

Appendix A. Oil Fate and Transport

The following papers were prepared to better understand (1) surface transport of oil downcoast using NOAA's GNOME model, and (2) to better understand basic physical properties that cause oil to mix within the water column. The first paper, 'Modeling Transport of Oil from the Refugio Beach Oil Spill' was prepared as part of the 2017 International Oil Spill Conference, largely for the response community. The second paper, 'Mixing depth estimates for nearshore oil from Refugio Beach Oil Spill' was prepared for the Trustees in October 2016.

Modeling Transport of Oil from the Refugio Beach Oil Spill

Amy MacFadyen

NOAA Office of Response and Restoration, Emergency Response Division
7600 Sandpoint Way NE, Seattle, WA 98115

2017-288 ABSTRACT

The Refugio Beach oil spill originated from a pipeline break on 19 May 2015 near Refugio State Beach, which is located approximately 20 miles west of Santa Barbara, California. An estimated 500 barrels (21,000 gallons) of crude oil flowed from the shore side of Highway 101 into the Pacific Ocean. Trajectory and fate modeling of the oil were provided to the Incident Command to support the response. Several factors were particularly challenging for oil spill modeling in this incident. The spill entered the ocean through the surf zone, a distinct dynamical region with variability on small spatial and temporal scales, which coastal circulation models generally do not resolve. The regional winds were also highly variable and in some locations forecast models did not reflect the on-scene observations. A final complication was the presence of numerous natural oil seeps in the region. This posed challenges both for model initialization and validation of modeling results.

In the days following the spill, above-background levels of tarballs were observed coming ashore on various beaches remote from the spill. Chemical analyses indicate that some of the tarballs likely originated from the spill. Hindcast modeling of the spill was conducted to examine transport between these locations and the spill source. Modeling simulations showed regional connectivity in approximately the correct time frame between the spill site and beaches in Ventura County and Santa Monica Bay.

INTRODUCTION

On 19 May 2015, a break in Plains Pipeline Line 901 resulted in a spill of approximately 2,500 barrels (105,000 gallons) of oil. An estimated 500 barrels (21,000 gallons) of the oil flowed from the shore side of Highway 101 into the Pacific Ocean at Refugio State Beach, near Santa Barbara, California (Figure 1). The oil released from the pipeline was a blend of crude oils being transported from the Heritage, Harmony, Hondo, and Holly oil production platforms.

As part of the oil spill response effort, NOAA's Office of Response and Restoration provided scientific support including overflight observation of the spill, information on fate and effects of the crude oil, and forecasts of surface oil movement. Operational forecasting of surface oil movement is critical to the response for planning, allocation of resources, and timely direction of response assets. This particular spill presented several unique challenges for oil trajectory modeling.

One challenge was the location of the release. Oil flowed down the beach and entered the ocean through the surf zone. The surf zone, the nearshore region of breaking waves, is dynamically distinct from the coastal ocean. Transport and dispersion within the surf zone is influenced by much smaller scale dynamic features (e.g., longshore currents, rip currents). Oil is moved alongshore by breaking-wave and wind-driven currents, and may be ejected offshore from the surf zone to the inner shelf by transient rip currents and/or offshore winds. Although detailed surf zone modeling is possible, it requires high resolution and inclusion of wave-current interactions. The surf zone is not typically resolved by the regional coastal ocean models that are used to drive transport in oil spill modeling. This is also a limitation for trajectory modeling of oil spills that originate offshore. In this case, it limits the ability to provide detailed information

on variability in shoreline oiling below the model grid scale (typically >1 km). However, in the case of the Refugio spill, the origination of the spill on the beach affected the *initialization* of the model, requiring assumptions to be made about the initial transport and footprint of the floating oil.

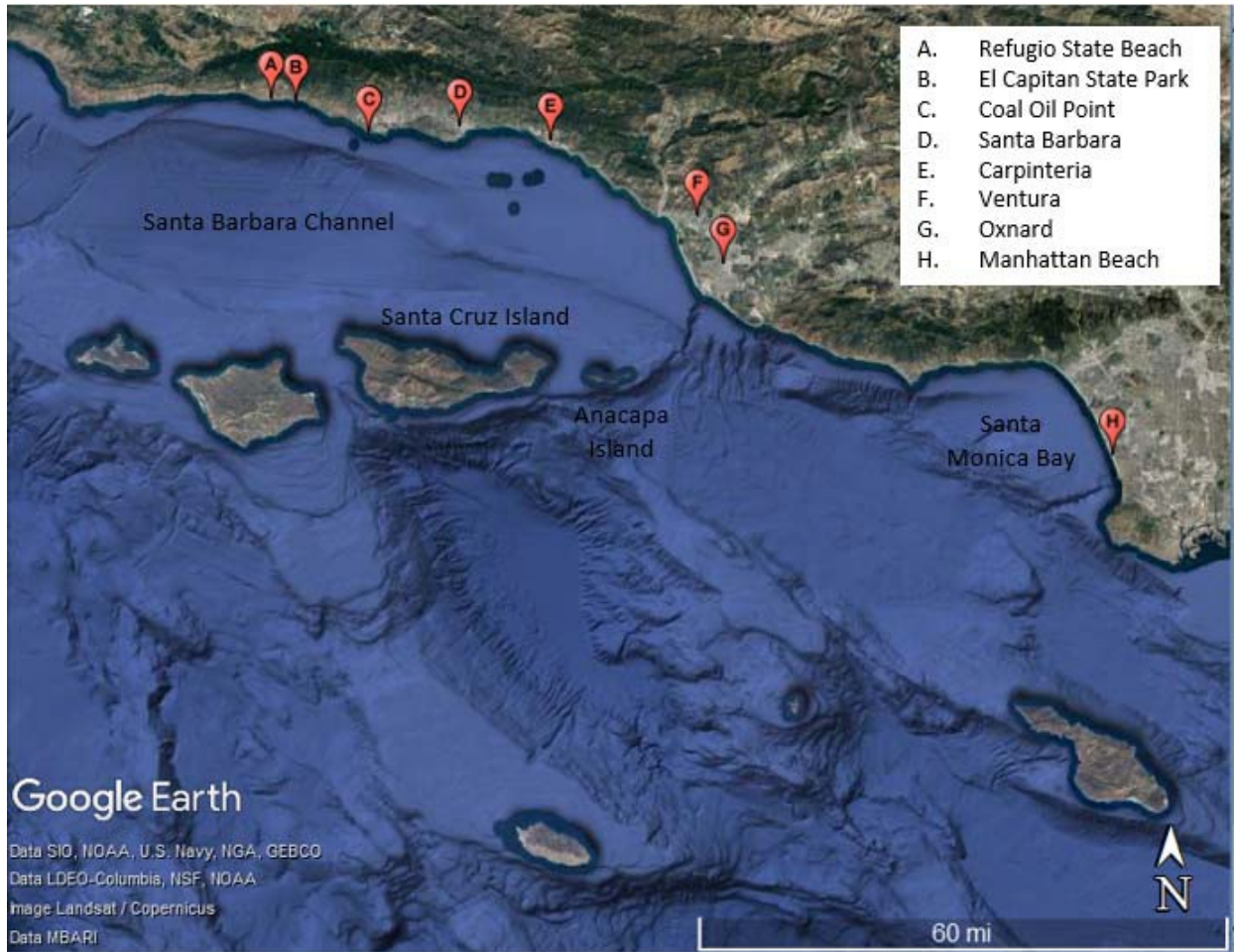


Figure 1 Location of Refugio State Beach and other locations mentioned in the text.

Uncertainty in the oil footprint used in the model initialization can be reduced by overflight surveys, which map the observed floating oil. NOAA overflights began the morning of 21 May, two days after the initial release, which occurred in an area known for its abundant natural oil seeps. The Coal Oil Point area is home to seeps that release on the order of 100 barrels of oil per day and are among the most active in the world [Hornafius et al., 1999]. It is not

generally possible for aerial observers to determine if observed floating oil is from a spill or a natural source, unless the oil can be clearly traced back to an origin point. In the Refugio spill, the oil from the local natural seeps and the leaking pipeline both originated from the same geologic formation so even their chemical makeup was similar, requiring sophisticated chemical analyses to differentiate the two.

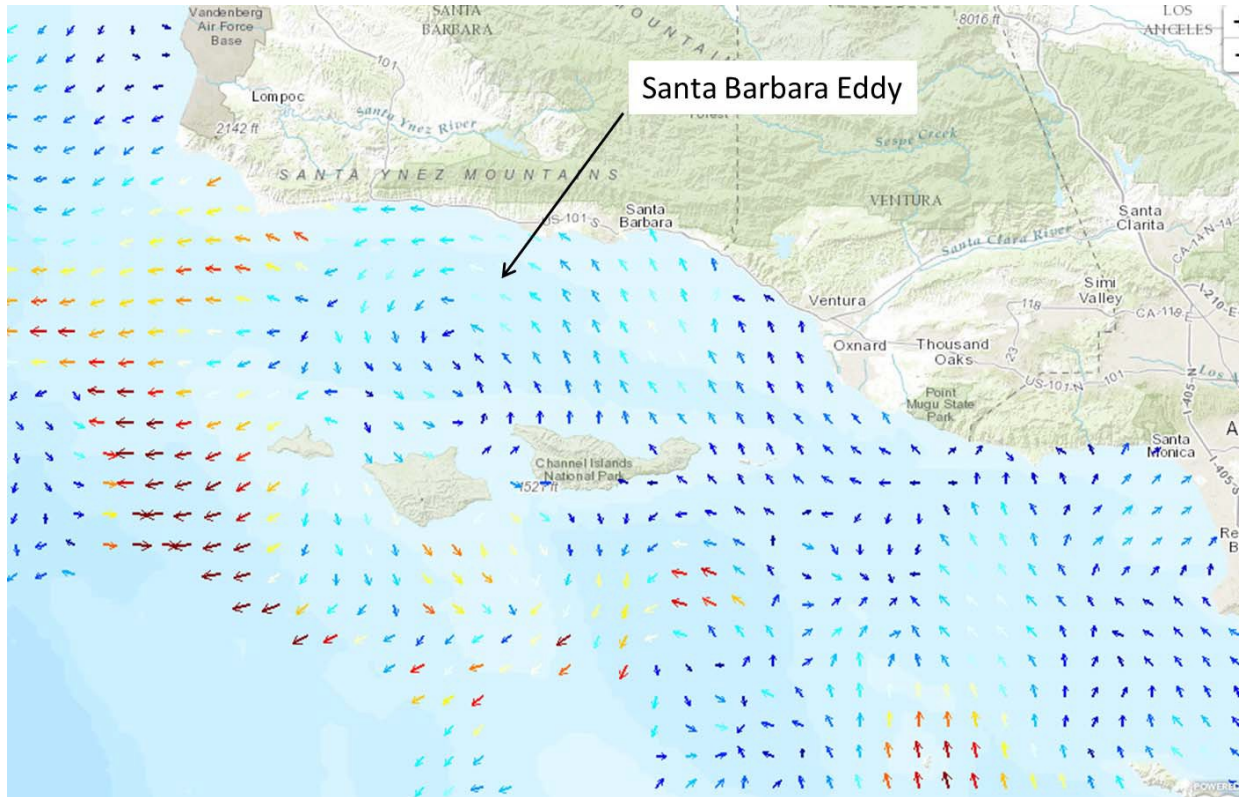
In spite of these challenges, oil spill trajectory forecasts were produced and utilized by the response to guide operations from the first day of the spill through 26 May. These forecasts identified with reasonable accuracy the heaviest regions of shoreline oiling along the coast adjacent to the spill site and extending several miles. However, several incidents of above-background levels of tarball deposition also occurred on beaches remote from the spill site, e.g., along the Ventura coastline, in Santa Monica Bay, and in the Channel Islands. This prompted a hindcast analysis to examine regional transport pathways and time scales of transport to examine the likelihood of these incidents arising from the Refugio spill. This hindcast modeling was further refined as part of the Natural Resource Damage Assessment following the spill response.

MODELING APPROACH

Movement of oil was modeled using the General NOAA Operational Modeling Environment (GNOME) [Zelenke et al., 2012]. GNOME is an oil spill trajectory model in which the surface oil is divided into a large number of small particles of equal mass that move under the influence of surface ocean currents, wind drift, and horizontal mixing. GNOME also includes algorithms that simulate surface oil weathering, e.g., evaporation and dispersion.

Oil spill trajectory models rely on hydrodynamic model forecasts and/or observations of winds and currents as inputs. Real-time forecasting during spill response necessitates reliance on

meteorological and ocean forecast model results, increasing the uncertainty associated with the oil trajectories. In contrast, hindcast modeling can incorporate observational data from the time of the spill or reanalysis products (models that are re-run with available observational data assimilated).



*Figure 2 Surface current data (6 km) from coastal radar obtained early in the spill.
Source: NOAA CENCOOS*

For the hindcast analysis presented in this paper, surface currents were obtained from coastal radar data operated with funding from the Southern California Coastal Ocean Observing System (sccoos.org). Coastal radars measure surface currents in the coastal ocean with coverage throughout the Southern California Bight at 6-km resolution (Figure 2; a higher resolution of 2 km is available for the region within the Santa Barbara Channel). These data resolve the

mesoscale features of the surface circulation (e.g., counter-clockwise Santa Barbara Eddy, Southern California Countercurrent [Hickey, 1992]).

Wind forcing was obtained from the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®), developed and run by the Naval Research Laboratory in Monterey, CA (<http://www.nrlmry.navy.mil/coamps-web/web/home>). COAMPS is a numerical model used for wind nowcasts and forecasts. The implementation of COAMPS used in this study has a spatial resolution of 4 km and covers the coastal ocean from Oregon to Mexico. COAMPS was run as a forecast with re-initialization every 12 hours with available observations interpolated together with the previous model forecast. Atmospheric fields were then projected forward in time.

In spill trajectory models, it is common to combine a number of physical processes related to wind forcing (e.g., Stokes drift, surface drift, Langmuir circulation) into a wind-drift factor [Galt, 1994]. This has been determined experimentally to be ~3-4% of the wind speed for fresh oil in light winds without breaking waves [Reed et al., 1994]. As the oil weathers and/or if wind speed increases, the oil may spend a significant portion of time away from the surface and out of the influence of many of the processes associated with the wind forcing, and the average drift factor may be much lower. In general, this parameterization is a very useful approach but requires observational feedback during spill events [Galt, 1994]. GNOME allows the user to specify a range of values for the wind drift along with a persistence time scale, simulating the time-varying windage as the wind and wave conditions are not generally spatially or temporally constant. A base-case model run used a range of windage values from 1-4% with a persistence time scale of 15 minutes, i.e., individual particles are randomly re-assigned a windage value

between 1-4% every 15 minutes. Sensitivity studies were performed using reduced (1-2%) and increased (3-4%) windage values.

Turbulent diffusive processes that spread spills horizontally are simulated in GNOME by a random walk. A diffusion coefficient of $1 \text{ m}^2\text{s}^{-1}$ was used to calculate random step lengths in the x- and y-directions from a uniform distribution. The current version of GNOME does not allow for spatial variability in the horizontal diffusion, so this results in a uniform spreading of the particles over time.

MODEL INITIALIZATION

As discussed previously, the 6-km resolution regional coastal radar derived surface currents do not include data in the surf zone where the oil first entered the ocean. Due to this limitation, rather than initiate the spill as a point source, observations during the first 24 hours of the spill were used to initialize floating oil nearshore. Although detailed NOAA overflight surveys did not begin until 21 May, aerial photographs indicated some of the floating oil began moving offshore the afternoon of 19 May, coincident with the development of an offshore wind in the late afternoon. U.S. Coast Guard personnel flying over the site observed a 2-mile alongshore extent of shoreline oiling at 5:30 PM on 19 May and observed some floating oil remaining in the surf zone and extending offshore during a mid-morning overflight on 20 May.

Based on these limited observations, particles were initialized in the GNOME model within a polygon in a nearshore area extending out to $\sim 1/3$ km off the coastline with an east-west extent similar to the 19 May overflight. For each simulation, $\sim 100,000$ particles were released over a 24-hour period beginning 19 May 5:30 PM. A linear decay rate in the number of particles released per timestep was applied.

Without a detailed surf zone modeling component or a quantitative estimate on how much oil beached along the shoreline adjacent to Refugio Beach, we did not think it reasonable to estimate how much oil may have moved offshore versus oil that remained in the surf zone and beached in the near-field. Model results are therefore reported as relative particle densities rather than oil concentrations. For the same reason, oil weathering is not included in this analysis and the particles are conservative with no loss processes.

SHORELINE OIL OBSERVATIONS

Shoreline Cleanup Assessment Technique (SCAT) teams began surveying the coastline adjacent to the spill site very early in the response. SCAT survey data are presented in Figure 3. This map includes data collected over multiple days: the coloring of shoreline segments represents the maximum level of oiling observed on any survey. For a temporal perspective, on 20 May, SCAT teams reported observing oiled shoreline extending approximately 7 miles from Arroyo Hondo Preserve (western extent) to El Capitan State Beach (eastern extent). By 23 May, SCAT maps indicated moderate shoreline oiling extending several miles further east of El Capitan and also variable degrees of shoreline oiling around Coal Oil Point and University of California, Santa Barbara.

High densities of tarball deposition were subsequently reported by the public at Manhattan Beach in southwestern Los Angeles County on May 28 and in Ventura County between Carpinteria and Oxnard around the same time. Surveys were also conducted in these areas and reported light to moderate oiling conditions. An atypical tarball event was also reported by U.S. Fish and Wildlife in the Channel Islands between 1-7 June.

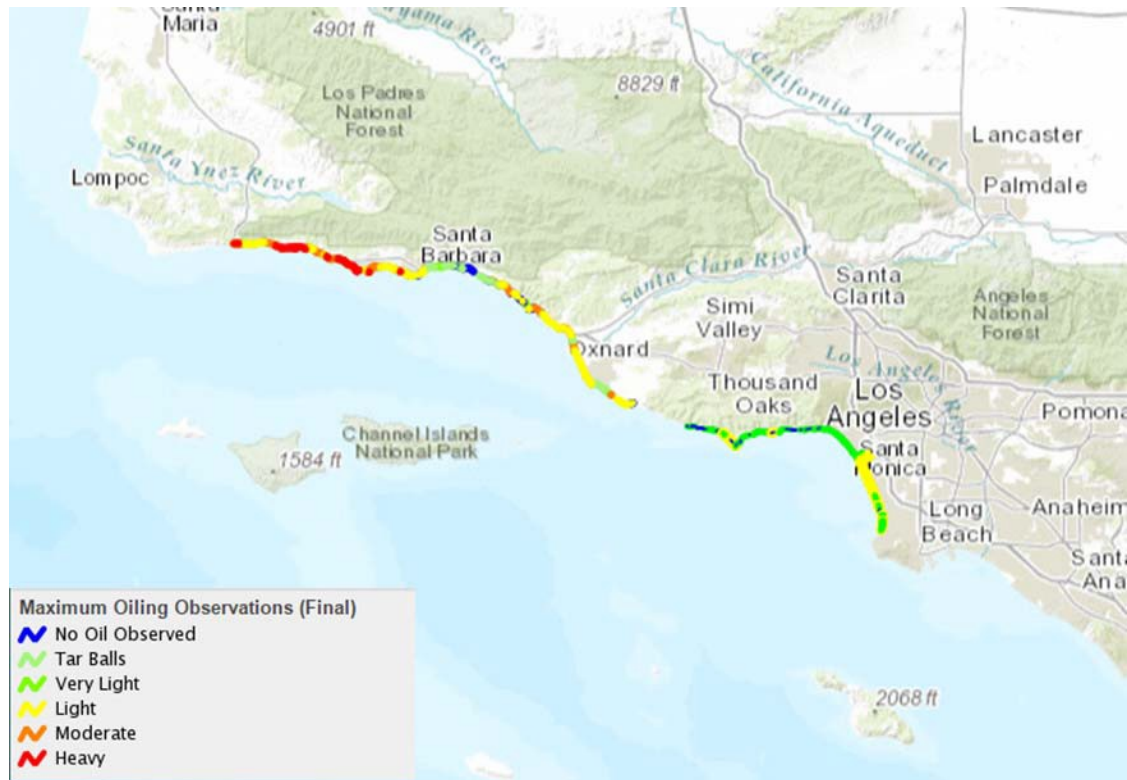


Figure 3 SCAT survey map showing maximum oil observed at each segment. Image from the Environmental Response Management Application (ERMA®) Southwest.

This region has a level of background shoreline oiling due to the active natural seep field, which is an order of magnitude higher in summer than winter [Del Sontro et al., 2007, Lorenson et al., 2009]. This complicates interpretation of the semi-quantitative SCAT data. The map shown in Figure 3 certainly incorporates both spill oil and natural seep oil. In the first few days of surveys described previously, the proximity to the source and nature of the oiling indicated much of this oiling was likely due to the pipeline release. As the observations become more remote in time and space from the spill origin, sophisticated chemical analyses are required to differentiate between the two possible sources. The model results described in the next section can also aid in describing potential connectivity between the spill site and the impacted regions.

MODEL RESULTS

Snapshots of relative particle densities at various model times are shown in Figure 4 for the base-case run described previously (windage values ranging from 1-4%). In this simulation, model particles move offshore into the Santa Barbara Channel and enter the counter-clockwise Santa Barbara Eddy on 20-21 May. Very few particles make landfall on the Channel Islands. Instead, particles move east, making landfall along the Ventura coastline by 25 May. The remaining floating particles move southeast, with some portion advected eastward into Santa Monica Bay and making landfall by 29 May, approximately one day later than the observed event. The highest beached particle densities occur near Refugio Beach and in the eastern Santa Barbara Channel.

A sensitivity study with the wind influence reduced to 1-2% of the wind speed (Figure 5) demonstrates the importance of westerly winds prevalent in the Santa Barbara Channel in reducing landfall on the Channel Islands. In this lower windage simulation, particles make landfall initially on the north facing shorelines of Santa Cruz and Anacapa Islands within several days of the release. Shoreline impacts still occur in Ventura County but are delayed by several days. However, in this case, no particles enter Santa Monica Bay.

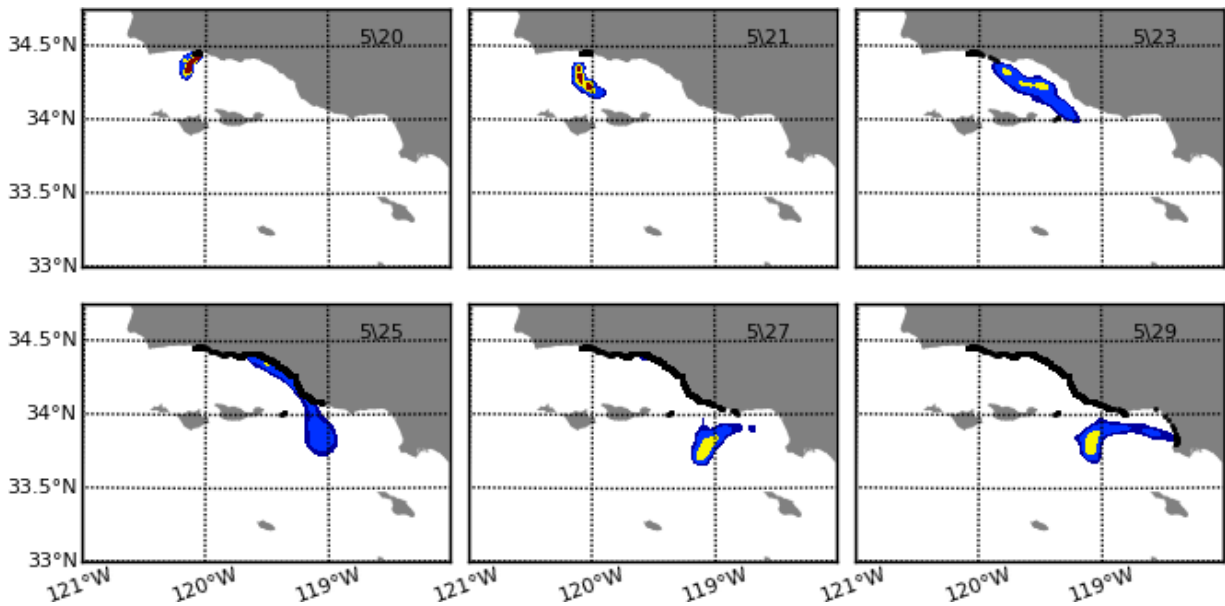


Figure 4 Particle densities (relative to maximum for the entire simulation) for the base-case of 1-4% windage. Black dots mark the locations where particles contact the shoreline.

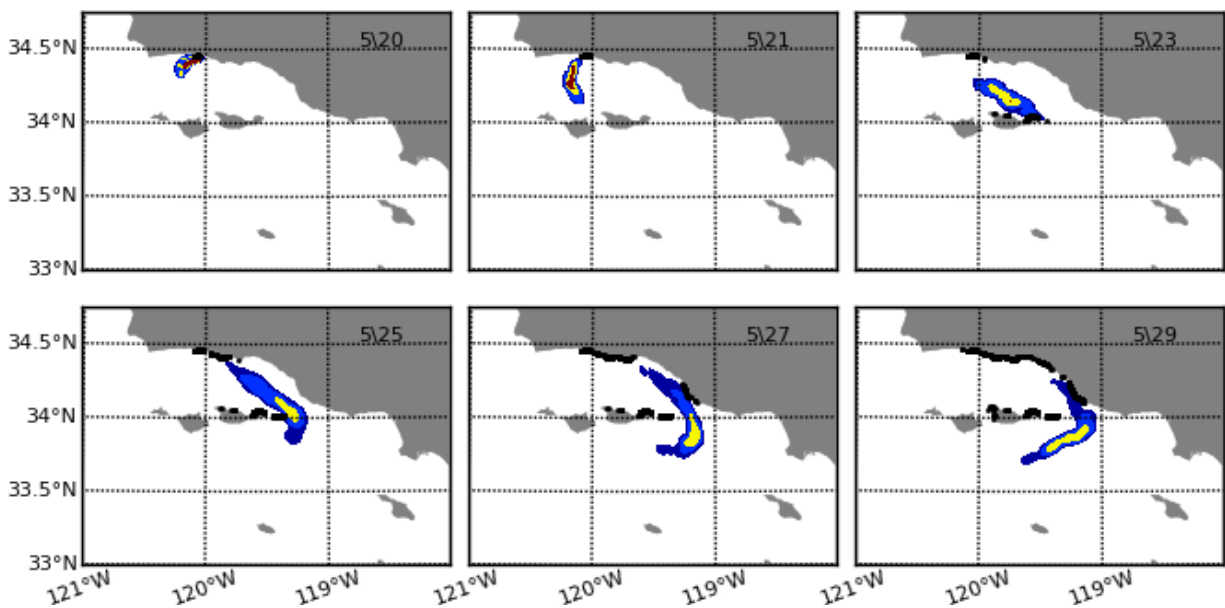


Figure 5 As in Figure 4, for the reduced windage, 1-2% case.

A sensitivity study with a larger wind influence, a 3-4% range, was also conducted (not shown). In this case, particles move eastward in Santa Barbara Channel much quicker, making

landfall in Ventura County by 23 May. The impacts in Santa Monica Bay are also magnified and occur by 27 May, preceding observations slightly.

SUMMARY AND DISCUSSION

Following the Refugio Beach Oil Spill on 19 May 2015, several incidents of increased tarball accumulation occurred on beaches remote from the spill site. This study examined the movement of modeled particles simulating floating oil that originated nearshore of Refugio Beach, with the goal of elucidating regional transport pathways and time scales of transport.

The model simulations show particles making landfall in southern Santa Monica Bay and Ventura County in a time frame approximately agreeing with observations. In the base-case scenario, a range of values of 1-4% were used for the model windage parameter, resulting in downwind movement averaging about 2.5% of the wind speed. This resulted in initial landfall impacts in Ventura County by 25 May and at Manhattan Beach by 29 May. Interestingly, the majority of public reporting of tarballs were around the same time for both sites, with Santa Monica Bay (28 May) actually leading Ventura slightly. Based on the modeling studies alone, this seems confounding—however, the modeling studies only considered movement of oil originating from the spill. Oil observations from overflights indicated very active natural seep activity throughout the time period of surveys, which under the right environmental conditions, could also manifest as notable tarball events on remote beaches. We would expect tarballs that arrived on beaches in both these locations during this time frame to likely contain a mixture of spill and seep oil.

Another notable event was the increased tarball accumulation observed in the Channel Islands beginning around 1 June. By this time, the modeling simulations suggest most of the

floating oil had moved to the southeast or already beached. A NOAA overflight on 29 May saw little oil remaining in nearshore waters off Refugio Beach, but traced an approximately 10 mile long band of dark oil several miles offshore of the spill location back towards the Coal Oil Point seep field (Figure 6). By this time, the position of the Santa Barbara Eddy as observed by the coastal radar data had shifted westward in the Santa Barbara Channel. When combined with prevailing wind patterns, this shift in the position of the eddy made transport from the spill region to the Channel Islands much more likely during this time period. These data suggest the Channel Islands event may have been a result of natural seep activity rather than from the Refugio spill.

Finally, due to the lack of data in the surf zone region, the model likely underestimates shoreline oiling in the “near-field,” i.e., the coastline adjacent to Refugio Beach extending several miles. Observations indicate a significant portion of oil initially beached along this shoreline (Figure 3). The volume that beached in this near-field region was likely a function of many processes that were not included in this regional scale modeling effort, for example, variability in local onshore/offshore winds (sea breeze), the phase of tides, the strength of longshore currents, and the holding capacity and orientation of the shoreline. Higher resolution re-analysis ensemble wind products could better capture the temporal and spatial variability in the wind patterns. This, combined with high resolution surf zone modeling, could potentially provide a better prediction of alongshore transport in the near-field, including exchange between the surf zone and inner shelf, and hence provide a better prediction of shoreline oiling probabilities along this section of coastline.

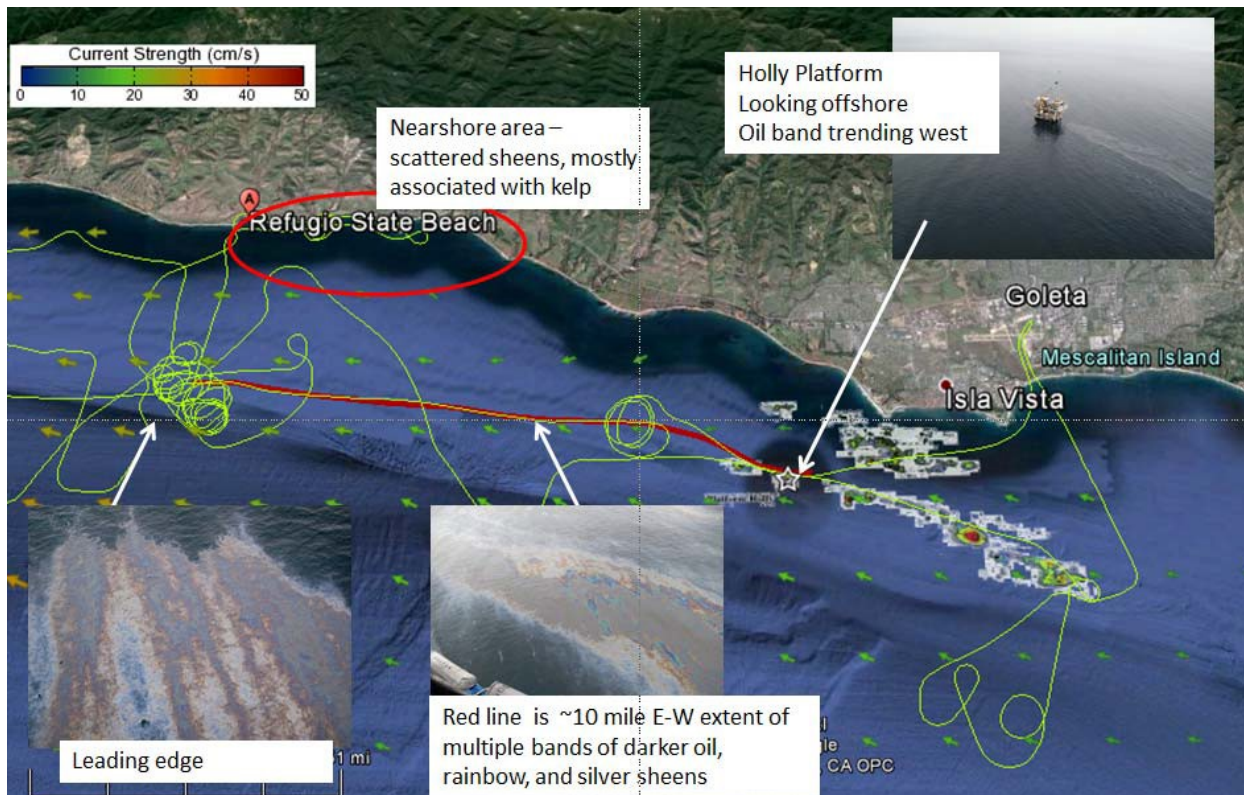


Figure 6 Summary of observations from 29 May NOAA overflight. Green track shows the flightpath. Important observations are annotated. Seep field heat map courtesy of Ira Leifer, UCSB.

ACKNOWLEDGEMENTS

Thanks to Chris Barker and Glen Watabayashi (NOAA Office of Response and Restoration) for input on the modeling approach and assumptions. Libe Washburn and Brian Emery at University of California, Santa Barbara (UCSB) kindly provided information about coastal radar data in the region operated through NOAA SCCOOS.

REFERENCES

- Del Sontro, T.S., Leifer, I., Luyendyk, B.P., and Broitman, B.R. 2007. Beach tar accumulation, transport mechanisms, and sources of variability at Coal Oil Point, California. *Mar Pol Bull*, v. 54, p. 1461-1471.
- Galt, J. 1994. Trajectory analysis for oil spills. *J. Adv. Mar. Technol. AMTEC*, Tokyo, Japan. 11: 91-126.
- Hickey, B.M. 1992. Circulation over the Santa Monica-San Pedro basin and shelf. *Prog Oceanogr*. 30: 37-115.
- Hornafius, J.S., D. Quigley, and B.P. Luyendyk. 1999. The world's most spectacular marine hydrocarbon seeps (Coal Oil Point, Santa Barbara Channel, California): Quantification of emissions. *J. Geophys. Res.* 104(C9), 20703–20711, doi:10.1029/1999JC900148.
- Lorenson, T.D., Hostettler, F.D., Rosenbauer, R.J., Peters, K.E., Kvenvolden, K.A., Dougherty, J.A., Gutmacher, C.E., Wong, F.L., and Normark, W.R. 2009. Natural offshore seepage and related tarball accumulation on the California coastline; Santa Barbara Channel and the southern Santa Maria Basin; source identification and inventory: U.S. Geological Survey Open-File Report 2009-1225 and MMS report 2009-030. 116 p. and spreadsheets.
- Reed, M., C. Turner, and A. Odulo. 1994. The role of wind and emulsification in modeling oil-spill and surface drifter trajectories. *Spill Sci. Technol. Bull.* 1(2): 143-157.
- Zelenke, B., C. O'Connor, C. Barker, C.J. Beegle-Krause, and L. Eclipse (Eds.). 2012. General NOAA Operational Modeling Environment (GNOME) Technical Documentation. U.S. Dept. of Commerce, NOAA Technical Memorandum NOS OR&R 40. Seattle, WA: Emergency Response Division, NOAA. 105 pp.

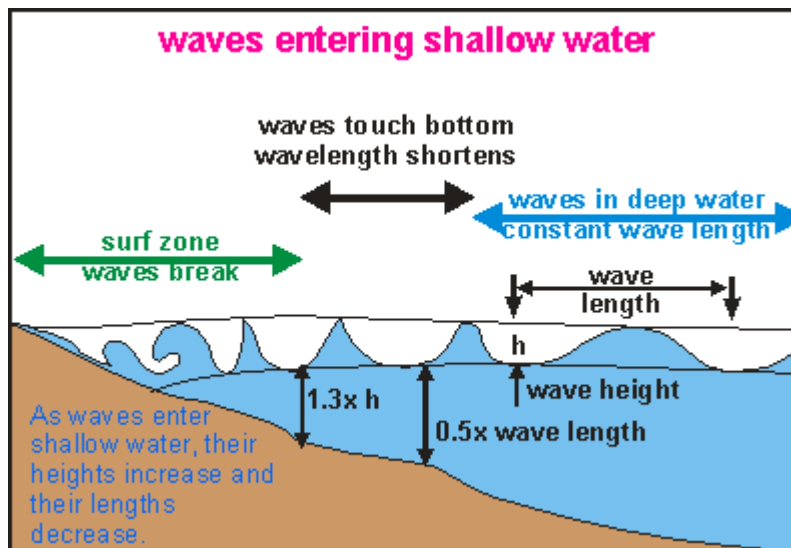
Mixing depth estimates for nearshore oil from Refugio Beach Oil Spill

Prepared by:

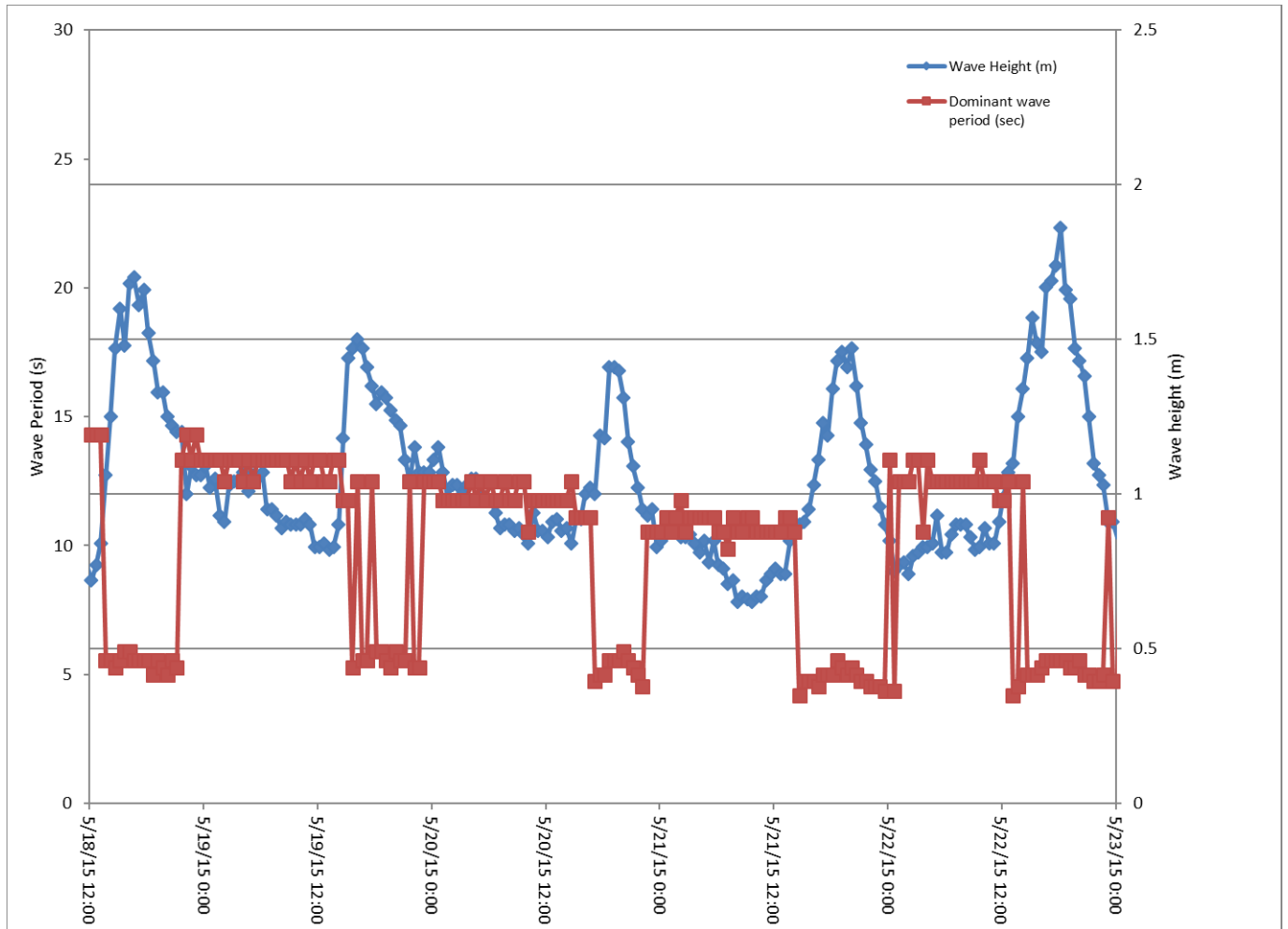
Amy MacFadyen
NOAA Office of Response & Restoration
Emergency Response Division
Seattle, WA

Estimation of surf zone depth during Refugio Spill

The surf zone is defined as the region which contains waves that are breaking due to the shallow water depth. Within the surf zone we would expect soluble components of oil and oil droplets to be mixed throughout the water column. The width and character of the surf zone continually vary with changes in tide level, incident waves, and local wind speed and direction. However, by examining wave conditions during the time of the spill, we can estimate the water depth at which waves begin to break, i.e. the water depth at the outer (offshore) edge of the surf zone.



Wave breaking equations can be used to estimate the offshore depth of the surf zone. As the waves approach shallow water, they shoal and get shorter and steeper. Once the wave height reaches about 0.8 of the water depth, the wave begins to break. By matching the energy flux from deep to shallow water, the water depth at initiation of wave breaking as a function of offshore wave length and height can be derived (Fredsoe et al, 1992). Using the deep water dispersion relationship, wavelength can be converted to wave period – both wave height and period are measured at offshore wave buoys. The plot below shows wave conditions during the first few days of the Refugio Oil Spill measured at the Scripps Waverider Buoy off Goleta Point (ID: 46216).



In this time series, there are two dominant wave periods. The swell (longer wave period, smaller wave height) was approximately 1 m at 12 s. Associated with higher winds that typically occur in the afternoon, wave heights would increase and periods decrease. During these periods, the seas were up to almost 2 m at 5 s (although more often reaching a maximum around 1.5 m). Using these relationships, the surf zone depth for 12 seconds and 1.00 m wave height is 1.90 m and the surf zone depth for 5 seconds and 2.00 m wave height is: 2.33 m. This suggests oil would be mixed in the surf zone to a maximum depth of ~2m.

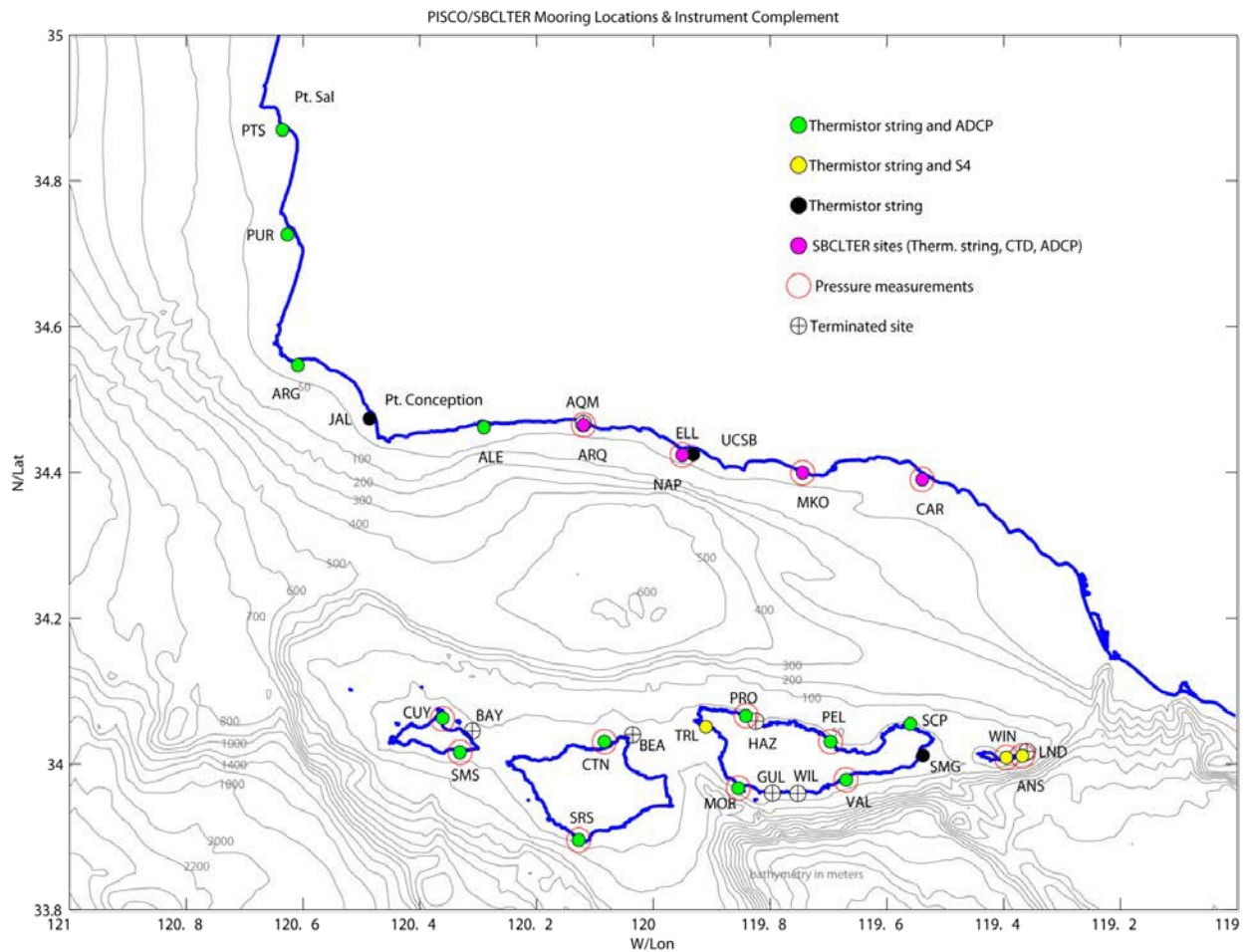
Since the oil entered the water through the surf zone, there is also potential that the oil interacted with sediments and formed oil-sediment aggregations which would be potentially dense enough to sink to the bottom. These aggregates could also be transported around in the surf zone and move offshore onto the inner shelf.

Inner shelf

The inner shelf region begins just offshore of the surf zone. The exchange of tracers (e.g. dissolved oil components) between the surf zone and the inner-shelf is poorly understood. Rip currents (both transient and bathymetrically controlled) can eject water from the surf zone onto the inner-shelf.

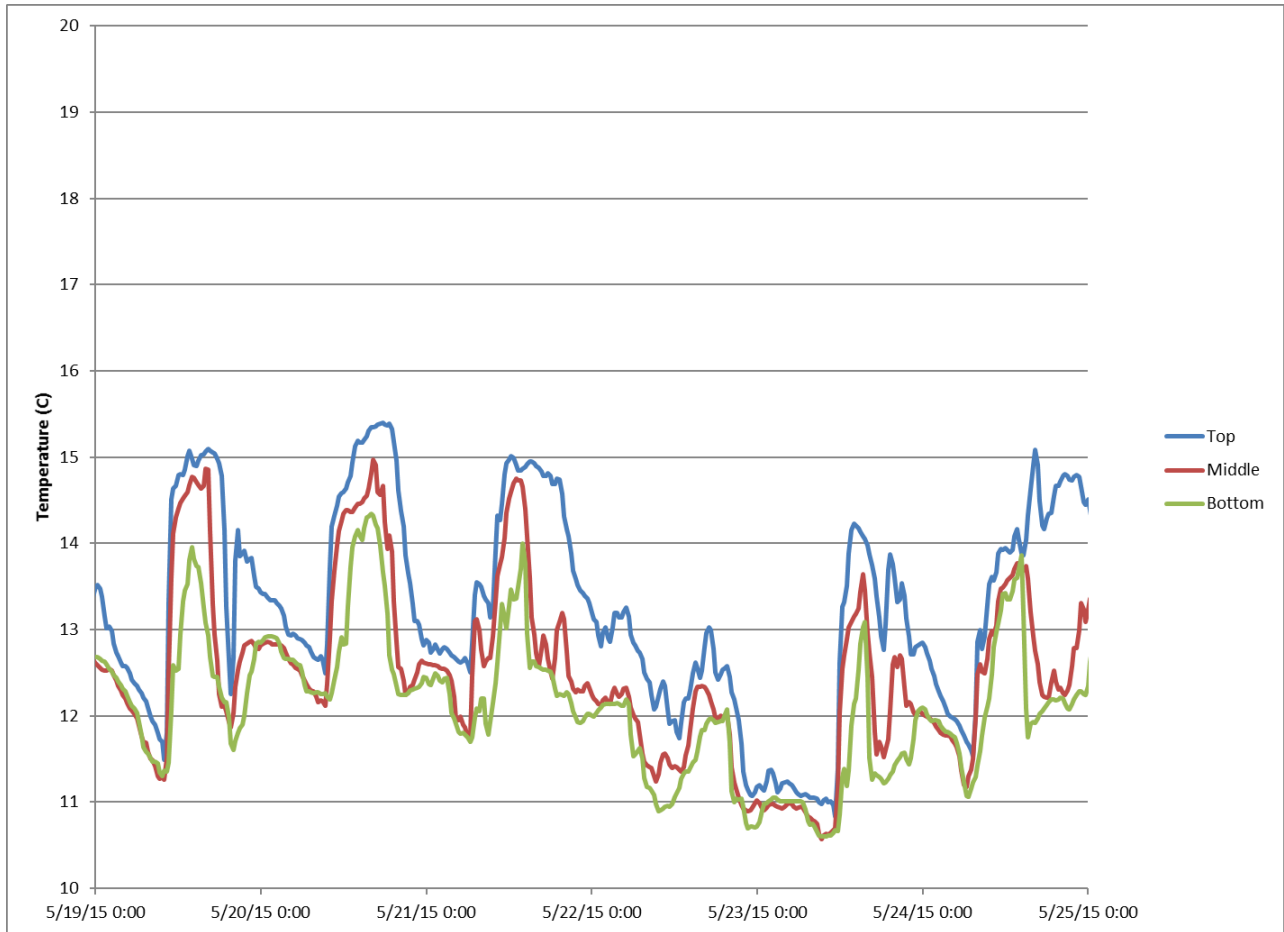
Dissolved oil components and floating slicks ejected from the surf zone can be mixed vertically on the inner shelf, due to waves, winds, and surface heat fluxes.

To examine the amount of mixing on the inner shelf, data is available from nearshore moorings with thermistors placed near the surface, at mid-depth, and near the bottom. The locations of these moorings, which are part of the Santa Barbara Coastal Long Term Ecological Research Project (sbc.lternet.edu), are shown in the figure below. The moorings are generally in 10-15 m of water.

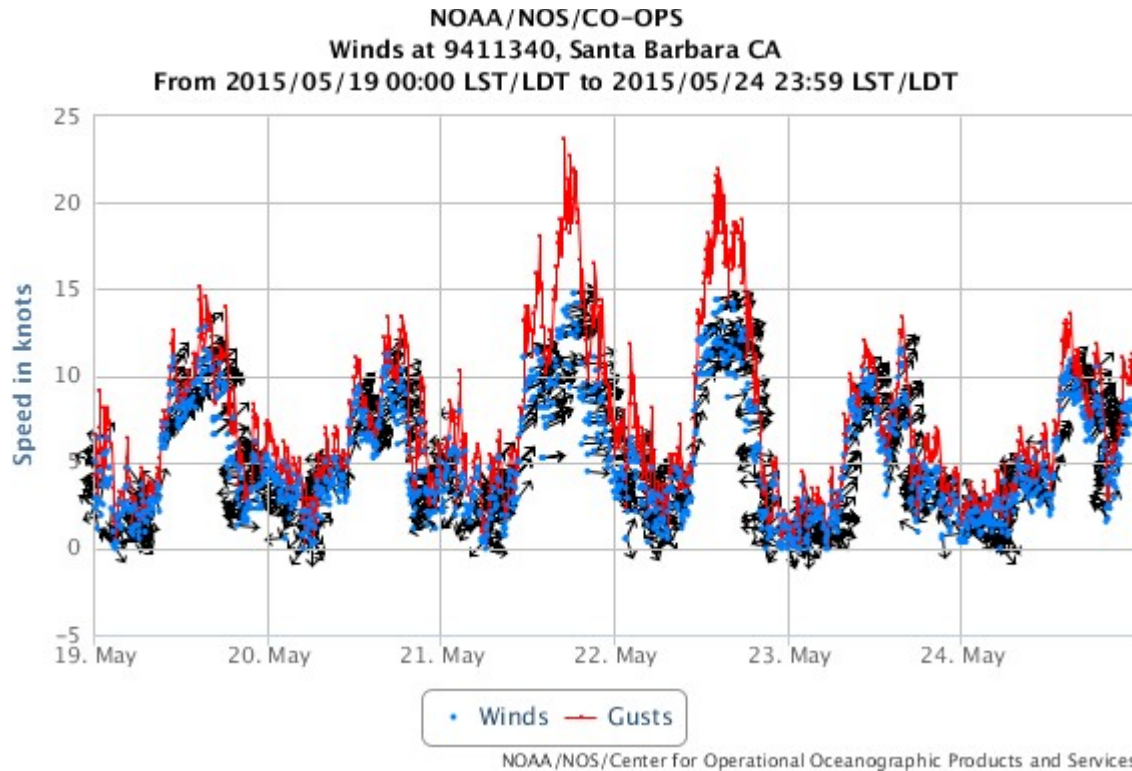


Temperature data from the ARQ mooring (west of Refugio) is shown below. This mooring is in ~15 m of water and is the closest site to where the oil entered the water at Refugio beach. The mooring has three thermistors, located near-surface (at about 3-4m depth), mid-water column, and ~1m above the bottom.

Temperature (°C) at ARQ LTER mooring (15 m)



The diurnal cycle of daytime heating and night time cooling is evident at this location and other sites along the coast. Stratification is generally quite low, suggesting a well-mixed water column at least to mid-depth (~7.5 m) much of the time.



Mixing is driven by surface wind and wind-wave interactions (e.g. Langmuir circulation or windrows). Winds measured at the NOAA COOPS buoy near Santa Barbara are shown above. They tend to be strongest during the afternoon (land/sea breeze effect), typically exceeding 10 kts by late afternoon. In the absence of winds, the signature of daytime heating would be confined to a thin layer at the surface. However, the strong afternoon winds mix heat downwards through the water column so the diurnal heating and cooling signature is evident at all depths.

Mixing also occurs at night due to cooling surface waters, which leads to convection. This is evident in the nearly uniform temperatures at all 3 depths at night.

Based on these data, it is reasonable to assume that dissolved oil constituents and small oil droplets could have been mixed to the depth of the lowest thermistor – approximately 14 m.