extent developed as part of the National Oceanic and Atmospheric Administration's (NOAA's) Damage Assessment and Remediation Plan (DARP) final report. After model tuning parameters were optimized, SHARC predicted an oil impact area of 100 square miles in San Francisco Bay from the *Cosco Busan* IFO-380 spill. To compare SHARC surface oil footprint to published oil extent data, the DARP-published footprint was reduced to surface oiling from the western extent of the Golden Gate Strait and eastward in-bay, where the bulk of the spilled oil remained. SHARC model predictions were with 3% of the in-bay footprint (97 mi²). The extremely low error in the observed oil footprint (3%) combined with the observed maximum 10% error in model-predicted thickness show that SHARC's oil spill model, with the best available environmental forcing, can reliably and accurately predict the fate and transport of oil in waterborne environments. SHARC model output is well-suited to provide actionable information to planners for response actions such as route analyses to minimize potential ship fouling, response tool deployment, and identifying the location and timing of potential impacts to shoreline resources within and beyond its baseline 48-hour forecast target.

Several recommendations to improve the accuracy of SHARC's operational material fate and transport capability arose from the analysis of these simulations:

1. Increase default turbulent dispersion coefficients for oils to $10 \text{ m}^2 \text{ s}^{-1}$, especially in regions with significant variations in meteorological forcing over short spatial scales.
2. Default slick spreading factors for highly viscous oils showed less variability in model results than expected, but an increased slick spreading factor improved agreement in transport timing.
3. Shoreline stranding and resuspension physics play an important role in material fate and transport simulations that extend beyond the default 48-hour operational time window. Developing and implementing algorithms to model the resuspension of stranded oils would significantly improve material transport and slick thickness predictions for longer-term simulations, two critical parameters for accurate material fate and transport predictions involving extremely viscous materials where complex shoreline environments become heavily oiled.

Extending SHARC's shoreline transport and fates kinetics to include tarball generation algorithms may improve material resuspension physics; however, potential forecast improvements need to be weighed against the computational complexity associated with algorithms to simulation this phenomenon. For near-instantaneous, low-volume release incidents such as the *Cosco Busan*, the additional complexity would provide a modest improvement at best.

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SECTION 1. SHARC MODEL BACKGROUND

The System for Hazard Assessment of Release Chemicals (SHARC) is a waterborne hazard fate and transport model that provides operators the ability to construct and visualize waterborne release scenarios for predicting the fate and transport of chemical warfare agents (CWAs), toxic industrial chemicals and materials (TIC/TIMs), radiological materials, oils, and biological materials. SHARC is a Lagrangian particle-based model which utilizes hydrodynamic and meteorological forcing conditions to simulate the transport and dispersion of spilled material in the coastal environment. Although SHARC can model a full suite of chemicals and materials, this study is focused on validating SHARC's oil spill model.

Slick forming materials, such as oils, are significantly impacted by wind-driven transport as well as tidally driven surface water current velocities and seasonal coastal circulation patterns. Forcing data provided to the modeling framework in the form of a local file, access to the hydrologic data server (HDS), or user-specified serves to provide the main mechanism of physical transport.

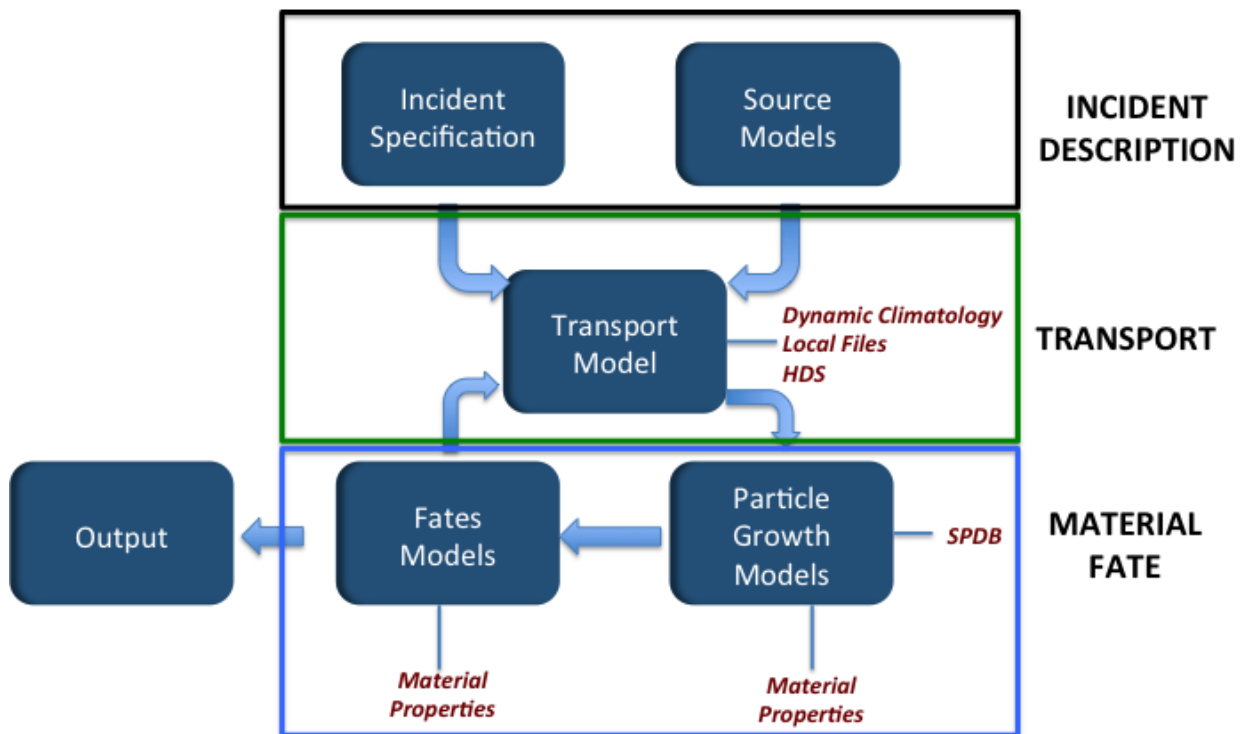


Figure 1. Schematic of the SHARC model.

There are four main components required by the SHARC model:

1. **Incident Description:** This is where the incident specifics are defined. This includes the location, date, time, type of release (instantaneous, continuous), and release geometry (point, polygon, HPAC deposition shapefile).
2. **Transport:** The transport component is where the physical forcing used to move materials around is specified. Wind and tidally influenced current data are generally used in the model. Buoyant, slick forming materials, such as oils, are subject to wind-driven transport as well. Forcing data may come from a local file, the hydrological data server, or user-specified constants. Additional transport via density-driven material buoyancy or adsorption to suspended particulate materials is also captured in the model and is determined from the specific chemical or chemicals released in an incident.
3. **Material Fate:** This modeling component determines the fate of released material properties and simulates the chemical and physical transformations of materials released into the aquatic environment. Released materials are subject to a particle growth model and a material fates model. The particle growth methodology is specified by material type, with three models of particle growth.

Oils and other buoyant, low solubility chemicals are dispersed as a function of a balance between different forces due to changes in bulk properties. Gravitational forces cause oil released at the surface to spread outwards, forming a slick. Slick spreading terminates when the gravitational forces are countered by either inertial, viscous, or friction forces. For the timescales of interest, the balance between gravitational and viscous forces is the main process considered. The volume in the oil growth model, unlike turbulent driven dispersion, typically stays constant or decreases. As a result, surface area is the parameter of interest for this type of growth model. Refer to the SHARC Analytical Foundations (MPA, 2021) for additional growth model details.

4. **Output:** Geo-referenced model output can be visualized in SHARC's graphical user interface (GUI), including the model-predicted transport and concentrations of the released materials. Additional visualization features in SHARC include maximum material concentration and arrival time to clarify when modeled materials may reach specific locations (shorelines, beaches, water intakes). The extent of surface contamination for slick-forming materials, such as oils, can also be visualized.

Additional information on SHARC's transport and oil spill material fates kinetic components is detailed below.

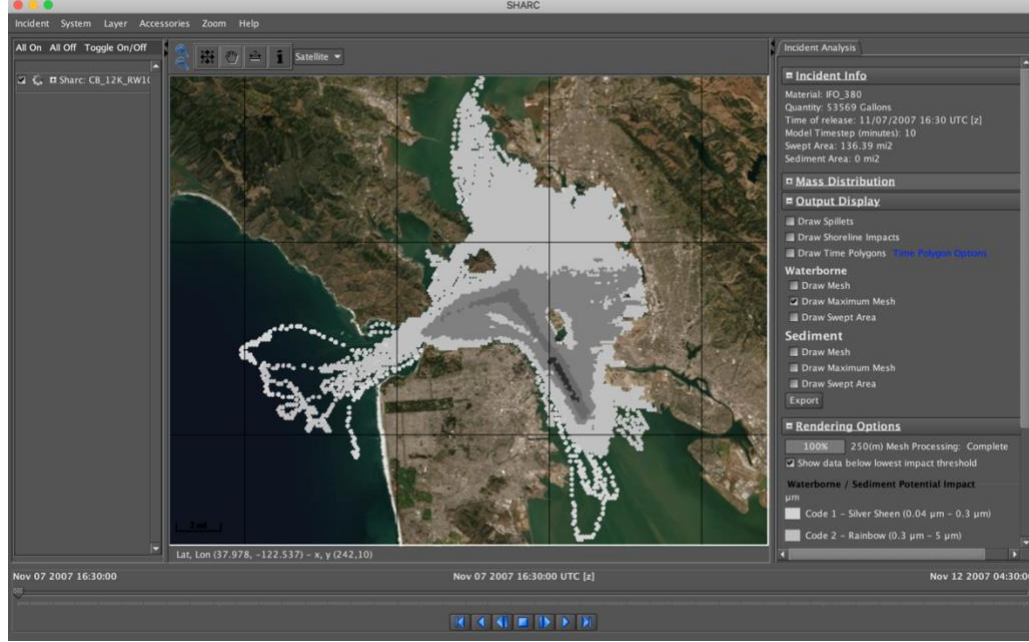


Figure 2. SHARC GUI and model output visualization.

1.1 TRANSPORT

Lagrangian particle-based models simulate the transport of released material as small parcels – known as “puffs” in atmospheric applications and “spillets” in waterborne applications – that move according to temporally-dependent forcing conditions. As such, waterborne models require hydrodynamic and meteorological input data from Eulerian observations or prediction models to effectively characterize the forcing conditions in time and space. Model spillets are initialized with a defined mass, volume, and shape, all of which are tracked and change throughout a simulation according to the transport, dispersion, and fate of the released material in the aqueous environment.

At each model timestep, a model spillet is transported by four forcing velocities (in units of m s^{-1}):

$$\vec{V}_{Total(t)} = \vec{V}_{Hydro(t)} + \vec{V}_{Wind(t)} + \vec{V}_{RW(t)} + V_{Stokes(t)} \quad (1)$$

where:

$\vec{V}_{Hydro(t)}$ is the observed or predicted two-dimensional surface water current velocity

$\vec{V}_{Wind(t)}$ is the calculated two-dimensional current velocity due to wind-driven transport

$\vec{V}_{RW(t)}$ is the parameterized two-dimensional current velocity due to turbulent flow

$V_{Stokes(t)}$ is the buoyancy-driven vertical settling velocity

The hydrodynamic input data directly provides SHARC’s Aqueous Transport Model with U-component (Eastward positive) and V-Component (Northward positive) current velocities for

the nearest point in time and space to the spilllet. Likewise, the meteorological input data provides the U-component (Eastward positive) and V-Component (Northward positive) wind velocities. Leveraging this data, the wind-driven transport velocity is calculated according to Youssef and Spaulding (1993) as 3.5% of the observed or predicted wind velocity with a random deflection ranging from 0° to 25° clockwise in the Northern Hemisphere. Within SHARC, only materials within the surface mixed layer – operationally defined as 0.5 meters – experience wind-driven transport.

The transport velocity due to turbulent processes is parameterized within SHARC with the user-defined random-walk horizontal dispersion coefficient. At each model timestep, the turbulent transport velocity of each model spilllet is calculated according to the following equation:

$$\overrightarrow{V_{RW(t)}} = \sqrt{\frac{2K_{disp}}{T_{trans}}} * RN \quad (\text{Equation 2})$$

Where:

K_{disp} is the random-walk horizontal dispersion coefficient ($m^2 s^{-1}$),

T_{trans} is the Aqueous Transport Model timestep (s), and

RN is a random number ranging from -1.0 to 1.0.

This technique, performed separately on each component velocity, is a tuning parameter common to many Lagrangian models to accommodate for the random nature of turbulent motion.

Within SHARC, the buoyancy-driven vertical settling velocity is calculated using a modified Stoke's settling equation. The basic Stokes' equation (below) is a function of the relative difference in density between materials, as well as the typical size of the settling particle (Lamb, 1993):

$$\overrightarrow{V_{Stokes(t)}} = \frac{2}{9} * g * \frac{\Delta\rho}{\mu} * R^2 \quad (\text{Equation 3})$$

Where:

g = the gravitational acceleration constant

$\Delta\rho$ = the density difference between the material density and freshwater or seawater

μ = the dynamic viscosity of freshwater or seawater

R = the spilllet radius

For the *Cosco Busan* incident, the released IFO-380 fuel oil is expected to remain positively buoyant and stay within the surface mixed layer of San Francisco Bay.

1.2 KINETICS

SHARC's material fates modeling components are designed to capture the chemical and physical transformations of materials when they are released into aquatic environments. SHARC's fates models are unique in several respects. The physical and chemical transformations that a released material may undergo during a modeling simulation are specified within the individual material file. This construct allows material-specific degradation and reaction rates to be implemented that include the impact of in-situ environmental variability for each of the material fates modeled processes. For materials that react with water and hydrolyze, all daughter products are treated as constituents and are tracked within the model.

The material fate and transport of oil in aquatic environments is determined primarily by the interaction of the physical and chemical properties of the oil with environmental forces, including winds, currents, and tides. Oils are typically considered persistent or non-persistent based upon the speed at which they disperse and degrade in the environment. Examples of persistent oils include crude oils, heavy fuel oils, and lubrication oils. Non-persistent oils, such as gasoline, light diesel fuels, and kerosene, are more quickly dispersed in the environment and are not typically subject to long-term cleanup and remediation efforts.

Oils undergo eight major degradation and transport processes when spilled in aquatic environments (Figure 3, Figure 4). These eight processes are collectively called weathering. In the short term – hours to days – the five fundamental physical processes that determine the spatial extent and persistence of spilled oil are spreading, evaporation, dispersion, dissolution, and emulsification. In the longer term – weeks to years – spilled oil may also be subject to chemical changes from biodegradation and photo-degradation and may also sorb to suspended particulate material and sediment.

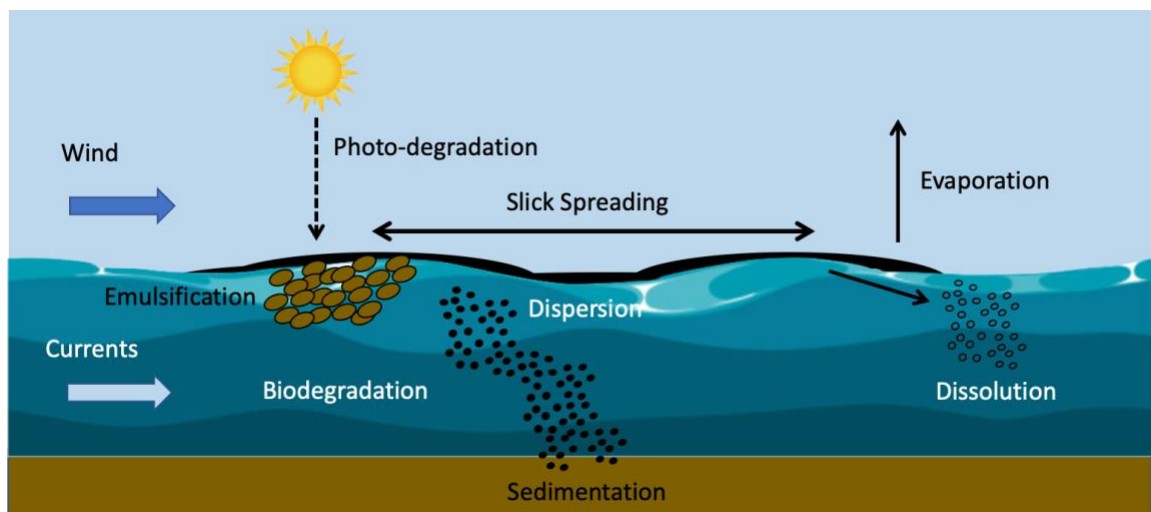


Figure 3. The major oil weathering processes.

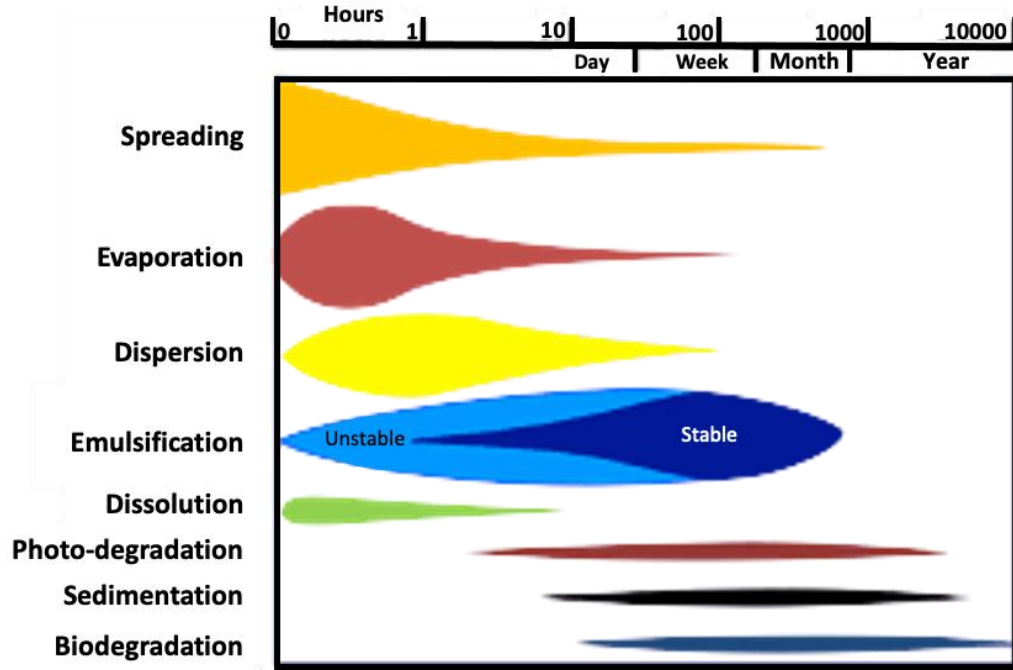


Figure 4. Timeline and relative importance of the eight major oil weathering processes.

SHARC's oil spill model focuses on three short-term processes to provide an operational oil spill modeling capability: slick spreading, evaporation, and emulsification. Dissolution, although significant for deepwater blow-out simulations, is generally negligible for surface oil spills. Dispersion, driven by wave-induced slick break-up, requires detailed knowledge of the wave state, often unavailable on operational response timeframes. For these reasons, SHARC excludes dissolution and wave-driven dispersion in its oil spill model. Detailed in the following sections are the fundamental assumptions for the three primary oil fates processes.

1.2.1 Slick Spreading

Slick spreading, which is the process by which oil is distributed on the sea surface, is a function of gravitational and viscous forcing. Slick spreading rates in SHARC are based on Fay's equations (1969, 1971). The radius of the Lagrangian particle is determined as a function of time according to the following equation:

$$radius (m) = SF \left[\left(\frac{\rho_{sw} - \rho_{oil}}{\rho_{sw}} \right) * g * \frac{V^2 t^{1.5}}{\nu^{0.5}} \right]^{\frac{1}{6}} \quad (\text{Equation 4})$$

Where:

SF = the slick spreading factor, unitless

ρ_{sw} = the density of seawater, or the surrounding aqueous environment (kg m^{-3})

ρ_{oil} = the density of the released oil (kg m^{-3})

g = acceleration due to gravity (m s^{-2})

t = time (in hours)

v = the kinematic viscosity of the released oil ($\text{m}^2 \text{s}^{-1}$)

V = the volume of released oil (m^3)

The maximum surface that an oil slick (A) is projected to have can be calculated according to Fay (1969):

$$A(\text{m}^2) = 10^5 [V]^{0.75} \quad (\text{Equation 5})$$

Where:

V = the volume of released oil (m^3)

Total oil volume, divided by the model output mesh surface area, is equal to the surface oil thickness. Although this assumes that the thickness is essentially uniform for each spilllet, SHARC's Lagrangian modeling approach applies the thickness calculation to each spilllet, so spilllets with different ages/weathering states or composition have different thicknesses. Surface oil slicks range in thickness from less than 0.1 microns for non-emulsified oil to several millimeters or more for emulsified oil (NOAA 2012). For typical surface oil slick thicknesses, the Biot number, which is the ratio of internal to external thermal resistance, is less than or equal to one. This value indicates that oil slicks are thermally thin and uniform relative to the environment (Cragan, 2016), supporting the implementation of uniform spreading rates.

1.2.2 Evaporation

Evaporation, the conversion of a chemical from liquid to gas at a temperature below its boiling point, is the largest loss process for newly spilled oil, with >30% of spilled oil mass lost to the atmosphere in the first 24 hours (Payne, 1991), depending on the type of oil. Surface-spreading oil is subject to the evaporation of its more volatile components. Oil slicks form as the result of the (typically) less dense and insoluble oil spreading on the water surface due to the balance between gravitational and viscous forces, as well as inertial and frictional forces. Slick spreading rates determine both the surface area of spilled oil and the slick thickness, which both impact the evaporation rate. Most oil spill models (OSMs) employ one of three approaches to modeling evaporation: 1.) The pseudo-component approach (Li, 1985), 2.) calculated evaporative exposure (Stiver and MacKay, 1984), or 3.) predetermined loss rates (Fingas, 1997). Pseudo-components are groups of compounds delineated by boiling point and solubility. Each pseudo-component group is assumed to behave uniformly (French-McCay and Payne, 2001). The evaporative exposure approach (Stiver and MacKay, 1984), developed from empirical data, assumes that evaporation is a function of oil composition and temperature only, using a bulk mass transfer coefficient that is a function of wind speed. Predetermined loss rates are empirically derived equations to describe overall evaporation as a function of time and temperature. SHARC's oil spill model is unique in its approach to evaporation and implements a more granular multi-component construct that leverages time-varying density and viscosity to determine instantaneous evaporation rates that reflect changing bulk oil properties.

Fingas (2013) refuted the typical assumption of air-boundary layer limited evaporation rates based upon a comparison to empirical data. Unlike water evaporation, which is air-boundary limited, the atmospheric background concentration of the constituents of oil is effectively zero, meaning that oil component evaporation from the bulk oil is diffusion-limited by the oil itself. Oil temperature and bulk properties are the main factors that determine the evaporation rate (Fingas, 2013). The air boundary-layer limitation assumption has been the basis for the evaporation algorithms in most modern OSMs. Additionally, most oil spill model evaporation rate algorithms are formulated as a function of wind speed. The variation of existing model short-term (hours) evaporative predictions is not significant but can be more than 100% after several days because the wind-speed dependence generates unrealistic evaporation rates.

Crude and heavy fuel oils like IFO-380, the heavy fuel oil spilled from the *Cosco Busan*, consist of a complex mixture of thousands of organic chemicals, many of which are toxic to aquatic organisms and may bio-accumulate (Almeda et al. 2013), while lighter fuel oils, such as gasoline, consist of a smaller, more well-defined group of chemicals. SHARC's oil spill model leverages a multi-component approach to quantify evaporative loss by calculating evaporation rates for each chemical constituent and quantifying the impact that evaporative losses have on an oil's bulk material properties – density and viscosity. By quantifying these bulk properties, the slick spreading rate and the emulsification potential of an oil can be dynamically determined as a function of environmental conditions. Despite a lack of complete knowledge of the vast number of constituents of crude oil, oil exploration and refining processes typically rely on mass percentages of the four major oil and fuel components classes: saturates, aromatics, resins, and asphaltenes (SARA), a standard petroleum assays (Sanchez-Minero et al., 2013). In conjunction with relative amounts of the most typical chemical constituents in these classes, the SARA percentage data are used in SHARC's OSM to track specific components critical to determining the evaporation rate of oil in aqueous environments. A typical crude oil in SHARC is composed of over 300 individual chemicals. The more volatile components within the saturate and aromatic classes are generally thought to stabilize the resinous and asphaltenic components by suspending them in solution (Fingas, 2014). Evaporation reduces the amount of the most volatile saturate and aromatic components, decreasing the stabilizing effect on the resins and asphaltenes and increasing the relative amount of these classes. At high enough percentages, the asphaltenic components can precipitate and may form persistent water-in-oil emulsions. With this more granular approach to determining the evaporation rate, bulk oil properties and the impacts on the slick spreading rate and slick surface area are more tightly coupled. The tighter coupling used by the SHARC model provides a more robust method for determining the fate and transport of spilled oil.

The amount of each oil constituent within the mass-weighted bulk material composite evaporating at each timestep is calculated in the following manner:

$$M_{evap} = F_{evap} * A_{surf} * t \quad (\text{Equation 6})$$

Where:

t is the model timestep (s)

A_{surf} is the surface area (m^2) of the slick (here parcel of the slick)

F_{evap} is the calculated evaporative flux ($mol\ m^{-2}\ s^{-1}$)

The evaporative flux for each oil constituent is calculated as a function of the overall mass transfer coefficient and the mass fraction of material in the surface oil, using a film-based exchange model. The overall transfer coefficient (k) determined as a function of bulk oil viscosity. Oil viscosity is key to determining the instantaneous mass transfer rate of components during evaporation. Each oil constituent's material diffusivity within the oil is used to determine the liquid phase transfer velocity. (Dalton, 1963). Refer to the SHARC Analytical Foundations (MPA, 2021) and Cragan (2016) for additional details on the evaporation model.

Estimation of bulk crude oil viscosity is a challenging task and has been the source of significant investigation (Quiñones-Cisneros et al. 2001a; Quiñones-Cisneros et al. 2001b; Quiñones-Cisneros et al. 2004; Baylaucq et al. 2006; Quiñones-Cisneros & Deiters 2006; Quiñones-Cisneros et al. 2008; Quiñones-Cisneros et al. 2015). The viscosity of oils varies greatly as a function of gas content, with dead oil – oil with no gas content – viscosity correlations exhibiting very different dependencies than live oils – freshly released oil from a reservoir with significant gaseous components. To develop a generic approach to oil spill modeling, oils were assumed to be dead.

SHARC leverages the linear friction theory method developed and proposed by Quiñones-Cisneros et al. (2000, 2001a, 2001b, 2004, 2006, 2008). Briefly, this approach posits that viscosity can be treated as the sum of two components: the dilute gas viscosity of a constituent and the residual friction viscosity. The frictional components of viscosity for each constituent are ultimately reduced to attractive and repulsive components, with universal friction coefficients assigned and residual friction components determined as a function of critical reduced parameters, themselves dependent on the equation of state used. The Peng-Robinson, Stryjek-Vera Equation of State (PRSV-EOS) is used to determine bulk viscosity in SHARC's oil spill model. The PRSV-EOS is widely used in the determination of hydrocarbon mixture properties. Viscosity values for each component were calculated and summed to develop a mass-based mixture kinematic viscosity (η_{mx}) as the sum of the dilute gas and friction components:

$$\eta_{mx} = \eta_{0,mx} + \eta_{f,mx} \quad (\text{Equation 7})$$

Where:

$$\eta_{0,mx} = \exp \left[\sum_{i=1}^n x_i \ln(\eta_{0,i}) \right]$$

$$\eta_{f,mx} = \exp \left[\sum_{i=1}^n x_i \ln(\eta_{f,i}) \right]$$

$\eta_{0,mx}$ = the mass-weighted mixture dilute gas kinematic viscosity contribution

$\eta_{f, mx}$ = the mass-weighted mixture friction kinematic viscosity contribution
 x_i = the mass fraction of component i
 $\eta_{0,i}$ = the dilute gas kinematic viscosity contribution of component i
 $\eta_{f,i}$ = the frictional kinematic viscosity contribution of component i

Dynamic viscosity, divided by density, is equal to kinematic viscosity.

Most oil spill modeling systems do not account for how available energy is utilized in evaporating materials from the sea surface, resulting in faster evaporation rates than realistically could be expected (Cragan, 2016). To avoid this potential pitfall, SHARC's oil spill model includes an energy balance cap to check the energy used for evaporation and balance it according to the available net longwave radiation, acquired from publicly available NOAA NCEP/NCAR reanalyzed monthly averaged climatological data (1981-2010) (NOAA/ORA/ESRL PSD) and included in SHARC's seasonal profile database (SPDB). The estimated material flux for a given chemical is converted to the energy needed for evaporation using the latent heat of vaporization, and evaporation stops when all available energy has been allocated.

1.2.3 Emulsification

Water-in-oil emulsions may form, depending on the evolving oil composition. High asphaltene and resin content lead to a greater probability of emulsification. Emulsified oil is highly resistant to weathering. The increased water content within the oil slick from emulsification alters the physical properties and the transport characteristics, increasing the overall volume of oil-contaminated material. The bulk density changes caused by the inclusion of water in the oil mixture often result in a neutrally buoyant mousse that floats at or just below the water surface. Once a stable emulsion has formed, the effectiveness of booms, skimmers, and other response tools are significantly reduced, and in-situ burning ceases to be a response option (Reed, 1999). Knowing when and if spilled oil will emulsify helps guide the operational response tempo and choices, allowing response crews to direct and maximize effectiveness.

The emulsion state of spilled oil is critical when determining the overall fate and transport in aquatic environments. Emulsification reduces the natural degradation and dispersion of spilled oil while increasing environmental persistence and the volume of oil-contaminated water. The onset of emulsification has been hypothesized to be due to a decrease in the solvent content of oil. Once spilled oil becomes emulsified, it is no longer subject to any additional degradation in the model. Although degradation does continue to occur in the environment, the relative change in oil mass is small compared to the operational timeframe that SHARC was designed for (several days).

The kinetics of crude oil emulsification are not well understood (Fingas, 2010; however, it is generally considered rapid once the criteria for emulsification are present. Fingas (2010) has proposed a set of criteria that contribute to the formation of the various stability categories of

crude oil emulsions, developed from a large body of laboratory studies on component class compositions and emulsion formation. The interaction of these criteria was codified into a stability function, which defines whether an oil is emulsified and what type of emulsion is formed. Further details can be found in the SHARC Analytical Foundations (MPA, 2021).

According to Fingas (2014), an oil's emulsion state is determined by the saturate, aromatic, resin, and asphaltene content and the oil's density and viscosity. A stability index is used to determine whether an emulsion forms and whether the emulsion is stable, meso-stable, entrained, or unstable. Only non-emulsified oil is subject to all degradation processes and additional surface wind-driven transport in the model.

As implemented in the model, the emulsification state algorithm utilizes the calculated bulk density and viscosity values that include the impact that calculated changes in these properties have on the individual constituent evaporation rates. By re-determining the bulk properties at each timestep, the model's evaporation rate calculations incorporate changes in the external temperature of the surrounding seawater and the effects that these dynamic rates have on the overall oil bulk properties. By implementing the algorithms in this fashion, the emulsification state calculation is also linked to available environmental conditions.

1.2.4 Dissolution

The SHARC model excludes dissolution due to the small net impact on oil mass balance in the short term for surface oil spills. Evaporation, as mentioned above, is the critical short-term physical process that drives oil fate and transport, outpacing dissolution by one or more orders of magnitude depending on the oil for surface spills. Dissolution becomes significant in scenarios where evaporation is limited, such as deep-sea blowout modeling, but excluding dissolution from SHARC introduces an error of less than 10% to the overall mass balance calculation (ITOPF 2016).

1.2.5 Dispersion

Dispersion, the generation of oil droplets from surface wave breaking and turbulence, creates additional oil spreading. Dispersion is the primary driver behind the dissolution of the more soluble components of oils. Tiny oil droplets may resurface and rejoin the original surface oil slick or resurface at a different location than the original slick, elongating or breaking up the surface slick. Resurfacing droplets may introduce water into the original slick or lose mass through the dissolution of more soluble components. There are no droplet generation algorithms contained in SHARC's oil spill model. It is assumed that the slick spreading algorithm captures most of the dispersive transport.

SECTION 2. OBJECTIVES

MPA's scientists undertook a targeted verification and validation (V&V) study comparing SHARC model forecasts to a real-world incident to accomplish three primary purposes:

1. To validate SHARC's transport model.
2. To validate SHARC's oil material fates and kinetics.
3. To assess how well SHARC's oil spill model can accurately reproduce a documented oil spill incident.

The collision of the container ship Cosco Busan with the delta tower of the San Francisco Oakland Bay Bridge (SFOBB) on November 7, 2007, was selected as a V&V case for several key reasons:

- Observational data was available for comparison with model-predicted transport and slick spreading kinetics.
- Initial response efforts were inhibited by poor visibility; therefore, the observational data was not impacted by remediation efforts within the first 96 hours.
- The spill occurred in a region with dynamic environmental conditions and complex shoreline morphology where simulating forcing conditions is challenging.
- IFO-380 is a highly viscous fuel oil with prolonged environmental persistence, allowing for model-to-data comparisons for several days.

The availability of both environmental forcing data and observed surface oiling location and thickness provided a means to assess the quality of SHARC's oil spill model across San Francisco Bay, specifically the quality of SHARC's material transport and fate. Oiling observations from Shoreline Clean-up and Assessment Technique (SCAT) Teams, shoreline oiling observations, along with published information on the overall spill extent, provided another tier of data against which to quantify how well SHARC's transport and material fates models predicted the oil extent.

A statistical comparison of the model's predicted material arrival time to point observations from overflight observations was performed to provide a quantitative measure of how well SHARC's transport model accurately depicts oil transport within San Francisco Bay within the limits of the environmental forcing and the SHARC model. This comparison was used to validate SHARC's transport algorithms as a function of the calculated transport uncertainty. For each observed point from overflights conducted between 08NOV and 10NOV, a length scale derived from the calculated uncertainty in the advective forcing was applied to determine the temporal coincidence of observed oil and model predicted oil. Default model tuning parameters were also varied to determine the optimal agreement between the model and observational data, based on the absolute agreement of model predicted transport to observed oil locations.

The thickness of surface oil is the key model output from SHARC's oil spill model. Oil thickness forecasts provide meaningful information to oil spill responders on where, when, and for how long spilled oil can be effectively remediated. Surface oil thickness encompasses material changes due to evaporation, slick-spreading, emulsification, and material transport on the overall state of the oil. The thickness of oil on or near the surface was also documented during overflights. A statistical analysis of model-predicted and observed thickness values was conducted to provide a metric of how well SHARC's oil model kinetics and bulk property calculations accurately depict oil thickness given the potential uncertainties in the model. Sources of uncertainty in SHARC's oil model kinetics include material density and viscosity estimates derived from a subset of oil components, the associated impacts to the mass transfer and slick spreading rates, and the calculated emulsion state of a spilled oil.

System-level performance was assessed relative to two separate observational datasets: shoreline oiling and documented oil spatial extent. Extensive shoreline surveys conducted in the months after the spill resulted in a detailed map of heavy, moderate, and light oil from the *Cosco Busan* spill. Comparing SHARC's predicted near-term shoreline oiling to this longer-term shoreline survey data provides a method to determine the geospatial agreement between model-predicted and observed shoreline oil stranding. The agreement between model predictions and observations will be used to provide a qualitative assessment of shoreline impacts. The temporal offset between model predictions and observed shoreline oiling does not allow a more detailed analysis.

Additionally, the comparison between NOAA's published extent of oil impact and model predicted maximum surface oiling provides a means to quantify system-level uncertainty relative to the observed oil footprint with optimized modeling parameters. In addition to the length scale uncertainties employed for transport, a parametric matrix was developed to vary three key modeling parameters to optimize model output: Lagrangian particle numbers, the horizontal random walk factor, and the slick spreading factor. By varying these three factors, an assessment of the impact of model defaults on overall performance (defined as the agreement between model predictions and observations) was done.

The end goal of these analyses was to provide confidence that SHARC's oil spill model forecasts can accurately predict material fate and transport and document the uncertainties inherent in leveraging SHARC to perform operational waterborne fate and transport for an oil spill. Accurate predictions of where oil will be and what state it is in are critical to informing operational responders and implementing cost-effective response measures immediately after an oil spill. An accurate oil spill model allows for alternative shipping routes, increased remediation impacts, and reduced environmental impact. Contrary to more established atmospheric modeling methods, quantifying uncertainty in waterborne hazard modeling is still an area of active research. (Karama, 2021). While agreement within a factor of two and a 20-degree envelope of directionality is considered 'good' for atmospheric modeling of pollutant transport (Chang and Hanna, 2004), waterborne hazard benchmarks are still largely undefined. This validation study represents a step towards quantifying what is reasonable for operational waterborne hazard forecasting.

SECTION 3. INCIDENT DESCRIPTION

At 0620 on November 7, 2007, the pilot boarded the container ship *Cosco Busan*. With dense fog and visibility reported to be less than $\frac{1}{4}$ nautical miles all the way to the Golden Gate Bridge, the captain initially informed the bridge watch officer that the ship's departure, which was scheduled for 0700 from its berth at Pier 56, was tentative. Seventeen minutes later, at 0637, the captain informed vessel traffic services (VTS) of the *Cosco Busan*'s intended route through the Delta-Echo span of the Oakland-San Francisco Bay Bridge. At 0800, the *Cosco Busan* moved away from Pier 56 with the assistance of the *Revolution*, a tractor tug, and began its route to Busan, South Korea, fully loaded with cargo. At 0810, the *Cosco Busan* began to leave the Inner Harbor Entrance Channel on a heading of 288° . The navigation plan had a heading change to 272° through the Bar Channel, followed by a right turn to heading 310° to pass through the Delta-Echo span of the Bay Bridge. Figure 5 depicts the intended course with a dashed black line.

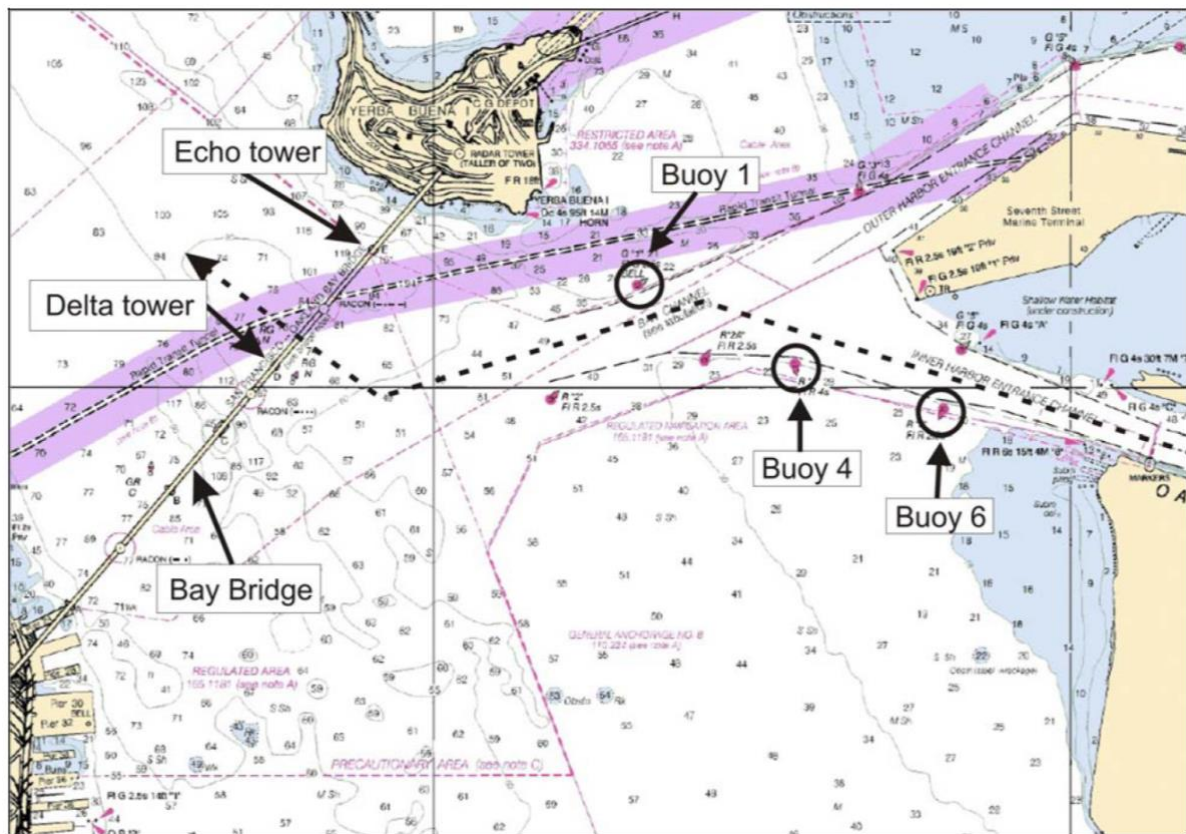


Figure 5: Chart of the intended course of the *Cosco Busan* on 07 November 2007.

At 0827, when the vessel was approximately one-third of a nautical mile from Bay Bridge, a VTS operator monitoring local ship traffic noticed that the *Cosco Busan* appeared to be deviating from its intended course through the Delta-Echo bridge span. At 0828, the ship's bosun radioed to the ship's master that he could see the bridge's column (support). Two minutes later, at 0830, the forward port side of the vessel struck the delta tower of the bridge. The collision resulted in

a 212 foot long, 10-foot-high gash on the port side of the *Cosco Busan*, breaching fuel tank #3, fuel tank #4, and the #2 water ballast tank. After the collision, the vessel transited to anchorage #7, 2 miles west of Treasure Island, arriving at 0850. At 0853, the relief pilot noticed that the *Cosco Busan* was spilling oiling; however, it was not reported to be significant. A USCG pollution team, deployed at 0846, reported an oil slick 3 feet wide from Anchorage #7 to the Bridge and took photos of the damage upon their arrival at 0930. At 1002, due to the shifting tide and concerns about the water level depth, the *Cosco Busan* switched to the deeper Anchorage 9, south of the Bay Bridge. Initial reports suggested that nearly 150 gallons of intermediate fuel oil 380 (IFO-380) had been spilled during the incident. This number would later be revised up to 53,569 gallons.

Due to the difficulty in visualizing oil spill extent from the water, overhead surveillance is heavily relied on in oil spill responses to assess the extent of oil spills and identify priority regions to deploy countermeasures such as booms, skimmers, and dispersants. By the end of the first day, there were eight skimmers, 20 support vessels, and 19,000 feet of boom on-scene. A helicopter survey was not conducted until 1336, and preliminary reports did not find a large pool of oil, likely due to limited visibility from the persistent heavy fog on the bay. In addition to hampering overhead surveillance efforts that usually inform response operations, the lack of an observed concentrated oil slick further hampered overall response as this was initially attributed to dispersion of the oil in this dynamic environment.

SECTION 4. INCIDENT DATA DESCRIPTION

At the time of the incident, winds were calm, the visibility forecast was $\frac{1}{4}$ nautical mile or less, with a flood tide. The observed current field was 1.25 knots at 168° true. Water level observations at the Golden Gate Bridge station (Figure 6, top) and Alameda station (Figure 6, bottom) indicated a high tide of 5.9 feet above MLLW at 0930 local time (1730 GMT) and 6.5 feet above MLLW at 1006 local time (1806 GMT) respectively. The amplitude of tidal forcing increased over the course of the incident, with a Neap Tide occurring on November 4th and a Spring Tide occurring on November 25th. Station 9414290 (Figure 6, top) is 5 miles to the west at the Golden Gate Bridge. Station 9414750 (Figure 6, bottom) is 4 miles to the east in Alameda, CA. The red highlighted area is the time between the *Cosco Busan* striking the delta tower and the estimated end of the active spill, approximately 30 minutes.

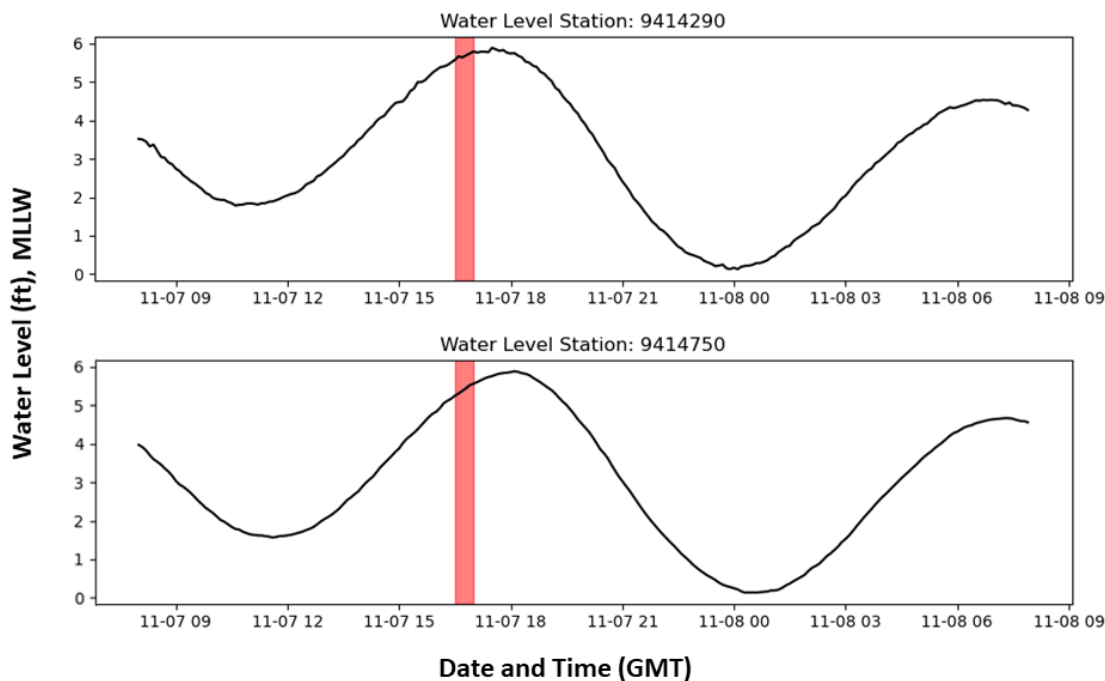


Figure 6. Observed water level at the two nearest observation stations relative to Mean Lower Low Water (MLLW) for November 7, 2007.

The predicted currents at the Bay Bridge Pier D during the *Cosco Busan* collision were toward the south-southeast (168° true) at 1.25 knots shortly after peak flood (Figure 7). These observed environmental conditions resulted in material transport out of San Francisco Bay within the first 6 hours of the release. The red highlighted area is the time between the *Cosco Busan* striking the delta tower and the estimated end of the active spill, approximately 30 minutes.

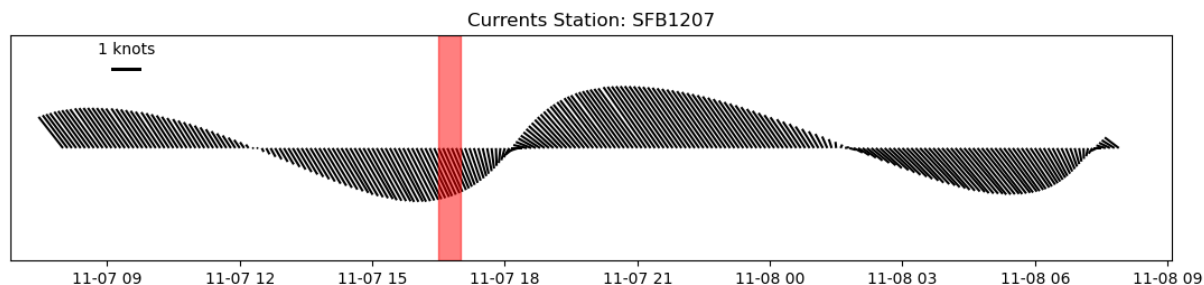


Figure 7. Predicted currents at the Bay Bridge Pier D (Station SFB1207) for November 7, 2007.

Persistent heavy fog severely limited visibility and hampered overhead surveillance efforts until mid-afternoon. NOAA conducted helicopter overflights with trained oil spotters aboard to determine where the spilled oil was and the potential to deploy response equipment effectively. Shoreline Cleanup and Assessment Teams (SCAT) were also deployed to quantify the shoreline oiling that resulted from the spill. Despite boom and skimmer deployments being hampered by the lack of overhead observations on the first day, the O'Brien group estimated that 33% of the spilled oil was recovered in the first four days (NTSB, 2009). The NTSB and Trustees determined that the low initial estimate of the spill did not hamper response as the protocol in the area was to deploy enough boom and skimming equipment to respond to the largest fuel tank spill for the vessel (250,000 gallons).

4.1 OVERFLIGHT DATA

At points along the overflight path for the overflight surveys, trained oil spotters recorded observations regarding the presence or absence of oil, as well as the type of oil observed. Each overflight resulted in a survey bulletin providing the approximate locations of observed slick features, or lack of slick, along the flight route (Figure 8).

Observations from these surveys provide two pieces of data that can be used to validate SHARC: the location of the oil at the fringes of the oil plume, which can be used to validate transport, and the observed slick thickness. The observed oil thickness can be used to assess how well the implemented oil spill model kinetics, specifically slick spreading and evaporation rates, characterize the material fate for oils.

The overflight surveys were geo-referenced, digitized, and buffered to provide an approximate observation point location utilizing the Open Source Quantum Geographic Information System (QGIS). The digitized surveys were leveraged to assess the agreement between the overflight observations and the SHARC material transport and kinetics forecast. The difference in arrival time between SHARC forecasted material and the overflight time window was used to determine how well material transport was captured with the SHARC simulation. Kinetic agreement was defined as equivalence in the SHARC forecasted oil thickness to the coincident overflight survey's oil observation description.

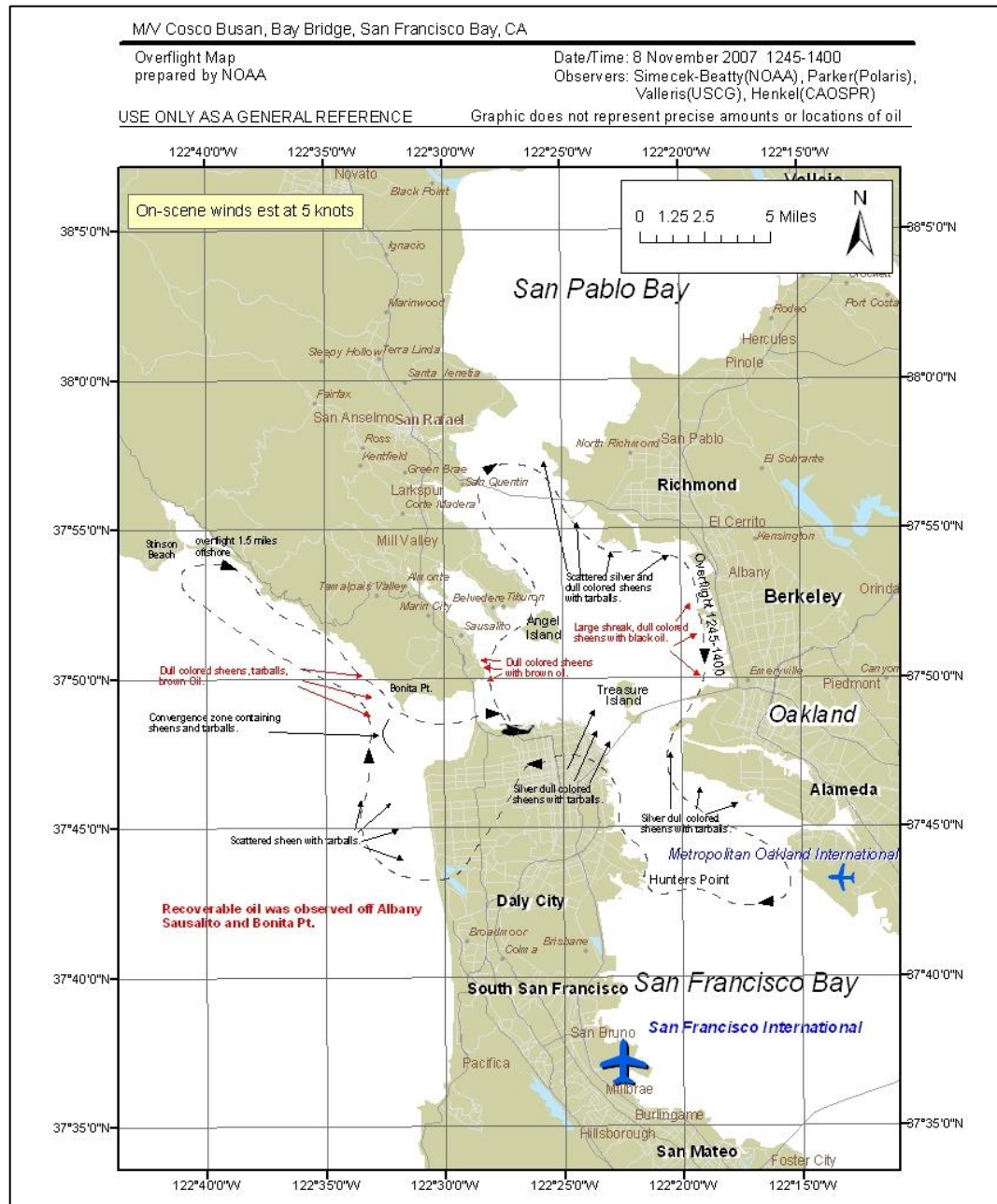


Figure 8. Example NOAA overflight survey from November 8, 2007, at 1245 - 1400 local time.

4.2 SHORELINE OILING DATA

NOAA deployed Shoreline Cleanup and Assessment Technique (SCAT) Teams to assess shoreline oiling during the *Cosco Busan* incident. SCAT Teams conducted shoreline oiling surveys for several months after the *Cosco Busan* spill to inform the Natural Resources Damage Assessment process and target shoreline regions for remediation efforts. As a result of these surveys, a detailed overall shoreline oiling map was generated for NOAA by the response team (Figure 9, *Cosco Busan* Oil Trustees, 2012). The digital data used to develop this map was

available from California Fish and Wildlife and was processed for potential comparison to SHARC shoreline model output.



Figure 9. NOAA SCAT surveys maximum oiling results.

4.3 INCIDENT EXTENT

The NRDA findings from the *Cosco Busan* Spill included a graphic of the total oil-impacted area derived from the helicopter overflight and SCAT Team shoreline assessment surveys. This image was geo-referenced and digitized utilizing the QGIS to provide a means of comparing the observed oil-impacted extent to SHARC's forecasted oil-impacted extent (Figure 10).

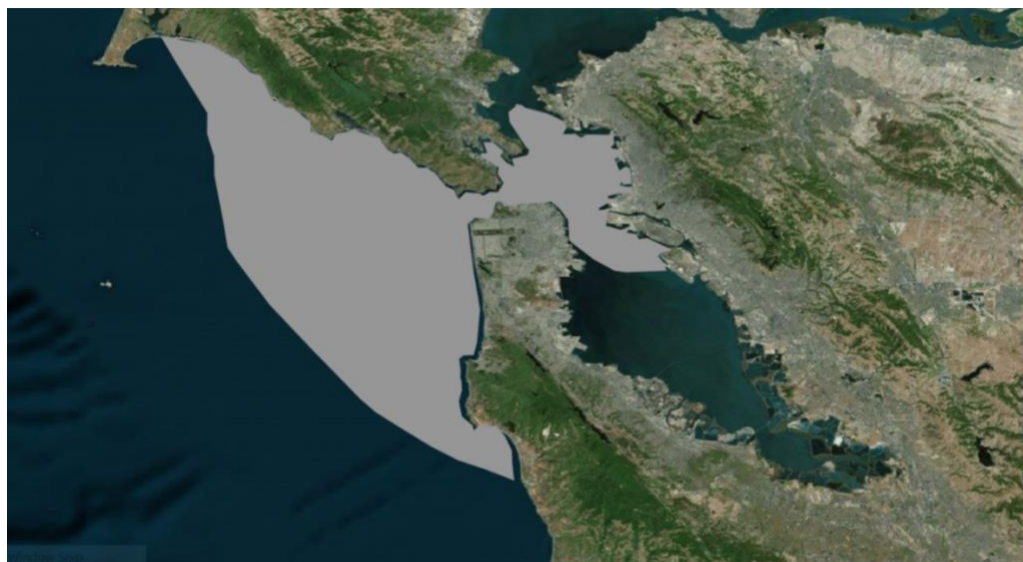


Figure 10. NRDA *Cosco Busan* oil-impacted extent.

SECTION 5. SYNTHETIC TESTING ENVIRONMENT

As slick forming materials, oils are significantly impacted by wind-driven transport, tidally driven surface water current velocities, and seasonal coastal circulation patterns. Forcing data provided to the modeling framework in the form of a local file or dynamic climatology database provides the primary mechanism of physical transport of model spilletts.

To accurately forecast an oil spill in the coastal environment, SHARC requires the highest resolution hydrodynamic and meteorological forcing data available. MPA scientists conducted an exhaustive review of the available environmental data to define the most accurate conditions for the modeling simulation. Today, San Francisco Bay is a highly instrumented water body, replete with meteorological and oceanographic observations across the entire bay and the nearby offshore environment. This is primarily to describe the many microclimates that make up the region created by the interaction of ocean, land, and the complexity of the coastal mountain ranges in the area. Physically, this is manifest by large gradients in atmospheric temperature, wind, current velocities, and visibility over short physical distances. There were far fewer instruments deployed in 2007; however, routinely collected meteorological data at the many airports that serve the San Francisco metropolitan area, and several National Oceanic and Atmospheric Administration (NOAA) monitoring stations were in operation in 2007, collecting meteorological and oceanographic data (water temperature, water level) and providing water level forecasts and tidal current predictions (Figure 11; Table 1). The approximate location of the *Cosco Busan* collision is depicted with a yellow star (Figure 11).

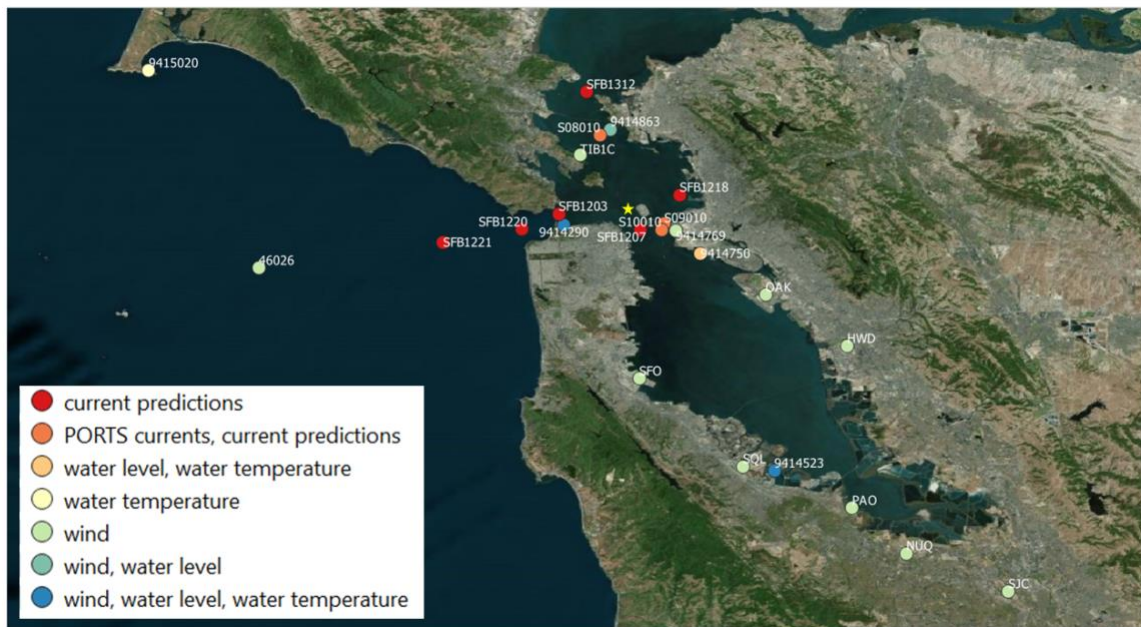


Figure 11. Environmental monitoring stations with data available during and after the *Cosco Busan* incident.

Table 1. Station ID, location, and data access points for observational data.

Station ID	Station Name	Station Type	Latitude	Longitude	Data Access
PAO	Palo Alto Airport	wind	37.4611	-122.1151	https://mesonet.agron.iastate.edu
OAK	Oakland Airport	wind	37.7213	-122.2207	https://mesonet.agron.iastate.edu
SFO	San Francisco Airport	wind	37.619	-122.3749	https://mesonet.agron.iastate.edu
HWD	Hayward Executive Airport	wind	37.6588	-122.1212	https://mesonet.agron.iastate.edu
NUQ	Moffett Airport	wind	37.4059	-122.049	https://mesonet.agron.iastate.edu
SJC	San Jose Airport	wind	37.3594	-121.9244	https://mesonet.agron.iastate.edu
SQL	San Carlos Airport	wind	37.5119	-122.2483	https://mesonet.agron.iastate.edu
46026	Offshore SF Bay Buoy	wind	37.754	-122.839	https://www.ndbc.noaa.gov
TIB1C	Tiburon Pier	wind	37.892	-122.447	https://www.ndbc.noaa.gov
9414769	Oakland Middle Harbor	wind	37.8	-122.33	https://tidesandcurrents.noaa.gov
9414290	Golden Gate	wind, water level, water temperature	37.80667	-122.46667	https://tidesandcurrents.noaa.gov
9414863	Richmond	wind, water level	37.92333	-122.41	https://tidesandcurrents.noaa.gov
9414523	Redwood City	wind, water level, water temperature	37.50667	-122.21	https://tidesandcurrents.noaa.gov
9414750	Alameda	water level, temperature	37.77166	-122.3	https://tidesandcurrents.noaa.gov
S09010	Oakland Harbor LB3	PORTS currents, current predictions	37.8082	-122.34433	https://tidesandcurrents.noaa.gov
S10010	Oakland Harbor LB4	PORTS currents, current predictions	37.80096	-122.34775	https://tidesandcurrents.noaa.gov
S08010	Southampton Shoal	PORTS currents, current predictions	37.91625	-122.42233	https://tidesandcurrents.noaa.gov
9415020	Point Reyes	water temperature	37.995	-122.97333	https://tidesandcurrents.noaa.gov
SFB1207	Bay Bridge Pier D	current predictions	37.8009	-122.3739	https://tidesandcurrents.noaa.gov
SFB1203	Golden Gate	current predictions	37.8201	-122.473	https://tidesandcurrents.noaa.gov
SFB1220	Point Bonita	current predictions	37.8011	-122.5184	https://tidesandcurrents.noaa.gov
SFB1221	San Francisco Bar	current predictions	37.7853	-122.614	https://tidesandcurrents.noaa.gov
SFB1218	Emeryville Marina	current predictions	37.8433	-122.3254	https://tidesandcurrents.noaa.gov
SFB1312	Point San Pablo	current predictions	37.9689	-122.4391	https://tidesandcurrents.noaa.gov

5.1 METEOROLOGICAL DATA

A total of twelve in-bay and one offshore meteorological station had both wind speed and direction data during the incident. Figure 12 shows the locations where wind observations were available leading up to and following the *Cosco Busan* collision with the Bay Bridge. Hourly meteorological data was available from two NOAA National Data Buoy Center (NDBC) stations and seven California Automated Surface Observing System (ASOS) stations. Six-minute meteorological data was available from four NOAA Center for Operational Oceanographic Products and Services (CO-OPS) stations and accessed according to Table 1. North American Mesoscale Model (NAM) forecasts were also available for the incident timeframe at 12 km resolution from NOAA National Centers for Environmental Information (NCEI).

To identify the most representative meteorological conditions for modeling the *Cosco Busan* spill, wind observational data from the identified stations (Figure 11, Table 1) were compared to

the 12 km resolution North American Mesoscale Model (NAM) forecasts for the November 7 – 29, 2007 timeframe. Archived wind data from NOAA and additional airport wind resources from Iowa State’s Environmental Mesonet access point for the Automated Surface Observation System (ASOS) network were used to generate wind roses for surface wind data at 13 stations. Wind roses for each monitoring station (Figure 12) and equivalent NAM predictions (Figure 13) within the oil-impacted area helped assess agreement between and provided insight into the shortcomings of the NAM predictions.

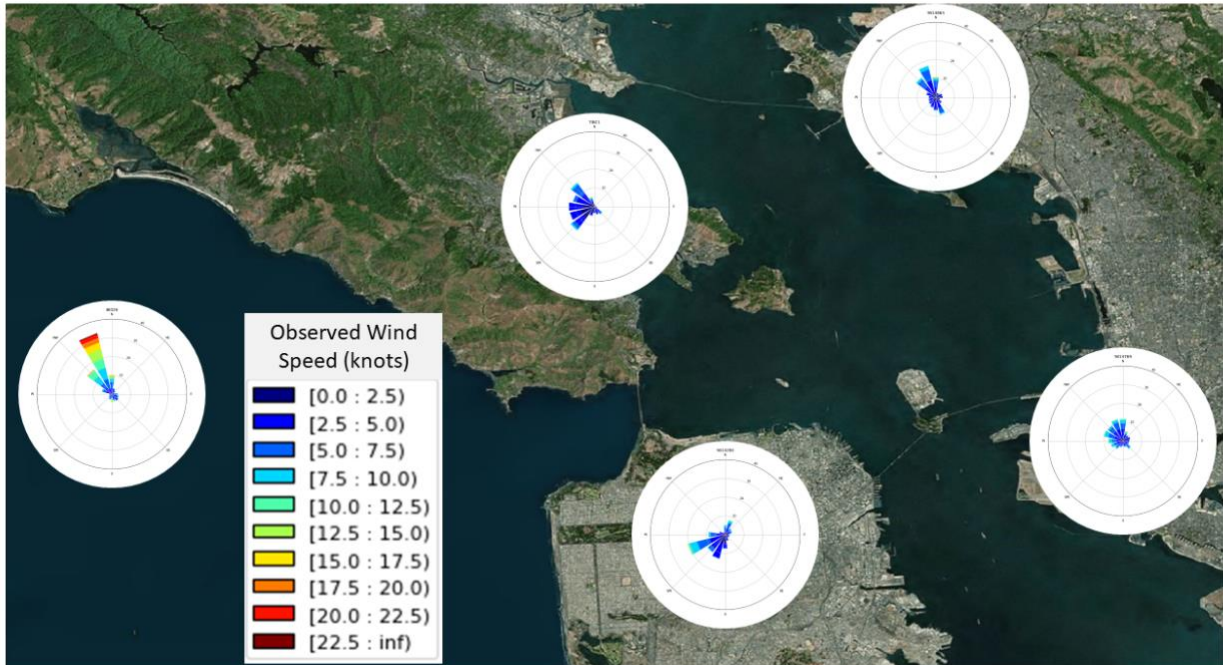


Figure 12. Observational wind roses for northern San Francisco Bay during the *Cosco Busan* collision timeframe of November 7 – 29, 2007.

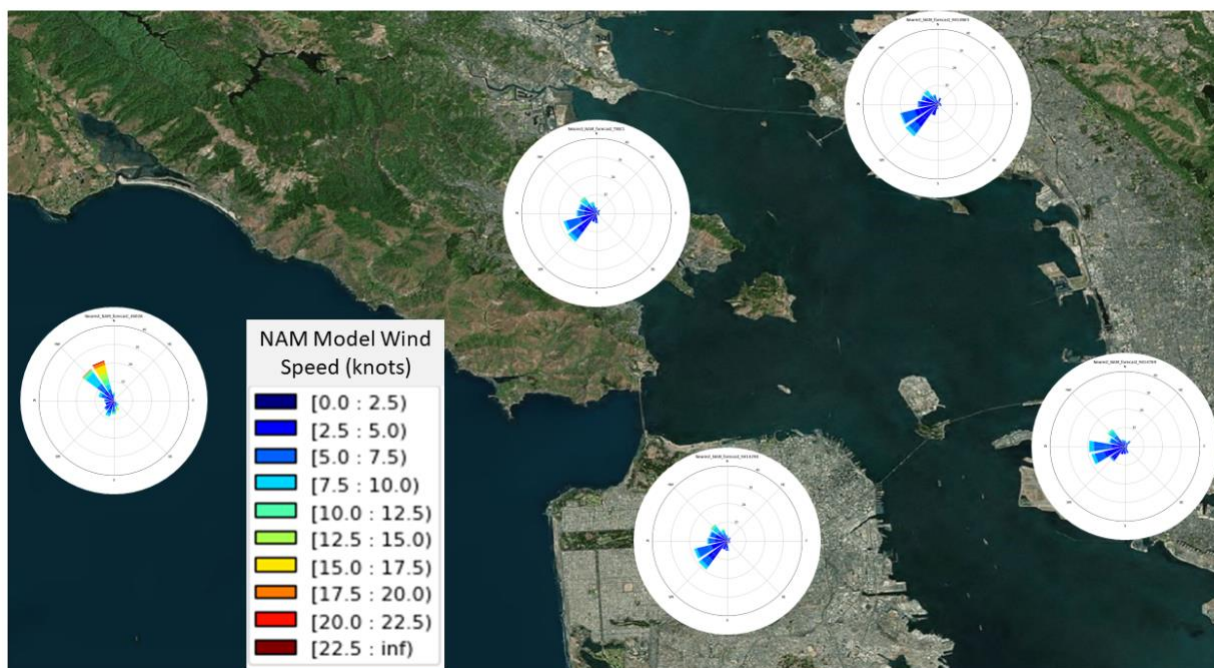


Figure 13. NAM Model wind roses for Northern San Francisco Bay during the *Cosco Busan* collision timeframe of November 7 – 29, 2007.

For the offshore station 46026, the NAM modeled winds agreed well with the observed measurements in both speed and direction. In comparing the NAM forecast's wind roses for stations near the oil spill location (9414290, 9414863, 9414769, and TIBC1), NAM forecast wind speed and direction were very similar for the four stations; whereas, the observational data showed more localized variability. The NAM forecast extracted near station 9414290 captured the primary wind direction observed at station 9414290, although predicted wind speeds were generally higher magnitude than observed values. For stations 9414863, 9414769, and TIBC1, the NAM forecasts did not capture the primary wind direction and did not capture the variability observed at the stations. Observations at TIBC1 were more variable, and wind speeds significantly lower. Immediately south and inside the Bay, airport stations OAK and HWD to the east and SFO to the west were also reviewed (not shown). At OAK, the primary wind speed and direction were captured in the NAM forecast; however, the overall variability of the wind field at this location was not well characterized. Comparisons between observational and forecast data at HWD and SFO revealed similar discrepancies. This analysis determined that a composite wind field derived from the observational data better captured the meteorological forcing during the incident compared to the region's NAM forecast.

The observational NOAA NDBC, NOAA CO-OPS, and California ASOS wind data were compiled into an unstructured (ncell) Network Common Data Form (NetCDF) file to serve as the SHARC meteorological forcing dataset. The file contains wind speed, wind direction, and wind component velocities for each station spanning November 7 – 29, 2007 at a 15-minute interval. Figure 14 presents the meteorological conditions spanning November 7th – November 13th for the region of northern San Francisco Bay impacted by the *Cosco Busan* collision.

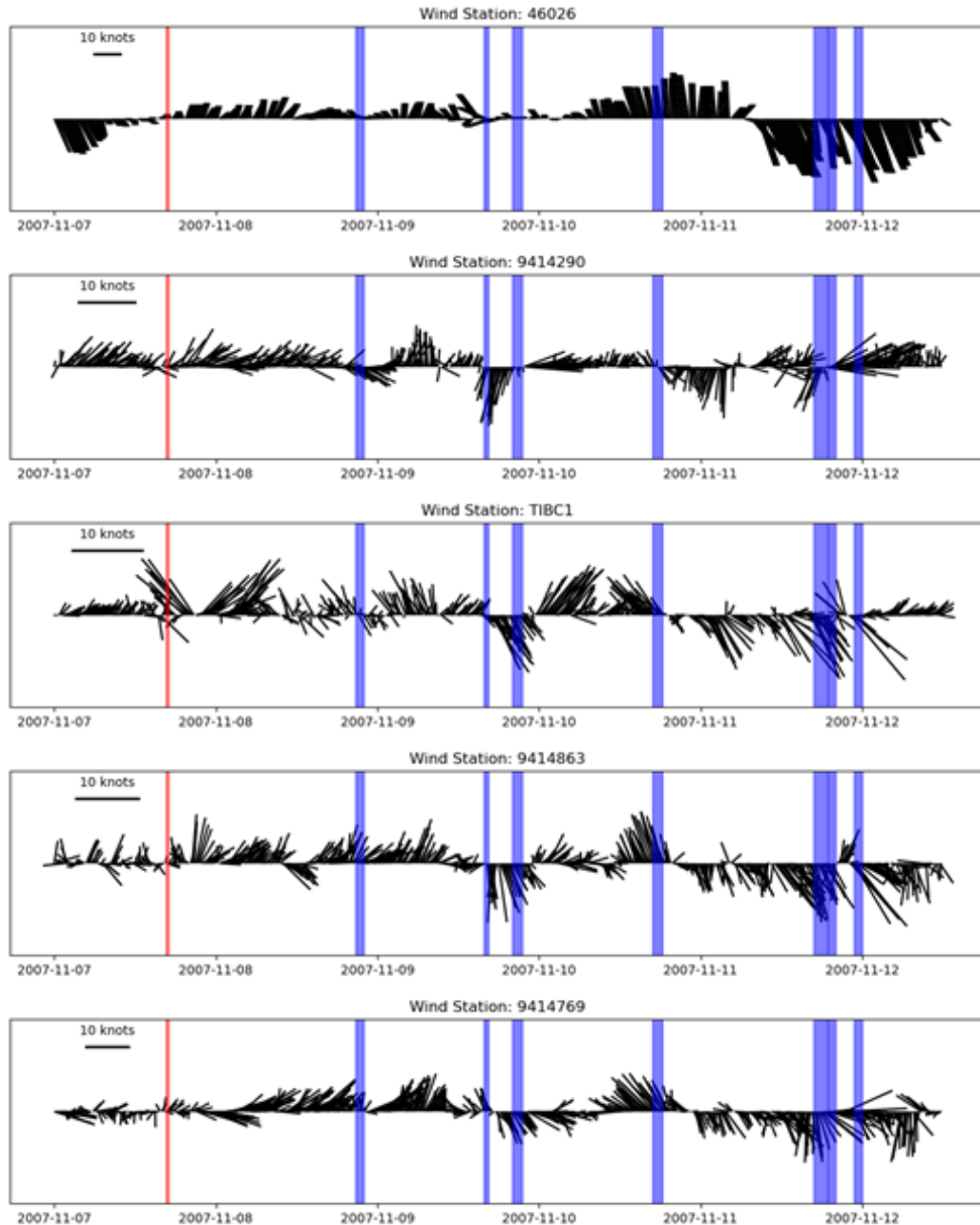


Figure 14: Observed wind conditions at station 46026 (18NM west of San Francisco), station 9414290 (Golden Gate Bridge), Tiburon Pier Station (TIBC1), station 9414863 (Richmond), and station 9414769 (Oakland Middle Harbor) for November 7 - 13, 2007.

The red highlighted area in Figure 14 corresponds with the Cosco Busan collision. The blue highlighted areas in Figure 14 correspond with the overflight surveys.

5.2 HYDRODYNAMIC DATA

The effective characterization of the spatial and temporal variability of the hydrodynamic forcing over the model domain is critical to capturing accurate material transport in dynamic environments like San Francisco Bay and the Northern California Coast. The Fleet Numerical Meteorology and Oceanography Center (FNMOC) Global Hybrid Coordinate Ocean Model (HYCOM) current velocity data is publicly available for the incident timeframe at a spatial resolution of 0.08° from NOAA NCEI. Daily HYCOM surface current velocity fields were compiled for November 7th – November 28th for the latitudinal domain of 35.0°N – 40.0°N and longitudinal domain of 121.0°W – 130.0°W to characterize the coastal transport during the incident. While the HYCOM data accurately characterized the offshore hydrodynamic regime, flow within San Francisco Bay was not captured at this spatial resolution (Figure 15).

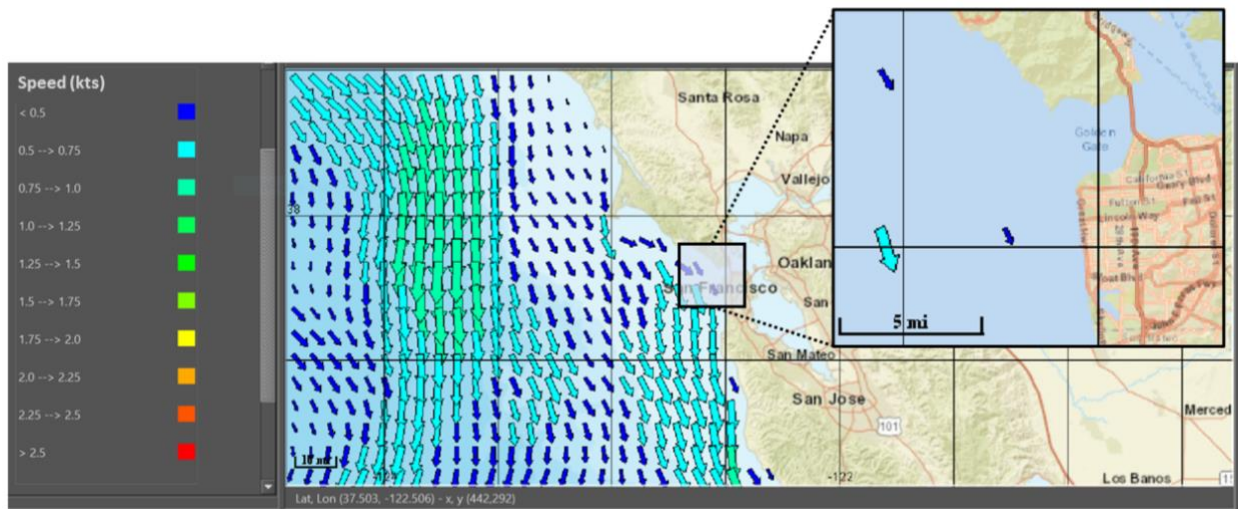


Figure 15. Representative HYCOM modeled coastal currents during November 7 – 12, 2007.

Within San Francisco Bay, real-time current speed and direction data were available from three NOAA PORTS Stations (Figure 11) – Station s09010 (Oakland Inner Harbor LB3), Station s10010 (Oakland Inner Harbor LB4), and Station s08010 (Southampton Shoal Channel LB6). These stations are currently operational but did not have in situ data available for November 2007. There are also several NOAA stations within the Bay that provide current velocity predictions based on tidal harmonic analysis (Figure 11, Table 1); however, their spatial distribution was insufficient to capture the fine-scale hydrodynamics of the region effectively.

With no in situ current velocity data available for the incident timeframe, available NOAA CO-OPS water level data was leveraged within a Deltares Delft 3D Flexible Mesh Hydrodynamic simulation to generate high-resolution surface current velocity fields within San Francisco Bay. Water level data is available from four NOAA CO-OPS Stations within San Francisco Bay during the incident (Figure 11; Table 1). Six-minute water level data – in units of meters above mean sea level (MSL) – from Station 9414290 (Golden Gate Bridge) was used as the open boundary forcing conditions of the Delft model (Figure 16), while the water level data from

Station 9414750 (Alameda) and Station 9414863 (Richmond) and current velocity predictions from Station s09010 (Oakland Inner Harbor LB3), Station s10010 (Oakland Inner Harbor LB4), Station s08010 (Southampton Shoal), Station 9415020 (Point Reyes), Station SFB1207 (Bay Bridge Pier D), Station SFB1203 (0.48nm East of Golden Gate), Station SFB1220 (Point Bonita), Station SFB1221 (San Francisco Bar), Station SFB1218 (Emeryville Marina), and Station SFB1312 (Point San Pablo) were used to validate the Delft simulation results. The red highlighted area in Figure 16 corresponds to the Cosco Busan collision, and the blue highlighted areas correspond with the overflight surveys.

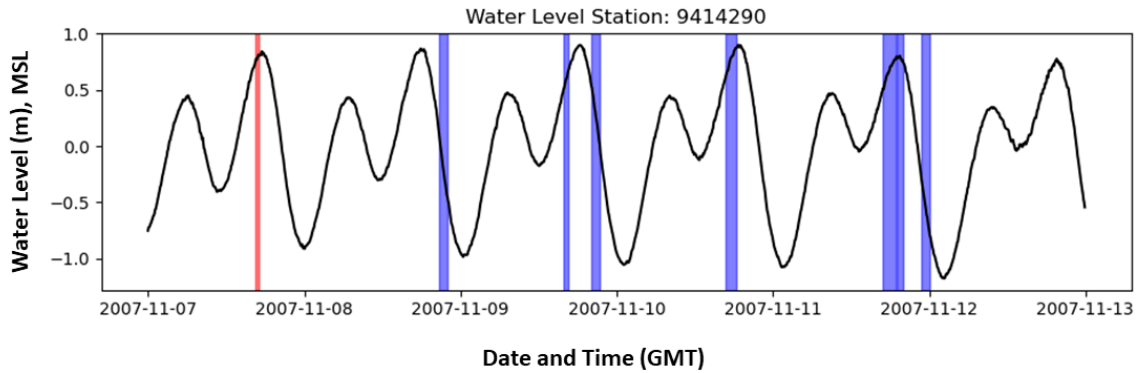


Figure 16. Observed water level at Station 9414290 relative to Mean Sea Level (MSL) for November 7 - 13, 2007.

The Delft 3D Flexible Mesh Suite (DELFT) is a multi-dimensional hydrodynamic simulation program developed by Deltares. DELFT solves the Navier Stokes equations for an incompressible fluid with free surface flow under the shallow water and the Boussinesq assumptions and calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on rectilinear or curvilinear unstructured boundary fitted grids. The flow can be forced by tides at the open boundaries, wind stress at the free surface, and pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). To generate the surface current velocity fields within San Francisco Bay during the *Cosco Busan* collision, DELFT simulations were performed under the following constraints:

- WGS84 [EPSG:4326] spherical coordinate system.
- A single depth layer (2D model).
- Tidal forcing only at the open boundary.
- A uniform water density of 1023 kg/m³.
- A uniform Manning friction coefficient of 0.023.

An unstructured, flexible mesh model grid was constructed for San Francisco Bay with grid cell resolution ranging from approximately 500 meters in offshore waters to approximately 30 meters in the region of the *Cosco Busan* collision. Grid resolution was refined in this region to accurately capture the fine-scale hydrodynamics in this critical area (Figure 17). NOAA NCEI's 3 arc-second Coastal Relief Model (CRM) bathymetric data was leveraged as the primary DELFT

model bed level asset with their higher-resolution, 1/9 arc-second Continuously Updated Digital Elevation Model (CUDEM) bathymetric data used within the region of the incident. Six-minute water level data – in units of meters above mean sea level (MSL) – from Station 9414290 (Golden Gate Bridge) was compiled for October 1, 2007 – March 1, 2008, to serve as the open boundary forcing conditions of the Delft model. This extended timeframe allowed for a one-month model “spin up” and a three-month model simulation to facilitate harmonic analysis of the results.

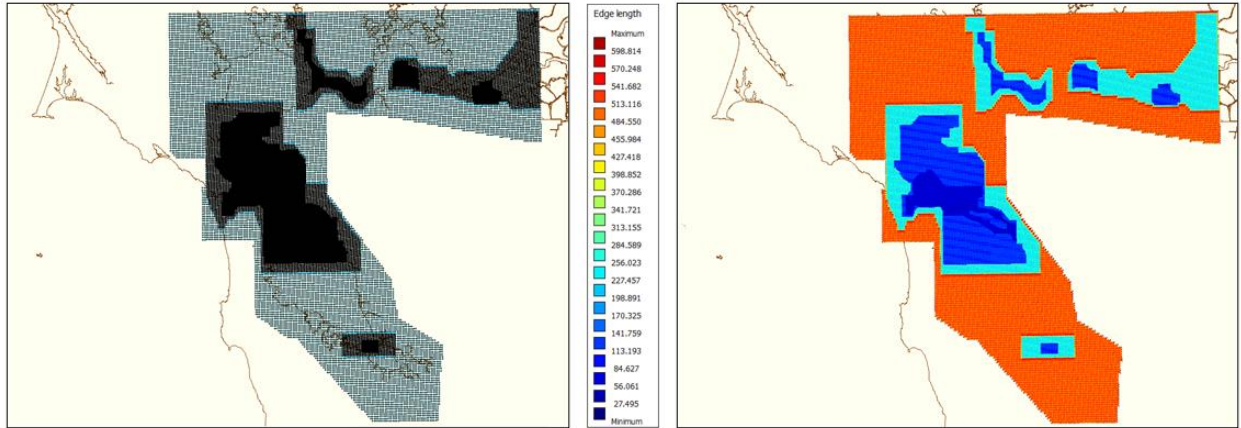


Figure 17. DELFT flexible mesh model grid for San Francisco Bay, CA.

Two DELFT simulations were performed for this effort utilizing a one-month model “spin up”, an open boundary smoothing duration of 12 hours to stabilize model initialization, and a 15-minute output timestep. The timeframe of the first simulation spanned October 1, 2007 – November 29, 2007. Results were compiled into an unstructured NetCDF file and combined with the daily HYCOM surface current velocity fields to create a SHARC-ingestible hydrodynamic forcing file covering San Francisco Bay and the surrounding coastal region. The timeframe of the second simulation spanned October 1, 2007 – March 1, 2008. This simulation was used as the model validation dataset. Results were harmonically decomposed and the resultant harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4, MN4) were compiled into an MPA Tidal Harmonic NetCDF (THNC) database. For each NOAA current prediction station, the harmonic constituents of the nearest grid cell were extracted from the THNC database and harmonically recomposed for the validation timeframe.

The root mean square error (RMSE) and mean absolute error (MAE) were calculated to serve as the quality measure for the resultant Delft water levels and component velocities using the following equations (Hibbert et al., 2015):

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (X_{NOAA} - X_{Delft})^2}{N}} \quad MAE = \sqrt{\frac{\sum_{i=1}^N |X_{NOAA} - X_{Delft}|}{N}}$$

where X_{NOAA} and X_{Delft} are the observed and modeled values and N is the number of validation samples.

For the timeframe of November 7th – November 29th, the Delft model slightly overpredicted the water level at Station 9414290 (Golden Gate), Station 9414750 (Alameda), and Station 9414863 (Richmond) by +/- 4 inches, equating to approximately 4% of the tidal range (Figure 18, Table 2). The observed water levels are depicted in black, and the DELFT modeled water levels are shown in red in Figure 18.

Table 2. RMSE and MAE of modeled water level.

Station ID	Location	RMSE (m)	MAE (m)	RMSE (in)	MAE (in)
9414290	Golden Gate	0.10	0.09	4.05	3.46
9414750	Alameda	0.12	0.10	4.66	3.74
9414863	Richmond	0.12	0.10	4.71	3.97

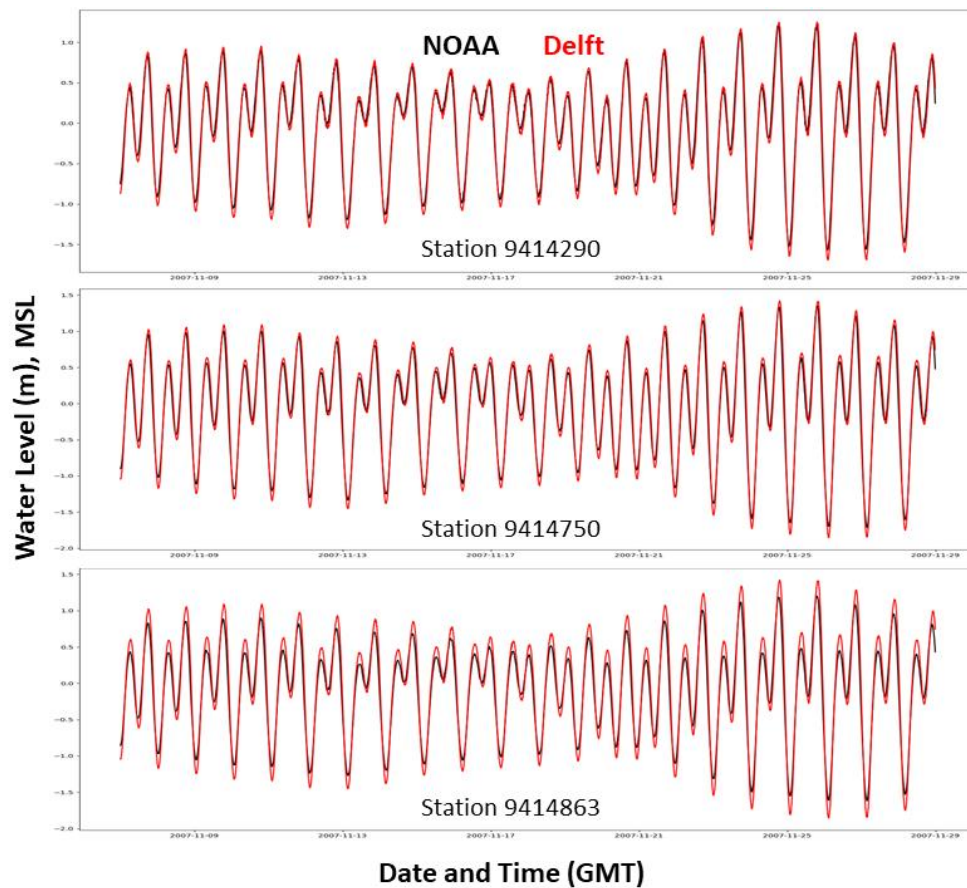


Figure 18. Observed and modeled water levels for November 7 - 29, 2007 at station 9414290, station 9414750, and station 9414863.

For the November 7th – 13th timeframe, modeled U-Component (East-West) and V-Component (North-South) current velocities were recomposed for 9 locations within the region of interest and compared to the corresponding NOAA current predictions for that location. Linear

regression analysis was performed on each station's modeled vs. predicted component velocities. The resultant regression slope and coefficient of determination (R^2) were tabulated along with the component RMSE and MAE values (Table 3 and Table 4, respectively).

Table 3. Statistical metrics of modeled u-component current velocities.

Station ID	Location	U Component Slope	U Component R^2	U Component RMSE (knots)	U Component MAE (knots)
SFB1221	San Francisco Bar	1.49	0.92	0.56	0.45
SFB1220	Point Bonita	0.97	0.93	0.37	0.29
SFB1203	Golden Gate	0.85	0.97	0.34	0.30
SFB1207	Bay Bridge Pier D	0.95	0.92	0.35	0.28
S09010	Oakland Harbor LB3	0.19	0.12	0.10	0.08
S10010	Oakland Harbor LB4	0.99	0.87	0.10	0.08
S08010	Southampton Shoal	0.39	0.53	0.12	0.10
SFB1218	Emeryville Marina	0.80	0.91	0.03	0.03
SFB1312	Point San Pablo	0.53	0.85	0.29	0.23

Table 4. Statistical metrics of modeled v-component current velocities.

Station ID	Location	V Component Slope	V Component R^2	V Component RMSE (knots)	V Component MAE (knots)
SFB1221	San Francisco Bar	0.26	0.41	0.28	0.24
SFB1220	Point Bonita	0.67	0.96	0.38	0.31
SFB1203	Golden Gate	0.78	0.61	0.33	0.25
SFB1207	Bay Bridge Pier D	0.84	0.96	0.26	0.21
S09010	Oakland Harbor LB3	0.59	0.90	0.24	0.19
S10010	Oakland Harbor LB4	0.57	0.93	0.40	0.34
S08010	Southampton Shoal	0.88	0.93	0.28	0.24
SFB1218	Emeryville Marina	0.10	0.31	0.14	0.12
SFB1312	Point San Pablo	0.63	0.81	0.73	0.62

In general, the Delft model accurately captured the speed, direction, and timing of surface water current velocities at most validation locations (Figure 19). NOAA current predictions are shown in black. Delft modeled currents are shown in red. The red highlighted area corresponds with the Cosco Busan collision. The blue highlighted areas correspond with the overflight surveys.

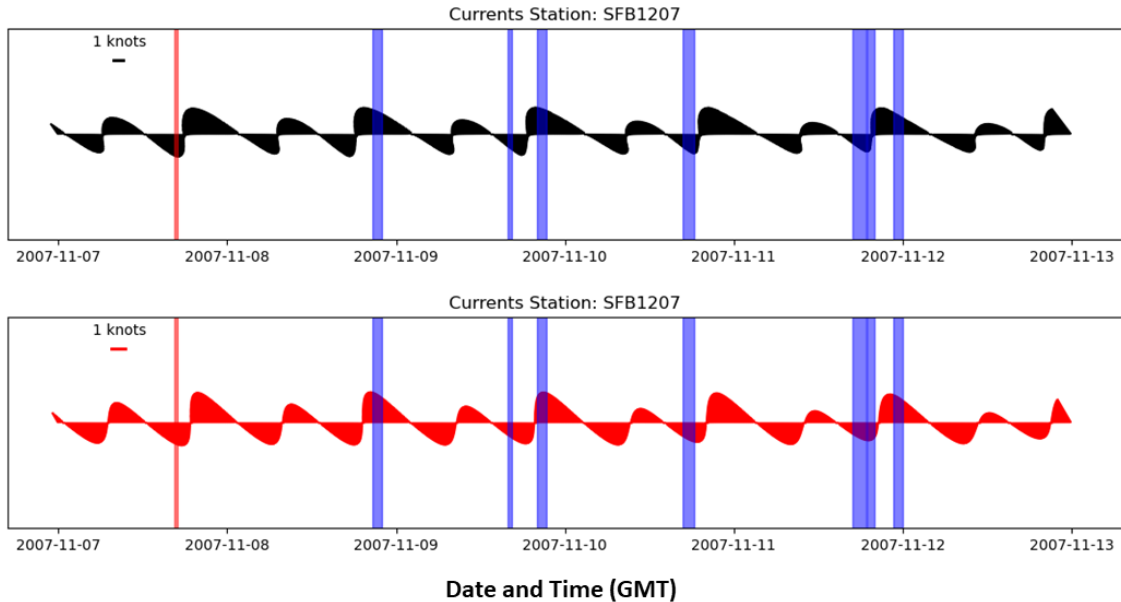


Figure 19. Observed and modeled current velocities for November 7 - 13, 2007 at the Bay Bridge Pier D (Station SFB1207).

The Delft model, on average, underestimated the component current velocities by 0.25 knots which equates to approximately 15% of the current velocity range. Improved agreement is found in the region of the *Cosco Busan* collision near the Bay Bridge Pier D, Oakland Harbor, and the mouth of San Francisco Bay, where the Delft model had higher spatial and bathymetric fidelity (Table 3, Table 4). The poor linear regression results and larger than average U Component errors at Oakland Harbor LB3 and Southampton Shoal and V Component errors at Emeryville Marina reflect the intrinsic uncertainty in modeling the generally weak component velocities (< 0.2 knots) at these locations. While the statistical metrics for the U Component velocity at Oakland Harbor LB3 were generally poor, the modeled U Component velocity at the nearby Oakland Harbor LB4 agreed extremely well with predicted values. For the coastal waters north of the shipping channel near the San Francisco Bar (Station SFB1221), the Delft model over-predicted the U Component current velocities by 21% while under-predicting the V Component current velocities by 21%. Therefore, while adequately capturing the transport mechanisms within San Francisco Bay, the hydrodynamics of the coastal zone were not effectively captured with the hydrodynamic simulation. Under these conditions, the surface currents move released material more rapidly in the east-west direction within the San Francisco Bay plume while limiting transport to the north and south.

The uncertainty in modeled current velocities directly relates to uncertainties in the location of model spilllets throughout a simulation. To parameterize this relationship, one-hour positional uncertainty distances were calculated using the component MAE values at each hydrodynamic comparison station (Figure 20). The one-hour positional uncertainty distance in the East-West direction ranged from 50 meters to 842 meters with a mean value of 380 meters. The one-hour positional uncertainty distance in the North-South direction ranged from 227 meters to 1141 meters, with a mean value of 517 meters. A similar analysis was performed on the observed mid-Bay meteorological data resulting in one-hour positional uncertainty distances due to wind-

driven transport ranging from approximately 150 meters to 250 meters. These calculated uncertainty distances provide the spatial bounds for the subsequent model accuracy analysis (see Analysis of Simulations section below).

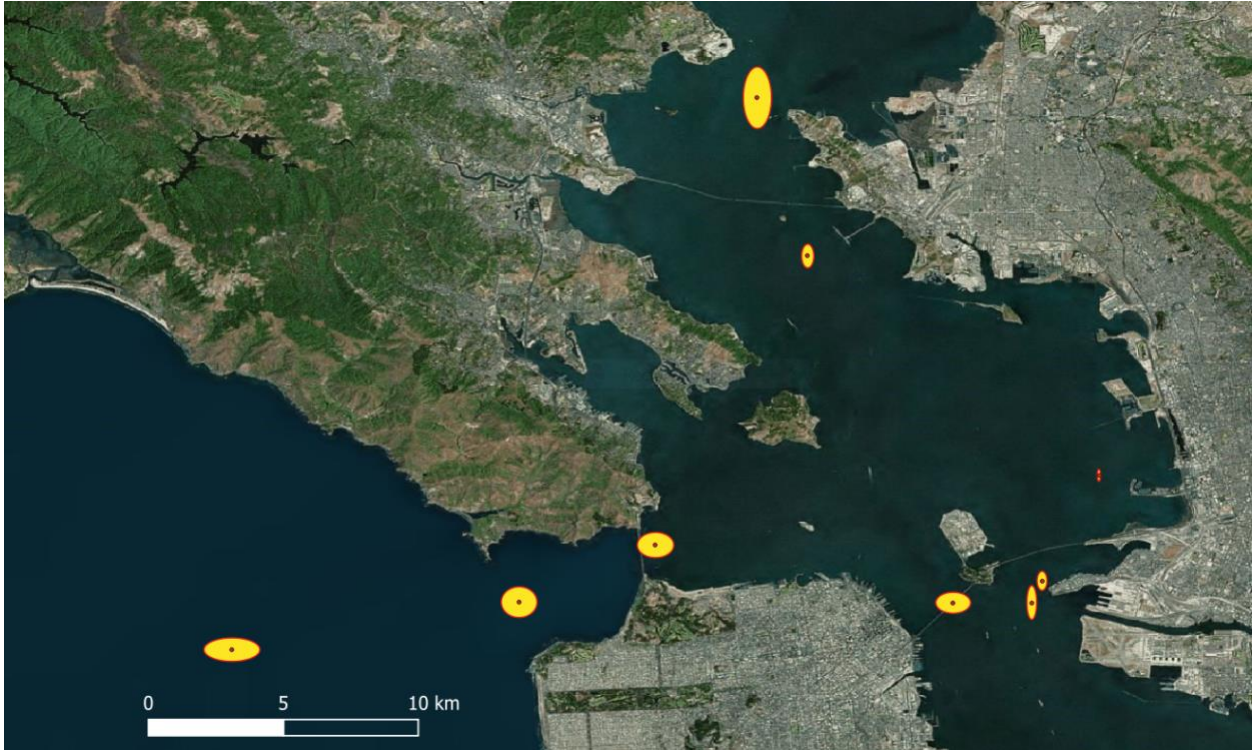


Figure 20. One-hour positional uncertainties derived from the mean absolute error in modeled current velocities.

5.3 OCEANOGRAPHIC DATA

The density-driven transport and dispersion, overall emulsion state, and evaporation rate of volatile oil components are significantly impacted by the water temperature at the spill location. SHARC leverages a Seasonal Profile Database (SPDB) to provide the external environmental properties necessary to perform simulations. The database includes monthly climatological values compiled from synoptic global assets at 0.25° resolution for water column temperature, salinity, and several other water quality parameters pertinent to modeling of CWA and TIC/TIM releases. At this resolution, the SPDB has limited coverage in the nearshore environment. Therefore, values better represent the more offshore coastal environment. In November, for the offshore region, temperatures in the SPDB varied between 12°C - 14°C (54°F - 57°F); however, data was not present in San Francisco Bay proper (Figure 21). Red circles depict locations with water temperatures of 12 °C, and blue circles depict locations with water temperatures of 14 °C (Figure 21).

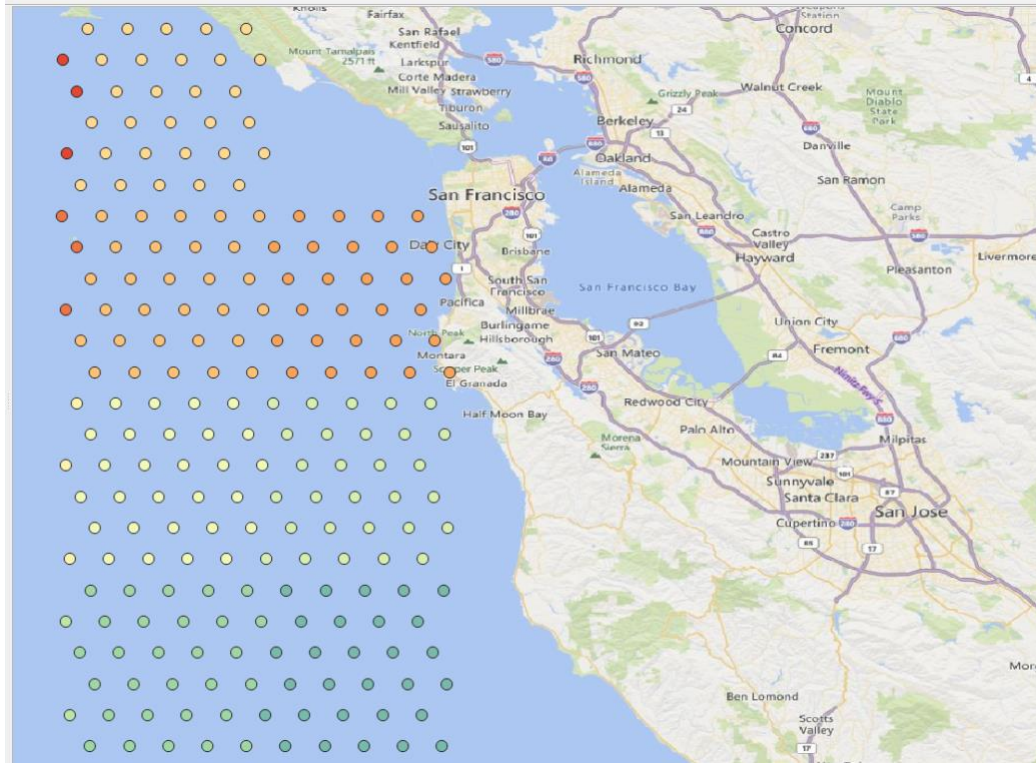


Figure 21. SPDB November water temperature near San Francisco.

During the *Cosco Busan* incident, six-minute water temperature data is available from two NOAA CO-OPS stations within San Francisco Bay – Station 9414290 (Golden Gate Bridge) and Station 9414750 (Alameda) – and one coastal station at Point Reyes – Station 9415020. Throughout the incident, surface water temperatures were consistent throughout the region with offshore water temperatures ranging from 10°C - 13°C (50°F - 55°F) while water temperatures within San Francisco Bay ranged from 12°C - 16°C (54°F - 61°F). Over the temporal and spatial domain of the *Cosco Busan* incident, the average water temperature was 14.5°C +/- 1.2°C (56°F +/- 2°F). A synthetic water environment was created to fulfill SHARC's environmental data requirement with a constant water temperature of 14.5°C and a salinity of 35 psu (Peng and Zang, 2014).

5.4 SOURCE TERM

The location of the collision between the *Cosco Busan* and the SFOBB is well documented, and the total amount of spilled oil, 53,569 gallons, was determined to the gallon from tank soundings. Due to the speed and nature of the release, the release geometry was assumed to be circular and slightly to the southeast of the Delta Tower. Although small quantities of oil may have continued to be released as the *Cosco Busan* transited to Anchorage 7 (west of Treasure Island), the spilled material was assumed to have been released in the immediate vicinity of the tower. A constant release rate for one hour was used to simulate the spill. The IFO-380 spilled in the *Cosco Busan* incident is a very viscous bunker fuel that must be heated to flow easily and was available in SHARC's material database. Although the geometry may represent a source of uncertainty,

transport-derived uncertainty length scales were larger than the expected source term error from choosing a circular release geometry over a more elongated shape.

5.5 PARAMETRIC MATRIX

Lagrangian transport models like SHARC calculate the effects of turbulence-driven and diffusion-driven mixing to define the evolution of material concentrations in space and time. Two dispersive processes are modeled in SHARC – material dispersion and random-walk (turbulent) dispersion. Material dispersion controls the rate at which a Lagrangian element “grows” due to spreading (in the case of low solubility slick forming materials) or the incorporation of the surrounding water and associated materials (in the case of soluble materials). Random-walk turbulent dispersion controls the rate at which spillets disperse from one another during transport. SHARC’s default material and turbulent random walk-based dispersion coefficients were tuned to match literature values from drifter and tracer studies (Proehl et al., 2005; Shanahan and Gaudet, 2000) and vary as a function of material type.

Turbulent dispersion directly impacts material transport by spreading out individual spillets, potentially subjecting them to greater variability in both hydrodynamic and meteorological forcing. The turbulent distribution of the spillets can affect the model calculated concentration (for soluble materials) or thickness for oils. In less turbulent environments, for the same number of particles with the same spreading rate, the calculated concentration/oil thickness may be skewed towards a larger value because of the proximity of the particles. For oils, the default turbulent dispersion coefficient is currently $5.0 \text{ m}^2 \text{ s}^{-1}$.

Material dispersion for fuel oils is incorporated into the slick spreading rate by fuel-oil-specific slick spreading coefficients and controls the evolution of the area of slick spreading. Slick spreading rates are generally slower for more viscous materials. This slower spreading rate results in a smaller calculated surface area for each spillet. A lower surface area results in a lower relative evaporation rate for the same material. Additionally, as oil evaporates and spreads, evaporative changes in the composition of the material cause an increase in overall viscosity. The increase in viscosity also reduces the calculated material transfer rate. Combined with a reduced surface area, the net effect of a slower spreading rate is a reduction in the overall evaporative mass over time. SHARC employs coefficients to modulate the rate of slick spreading and capture the effects of fuel oil viscosity on the overall fuel characteristics balanced against the uncertainty in overall fuel composition. The slick spreading coefficient for IFO-380 was initially tuned to a value of 0.2 (unitless).

To determine the impact of varying these key modeling tuning parameters on model output, MPA scientists developed a parametric matrix of modeling simulations. Turbulent dispersion coefficients were increased by a factor of two and three. Previous modeling runs with a lower ($2.5 \text{ m}^2 \text{ s}^{-1}$) value showed poorer transport timing agreement. New IFO-380 material files were created to vary slick spreading coefficients and assess the impact on both transport and model-

derived material thickness. Modeling simulations were generated to test slick spreading factors of 0.1, 0.2 (default), 0.4, and 0.8.

In the SHARC model, slick spreading and evaporation are the primary kinetic processes impacting the temporal evolution of oil amount and thickness. Both processes are a function of the temperature of the aqueous environment and the viscosity of the released material. In reviewing the environmental data on water temperature, analysis of the offshore and in-bay water temperature stations indicated an average temperature of 14.5°C (+/- 1.2°C). To determine the overall impact of temperature variability between the in-bay and offshore regions on evaporation, SHARC modeling runs were conducted at high, average, and low temperatures observed during the incident: 15.7°C, 14.5°C, and 13.3°C. The average evaporative mass was 18.1%, with a standard deviation of 0.15%. This result agrees with differences calculated from empirically derived bulk evaporation equations derived from laboratory evaporation studies on IFO-180 and IFO-300 (Environmental Technology Centre database). Using the time and temperature-dependent empirical equation for these fuel oils, the standard deviation for the specified temperature condition was $\pm 1\%$ for the less viscous IFO-180 and $\pm 0.03\%$ for the more viscous IFO-300 after four days. Both the model and empirically derived results suggest that at the lower temperatures and low magnitude variability in the temperature range observed in San Francisco Bay at that time, using the specified average water temperature did not add significant error to the kinetic results from the model.

Finally, spillet numbers were increased to improve spatial resolution and assess the impact on the overall accuracy of the higher resolution model simulations relative to the default model spillet numbers. The resulting parametric matrix is detailed in Table 5.

Table 5. Targeted simulation matrix used for transport and kinetics analysis.

Simulation	Spilllets	Turbulent Dispersion Coefficient ($\text{m}^2 \text{s}^{-1}$)	Slick Spreading Factor
1	3,000	5	0.2
2	3,000	10	0.1
3	3,000	10	0.2
4	3,000	10	0.4
5	3,000	15	0.2
6	16,000	10	0.1
7	16,000	10	0.2
8	16,000	10	0.4
9	16,000	10	0.8
10	16,000	15	0.2
11	16,000	15	0.4

Model runs 1 through 5 (Table 5) were used to screen the model output relative to overflight observations and develop higher-resolution simulations to assist in determining the quality of the transport and kinetics in SHARC. Model runs 6-11 were used for the analysis of transport model accuracy and oil model kinetics.

SECTION 6. ANALYSIS OF SIMULATIONS

6.1 PERFORMANCE METRICS FOR OIL SPILL MODELS

Oil spill modeling is constrained by the external environmental forcing and the internal processes for oil weathering. Recent reviews on oil spill modeling performance have suggested that modeling uncertainties limit the predictive ability of deterministic oil spill models to a maximum of 3 days (Barker et al., 2020). Although well-documented methods for assessing the overall performance for atmospheric transport and dispersion models exist (Warner et al., 2001; Chang and Hanna, 2004), rigorous methods for performance evaluation of oil spill models are still under development (Karamea et al. 2021). Atmospheric performance metrics such as 1-D and 2-D Measures of Effectiveness (MOE) and Figures of Merit in Space (FMS) (Chang and Hanna, 2004; Warner et al., 2001) have been applied to evaluate model-predicted plumes relative to field experiments with fixed multi-sensor arrays to measure both concentration and meteorological forcing. These metrics can provide a toolset to compare concentration-based model output to analytical measurements in waterborne hazard modeling. The oil thickness observed and documented from overflights in the wake of the *Cosco Busan* is categorical data. The data density is sparse relative to the expected physical extent of the oil plume, and there is significant potential for observer error, especially for thinner surface oil slicks. The lack of an observed time-varying oil plume extent and the categorical nature of the observational data make implementing absolute comparisons between model prediction and observed oil thickness problematic.

To develop clear metrics that capture the uncertainties in the transport and oil kinetics models, the uncertainty associated with the underlying hydrodynamics was leveraged to create a physical length scale associated with the intrinsic uncertainty. For coincident model predictions, a categorical comparison between observed and model-predicted oil thickness was performed. The details of the approach and the anticipated sources of uncertainty are presented in the following sections.

6.2 METHODOLOGY

In the wake of the *Cosco Busan* spill, NOAA and other Trustees collected multiple types of observational data to inform the immediate response effort and quantify the long-term damage caused by the spilled oil as part of the Natural Resources Damage Assessment (NRDA) process. This data included overflights for defining the extent of oiling, waterborne sample collection, biological tissue analysis, and shoreline surveys. MPA scientists leveraged this observation information to develop quantitative metrics to validate the transport and kinetics of SHARC's oil model. Specifically:

- Government Trustee overflight observations.
- Shoreline oiling surveys.
- Published oil extent information.

These data provided a method to compare model output to real-world data and verify and validate the transport and material kinetics in SHARC's oil spill model. Available empirical data was collected and digitized to generate a geospatially and temporally varying dataset to validate the quality of SHARC's model predictions.

Environmental modeling systems have yet to recreate the world in silico accurately and therefore include uncertainty. Underlying modeling assumptions based upon mathematical simplifications or driven by incomplete knowledge and diminishing returns for increased computational complexity all introduce error into modeling system predictions. When attempting to simulate a real-world scenario, there are sources of uncertainty not only from modeling algorithms and assumptions but also from the observational data used as 'truth'. These sources of uncertainty directly limit the degree to which a model prediction agrees with observational data. In leveraging the *Cosco Busan* incident to validate the SHARC model, sources of uncertainty can be grouped into three categories:

- Transport
- Oil material fate kinetics
- Observational data

Despite the inherent uncertainty in overflight observations and uncertainties in the transport and kinetics modeling components, the agreement between model-predicted oil transport and observed oil, and the difference between observed and modeled oil thickness, can be used to assess the quality of SHARC. The frequency of agreement between model output and observations was tabulated for the four slick spreading factors investigated using different bounding circle sizes. From each of the simulations, the absolute error in model-predicted slick thickness for each observation point was calculated to provide a quantitative measure of performance and ultimately provide a metric to define how well SHARC can predict oil transport and provide meaningful forecasts to inform shipping concerns and oil spill responders.

The following sections detail the specifics of the observational data, the analysis methodology applied to assess model performance for each observational data type, and the potential sources of uncertainty.

6.3 OVERFLIGHTS

Overflights are one of the primary tools in oil spill response. Trained oil spotters fly overhead in aircraft, detailing the location and characteristics of oil, in the form of slick color, for floating oil, to provide a map of oiling location and assist in developing remediation efforts. The color of surface oil is a function of the thickness of the oil. Oil color, and hence thickness, provides actionable information to responders on where and when potential remediation efforts would be most effective. The heavy fog that was present when the *Cosco Busan* collided with the SFOBB persisted for more than 24 hours after the incident, delaying these overflights. When visibility

was sufficient to conduct aerial surveys, thick recoverable oil was only found in the first three days following the incident, corresponding to four of the eleven overflights that were conducted (Table 6). Of these four overflights, three covered the physical extent of the oil plume in San Francisco Bay and San Pablo Bay, indicated with a star (*). Observations from the remaining overflights were predominantly tarballs, which are generated in higher wave energy environments and from the stranding and subsequent resuspension of shoreline oil. Information from the three identified overflights provided a means to quantify overall model performance within San Francisco Bay with a synthetic environment created from the available environmental forcing and physical conditions.

Table 6. Overflight timing, observed oil, and region.

Overflight	Start Time (Local)	End Time (Local)	Heaviest Observed Oil	Region
08NOV 2007*	1245	1400	Black Oil	Bay and Offshore
09NOV2007	0750	0830	Patches of Brown Oil	Offshore
09NOV2007*	1205	1325	Brown Oil	Bay and Offshore
10NOV2007*	0845	1015	Patches of Brown Oil	Bay and Offshore
11NOV2007	0850	1025	Mostly Tarballs/little sheen	Bay and Offshore
11NOV2007	1100	1200	Tarballs, Streamers @Angell Island	Bay
11NOV2007	1440	1600	Tarballs	Bay
13NOV2007	0850	1020	Sheen from wave breaking tarballs	Bay and Mouth of Bay
14NOV2007	0930	1100	Mostly Tarballs/little sheen	Offshore, San Pablo Bay
18NOV2007	1630	1730	No oil due to weather conditions	Central Bay
19NOV2007	1630	1700	Silver and rainbow sheen	Bay

The second overflight on November 9th mainly was offshore, heading 30 miles east to the Farallon Islands to look for oil. Finding none, as most of the oil remained inside San Francisco Bay, the model-to-data agreement for these “no oil” cases, though 100%, was not included in the ultimate analysis due to forcing limitations at the boundary between the bay and offshore, which limited offshore transport.

6.3.1 Transport

The most significant source of uncertainty in any OSM is derived from uncertainties in the underlying physical forcing (Keremea et al., 2021). The ability to accurately represent or recreate currents, winds, wave fields, and tidal states are the primary limitations of any environmental model. Model-predicted material transport is limited by the ability of algorithms based on first principals to describe physical processes implemented and the quality of the underlying environment forcing. The quality of SHARC’s transport model was assessed by analyzing the overflight observation points against SHARC’s model output to determine how well the model predicted the presence of oil at each overflight point.

Vertical and horizontal transport are typically treated as individual processes in oil spill models. As a surface oil spill model, SHARC is focused on horizontal transport and includes advective transport from currents, tides, and wind. SHARC does not directly include wave-induced vertical transport; instead, turbulent flux in the horizontal and vertical directions is captured by adding a random-walk parameter, typical of Lagrangian particle tracking models (Visser, 1997). Additional uncertainty is inherent in the observational assessments of surface oil. Surface oil appearance observations are difficult for even the most highly trained oil spotters. Very light silver sheens correspond to oils that are just perceptible to the human eye. Additionally, marine organisms generate biological exudates and slicks that can easily be mistaken for oil. An observed oil slick location can contain significant uncertainty when a point is used to represent a large-scale spatial feature.

To represent these identified potential sources of uncertainty in transport, the 1-hour uncertainty length-scale (500 meters) was converted into four separate bounding circles at each overflight observation point for overflights 1 through 4. These bounding circles were varied in 250-meter increments from 250 to 1000 meters to span a range of one-half to a factor of two, capturing increasing uncertainty in model-predicted transport as well as potential error in the observer-identified location. Variations in the horizontal random-walk parameter were implemented in the parametric run matrix to determine the suitability of model defaults.

The coincidence of in-bay model predictions within the bounding circles was used to determine the overall agreement between model predictions and observations. A review of the overall quality of the environmental forcing results indicated that the underlying hydrodynamics limited out-of-bay transport. Therefore, analyses were confined to the bay, where most of the oil remained.

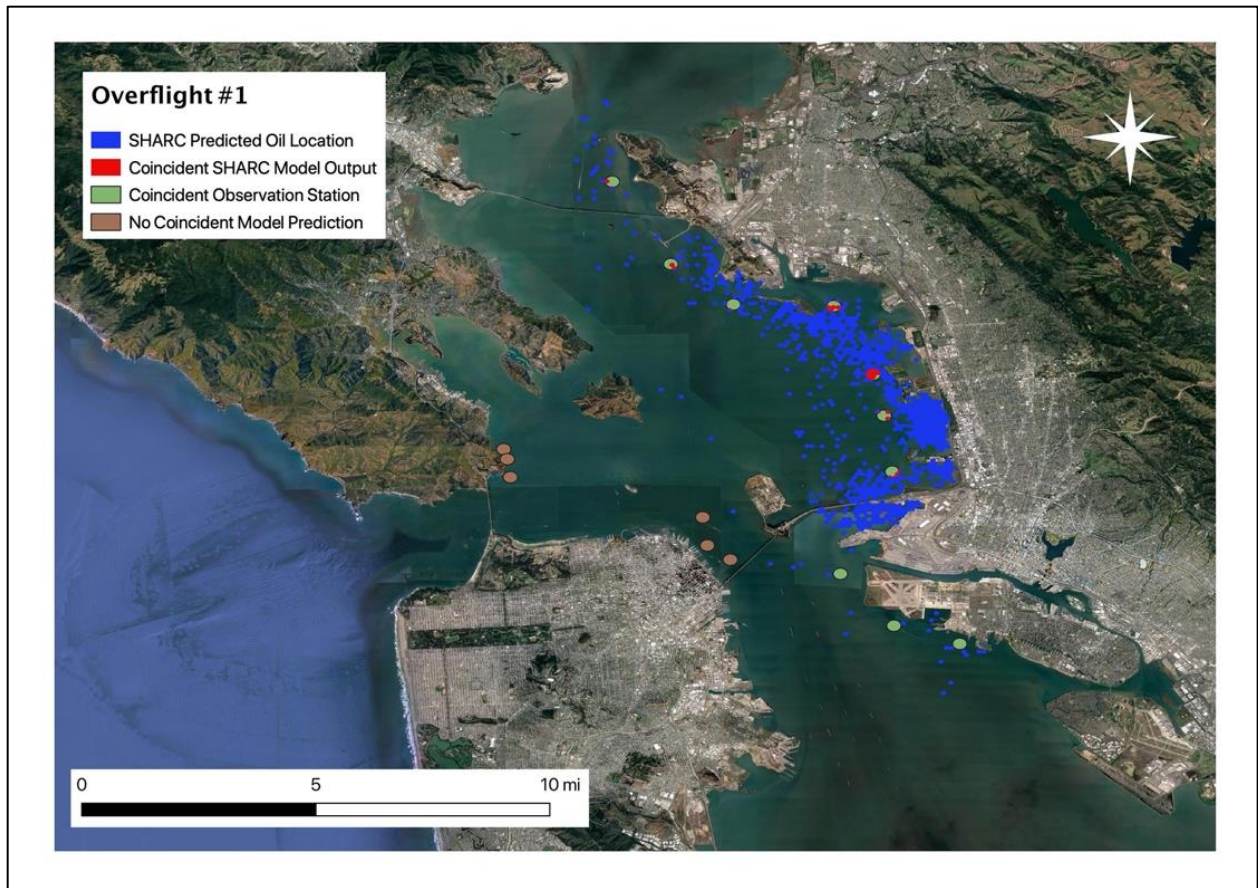


Figure 22. Example of output SHARC mesh (blue), oil observation points with a bounding radius of 250m (green and brown circles), and coincident points (red) at a snapshot in time for the first overflight.

6.3.2 Kinetics

A key reason for conducting overflights in the wake of an oil spill is to determine the spatial extent of oil and provide information on the visual characteristics of the observed oil. This provides actionable information for oil spill responders. Thicker continuous oil slicks, usually brown or black, can be effectively remediated using traditional response tactics: booms, skimmers, sorbent pads, or potentially in-situ burning. Thinner oil, which is harder to discern and is largely broken up, is not easy to remediate and is typically more rapidly dispersed. Oil spotters are trained to classify surface oil by appearance and relate it to a visual reference scale. The Bonn Agreement Oil Appearance Codes (BAOAC) (Bonn Agreement Report) is a standard scale for classifying surface oil thickness based upon oil appearance and true color of oil on water surfaces (Table 7). For convenience, thickness limits are typically assigned to the appearance codes – Code 1 through Code 3 – although the appearances are highly subjective and there is no clear delineation between appearance, but rather variations in the effect of adjacent appearance codes. Code 5 typically does not have an upper limit in the BAOAC table; however, SHARC model output also includes emulsified oil, and a cut-off of 5 mm, denoted in Table 7 with a star (*), was assigned to Code 5 to create a continuous scale that reflected the maximum potential oil thickness for non-emulsified oil.

Table 7. Bonn Agreement oil appearance codes and corresponding thickness ranges.

Oil Appearance	Layer Thickness Min - μm	Layer thickness - Max μm	Code
Silver Sheen	0.04	0.3	1
Rainbow Sheen	0.3	5	2
Metallic Sheen	5	50	3
Discontinuous True Color	50	200	4
Continuous True Color	200	5000*	5

Model calculated surface oil thickness for all observation locations was compared to observational codes. Agreement between the observed and model-predicted thickness was set as a benchmark to validate the kinetics in the model, namely evaporation and slick spreading. For each point where the model predicted thickness agreed with the observational code, a thickness difference of zero was assigned to the model. When predicted oil thickness exceeded the upper end of the observational oil code, the model thickness was subtracted from the upper end of the oiling code thickness. When predicted oil thickness was less than the lower end of the observational oil code, the model thickness was subtracted from the lower end of the oiling code thickness. True color (Code 4 and Code 5) oil overflight observations were assigned a BAOAC scale for each observation location for each of the four overflights analyzed. For this validation study, the appearance codes (Codes 1 – 3) were grouped into a single category for thin oil due to the subjective nature and the small absolute differences.

SHARC's oil model kinetics are designed to focus on determining the onset of oil emulsification and providing oil weathering forecast information pertinent to response efforts. Tarball generation is the ultimate fate of most spilled oil; however, there are no operational models available for tarball formation (Barker et al., 2020). SHARC does not include the resuspension of shoreline-stranded material or tarball generation algorithms. Sources of error in the kinetics are centered on material density, viscosity, and emulsification potential calculations, and the associated impacts to the mass transfer and slick spreading rates, as well as the calculated emulsion state of a spilled oil. Despite being a more granular approach to oil composition, the multi-component approach may represent the physical properties of some types of oil better than others. A review of model-predicted density from assigned component fraction percentages showed that SHARC's calculated bulk density agrees well with documented empirical density values for 110 different oils over a range of oil types and densities ($R^2 = 0.9$) (Cragan, 2016). The relative errors in the calculated density values were generally less than 5%, with model calculations over and under predicting oil bulk density values at all density ranges.

Predicting dynamic oil viscosity shows less agreement when compared to laboratory observations for non-weathered oil. The normalized root means squared error (NRMSE) for a 17-oil comparison was 30% for dynamic viscosities ranging from 10 mPa.s up to 500 mPa.s; however, this variability was significantly lower than a simple mass-weighted approach (NRMSE = 100%). This variability introduces a maximum of 20% error in the initial calculated slick radius, has minimal impact on the initial evaporation rate, and provides a method to track

the effects of viscosity changes on material evaporation rates. Additional details on the analyses can be found in (Cragan 2016).

SHARC also excludes dissolution processes when modeling spilled oil. This introduces an error of less than 10% to the overall mass balance calculation (ITOPF 2016). Recent studies on dispersive oil droplet formation and the potential for chemical dispersants to be effectively applied reported that droplet formation potential decreases as oil viscosity increases and that droplet formation is limited to conditions where winds speeds exceed 5 meters per second (Zeinstra-Helfrich et al., 2015). Therefore, neglecting this process introduces little error except in the most dynamic wind environments. This is especially true for IFO-380, a viscous fuel oil.

SHARC's oil spill model, even with the observed discrepancies in viscosity, accurately predicted the emulsion state for 14 of 17 well-documented oils (Cragan, 2016), supporting the utility of an approach focused on the three fundamental weathering processes for predicting oil fate on operational timescales. The slick spreading algorithm, derived from fundamental principles and first published by Fay in the 1970s, has been documented (Lehr 2001) to be inaccurate under certain conditions. However, there is little consensus on the best approach to slick spreading. SHARC's slick spreading algorithm captures oil weathering in the early stages of an oil spill when weathering occurs most quickly, as there were no significant differences between the model-predicted evaporation rate and empirically derived equations within the first 5-10 hours (Cragan, 2016). The slick spreading factor provides a method to leverage the fundamental slick spreading equation and tune model output to observations. The ability to leverage the slick spreading factor for heavy viscous fuel oils such as IFO-380 to accurately predict oil thickness is one of the components validated in this study.

Observationally, the angle and height of view can cause significant bias in observations. Meteorological conditions and even the color of the seawater can also reduce the accuracy of overhead oil thickness. Oil slicks thinner than 0.04 microns are not visible to the human eye, and even with slicks in the true color code range (greater than 50 microns), poor visibility can hamper visual detection of these thicker oil slicks. Emulsified oil is typically thicker than brown and black oil, despite having a water to oil ratio on the order of 5 to 1. There was no evidence of emulsification documented for the *Cosco Busan* spill, and SHARC did not predict emulsification.

6.4 SHORELINE OILING

SHARC calculates shoreline oil stranding using the radius of each oil spillet and the fraction of the mesh surface area overlapping a shoreline segment. The entire spillet mass is transferred from water to shore when more than 50% of the spillet surface area overlaps the shoreline. Stranding is also a function of the shoreline category type in SHARC's database. Detailed shoreline surveys continued through January of 2008. Shoreline cleanup efforts and the resuspension of shoreline-stranded oil add uncertainty to any absolute comparison of observed to predicted shoreline oiling. The overall extent of shoreline oiling and a comparison between

model-predicted and stranded oil provides an additional avenue for reviewing the validity of SHARC's transport forecast and further clarity on potential discrepancies between observed and model forecasted oil slick thickness.

NOAA-documented shoreline oiling was compared to SHARC predicted shoreline oiling to assess how well SHARC's initial near-term shoreline stranding represented the NOAA detailed shoreline oiling surveys. NOAA categorized observed shoreline oiling as heavy, moderate, or light. SHARC predicted shoreline oiling was compared to these categories to determine agreement, as defined by the same shoreline mass category.

6.5 SPILL EXTENT

NOAA developed a geographical estimate of the water surface area impacted by the oil spilled by the *Cosco Busan*. The extent of surface oiling (Figure 10) included minor oiling observations from the western edge of the overflight surveys. It was noted that the location of the western boundary was highly uncertain. Confining this estimated surface oiling to the bay and Golden Gate Strait, the difference between model-predicted and observed in-bay oil-impacted surface area was calculated to assess the overall transport footprint and how closely model predictions matched these observations.

SECTION 7. RESULTS

The high-resolution synthetic environment developed for this study did exceptionally well in representing material transport within the extremely dynamic San Francisco Bay. Despite the anticipated decrease in overall model to data agreement due to uncertainties in environmental forcing and the identified model constraints, the accuracy of the transport modeling out to 72-hours was 67%. The temporal range for the analyses was confined to the first three days after the spill. After November 10th, overflight observations reported mostly tarballs and sheens generated from wave-induced tarball disintegration. An estimated 30% of the spilled oil was recovered from nearshore waters and shorelines in quiescent areas by November 11th. Model-predicted oil distribution by this time indicated significant shoreline stranding (82%) with 17% evaporated and only 1% remaining in the water column.

The analysis of modeling simulation results from several random walk and slick spreading variations defined in the parametric matrix indicated that model predictions agreed best with observational data for the combined set of three overflights by implementing a random walk turbulent dispersion of $10 \text{ m}^2 \text{ s}^{-1}$ and a slick spreading coefficient of 0.4 based upon the number of coincident stations (Tables 8 - 14). This optimal set of model tuning parameters provided an accurate geospatial picture of surface oiling location and predicted surface oil slick thickness with a maximum absolute error of 20 microns for thick oil during the first 72 hours of the simulation for the 14 in-bay stations. This is an error of 10%. Beyond the 48 hour time-period, model prediction accuracy, defined by the frequency of model observations that fell within the prescribed 250, 500, 750, and 1000 meter bounding circles, declined. This decrease resulted from excess shoreline oil stranding, an identified source of uncertainty in SHARC's oil spill model. Model tuning results indicated that with a random walk factor of $10 \text{ m}^2 \text{ s}^{-1}$, transport agreement ranged between 69% to 100% as the bounding circles increased to 1000 meters for the four different slick spreading factors investigated. The model accurately predicted oil at 14 of 16 stations for Overflight 1 (87%) under the designated optimal tuning conditions. During overflight 2, the agreement was (81%) [10 of 16 stations], but for overflight 3, the model accurately predicted material transport at two of the three observation stations (67%).

When transport and thickness agreement, shoreline oiling amounts, and the overall predicted oil extent are considered together, SHARC captured oil location, slick characteristics, and shoreline estimated oiling extremely well. SHARC shoreline oiling overpredicted oil quantities to the east and underpredicted shoreline oiling to the west; however, this discrepancy resulted from issues at the current field transition zones, areas which are extremely difficult to represent in hydrodynamic forecasts. In San Francisco Bay, the surface area predicted by SHARC matched the documented oil extent within 3%.

7.1 TRANSPORT

All simulations showed 69% agreement or better between model-predicted material transport and the time window of the first overflight (Table 8). The agreement decreased to 63% between

overflights 1 and 2 for simulation 8 [RW10 $\text{m}^2 \text{s}^{-1}$, SF04] when accounting for modeling limitations for tarball formation. By November 10th, the model predicted most of the oil to be stranded ashore. Offshore observations were almost entirely composed of tarballs. This modeling limitation, combined with underpowered currents at the bay-offshore transition, made transport and accurate model predictions of material to these locations impossible. Simulation 8 (Overflight 1, Figure 23) showed the best model to data agreement based upon transport agreement for all three identified overflights. A composite thickness plume shows where the model forecasted oil within 1 hour of the total overflight time window (Figure 23).

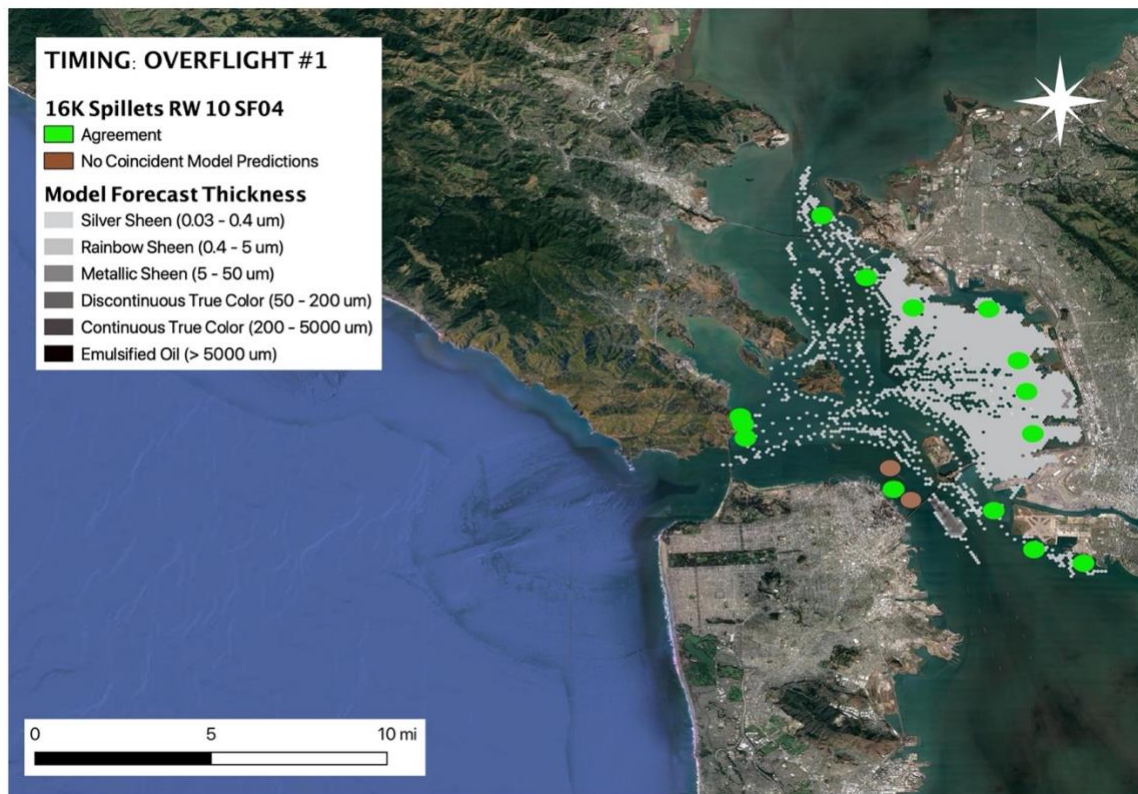


Figure 23. Model transport analysis generated from the difference between the overflight time window and the model-predicted arrival time for simulation 8.

7.1.1 Overflight 1

Analyses were conducted on the six identified simulations for turbulent dispersion coefficients of $10 \text{ m}^2 \text{s}^{-1}$ and $15 \text{ m}^2 \text{s}^{-1}$ and slick factors ranging from 0.1 to 0.8 for the three in-bay three overflights on November 8th, 9th, and 10th. All simulations showed 75% or more agreement between model-predicted material transport and the time window for in-bay overflight 1 (Table 8). The best agreement for each of the turbulent dispersion coefficient values is presented in bold.

Table 8. Modeling Simulation Arrival Time Agreement: Overflight #1 November 8th, 2007.

Simulation Conditions	Number of Coincident Stations (N = 16)	In-Bay Agreement
6 [RW10 m ² s ⁻¹ , SF01]	14	87%
7 [RW10 m ² s ⁻¹ , SF02]	16	100%
8 [RW10 m ² s ⁻¹ , SF04]	14	87%
9 [RW10 m ² s ⁻¹ , SF08]	16	100%
10 [RW15 m ² s ⁻¹ , SF02]	13	81%
11 [RW15 m ² s ⁻¹ , SF04]	12	75%

As the slick spreading factor increased, in the highest turbulent dispersion cases, the degree of agreement in the Golden Gate Strait degraded slightly, missing a station captured in the SF04 case. The higher turbulent dispersion coefficient cases resulted in higher in-bay transport timing agreements and some increased agreement; however, the arrival timing became skewed toward arriving too early rather than arriving slightly late. Early arrival would be expected if the turbulent dispersion coefficient was too large. In this instance, it created excess meridional transport. Late arrival within the model is due to both the currents being slightly under-powered outside of the predominant high-velocity region of east-west transport in and out of the bay and early predicted shoreline stranding within the model without subsequent resuspension.

Comparing the synthetic environment transport in the transition zone between the in-bay and offshore regions indicated that the synthetic environment in the Golden Gate Strait and slightly to the east compared extremely well to the predicted currents. Observed winds at Golden Gate (9414290) and Oakland Middle Harbor (9414769) during the first overflight showed winds from the northwest (Golden Gate) (Figure 24, top) and the south (Oakland) (Figure 24 second from the top). Tidally driven water levels predicted in the synthetic environment at Alameda (9414750) indicated an outgoing tide (Figure 24, second from the bottom), and the analysis of water level values matched observed water levels within four inches. In all cases, the synthetic hydrodynamic and meteorological forcing environments for the simulation exhibited high accuracy inside the bay, and the transport model accurately predicted the observed material transport. West of the Golden Gate Strait and to the east, especially in the coastal area north of Emeryville, the modeled hydrodynamics were slightly underpowered relative to observed conditions. The overflight time window is highlighted in blue.

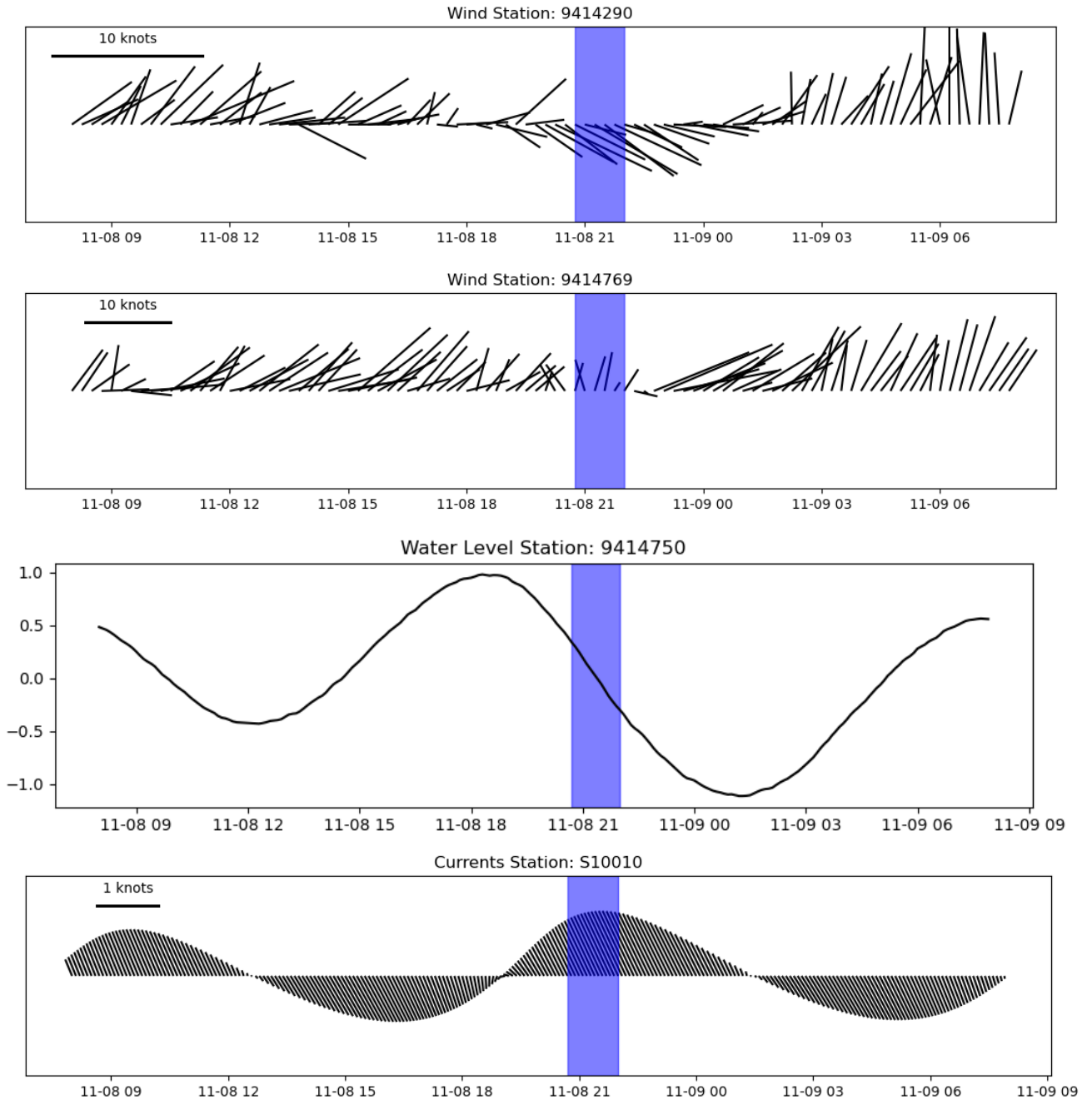


Figure 24. Environmental Observations During Overflight #1.

7.1.2 Overflight 2

Due to significant model-predicted shoreline oil stranding by November 9th, the percent agreement for transport timing for the second overflight (Table 9, Figure 25) showed an overall decrease from the first overflight, missing oil observations in San Pablo Bay, Richardson Bay, and to the south. Although the calculated agreement was below 60% when all 21 observation stations are included, removing the five observation locations where only tarballs and light sheen

were observed increased the overall agreement to 81% for simulation 8. As mentioned previously, current conditions at the northern and eastern edge of the oil plume were underpowered relative to observations, creating a timing discrepancy in the north and a barrier to transit into this region. Additionally, the model predicted shoreline stranding of nearly 80% after 48 hours. A shift from a high tide to an ebbing tide which occurred just before the overflight (Figure 26) likely resuspended a significant amount of stranded shoreline oil. The tarballs and sheens observed in Richardson Bay and to the south of the collision would result under these conditions. Due to the combined effect of heavy shoreline oil, no material resuspension, and the absence of tarball generation, agreement in these areas was unlikely without increased turbulent dispersion. For locations where the model predicted material arrival at or ahead of the overflight observation, a combination of rapid current-driven transport to the west and weaker return transport outside the mouth of San Francisco Bay, particularly in the most turbulent simulations (simulation 10 and 11). Figure 25 also depicts a composite thickness plume to show where the model forecasted oil within 2 hours of the total overflight time window.

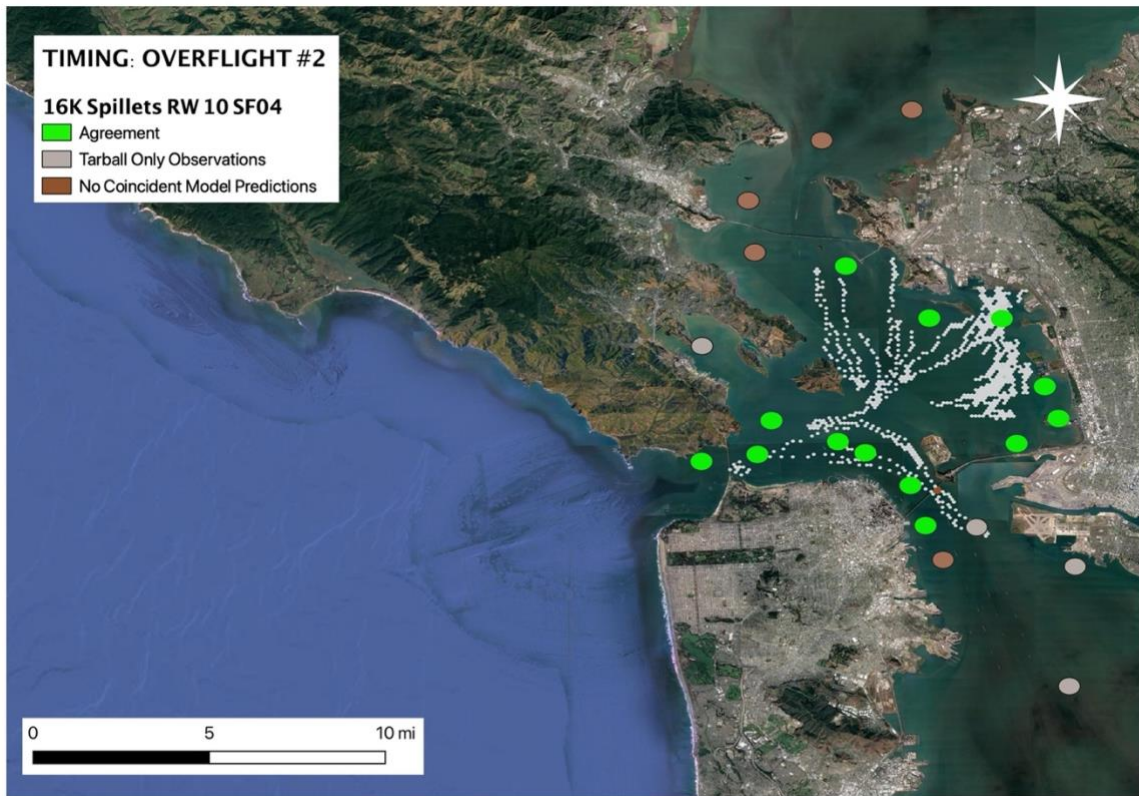


Figure 25. Model transport analysis generated from the difference between the overflight time window and the model-predicted arrival time for simulation 8, overflight 2 with 500 meter buffers.

Table 9. Modeling Simulation Arrival Time Agreement Calculated for Overflight #2 on November 9th, 2007.

Simulation Conditions	Number of Coincident Stations (N=16)	Percent Agreement
6 [RW10 m ² s ⁻¹ , SF01]	8	50%
7 [RW10 m ² s ⁻¹ , SF02]	8	50%
8 [RW10 m ² s ⁻¹ , SF04]	13	81%
9 [RW10 m ² s ⁻¹ , SF08]	8	50%
10 [RW15 m ² s ⁻¹ , SF02]	9	56%
11 [RW15 m ² s ⁻¹ , SF04]	7	44%

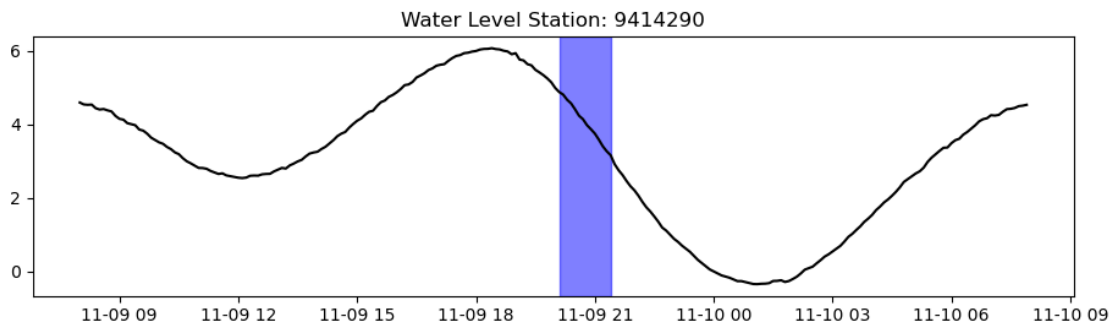


Figure 26. Water level Predictions Near the Golden Gate Bridge.

In reviewing arrival timing agreement from the second overflight (Table 9), although oil transport in modeling simulation 10 reached further into San Pablo due to the higher turbulence, slower transport just south of the incident location was associated with thick oil, for this reason, this higher turbulence simulation performed worse than simulation 8. Tarball and sheen only observation points were removed from the analysis set.

7.1.3 Overflight 3

By the third in-bay overflight on November 10th, SHARC predicted very little oil (< 1%) remained in the water column with significant shoreline stranding and little change in calculated evaporative mass. The remaining waterborne oil consisted of pockets of thicker oil in the east near Berkeley and smaller pockets at the mouth of the bay. All overflight oil observations in the offshore zone were tarballs except for the easternmost point at the mouth of the bay. Despite the low amounts of oil predicted to be floating in the water column, SHARC captured all three in-bay overflight stations for SF01, SF04, and SF08, while the current default slick spreading factor resulted in no coincident model predictions (Table 10).

Table 10. Modeling Simulation Arrival Time Agreement Calculated for Overflight #3.

Simulation Conditions	Number of Coincident In-Bay Stations (N = 3)	In-Bay Agreement
6 [RW10 m ² s ⁻¹ , SF01]	3	100%
7 [RW10 m ² s ⁻¹ , SF02]	0	0%
8 [RW10 m ² s ⁻¹ , SF04]	3	100%
9 [RW10 m ² s ⁻¹ , SF08]	3	100%

7.2 KINETICS

Additional analyses on the frequency of coincident material as a function of bounding size were also conducted as a means of capturing material transported to observation locations outside of the defined overflight time window. Analyses were conducted for bounding circle sizes of 250, 500 (as above), 750, and 1000 meters for all slick factors and a turbulent dispersion coefficient of 10 m² s⁻¹. The coincidence frequency for the various bounding circles showed minimal variability across the four different slick spreading factors; however, the number of coincident stations changed (Tables 11 – 14). The number of SHARC-predicted coincident stations from Overflight 2 was largest for slick-spreading factor 0.4, with a slick-spreading factor 0.8 showing best predictions for Overflight 1. The significant difference in the number of coincident stations during overflight 2, combined with the similarity of results for the other two overflights investigated, was used to determine the optimal pair of model tuning conditions. Overall, as expected, increasing the bounding circle size increased the number of SHARC-predicted stations. Predictions from modeling simulations run using the default slick-spreading factor (0.2) resulted in the lowest number of coincident station predictions for overflight 3. Analysis of the calculated coincidence for slick factor 0.4 and 0.8 showed that results were statistically different for overflights 1 and 2 ($t(6) = -2.5$, $p = 0.03$ and $t(6) = 7$, $p = 0.0004$, respectively) but not for overflight 3 ($p > 0.05$) across all bounding circles, supporting the selection of SF = 0.4 as the optimal slick spreading factor.

Table 11. Coincident station observations for each bounding circle size: SF01.

Bounding Circle	Overflight #1 (N = 16)	Overflight #2 (N = 16)	Overflight #3 (N = 3)
250 meters	12	6	0
500 meters	13	6	2
750 meters	14	6	3
1000 meters	14	8	3

Table 12. Coincident station observations for each bounding circle size: SF02.

Bounding Circle	Overflight #1 (N = 16)	Overflight #2 (N = 16)	Overflight #3 (N = 3)
250 meters	12	5	0
500 meters	15	6	0
750 meters	15	6	0
1000 meters	16	8	0

Table 13. Coincident station observations for each bounding circle size: SF04.

Bounding Circle	Overflight #1 (N = 16)	Overflight #2 (N = 16)	Overflight #3 (N = 3)
250 meters	10	11	0
500 meters	11	11	2
750 meters	14	13	2
1000 meters	14	13	3

Table 14. Coincident station observations for each bounding circle size: SF08.

Bounding Circle	Overflight #1 (N = 16)	Overflight #2 (N = 16)	Overflight #3 (N = 3)
250 meters	14	6	1
500 meters	15	7	1
750 meters	15	7	3
1000 meters	16	8	3

For a slick spreading factor of 0.4, the number of coincident stations was higher for overflight 2 than the faster slick spreading rate. There was no significant difference beyond the 750-meter bounding circle, corresponding to a transport uncertainty of approximately 1.5 hours.

From the coincident stations for slick factor 0.4, the absolute error in model-predicted thickness was calculated for each bounding circle. The calculated absolute errors showed no difference across the bounding circle sizes for each overflight. Station-specific absolute errors for overflight 1 were a maximum of 20 microns for stations 14-17, where thick oil was observed, corresponding to an uncertainty in model-predicted thickness of 10%. An absolute error of 5 microns was observed for stations 9-11, and errors less than 1 micron for the other seven stations that were captured. Absolute errors were largely independent of bounding circle size, with the smallest bounding circles showing the same absolute error as the largest bounding circles.

SHARC oil model kinetics characterized slick thickness very accurately when transport agreement was greatest. SHARC accurately reproduced oil thickness observations within 20 microns for 73% of coincident model predictions, with a maximum of 20 microns observed at

the stations near Berkeley, where the thickest oil was observed for overflight 1. All predicted thicknesses for coincident stations were within 20 microns for overflight 2, with 84% having a calculated error of 5 microns or less. The absolute thickness error for overflight 3 was zero for all coincident stations. Changing the slick spreading factor had minimal impact on the overall ability of the model to accurately depict slick thickness because significant shoreline stranding masked the effect of these variations and did not improve agreement between observed and modeled slick thickness; however, it did improve the calculated agreement in the transport timing analysis.

7.3 SHORELINE OILING

Model-predicted shoreline oiling agreed well with the documented spatial extent of shoreline oiling within the east bay. The west bay and offshore showed a greater number of false negatives (Figure 27), but this was likely due to discrepancies in timing between the model predictions and the shoreline surveys, excess near term shoreline stranding, and the absence of stranded oil resuspension in the immediate 24 hours after the incident, and the current field boundary errors. Because shoreline surveys were conducted over several months, it is difficult to accurately compare these surveys to the more immediate shoreline impacts of SHARC's operational modeling capability. Simulation 8 (Figure 28) predicted moderate shoreline oiling in the Berkeley and Emeryville area. The difference in material stranding amongst all simulations in the parametric run matrix after the first 24 hours is minor (2.5% difference). By Assigning NOAA's mass-based shoreline oiling to the SHARC predicted shoreline oiling, SHARC's shoreline oiling was predicted to be primarily light and moderate. Without resuspension in SHARC's shoreline model, early predicted high shoreline retention of oil overpredicted oiling where oil first hit the shore and underpredicted oiling later in the simulation. The extrapolation of modeled shoreline to the more detailed surveys is qualitative at best. However, the difference between modeled and observed shoreline oiling provides a means of validating the location and implemented methodology for initial shoreline stranding and providing additional information on potential causes for model underpredictions of oil thickness.

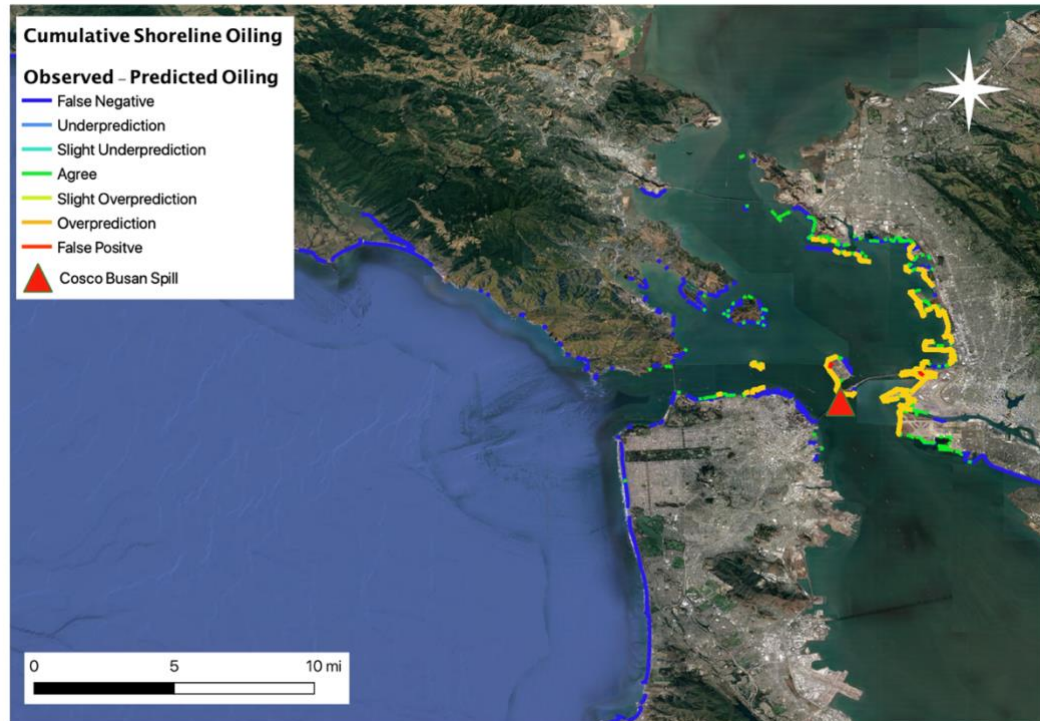


Figure 27. Comparison of observed and model-predicted shoreline oiling for simulation 8 after 24 hours.

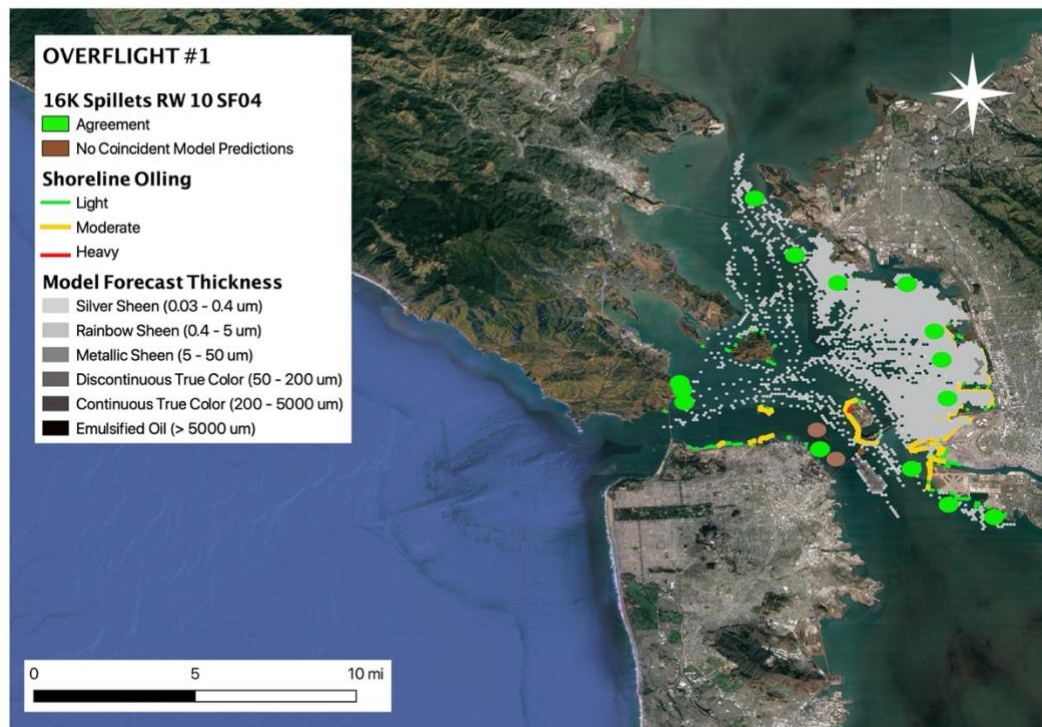


Figure 28. Model predicted shoreline oiling at the time of overflight #1, with surface oil transport observations.

Treasure Island, the Berkeley/Emeryville shore regions, and Fisherman's Wharf were all predicted to have moderate shoreline oiling, and the model overpredicted shoreline oiling in these areas. For the Berkeley/Emeryville area, this corresponded to slight to moderate underprediction of slick thickness where dark oil was observed. As mentioned previously, resuspension of shoreline-stranded materials would result in potentially thicker observed oil, and excess model-predicted stranding would result based upon the comparison. Additionally, oil stranded along the western shore of Treasure Island would be resuspended and then transported to the northeast and out on an outgoing tide, which was observed during the first overflight. The lack of offshore transport and the extreme model predicted shoreline stranding indicate that offshore shoreline would be under-predicted.

7.4 SPILL EXTENT

Oil spill extent is the ultimate determinant for system-level performance. Due to the documented discrepancies in offshore transport, the surface area from documented NRDA swept area from the mouth of the Golden Gate Bridge east was confined to the bay and Golden Gate Straits to compare this published result to the model-predicted surface area. The NRDA surface for the bay-only region was 97 square miles. To compare SHARC output to this region, in-bay swept areas were derived for each parametric run from the predicted maximum mesh extents (Table 13). Simulation 8 (Figure 29) agreed with the modified extent within 3%, indicating that SHARC accurately captured the overall oil extent within San Francisco Bay despite the identified model uncertainties. The model default slick spreading factor also provided an accurate swept area forecast. The degree of accuracy of the model-predicted surface oiling footprint, along with low absolute thickness errors, indicate that planning teams can cost-effectively deploy operational response assets, alter shipping routes to minimize vessel fouling, and protect critical shoreline resources. Varying turbulence conditions resulted in somewhat smaller overall swept areas due to shoreline stranding, and simulation 8 produced the greatest swept area.

Table 15. Modeling simulation surface area from model generated swept area.

Simulation Conditions	Calculated Swept Area (mi ²)
6 [RW10 m ² s ⁻¹ , SF01]	81.1
7 [RW10 m ² s ⁻¹ , SF02]	99.5
8 [RW10 m ² s ⁻¹ , SF04]	100
9 [RW10 m ² s ⁻¹ , SF08]	87.5
10 [RW15 m ² s ⁻¹ , SF02]	84.0
11 [RW15 m ² s ⁻¹ , SF04]	83.6

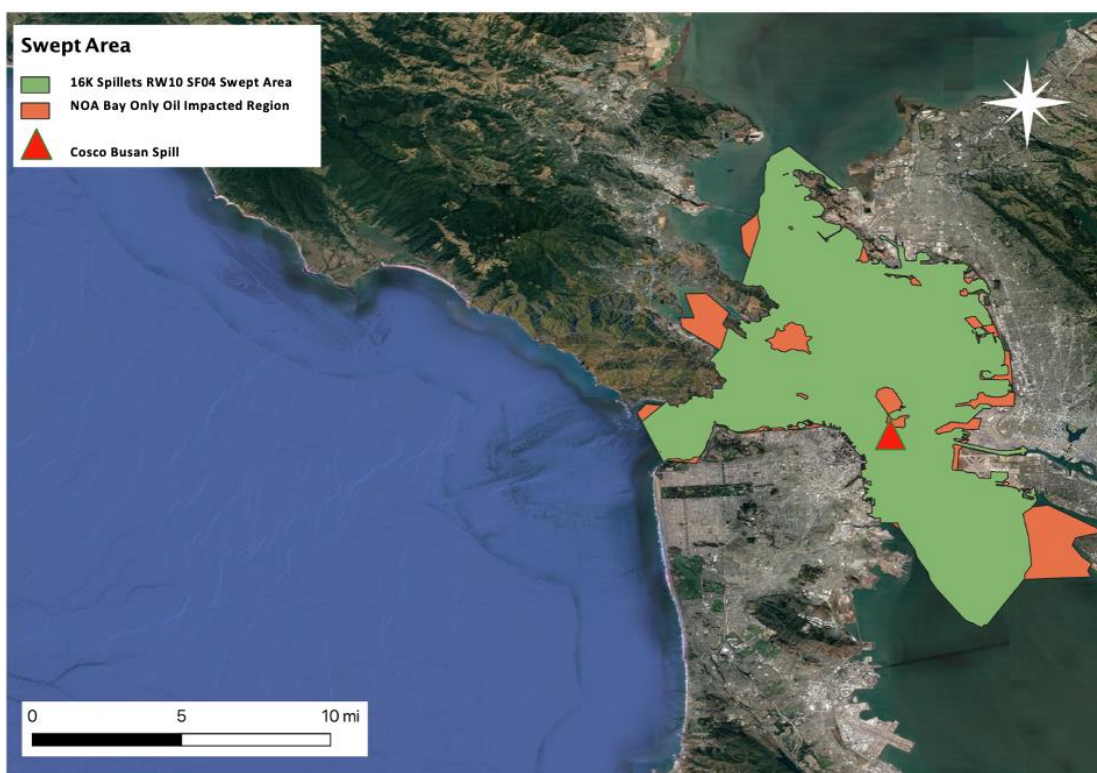


Figure 29. Swept area from SHARC Model output for model simulation #8 and the NOAA estimated surface area impacted by oil.

SECTION 8. SUMMARY

SHARC accurately predicted oil transport and oil slick thickness within San Francisco Bay across a 72 hour time window. A comparison of model-predicted and observed oil locations indicated 87% station-based transport agreement 24 hours after the collision occurred for the best set of model tuning parameters. After 48 hours, agreement declined slightly to 81% and was between 67% and 100% after 72 hours, depending on the size of the bounding circle used to represent hydrodynamic transport uncertainty. Analysis of the station coincidence for the two best cases, slick-spreading factor 0.4 and 0.8, revealed that the results were statistically different for overflight 1 and overflight 2, supporting the adoption of a slick-spreading factor of 0.4 the model default. Shoreline oil and swept area comparison further demonstrated that SHARC's transport and kinetics are well-tuned to its intended operational support mission. Slick thickness errors over all modeling simulations conducted were less than 20 microns for the thickest observed oil and 5 microns for the oil appearance codes, both providing a relative error of 10%. The predicted oil footprint was within 3% of the published impact area. The component-based oil model showed less variability in overall material evaporation than anticipated, but this is mainly because material transport onshore resulted in shorter timescales against which evaporation rate variability from slick spreading variations could be observed.

The analysis showed that SHARC modeled a real-world event with a high degree of accuracy. This analysis also validated that the utility and accuracy of model forecasts for oils can be improved by modifying the two default parameters investigated in this V&V effort: turbulent dispersion and slick spreading coefficients. The analysis provides an approach to assessing the quality of waterborne hazard modeling forecasts for surface spilled oil that can be tied to maximum spatial and absolute thickness errors. As validation for the numerous oil spill models, this type of analysis can provide quantitative errors bounds for model predictions over time. Given the lack of industry-standard waterborne hazard model forecasting validation methodologies, leveraging the frequency and spatial agreement and absolute thickness errors to determine the validity and operational utility of the model is an excellent first step for categorical data like oil thickness.

8.1 GAPS AND LESSONS LEARNED

Common to all model validation efforts, more observational data improves confidence in model forecasts. SHARC's bay-wide modeling skill can only be assessed relative to three temporal snapshots and a total oil extent for the selected validation incident, limiting the overall analysis of transport and categorical slick thickness data to a point-based study, making the applicability of well-established atmospheric modeling skill assessment techniques to SHARC's waterborne hazard predictions difficult. Future validation studies should also leverage continuous data to leverage these analysis techniques. SHARC's operational modeling assumptions relative to both tarball generation and shoreline oil stranding limited the overall temporal window of the analysis. Although the total impact to oil distribution by excluding tarball formation is minimal, the lack of shoreline material resuspension impacted oil transport beyond the first 24 hours.

Variability in the slick spreading factor did not affect the slick thickness comparisons as much as was anticipated. Slick spreading variability showed more impact in material transport and timing, which was attributed to shoreline stranding. Overspreading and excessively high turbulent dispersion coefficients resulted in poorer transport timing agreement. Re-assessing model predictions with shoreline resuspension may alter the recommended model tuning parameters.

Even though SHARC does not include tarball generation and the resuspension of shoreline-stranded oil, model-predicted shoreline oil stranding is expected to create areas where significant tarball generation would occur as a function of tidal stage and wave energy, and this explained several areas where transport agreement declined.

Although SHARC does not account for oil recovery efforts in modeling simulations, the delay in response efforts and the inclusion of shoreline oil in these estimates supported the validity of comparing model-predicted oil transport and thickness in the immediate aftermath of the spill. The development and implementation of oil fate and transport modifications due to the application of dispersants, the use of booms, skimmers, and other oil response tools would improve SHARC oil predictions from reliable worst-case scenarios to an evaluation tool for the effectiveness of oil response measures.

Finally, the dynamics of oil resuspension in marshes and mudflats, a predominant feature of the San Francisco Bay estuary, are notoriously difficult to model. The retention of any spilled material in vegetated shoreline environments is the highest for all SHARC shoreline material categories, and oils are extremely likely to stick to any shoreline. For these reasons, the analysis focused on the first three days after the spill. Material resuspension was the suspected source of many of the nearshore thin oil observations in this time.

8.2 RECOMMENDATIONS

Despite the high degree of model accuracy in predicting oil transport and weathering, the analyses point to several key findings regarding SHARC's oil modeling capability and several recommendations to improve SHARC's operational material fate and transport capability. The more quantitative analysis of transport timing and oil thickness agreement resulted in two major findings upon review of the data:

1. The model default turbulent dispersion and slick spreading coefficients did not capture the plume transport in San Francisco Bay as well as higher turbulence values.
2. The default slick spreading coefficients, while showing little variability in the overall thickness agreement, underestimated overall material transport.

As a result of these findings, the following recommendations for improving model performance are:

1. The default turbulent dispersion coefficient for oils should be increased to $10 \text{ m}^2 \text{ s}^{-1}$ within more dynamic regions with significant variation in meteorological forcing over short spatial scales.
2. An increase in the slick spreading factors for the more viscous fuel oils (Bunker C, IFO-180, and IFO-380), although having a minimum impact on the evaporation rate, improved transport timing, and given the current constraints of the model, should be implemented. Modification of the slick-spreading factor for lower viscosity fuels and oils may not be necessary and should be determined from a similar validation study.
3. When running extended modeling simulations outside of the default 48-hour operational time window, the resuspension of stranded oil and slick forming materials is critical to accurate material transport and slick thickness prediction in regions with complex shoreline.
4. The inclusion of tarball generation algorithms may further refine model output. Still, the inclusion of these processes would be secondary to improvement in shoreline oiling and resuspension physics, as the transport and associated sheen-based oiling are not as significant in the overall volume of surface oiling. The initial assessment of the utility of adding tarball generation and disintegration relative to the necessary wave-state data requirements did not support inclusion when SHARC's OSM was developed. This analysis should be revisited to determine whether the limitations remain prohibitive relative to computational cost.

SECTION 9. REFERENCES

- Almeda R., Z. Wambaugh, C. Chai, Z. Wang, Z. Liu, and E. J. Buskey (2013). Effects of Crude Oil Exposure on Bioaccumulation of Polycyclic Aromatic Hydrocarbons and Survival of Adult and Larval Stages of Gelatinous Zooplankton. PLOS ONE **8**(10): e74476.
- Barker, C. H., V. H. Kourafalou, C. Beegle-Krause, M. Boufadel, M. A. Bourassa, S. G. Buschang, Y. Androulidakis, E. P. Chassignet, K.-F. Dagestad, D. G. Danmeier, A. L. Dissanayake, J. A. Galt, G. Jacobs, G. Marcotte, T. Özgökmen, N. Pinardi, R. V. Schiller, S. A. Socolofsky, D. Thrift-Viveros, B. Zelenke, A. Zhang, and Y. Zheng (2020). Progress in Operational Modeling in Support of Oil Spill Response. Journal of Marine Science and Engineering **8**(9): 668.
- Baylaucq, A. C. Boned, X. Canet, C. K. Zéberg-Mikkelsen, S. E. Quiñones-Cisneros and H. Zhou (2006). Dynamic Viscosity Modeling of Methane + n- Decane and Methane + Toluene Mixtures: Comparative Study of Some Representative Models. Petroleum Science and Technology. **23**(2): 143-157.
- Deacon, E.L., (1977). Gas transfer to and across an air/water interface. Tellus, **29**(4): 363–374.
- Report 07/2/2 "The Bonn Agreement Oil Appearance Code, Report of the Meeting to Evaluate the Validation Test and Report" "Current Status of the Bonn Agreement Oil Appearance Code."
- Cosco Busan Oil Spill Trustees. 2012. Cosco Busan Oil Spill Final Damage Assessment and Restoration Plan/Environmental Assessment. Prepared by California Department of Fish and Game, California State Lands Commission, National Oceanic and Atmospheric Administration, United States Fish and Wildlife Service, National Park Service, Bureau of Land Management.
- Cragan, J. A. 2016. "A Multi-component evaporation model to determine the onset of crude oil emulsification in seawater", Master's Thesis, University of Rhode Island.
- Environmental Technology Centre (ETC) (2003). Accessible at: http://www.etc-cte.ec.gc.ca/databases/spills_e.html.
- Fay, J.A., (1969). The spread of oil slicks on a calm sea. Proceedings of a Symposium on the Scientific and Engineering Aspects of Oil Pollution of the Sea. 53–63.
- Fay, J.A., (1971). Physical processes in the spread of oil on a water surface. International Oil Spill Conference Proceedings **(1)**: 463–467.
- Fingas, M., (2014). Handbook of Oil Spill Science and Technology. In M. Fingas, ed. Hoboken, NJ: John Wiley & Sons, Inc, p. 728.
- Fingas, M., (2011). Models for Water-in-Oil Emulsion Formation. International Oil Spill Conference Proceedings **(1)**: 243-273.

Fingas, M.F., (1999). The Evaporation of Oil Spills: Development and Implementation of New Prediction Methodology. International Oil Spill Conference Proceedings **(1)**: 281–287.

Fingas, M.F., (2014). Water-in-oil emulsions: formation and prediction. Journal of Petroleum Science Research, **3**(1):38.

Hibbert, A., Royston, S.J., Horsburgh, K.J., Leach, H. and Hisscott, A., (2015). An empirical approach to improving tidal predictions using recent real-time tide gauge data. Journal of Operational Oceanography, **8**(1): 40-51.

ITOPF (International Tanker Owners Pollution Federation Limited) 2016. Fate of Marine Oil Spills. Technical Information Paper No. 2. London, UK: ITOPF. 12 pp.

Lamb, S. H., Hydrodynamics, (1993). Cambridge University Press.

Lehr, W.J., (2001). Review of modeling procedures for oil spill weathering behavior. Advances in Ecological Sciences, **9**: 51–90.

Li, D.D. and M. L. Greenfield (2014). Chemical compositions of improved model asphalt systems for molecular simulations. Fuel, **115**: 347–356.

Li, Yau-Kun, L. X. Nghiem, and A. Siu, (1985). Phase Behaviour Computations for Reservoir Fluids: Effect of Pseudo-Components on Phase Diagrams and Simulation Results J Can Pet Technol **24**(06). Paper Number: PETSOC-85-06-02

MPA, 2021. SHARC Analytical Foundations.

National Transportation Safety Board (2009). Collision of Hong Kong-Registered Containership M/V Cosco Busan with the Delta Tower of the San Francisco–Oakland Bay Bridge, San Francisco, California, November 7, 2007. Marine Accident Report NTSB/MAR-09/01. Washington, DC.

Peng, M., and A. Zhang (2014). Towards the development of the National Ocean Service San Francisco Bay operational forecast system. Journal of Marine Science and Engineering, **2**(1): 247-286.

Proehl, J.A., D. R. Lynch, D. J. McGillicuddy Jr., and J. R. Ledwell (2005). Modeling turbulent dispersion on the North Flank of Georges Bank using Lagrangian Particle Methods, Continental Shelf Research, **25**: 875-900.

Quiñones-Cisneros, S.E. et al., (2008). Friction Theory Modeling of the Non-Newtonian Viscosity of Crude Oils. Energy Fuels **110**(25): 799–804.

Quiñones-Cisneros, S.E., A. Dalberg, and E. H. Stenby (2015). PVT Characterization and Viscosity Modeling and Prediction of Crude Oils. Petroleum Science and Technology **22**(9-10): 1309 - 1325

Quiñones-Cisneros, S.E. et al., (2004). Viscosity modeling and prediction of reservoir fluids: From natural gas to heavy oils. International Journal of Thermophysics, **25**(5): 1353–1366.

Quiñones-Cisneros, S. E., and U. K. Deiters (2006). Generalization of the friction theory for viscosity modeling. Journal of Physical Chemistry B, **110**: 12820–12834.

Quiñones-Cisneros, S.E., C. K. Zéberg-Mikkelsen, and E. H. Stenby (2003). Friction theory prediction of crude oil viscosity at reservoir conditions based on dead oil properties. Fluid Phase Equilibria, **212**: 233–243.

Quiñones-Cisneros, S.E., C. K. Zéberg-Mikkelsen, and E. H. Stenby (2001a). One parameter friction theory models for viscosity. Fluid Phase Equilibria, **178**: 1–16.

Quiñones-Cisneros, S.E., Zéberg-Mikkelsen, C.K. & Stenby, E.H., (2001b). The friction theory for viscosity modeling: Extension to crude oil systems. Chemical Engineering Science, **56**: 7007–7015.

Sanchez-Minero, F., J. Ancheyta, G. Silva-Oliver, S. Flores-Valle (2013). Predicting SARA composition of crude oil by means of NMR. Fuel, **110**: 318–321.

Shanahan, P., and S. C. Gaudet (2000). Mixing and Transport of Pollutants in Surface Water. In Lehr (Ed) *Standard Handbook of Environmental, Science, Health and Technology* (5B1 – 5B41). McGraw Hill, New York.

SINTEF. (2011). Gjøa crude oil -Weathering properties related to oil spill response, and chemical and toxicological characterization of WAF, Trondheim. Sørheim, K.R., Altin, D. & Leirvik, F.

Visser, A.W. (1997). Using random walk models to simulate the vertical distribution of particles in a turbulent water column. Mar. Ecol. Prog. Ser. **158**: 275–281.

Youssef, M., and M. Spaulding. (1993). Drift current under the action of wind and waves, Pp. 587–615 in *Proceedings of the Sixteenth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Calgary, Alberta, Canada. Environment Canada. Ottawa, Ontario, Canada.

SECTION 10. ABBREVIATIONS AND DEFINITIONS

CRM	Coastal Relief Model
CUDEM	Continuously Updated Digital Elevation Model
CWA	Chemical Warfare Agent
HDS	Hydrologic Data Server
HYCOM	Hybrid Coordinate Ocean Model
IFO-380	Intermediate Fuel Oil-380
MLLW	Mean Lower Low Water
MPA	Maritime Planning Associates, Inc.
MSL	Mean Sea Level
NAM	North American Mesoscale Model
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
OSM	Oil Spill Model
SARA	Saturate, Aromatic, Resin, and Asphaltene
SCAT	Shoreline Clean-up and Assessment Team
SHARC	System for Hazard Assessment of Released Chemicals
SPDB	Seasonal Profile Database
TIC/TIM	Toxic Industrial Chemical/Material
U-Component	Eastward Positive Velocity
V-Component	Northward Positive Velocity