The Use of Saildrones to Examine Spring Conditions in the Bering Sea: Instrument Comparisons, Sea Ice Meltwater and Yukon River Plume Studies

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Instrument Comparisons, Sea Ice Meltwater and Yukon River Plume Studies

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***Abstract*—New technologies can help scientists measure and understand Arctic warming, sea ice loss and ecosystem change. NOAA has worked with Saildrone, Inc., to develop an unmanned surface vehicle (USV)—Saildrone—to make ocean surface measurements autonomously, even in challenging high-latitude conditions. USVs augment traditional research ship cruises, mitigate ship risk in high seas and shallow water, and make lower cost measurements. Under remote control, USV sampling strategy can be adapted to meet changing needs. Two Saildrones conducted 97-day missions in the Bering Sea in spring-summer 2015, reliably measuring atmospheric and oceanic parameters. Measurements were validated against shipboard values. Following that, the Saildrone sampling strategies were modified, first to measure the effects of sea-ice melt on surface cooling and freshening, and then to study the Yukon River plume.**

Keywords—Saildrone; Unmanned Surface Vehicle; USV; Autonomous sampling; Arctic; Bering Sea

I. Introduction

In 2014 and 2015 the eastern Bering Sea, home of America's most productive fishery, shifted to warmer conditions after a prolonged period (2007-2013) of cold years. North of ~60˚N, winters are sufficiently dark and cold such that sea ice formation is an annual occurrence [1]. Spring ice melt and retreat results in a fresher surface layer that stabilizes the water column and generally persists through the summer. In the south, ice retreat is earlier allowing spring storms to mix the water column to give higher surface salinities than in the north [1]. In addition, ice thickness and extent are more variable. In cold years, the Aleutian Low centered in the Gulf of Alaska blows northeasterly winter winds off the cold Alaskan mainland, freezing the ocean and pushing sea ice offshore where it melts and cools the water [2]. In warm years, the Aleutian Low centered over the Bering Sea blows southeasterly winds off the warmer ocean basin, and ice formation is minimal [2]. This ice variability can affect biological processes. During the last phase of warm conditions (2000–2005), zooplankton populations collapsed and were followed by a dramatic decline in pollock abundance, one of the largest single-species fisheries in the United States [3]. While long-term ship-based and mooring measurements exist in the eastern Bering Sea, there have been no studies utilizing autonomous vehicles capable of sampling the harsh environment, especially the critically important sea-surface conditions in early spring.

NOAA's Pacific Marine Environmental Laboratory (PMEL) partnered with the University of Washington Joint Institute for the Study of Atmosphere and Ocean (JISAO) and the University of Alaska Fairbanks Cooperative Institute for Alaska Research to form the Innovative Technology for Arctic Exploration (ITAE) research program [4]. That program has worked with Saildrone, Inc., to develop an unmanned surface vehicle (USV)—the Saildrone (Fig. 1)—to study ocean conditions in the Arctic [4]. We report on the first Saildrone scientific mission.

Fig. 1. Saildrone sd-126 after launch at Dutch Harbor, AK. Photo: Saildrone, Inc.

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II. METHODS

Two Saildrone USVs (sd-126 and sd-128) were launched dockside at Dutch Harbor, AK, in the Bering Sea on 23-24 April 2015 and returned on 28 July 2015 (Fig. 1) [5]. As with a conventional sailboat, each 5.8-m-long Saildrone hull with twin outriggers was propelled by the wind acting on a 4-m-high wing with sideways forces balanced by a 2-m-deep keel. Solar cells and batteries provided electrical power. The Saildrone course was specified and updated remotely via Iridium satellite as a series of waypoints and maximum corridor widths within which the Saildrone sailed autonomously. During each Saildrone's 97-day, 7800-km Bering Sea mission, it measured vehicle position and attitude, incoming photosynthetically active solar radiation (PAR), barometric pressure, wind speed and direction, air temperature, and relative humidity. In the water each measured ocean skin temperature, water temperature, salinity, dissolved oxygen concentration, magnetic field strength, red-light backscatter, and chlorophyll-a and colored dissolved organic matter (CDOM) fluorescence [5]. One-minute data were transmitted ashore via satellite and e-mailed every 6 hours with higher-frequency data stored aboard for later retrieval. All results presented here are from the transmitted data. Saildrone, Inc., also provided an on-line user interface with time-series plots, maps and data downloading capability for each sensor, along with periodic views of the sea surface and vehicle from four cameras.

III. RESULTS

The Saildrone mission had several goals: (A) to test the Saildrones' ability to operate in the harsh Bering Sea environment and make atmospheric and oceanic measurements; (B) to compare Saildrone to shipboard and oceanographic mooring measurements in side-by-side tests; (C) to measure the oceanographic fields on the eastern Bering Sea continental shelf following sea ice melting; and (D) to measure the properties of the Yukon River plume soon after river ice break-up. All four goals were accomplished.

A. Bering Sea Operations

Both Saildrones completed their missions. Fig. 2 shows the track for sd-128, color-coded by the wind speed, on its outgoing course from Dutch Harbor to Nome. The Saildrones measured winds in excess of 20 kn several times with maximum sustained gusts of 46 kn. The average Saildrone speed for sd-128 was 1.9 kn with a peak speed of 7.2 kn [5]. The only structural mishap during the mission occurred a few days in when a control actuator broke on sd-126, but it was able to sail unassisted into the Pribilof Islands for a brief repair. Sd-128 was turned back to Dutch Harbor to replace the same part that had been redesigned, and then it returned to service [5].

All of the scientific instruments worked on sd-126. On sd-128 there were two unrelated instrument failures. The wind

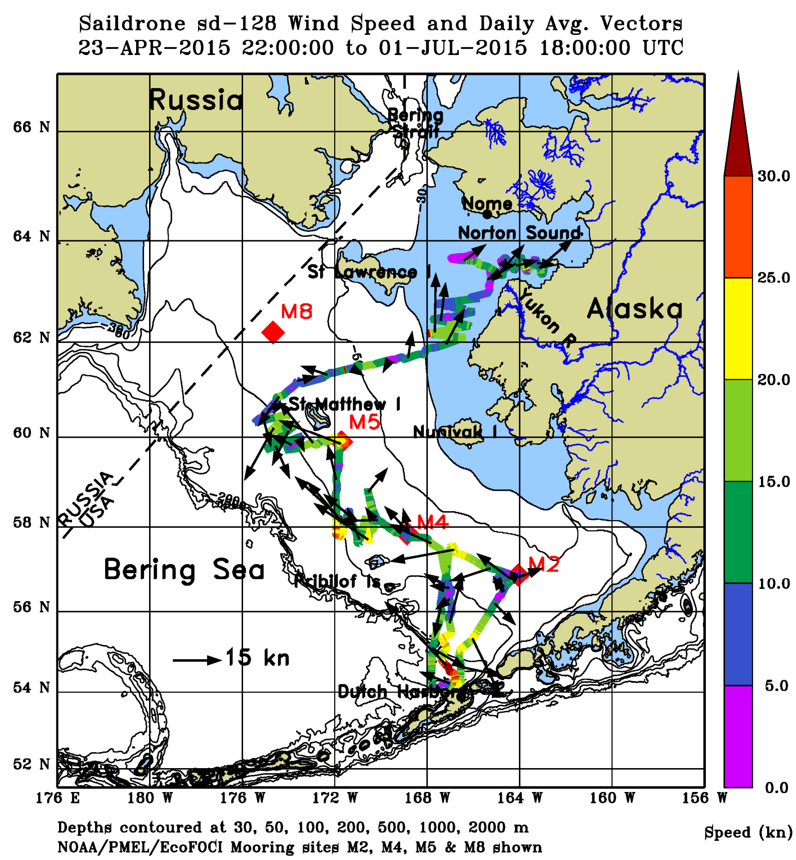

Fig. 2. Map of Saildrone sd-128 track on the eastern Bering Sea continental shelf during its outbound mission, 23 April–1 July 2015. The wind speed is color-coded along the track at 1-minute intervals, and the daily averaged wind vectors are shown. Red diamonds depict the locations of PMEL long-term oceanographic moorings.

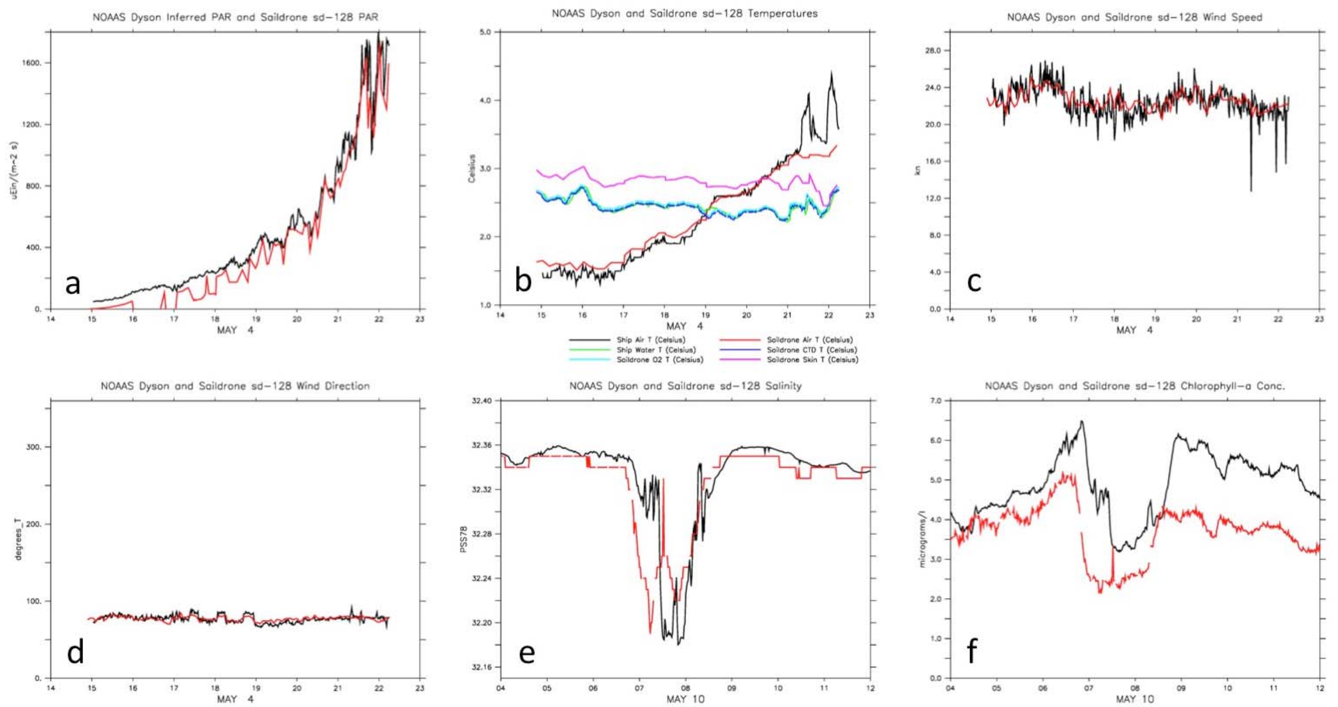

Fig. 3. Time series of ship-to-Saildrone comparisons. Ship values (usually black curves) are plotted every minute, and Saildrone values (usually red curves) are plotted every 10 minutes in (a)–(d) and every minute in (e)–(f). (a) PAR, (b) air temperature (ship: black, Saildrone: red), water temperature (ship: green, Saildrone: blue and cyan), and skin temperature (Saildrone: magenta), (c) wind speed, (d) wind direction (from), (e) salinity, and (f) chlorophyll-a concentration.

sensor cable suffered a fatigue failure due to inadequate securing, and the magnetic field sensor failed—both around 70 days into the mission near its northernmost extent. As originally planned, this would have been near the mission's end in Nome, AK. However, owing to difficult boat handling there and expensive shipping costs, we decided to sail the Saildrones 1200 km back to Dutch Harbor for retrieval, showing the confidence we had in them. The instrument failures had little impact on the scientific mission because they occurred near the end, and the second Saildrone carried the same instruments.

B. *Ship-to-Saildrone Comparisons*

Since this was the Saildrones' first scientific mission it was important to compare their results with standard shipboard measurements. Saildrone sd-128 rendezvoused with NOAA ship *Oscar Dyson* three times between 1 and 10 May 2015 for instrument comparisons. Figs. 3a-d show the comparisons for PAR, temperature, and wind speed and direction on 4 May when the PAR and temperature dynamic ranges and the wind speed were largest. The two vessels sailed rectangular courses of 9–22 km on a side with ship-to-Saildrone separation distances of 200–800 m. This put the Saildrone on four different tacks with varying speeds. In most plots, black curves represent ship observations and red curves Saildrone. *Dyson* measured the full spectrum of short-wave solar radiation; whereas Saildrone measured only PAR in the 400–700 nm range. The full spectrum was converted to PAR [6] and plotted in Fig. 3a. There is good relative agreement with an rms difference of 128 μEin/(m^2 s) between the two measurements that cover the time span from darkness (15:00 UTC=04:00 LT) to near local noon (22:15 UTC=11:15 LT). Notice in particular peaks at about 21:30 and 22:00 UTC detected by both sensors. Fig. 3b compares the air temperatures for both platforms that agree well (rms difference = 0.10˚C) until the times of the twin solar peaks that are mirrored in ship air temperature (black), but not the Saildrone's (red). The ship (green) and Saildrone (blue and cyan from two sensors) water temperatures agree (rms difference = 0.042˚C). The water was warmer than the air at the beginning of the comparison implying atmospheric instability, but as the day progressed the air became warmer than the water implying stability. The twin air temperature peaks at the ship sensor at 17 m were not detected at the Saildrone much nearer the water at 2.2 m under stably stratified atmospheric conditions. The relative humidity (not plotted) was about 3.2% higher nearer the water, also adding to the stability. The Saildrone barometric pressure (not plotted) exceeded the ship value with an rms difference of 0.18 hPa.

Figs. 3c-d show the wind speed and direction comparisons during winds exceeding 20 kn. Both measurements (at 17 m for *Dyson* and 4.5 m for Saildrone) were adjusted to a standard 10 m reference height using a logarithmic profile and a mixing length of 0.0005 m appropriate for oceanic conditions [7]. Relative agreement is good with an rms wind speed difference of 1.2 kn and an rms direction difference of 3.8 degrees.

Figs. 3e-f show the salinity and chlorophyll-a concentrations during the third inter-comparison (ship measurements at 2.5 m, Saildrone measurements at 0.5 and 0.2 m, respectively) on 10 May when these variables had their greatest dynamic ranges.

The Saildrone entered a lens of fresher water with a corresponding decrease in chlorophyll-a concentration a few minutes before *Dyson*. The salinities agree with an rms difference of 0.01 (PSS78) outside of the strong salinity gradient region. The chlorophyll-a concentrations have an rms difference of 1.1 mg/l in the same region. Chlorophyll-a concentrations determined from fluorometers factory-calibrated against freshwater plankton species, such as these, have less absolute accuracy than those calibrated against local phytoplankton populations.

Saildrones sd-126 and sd-128 were cross-compared on three occasions, and the differences between them were similar to those between sd-128 and NOAAS *Oscar Dyson*. The Saildrones executed several circuits around PMEL long-term oceanographic moorings M2, M4 and M5 (Fig. 2) for inter-comparisons. Those instruments were still at sea, and the data were not available for this manuscript.

C. Oceanography of Sea Ice Melt Regions

The autonomous Saildrones provided tools for studying the effect of sea ice on the Bering Sea shelf. Sea ice melting and wind mixing alter the ocean's surface temperature, salinity, density stratification and mixed layer depth that is critical plankton habitat. Fig. 4 shows the near-surface salinity along the combined Saildrone tracks. The sea ice concentration was monitored from satellite data, and the Saildrones did not enter areas of greater than 1% ice concentration to avoid hull damage. South of ~58˚N little sea ice formed in 2015, and that which did quickly melted. Any melt water was mixed with deeper water by winds, giving salinities above 31.5 (PSS78). To the north, sea ice was thicker and more persistent. When it melted back, a lens of fresher water remained as shown by salinity less than 31.5 in the vicinity of St. Matthew Island. The 31.5 isohaline is a convenient marker for the melt-water edge [8], and the Saildrones were programmed to sail a sawtooth course to detect that boundary (Fig. 4). The winter wind cools seawater to about –1.8˚C in polynyas downwind of coastlines and islands and pushes ice seaward. Melting ice cools seawater in areas where ice was not produced. Fig. 5 shows remnant cold water below 2˚C (the Cold Pool [9]) corresponding to salinities below 31.5 in the vicinity of St. Matthew Island and south through mid-June. After then, solar heating warmed the surface waters, and cold water owing to melting ice was no longer detectable at the surface; however, it persists in deeper layers [9]. Lower surface salinity remained as an indication of where the ice had been.

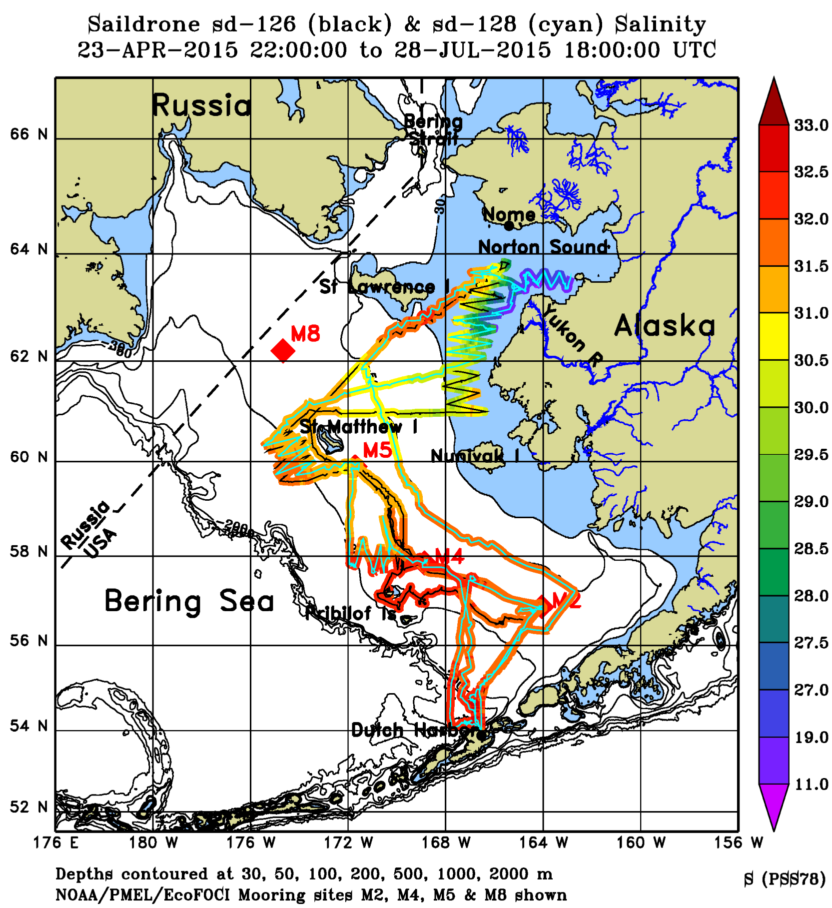

Fig. 4. Map of color-coded salinity at 1.5 m along Saildrone sd-126 (black center line) and sd-128 (cyan center line) tracks on the eastern Bering Sea continental shelf during 23 April to 28 July 2015.

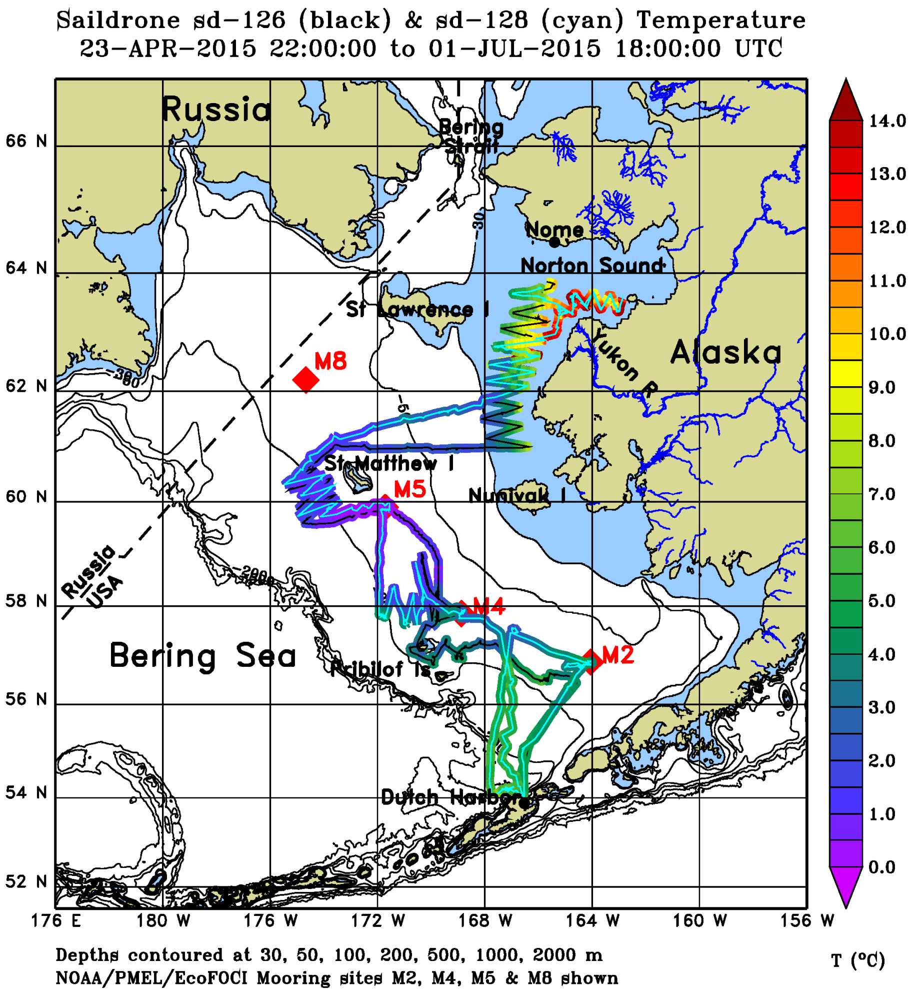

Fig. 5. Map of color-coded water temperature at 1.5 m along Saildrone sd-126 (black center line) and sd-128 (cyan center line) tracks on the eastern Bering Sea continental shelf during the outbound mission, 23 April to 1 July 2015.

D. Oceanography of the Yukon River Plume

After measuring the effects of sea ice melt, the Saildrones were directed northeastward to study the Yukon River plume. The two Saildrones were instructed to reach the coast at 61˚N and 62˚N, respectively, and sail a sawtooth course northward. The river ice broke up in mid-May [10], and a pulse of fresh water carrying organic matter (detectable as CDOM or "yellow substance") from the vast Yukon River watershed entered the Alaskan coastal waters and Norton Sound (Figs. 4 and 6). CDOM was detected there, but nowhere else on the shelf (Fig. 6), creating a clear marker for the plume waters. The water warmed on its journey and entered the Bering warmer than the ocean (Fig. 5). Saildrone sd-128 mapped the fresh (S<31), warm (T>6˚C), yellow (CDOM>20 ppb) water past the Yukon's mouth into Norton Sound in bottom depths of only a few meters. After the Yukon River plume study, the Saildrones were directed 1200 km back to Dutch Harbor. Both Saildrones passed southeast of St. Lawrence Island where they detected salty Anadyr Water (S>31.5, Fig. 4) that originates to the west and ultimately flows into Bering Strait [11][12]. They sailed south along the 70 m isobath at midshelf (sd-126) and the 50 m isobath (sd-128) that marks the boundary between the two-layer middle shelf and the vertically mixed inner shelf (Fig. 4).

IV. Conclusions

The Saildrones performed reliably in the harsh Bering Sea environment. Comparisons with shipboard measurements showed good agreement, inspiring confidence in these new instrument platforms. Using these unmanned surface vehicles, scientists directed months of sampling in real time to measure the changing ocean conditions of moving, melting sea ice and freshwater pulses from the Yukon River. The freshening effects of ice melt were measured from ~58˚N to St. Matthew Island. The Saildrones observed the Yukon River plume extending into the shallow waters of Norton Sound. Future Saildrone missions will carry hydroacoustic sounders to augment NOAA's biennial census of Bering Sea fish stocks and venture into the Arctic Ocean.

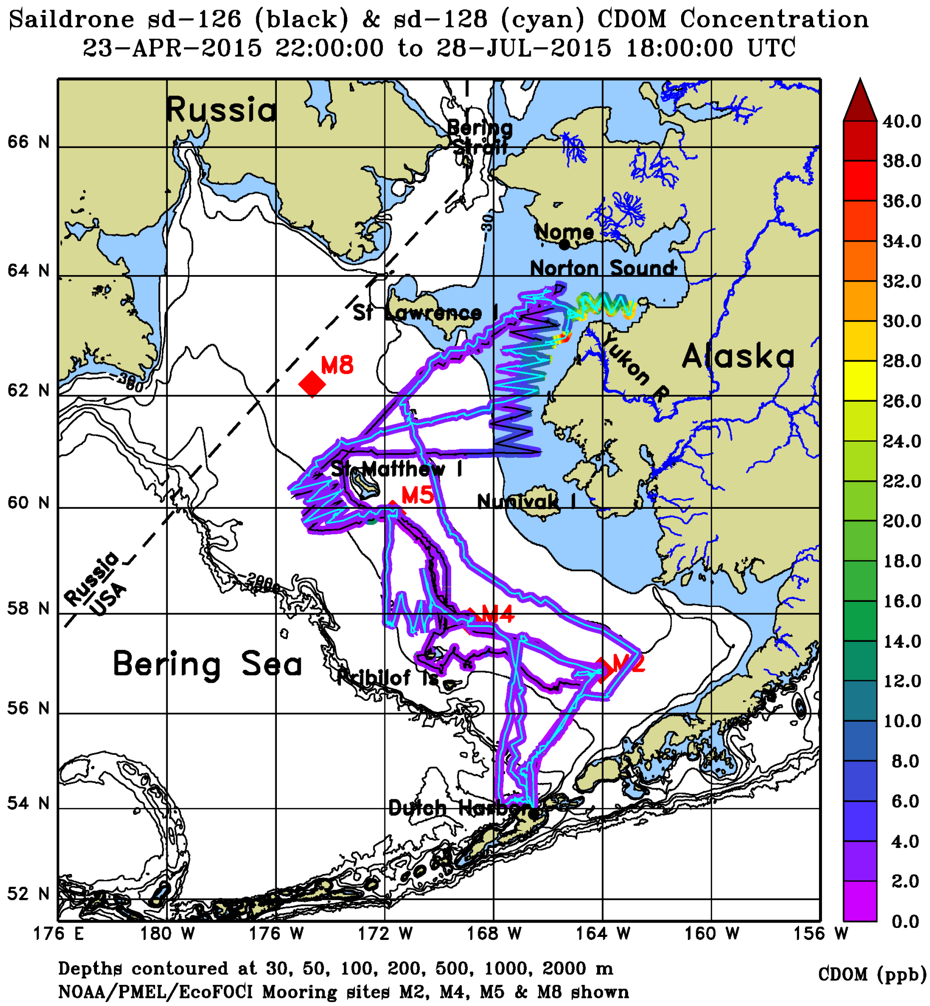

Fig. 6. Map of color-coded CDOM at 1.5 m along Saildrone sd-126 (black center line) and sd-128 (cyan center line) tracks on the eastern Bering Sea continental shelf during 23 April to 28 July 2015.

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