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Does Wave Height Matter for Effective Surface Dispersant Application?

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ABSTRACT 300076:

The Deepwater Horizon (DWH) crude oil release provided an occasion to test the delivery and effectiveness of dispersants on surface oil slicks to reduce the potential exposure of shoreline habitats and marine wildlife to spilled oil. In the beginning of the DWH response, there was concern that the calm sea conditions did not provide sufficient wave energy for dispersant action to occur. At one point a minimum 3-foot wave height requirement for dispersant application was set in an attempt to ensure sufficient mixing energy for dispersant activation was present at the time of application. Because of the ability of aerial dispersant application to rapidly treat large spatial areas and quantities of oil, there was a contrasting concern that a 3-foot (0.91 m) minimum wave height requirement was overly restricting dispersant operations; thereby, increasing environmental exposures.

To evaluate the wave heights that effectively dispersed the Macondo crude oil, the SMART (Special Monitoring of Applied Response Technologies) Tier II/III monitoring data of dispersant applications performed in low wave conditions, i.e., < 3 ft (0.91m) were analyzed. Of the 27 SMART Tier II/III monitoring operations conducted in significant wave heights (SWHs) of < 3 feet (0.91 m), 21 were reported as "effective," 4 were reported as "inconclusive," and only 2 were reported as "no observed dispersion." These results demonstrate dispersants were effective in low wave conditions and on weathered Macondo crude oil as a function of distance from the spill site.

The paper then estimates the impact that setting wave height restrictions has on dispersant operations showing that a > 3 feet requirement could reduce surface dispersant operational days by as much as 67%. With the dispersant assets available during the DWH response, this could have resulted in leaving up to 700,000 gallons of oil per day on the water,[a] thus exposing shoreline habitat and offshore wildlife to an increased risk of oiling.

[a] The calculation for the 700,000 gallons per day figure is provided on page 757.

The paper concludes that

- Wave height should not be used as a criterion for approving or conducting surface dispersant application operations, because
  - wave heights as low as 0.5-1.0 feet were effective in immediately dispersing fresh and weathered Macondo crude oil, and may be sufficient to disperse other oils, and
  - Research on dispersant application in calm sea conditions has shown that oils would rapidly and almost totally disperse when exposed to breaking waves after being left on a calm water surface for prolonged periods.

The paper recommends that government and response organizations should review and consider revising their guidance and operational procedures for dispersant application approval in light of the analysis presented in this paper.

INTRODUCTION:

During the DWH response, there was a concern that sea conditions were not adequate for the dispersants to effectively disperse oil on the sea surface. To ensure adequate mixing energy, a minimum wave height of 3 feet was set on May 17, 2013.[1] To determine if the 3-foot wave criteria would be met throughout the day, each morning at approximately 0600 the forecasted weather, National Data Buoy Center data, and reports from vessels in the response area were reviewed.

If these early morning reports did not clearly indicate the 3 ft wave height criterion would be met, then dispersant operations would not commence. Often, once a decision was made in the morning, it was not changed for the entire operational day.

Based on research and empirical information over the past 40 years, much is known about the function of dispersants and the behavior of dispersed oil. Wave action is one of the important factors which influence dispersant effectiveness. Other factors include the type of oil, the weathering state of the oil, the dispersant product, application dosage and water temperature and salinity. Most guidance on dispersant use does not specify a minimum wave height for dispersant application. For example:

- U.S. National Research Council (NRC) publications,
- ASTM Standards,
- Regional Response Team (RRT) plans,
- International Tanker Owners Pollution Federation, Ltd. (ITOPF) technical papers acknowledge that some wave action, i.e., mixing energy, is needed for dispersant treatment effectiveness, but do not specify any wave height necessary for application.[2,3,4,5,6]

The following organizations provide amplifying guidance on wave heights for dispersant operations as follows:

- Regional Response Team 3 (RRT 3) states that the optimum situation for the use of dispersants is that the "sea state is about 2 (4' - 6'), that is, sufficiently high to enhance mixing the dispersants, …"[4]
- Regional Response Team 9 (RRT9) Regional Contingency Plan has a pre-approval zone dispersant use checklist that requires a determination that oceanographic and weather conditions are potentially suitable for successful dispersant application.[5]

Only Oil Spill Response, Ltd. (OSRL), which provides worldwide dispersant capability with dedicated C-130 aircraft, shows in their chart of Beaufort Sea states that dispersant application is viable in wave heights of zero feet ("mirror-like" conditions) or greater.[7]

Because of the magnitude of the daily DWH oil release and the available aerial dispersant capability to treat square miles of oil slicks containing 1,000s of barrels of oil per day, there was a contrasting concern that a 3-foot (0.91 m) minimum wave height requirement was overly restricting dispersant operations; thereby, increasing potential environmental damages. To determine if lower wave heights could be adequate for dispersion of the Macondo crude oil, dispersant applications were made in wave heights of < 3 ft and monitored for effectiveness with SMART visual and fluorometric equipment. This paper presents the results of SMART Tier II/III monitoring of vessel and aerial dispersant application in low wave conditions and presents representative examples of the fluorometric readings and photographs of the onsite wave conditions. Additionally, the paper discusses research on dispersant activation in calm seas and how wave height restrictions affect dispersant operations to answer the following questions:

- What wave height is sufficient for dispersant application to be effective?
- What impact does setting wave height criteria have on dispersant response capability?

The data, conclusions, and recommendations presented in this paper should assist government and response organizations in setting sound, scientifically supported criteria for dispersant application to maximize the environmental benefits of this valuable response tool.

WHAT WAVE HEIGHT IS SUFFICIENT FOR DISPERSANT APPLICATION TO BE EFFECTIVE?

Method

To evaluate dispersant effectiveness of Corexit EC9527A and Corexit EC9500A applied at a dosage of 5 gallons per acre (gpa) on Macondo crude in sea state conditions with significant wave heights (SWHs) of < 3 feet the following methodology was followed:

(1) Significant wave height (SWH) was selected as the measure of wave height.
   - SWH is defined as "the mean or average height of the highest one-third of all waves in a swell train or in a wave generating region."
   - It approximates the value an experienced observer would report, if visually estimating sea height, and

- It is readily available as a reported forecast value and is recorded by U.S. national data buoys.

(2) The number of days with SWHs of ≤ 3 feet was obtained from the National Data Buoy Station 42040 which was located near the spill source.
(3) The forecasted days of SWHs of ≤ 3 feet were obtained from the morning Wilkins Weather Technologies forecasts for the spill site.
(4) The SMART Tier II/III monitoring results were identified for the days with forecasted and reported SWHs of ≤ 3 feet from the NOAA (National Oceanographic and Atmospheric Administration) Report to the Federal On-Scene Coordinator titled "Review of SMART Data for Aerial Dispersant Operations."[8] Only the Tier II/III monitoring results were used because they provide a fluorometric readings as well as close-up, visual and photographic records.
(5) On the days of SWHs of < 3 feet, the SMART Tier II/III fluorometric data at 1 m depth, wave height photographs, QA/QC (Quality Assurance/Quality Control) reports and other documentation were examined to confirm the determination of the dispersant applications as "effective," "inconclusive" or as "no observed dispersion" as reported in the Review of SMART Data for Aerial Dispersant Operations.

Results/Discussion

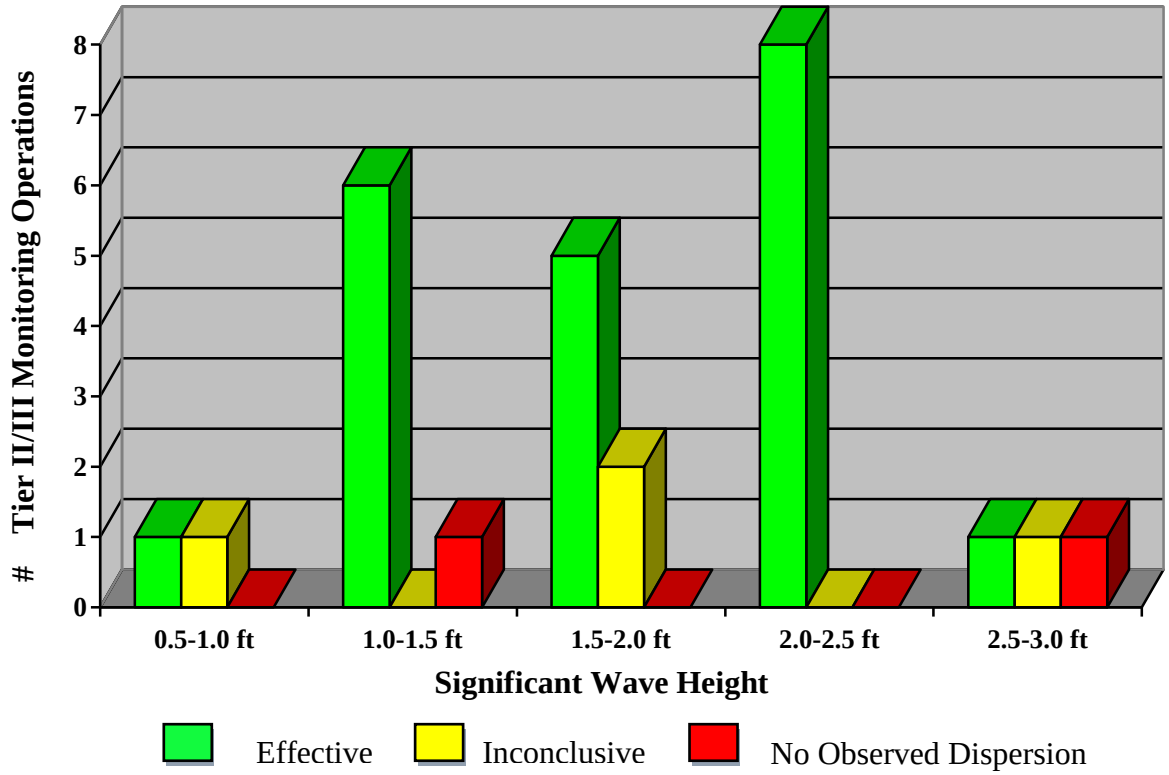
The analysis of the SMART Tier II/III field monitoring data presented in Figure 1 and Table 1 of Appendix 1 is summarized in Figure 2. There were 27 Tier II/III surface dispersant treatment monitoring operations conducted in low SWH conditions. During these low SWH conditions, surface application of dispersant was conducted almost equally between aircraft (15 times) and vessels (12 times). Of the total, 21 dispersant applications were evaluated as "effective," 4 were evaluated as "inconclusive" and only 2 were evaluated as "no observed dispersion." The "inconclusive" rating means that there was insufficient data collected during the SMART Tier II/III monitoring operation to make a determination on whether the dispersant was effective or whether there was no observed dispersion.

- One of the "no observed dispersion" ratings occurred at the furthest distance from the spill source (52.6 nm (97.4 km)). The SMART report stated the slick was very weathered and emulsified prior to the application.
- The "inconclusive" results occurred only when dispersant was applied by aircraft, which was more difficult to monitor.
- "The applications that were observed as either No Obvious Dispersion or Slow or Partial Dispersion cannot be ruled out as becoming effective over a longer setting time or with the potential increase of wave energy after the Tier 1 observers departed. In some cases there were reports of the oil being dispersed after longer curing times."[8]

Dispersant applications during DWH were effective over the SWH range from 0.5 to 3.0 feet (Figure 2) clearly showing that low SWH can provide sufficient mixing energy for dispersant activation. It is notable that dispersant activation in low SWH conditions occurred within 2 – 77 minutes of application, or almost immediately (Table 1 in Appendix 1).

Figure 2

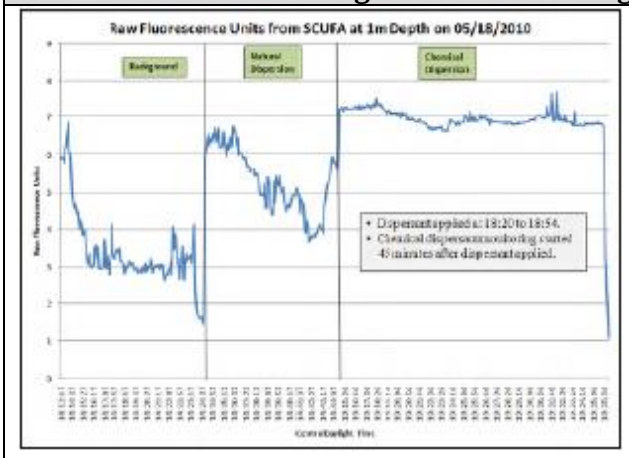
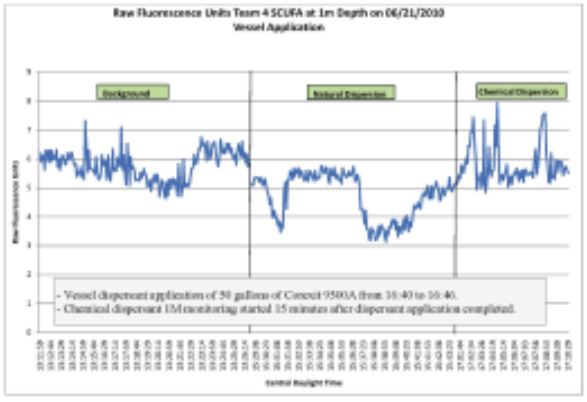
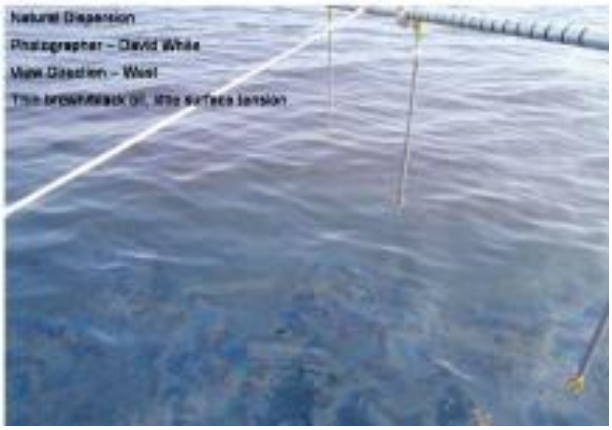
Effectiveness of Dispersant Applications in Low Significant Wave Heights (SWHs)*



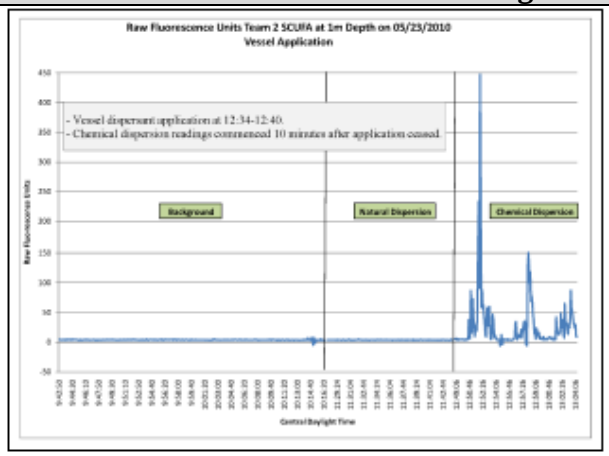
* When evaluating the effectiveness of a dispersant application the SMART Technical Specialist (TS) considered all the data available. For the DWH SMART operations this data included fluorometry readings taken at 1 and 5 meters (or 1 and 10 meters, depending on the methodology of the field team), photographs taken by the field team, and the field team's Operations Log. If there were any ambiguities or inconsistencies in the SMART data the Technical Specialist contacted the SMART Field Team Leader for clarification.
The fluorometry data from a SMART mission was examined for accuracy and reliability, then combined with the SMART photographs, Operations Log, and Field Team Leader comments to arrive at a final evaluation.[8]

Representative fluorometric recordings and sea state photograph for monitoring operations in each of the five low SWH ranges are shown in Figure 3. The photographs show increasing SWHs from the 0.5-1.0 ft range to the 2.5-3.0 ft range. SMART fluorometry data shows dispersed oil moving into the water column in each of the five low SWH ranges. Effective dispersion occurred in sea conditions that were very calm and without any white caps or breaking waves. The effective determination was made based on fluorometry, photographs, operations logs, and SMART Field Team Leader comments, and not a set percentage increase in the fluorometry readings.[8]

Figure 3
Representative Fluorometric Recordings and Significant Wave Height Photographs For Each Range of SWHs

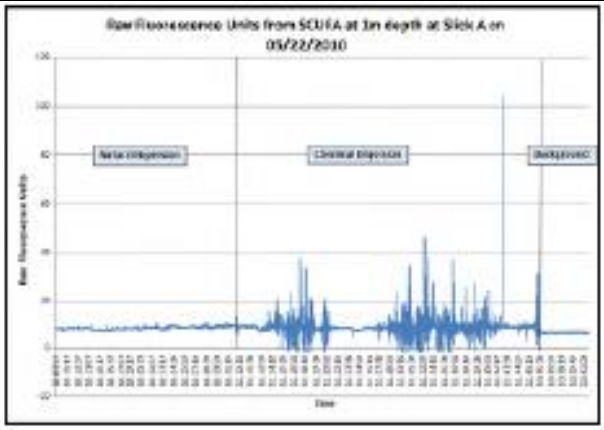
Significant Wave Height Range 0.5 to 1.0 Feet	
 Wave Height 0.95 ft (0.29 m) May 18, 2010 Dispersant Effective	
Significant Wave Height Range 1.0 to 1.5 Feet	
 Wave Height 1.18 ft (0.36 m) June 21, 2010 Dispersant Effective	

Wave Height Range 1.5 to 2.0 Feet



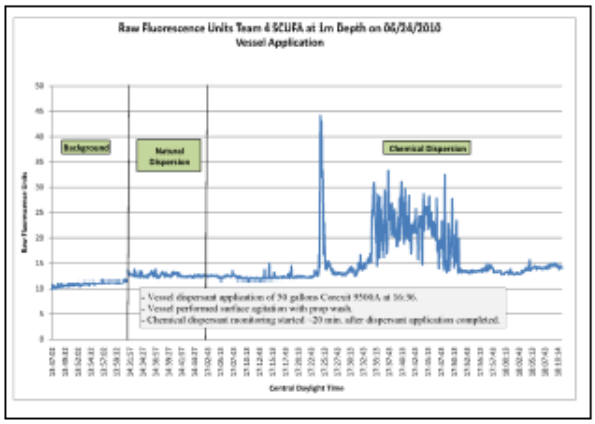
Wave Height 1.74 ft (0.53 m)
May 23, 2010 Dispersant Effective

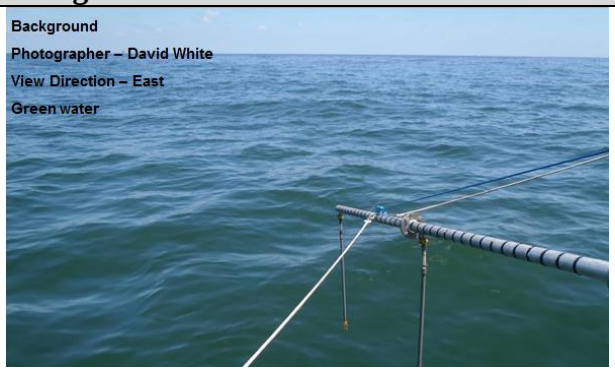
Wave Height Range 2.0 to 2.5 Feet



Wave Height 2.26 ft (0.69 m)
May 22, 2010 Dispersant Effective

Significant Wave Height Range 2.5 to 3.0 Feet





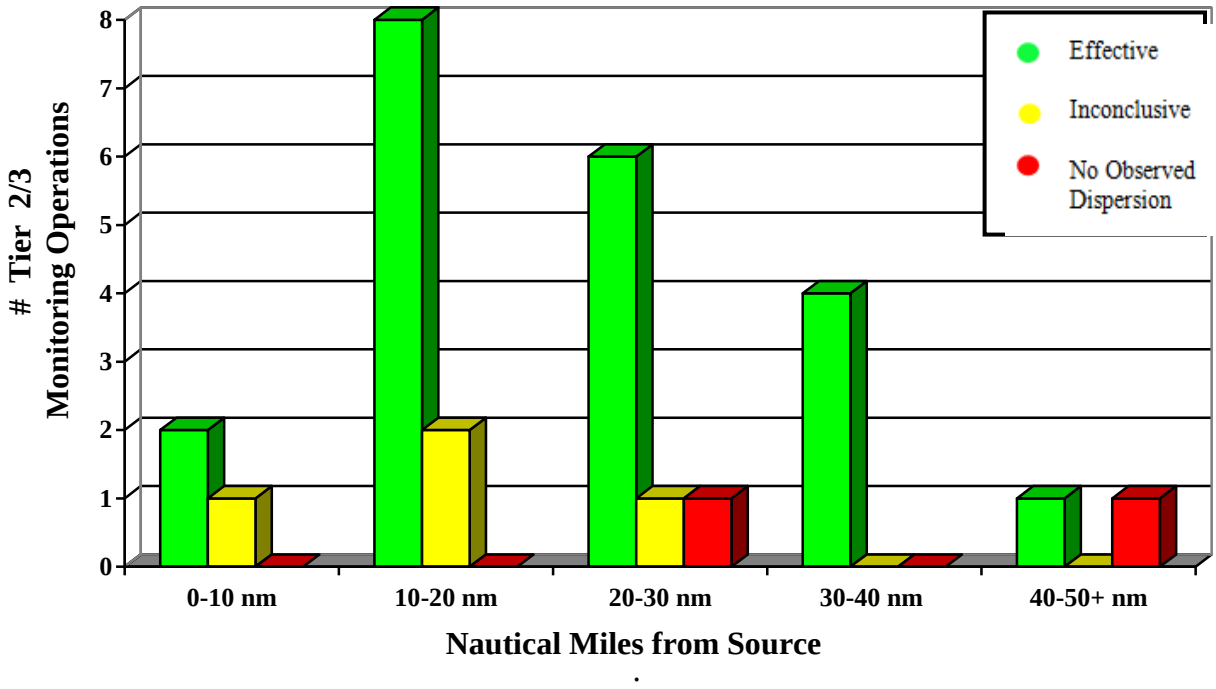
Wave Height 2.53 ft (0.77 m)
June 24, 2010 Dispersant Effective

The DWH response monitoring further proved that applying dispersants even to weathered/emulsified oil in low wave height conditions can be effective. This is shown in Figure 4 which groups the 27 low SWH dispersant operations and SMART Tier II/III monitoring by their distance from the spill source shown in Figure 1 in Appendix 1. After rising through at least 5,000 feet of water from its sub-sea release point to the sea surface and then traveling as far as 50 nm (92.6 km) from the source site, the Macondo crude oil was still dispersible. The dispersability of weathered Macondo crude oil was also confirmed by SINTEF which found

- As the distance from the spill source increased from 5 to 20 nm the slick samples showed increasing evaporative loss (44-50% by weight), water content (33-67%) and viscosity (1,350-7,200 mPas at 32^{o} C) and

- all of the weathered oil emulsions demonstrated good dispersibility using the SINTEF field kit effectiveness test with a Dispersant to Oil Ration (DOR) of 1:25[9]. It should be noted that this DOR is slightly less (~20%) than the application DOR used during the DWH response.

Figure 4
Effectiveness of Dispersant Applications in Low Significant Wave Heights At Various Distances from the Spill Source



Dispersant effectiveness in low SWH conditions was also revealed in photographs of surface dispersant application by vessels near the spill source. These dispersant applications were made for vapor suppression purposes to reduce responders' exposure to volatile organic

compounds (VOCs) and to facilitate on deck work. Because of the close proximity to multiple vessels and work activity near the source no SMART fluorometric data was able to be recorded. However, as shown in Figure 5a, nearly instantaneous dispersion occurred after spraying Corexit EC9500A neat (undiluted with water) at a dosage of 5 gpa applied by three fan spray nozzles in waves estimated to be < 1 ft (0.3m). The vessel is moving very slowly (<3 knots) towards the viewer, so dispersion is occurring on contact with the oil and not due to bow wave or propeller wash agitation. The oil being dispersed is the lighter tan areas (café au lait color) indicating an effective dispersant application.

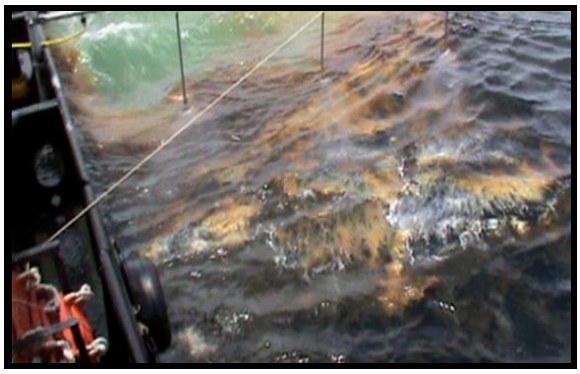


Figure 5a - Nearly instantaneous dispersion occurs after spray from a vessel at the spill source. (Data Buoy 42040 May 19, 2010 afternoon wind speed from 1.0-2.4 kts, significant wave height 0.5 - 1.0 ft)

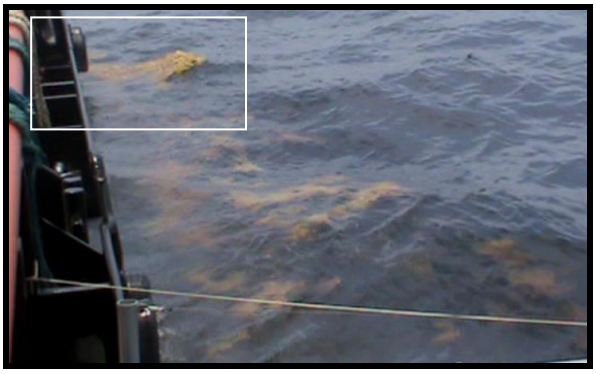


Figure 5b
Dispersion activated by small reflecting wave from vessel hull.

After spraying the Macondo crude oil near the spill source, small reflecting waves from the spray vessel's hull are shown in Figure 5b provided sufficient mixing energy for dispersion. (See the small breaking wave in the top left of the photograph inside the white box where the oil is dispersing.) This observation of very low wave height activation is supported by testing which verified that dispersant was effective on Macondo crude oil collected at the subsea source site in low energy wave conditions (~4 inch (0.10 m) waves) in a wave tank.[10]

Further support for the application of dispersants in calm sea conditions comes from research funded by the U.S. Minerals Management Service (now BOEM - Bureau of Ocean Engineering Management). Results from large scale wave tank tests at OHMSETT showed that if waves with a SWH of about 1.3 ft (40.5 cm) arise within 3-6 days after application of dispersant on a calm day, dispersion of the oil slick will occur without a reduction in effectiveness.[11] Unfortunately, SMART monitoring confirmation of these findings was not possible during the DWH response; however, anecdotal reports from mechanical recovery crews stated sometimes oil targeted for skimming operations would unexpectedly disperse upon approach by skimmers, booms, and/or boom towing vessels.

HOW DOES SETTING WAVE HEIGHT CRITERIA IMPACT DISPERSANT RESPONSE CAPABILITY?

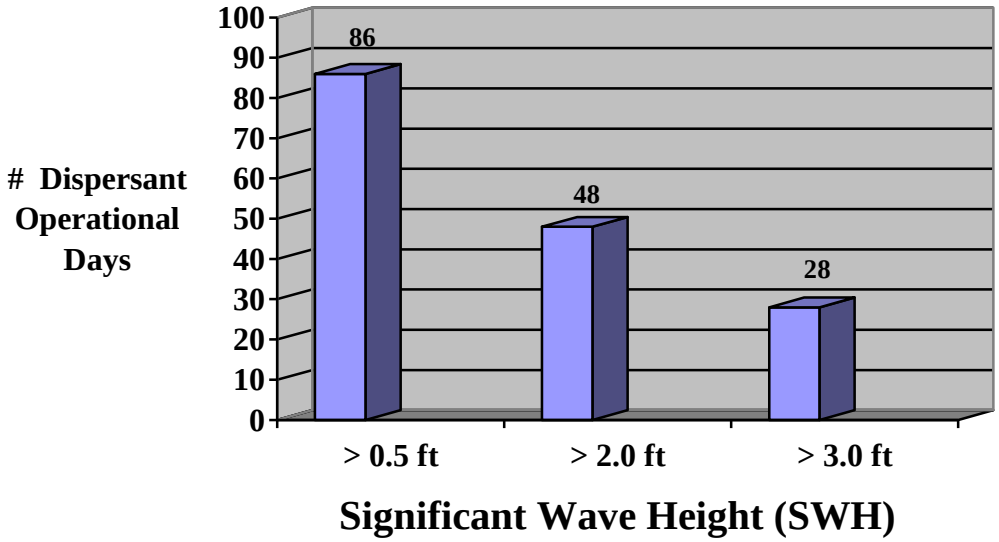
Setting criteria for a minimum wave height to commence aerial dispersant application greatly reduces the number of operational days when dispersant can be applied. During the DWH response, wave height criteria of > 3 feet, then > 2 feet and lastly > 0.5-1.0 feet were used

at different times to approve daily dispersant operations. To evaluate the influence of these varying criteria, Figure 6 shows the number of days when SWHs were recorded at 0550 each day for the three SWH criteria from April 25 to July 19, 2010, a total of 86 operational days.

- By requiring wave heights of greater than 0.5 ft surface dispersant operations could be conducted on 86 days or 100 % of the time as there were no recorded SWH of $\leq$ 0.5 ft recorded at 0550 in the morning or at any time during the cited response period.
- By requiring wave heights of greater than 2.0 feet, dispersant operational days would be reduced by 44% (from 86 to 48 days) as compared to the 0.5-1.0 ft criterion.
- By requiring wave heights of greater than 3.0 feet, the number of dispersant operational days would have been reduced by 67% (from 86 to 28 days) as compared to the 0.5-1.0 ft criteria.

Although these estimates are for a specific period of time, they should be representative of the likely impact on dispersant operational days if wave height restrictions are set. The number of days dispersant operations were grounded during DWH response due to wave height restrictions is less than the number shown in Figure 4 because the wave height restriction was gradually reduced over the course of the spill response to > 0.5 – 1.0 feet.

Figure 6 - Significant Wave Height versus # of Dispersant Operational Days
(Period 25 April 2013 to 19 July 2013)



Note: Significant wave height data was obtained at 0550 each day during the response from National Data Buoy 42040 located near the source of the DWH release.

The daily amount of Macondo crude oil that would not be dispersed, when aerial dispersant operations are grounded, can be estimated from the number and type of spray aircraft available. It is estimated that 12 spray aircraft consisting of C-130s, DC-3/4s and AT-802s available during DWH could apply more than 50,000 gallons of dispersant per day.

- This aerial operations capacity was actually reached on May 22, 2010, when 50,246 gallons of dispersant were applied using 11 spray aircraft.[1]
- If dispersant were applied at a dosage of 5 gpa (1:20 DOR) with an assumed 70% treatment effectiveness, then 50,000 gallon dispersant capability could disperse approximately 700,000 gallons (16,600 bbl) of oil per day. The amount is supported by calculation for the spray aircraft capability using the Dispersant Mission Planner 2 (DMP2) software available at the NOAA Office of Response and Restoration web site.

The inability to treat slicks on days with either SWH initially at <3 feet, or later at < 2 feet, resulted in missed opportunities to lessen the amount of oil remaining on the sea surface and increased the risk of exposure to shoreline habitat and offshore marine wildlife given the limited ability of other response tools to encounter significant quantities of oil once it has spread over a wide area.

CONCLUSIONS and RECOMMENDATIONS:

There has been little previous field data and response guidance to provide responders with information on wave heights appropriate for approving the application of dispersants. Setting a minimum wave height before dispersant operations commence and making the operational decision for an entire operational day based on early morning forecast and reports does not appropriately account for the low wave conditions which can be sufficient for dispersant activation, the rapidity with which wave heights can change with time and the research results which show that dispersants may remain effective for 3-6 days after being applied in calm conditions.

Analysis of SMART Tier II/III monitoring of aerial and vessel spraying operations during the DWH response documents that wave height should not be used as a criterion for approving or conducting surface dispersant operations because:

- significant wave heights (SWH) as low as 0.5-1.0 feet have been shown to be sufficient for dispersants to effectively disperse both fresh and weathered Macondo crude oil and may be sufficient to disperse other oils,
- research on dispersant application in calm sea conditions "showed that the oils would rapidly and almost totally disperse when exposed to breaking waves after being left on a calm water surface for prolonged periods (up to 6 days for IFO-30 fuel oil or nearly 3 days for Ewing Bank 873 crude oil.)"[11]

It is recommended that government and response organizations should review and consider revising their guidance and operational procedures for dispersant application approval in light of the analysis presented in this paper.

APPENDIX 1

SUMMARY OF DWH SMART TIER II/III MONITORING OF DISPERSANT APPLICATION DURING PERIODS OF LOW SIGNIFICANT WAVE HEIGHTS

Figure 1

Map of SMART Tier II/III Dispersant Monitoring Operation Site during Low Significant Wave Heights

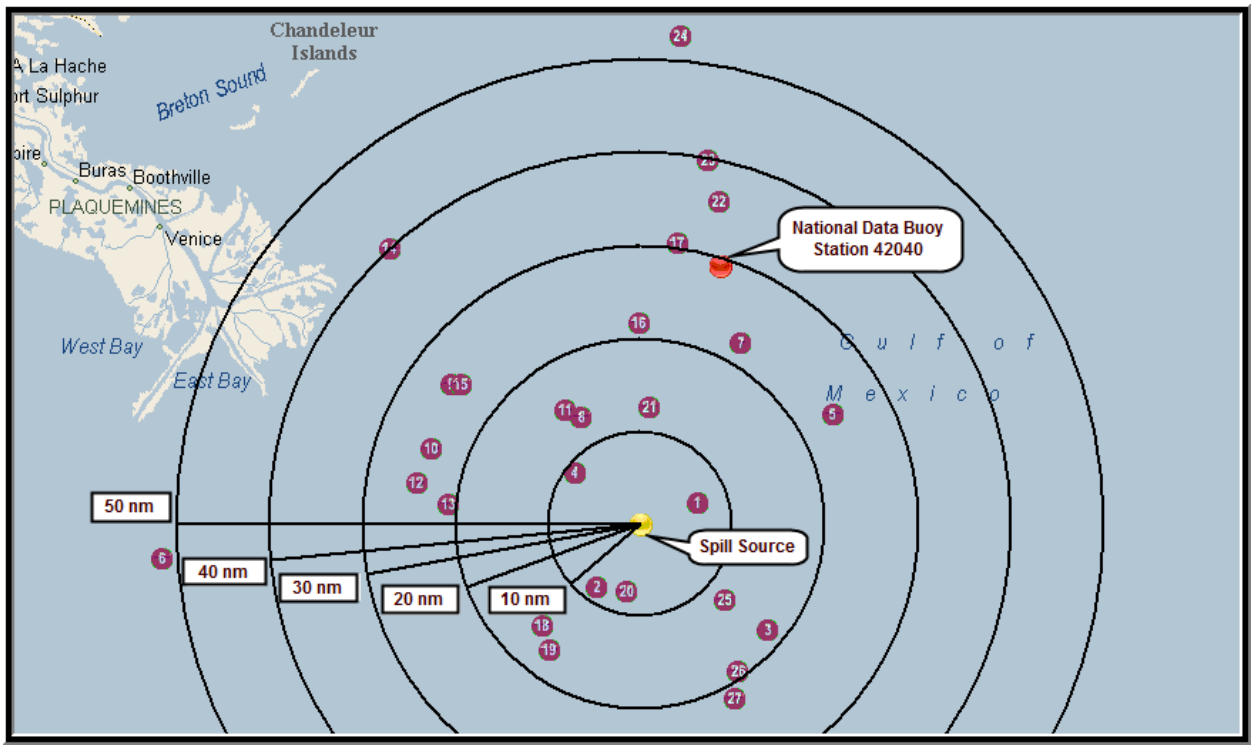


Table 1

Tier II/III Monitoring Operations in Significant Wave Heights (SWH) Less than 3 Feet

#	Date/ Time (CDT)	Latitude/ Longitude	Predicted SWH* (ft)	Recorded SWH** (ft)	Monitoring Results*** (1 meter)	Monitoring Time after Dispersant Applied	Dispersant Application Method	Distance From Source (nm)
1	4-27 1113	28°47.12' N 88°15.35' W	3.6	2.72	E	20 min	Aerial	6.4
2	5-05 1541	28° 38.13' N 88° 27.70' W	1.6	1.54	I/a	Data Not Available	Aerial	8.5
3	5-10 1122	28° 33.43' N 88° 06.75' W	2.9	2.76	I/a	54 min	Aerial	18.0
4	5-17 0928	28° 50.38' N 88° 30.25' W	2.2	2.36	E	23 min	Aerial	8.7
5	5-17 1518	28° 56.66' N 87° 58.67' W	2.1	2.00	E	34 min	Vessel	23.7
6	5-18 1916	28° 40.98' N 89° 20.89' W	1.1	0.95	E	21 min	Aerial	51.7
7	5-20 1736	29° 04.25' N 88° 09.97' W	2.1	1.18	E	10 min	Vessel	21.8
8	5-21 1651	28° 56.25' N 88° 29.65' W	1.8	1.61	I/a	26 min	Aerial	12.7
9	5-22 1110	28° 59.82' N 88° 45.65' W	2.8	2.26	E	17 min	Aerial	25.0
10	5-22 1416	28° 52.83' N 88°47.98' W	2.5	2.03	E	19 min	Aerial	23.7
11	5-23 1250	28° 57.01' N 88° 31.58' W	2.1	1.74	E	10 min	Vessel	14.3
12	5-23 1356	28° 49.27' N 88° 49.81' W	1.8	1.71	E	30 min	Aerial	24.5
13	5-25 1509	28° 46.99'N 88° 45.87'W	1.1	1.94	E	29 min	Aerial	20.9
14	5-27 1415	29° 14.30' N 88° 53.21' W	0.7	1.05	E	57 min	Aerial	39.7
15	5-28 1646	28° 59.82' N 88° 44.35' W	1.4	0.62	I/a	12 min	Aerial	24.3
16	6-13 1228	29° 06.48' N 88° 22.44' W	0.7	1.15	N/b	22 min	Aerial	21.1
17	6-17 1223	29° 14.95' N 88° 17.67' W	0.7	1.05	E	15 min	Vessel	30.0
18	6-18 1244	28° 33.97' N 88° 34.24' W	0.7	1.12	E	13 min	Vessel	15.4
19	6-18 1619	28° 31.34' N 88° 33.47' W	0.7	1.35	E	77 min	Aerial	17.1
20	6-21 1702	28° 37.69' N 88° 24.07' W	1.1	1.18	E	15 min	Vessel	7.5
21	6-22 1300	28° 57.45' N 88° 21.24' W	2.2	2.43	E	2 min	Vessel	12.4
22	6-24 1707	29° 19.51' N 88° 12.63' W	2.5	2.53	E	20 min	Vessel	35.6
23	6-26 1529	29° 23.86' N 88°14.05' W	2.8	2.43	E	9 min	Vessel	39.6

24	6-27 1202	29° 37.23' N 88° 17.29' W	3.2	2.92	N/c	10 min	Vessel	52.6
25	7-10 1324	28° 36.77' N 88° 11.91' W	1.8	2.23	E	6 min	Vessel	11.8
26	7-13 1130	28° 29.13' N 88° 10.48' W	2.5	2.07	E	2 min	Vessel	18.7
27	7-13 1559	28° 26.11' N 88° 10.80' W	2.4	1.94	E	21 min	Aerial	21.0

* Wilkins morning forecast weather report for the spill source site at the time of dispersant application

** National Weather Buoy Station 42040 recorded significant wave height at the time of dispersant application

*** N = No observed dispersion; I = Inconclusive; E = Effective

/a Inconclusive means that insufficient data was collected during the monitoring operation to make a determination on whether the dispersant was effective or no dispersion was observed.

/b The June 13th monitoring result was misidentified as inconclusive in reference 14. The June 13th poster presentation summarizing the analysis of this monitoring operation clearly states that the dispersant appears ineffective under these conditions.

/c The oil sprayed was described by the monitoring team as very weathered and emulsified and is the furthest distance from the source that was monitored.

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