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Physical, Chemical, and Biological Conditions during *Noctiluca* Blooms in an Urban Fjord, Puget Sound

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Introduction

Puget Sound is a deep urban fjord in the state of Washington, USA, with major population centers along its shores and freshwater inputs from several major rivers. Puget Sound's water quality has shown long term increases in nutrients, and excessive phytoplankton blooms in response to human influences have been well documented. Near the surface, human influences and ecosystem responses to human pressures are most visible.

As a time-efficient and cost-effective means of measuring a large area of the water surface, ferry-based monitoring with the *Victoria Clipper IV* began in 2010. Monthly aerial photography of the water surface began in 2011. We analyzed data from ferry routes, complemented with data from monthly water column stations and aerial photographs that document blooms. The importance and impact of *Noctiluca* as indicator for Puget Sound's water quality is explored for the spring and summer of 2011, 2012, and 2015.

Noctiluca blooms have been observed in Puget Sound as an "orange tide" since at least 1946. *Noctiluca* is a heterotrophic dinoflagellate that blooms into orange-red, tomato soup colors in late spring to early summer. Its appearance in large blooms is a potential indicator of eutrophication in coastal environments (Vasas et al. 2007). North of Puget Sound in the San Juan Islands, more *Noctiluca* were observed in 2010-2011 than in 1996-1997 (Runnells 2014). Recent large blooms of *Noctiluca* in Puget Sound suggest an overall increase of the species. *Noctiluca* grazes on diatoms and excretes ammonium into the water (Faust and Gulledge 2002, Vasas et al. 2007). Our data suggest that *Noctiluca* grazes on phytoplankton whose population then diminishes, and this is seen by temporary regional declines in chlorophyll in Puget Sound associated with *Noctiluca* blooms.

When *Noctiluca* is starved, its cell volume increases which then gives the dinoflagellate increased buoyancy (Tada et al. 2000). Higher buoyancy in cells brings *Noctiluca* to the water surface, where they accumulate and, thus, creates visible orange tides. We examine possible conditions that contribute to *Noctiluca* blooms.

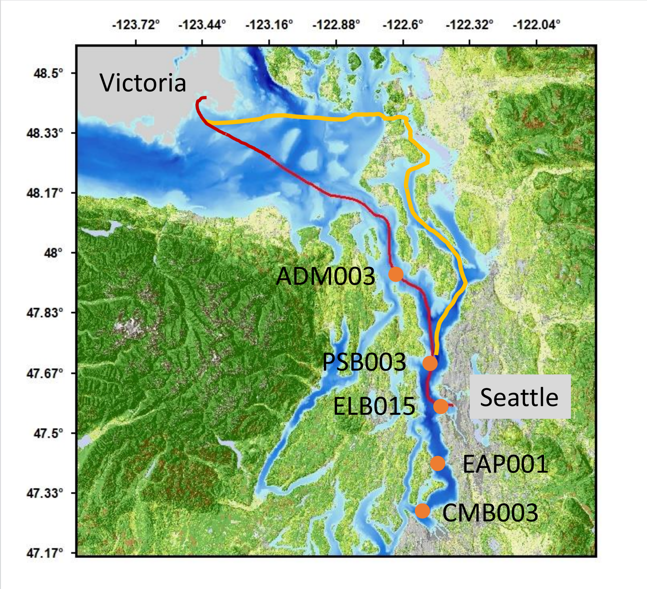

Figure 1. *Victoria Clipper IV* ferry routes and selected monthly water column stations. Orange dots are water column stations. Red line represents regular ferry route. Yellow line represents alternate route used in poor weather conditions.

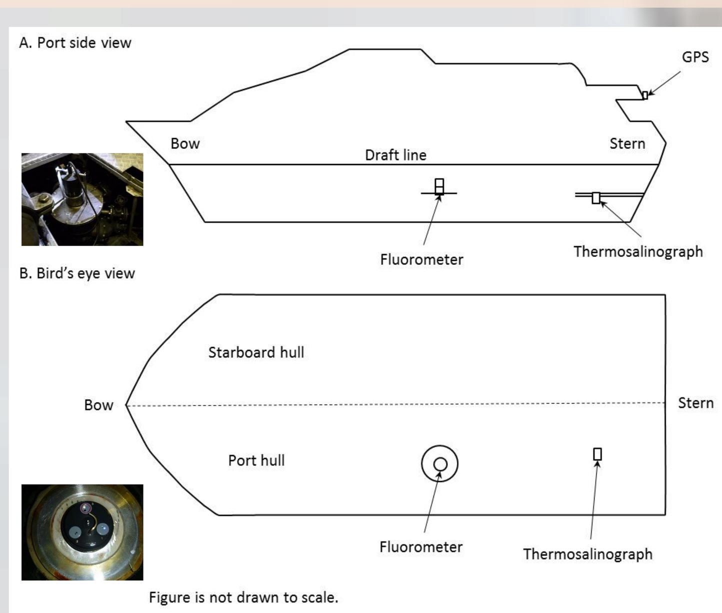

Figure 2. Fluorometer is installed through a modified sea chest cover. Optical lenses measure: 1) chlorophyll, 2) turbidity, and 3) CDOM.

Methods

Ferry-based Monitoring

- The ferry transits ~80 mi between Seattle, WA and Victoria, B.C., Canada (Fig. 1).
- An optical fluorometer is installed in the vessel's port engine room and measures temperature, chlorophyll fluorescence, turbidity, and CDOM at 5-sec intervals (Fig. 2).
- Data are geo-referenced with a GPS located above the stern deck (Fig. 2).

Data Reduction

- The large, high-frequency ferry data set was reduced to between April and August and to regular routes between Admiralty Sill (~48.2 °N) and Seattle (~47.6 °N).
- Raw chlorophyll fluorescence was converted to concentrations using ratios of extracted chlorophyll samples and optical fluorescence.

Data Analysis

- To compare continuous data with monthly discrete samples, we selected five water column stations with data on chlorophyll *a* and ammonium at 0, 10, and 30 m (Fig. 1).
- Median chlorophyll *a* concentrations and ammonium were compared against a baseline from 1999 to 2014.
- Fluorescence data are plotted over time and space.
- Resulting plots are used to identify regionally decreased chlorophyll fluorescence as an indicator of increasing *Noctiluca* blooms in spring or early summer, and they are verified by aerial photographs.

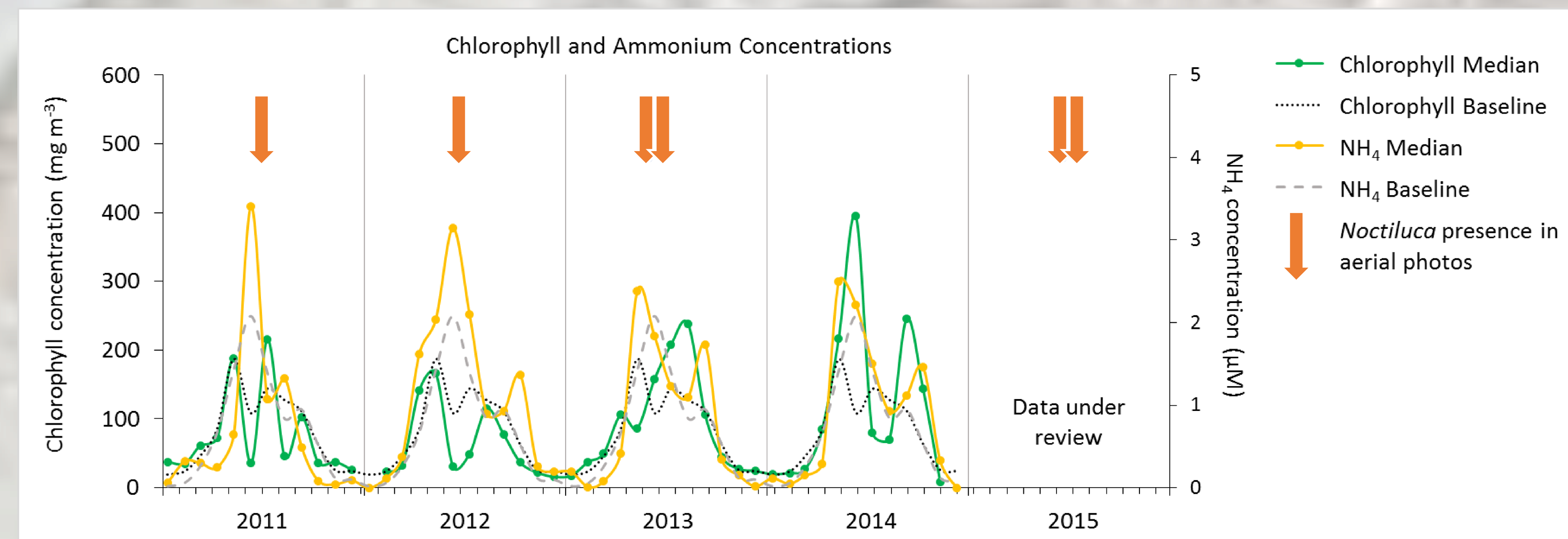

Figure 3. Median and baseline data are from discrete samples at five monthly sampled stations. Sampling depths are 0, 10, and 30 m. Baseline data are from 1999 to 2014.

Results and Discussion

- *Noctiluca* blooms coincided with high levels of ammonium and low chlorophyll concentrations in the water column (Fig. 3).
- Chlorophyll trends in water column samples coincide with similar trends in optical measurements (Figs. 4-6).
- *Noctiluca* blooms appear to occur between 10 and 13 °C, but their surfacing seem disconnected from the effect of temperature.
- *Noctiluca* blooms coincided with regionally low chlorophyll measured by the optical fluorometer and, thus, confirm the strong grazing impact of the species on phytoplankton.
  - *Noctiluca* blooms (albeit low chlorophyll) appeared stronger in 2011 than in 2012 and 2015 (Figs. 4-6).
  - *Noctiluca* blooms were also confirmed by other researchers in King County in 2012 (Hannach and Stark 2013) and in the vicinity of the ferry route in 2014 (Keister et al. 2015).
  - Near the ferry route north of Seattle, ORCA Point Wells moored profiler also measured low chlorophyll at 3-m depth in June and July 2011 and early July 2015 (data courtesy of Wendi Ruef, APL-UW).
- Chlorophyll fluorescence was high during late spring, mid-summer, and late summer when *Noctiluca* was not present (Figs. 4-6).
- Optical turbidity and colored dissolved organic matter (CDOM) did not reveal apparent patterns when compared to chlorophyll fluorescence patterns or *Noctiluca* blooms.

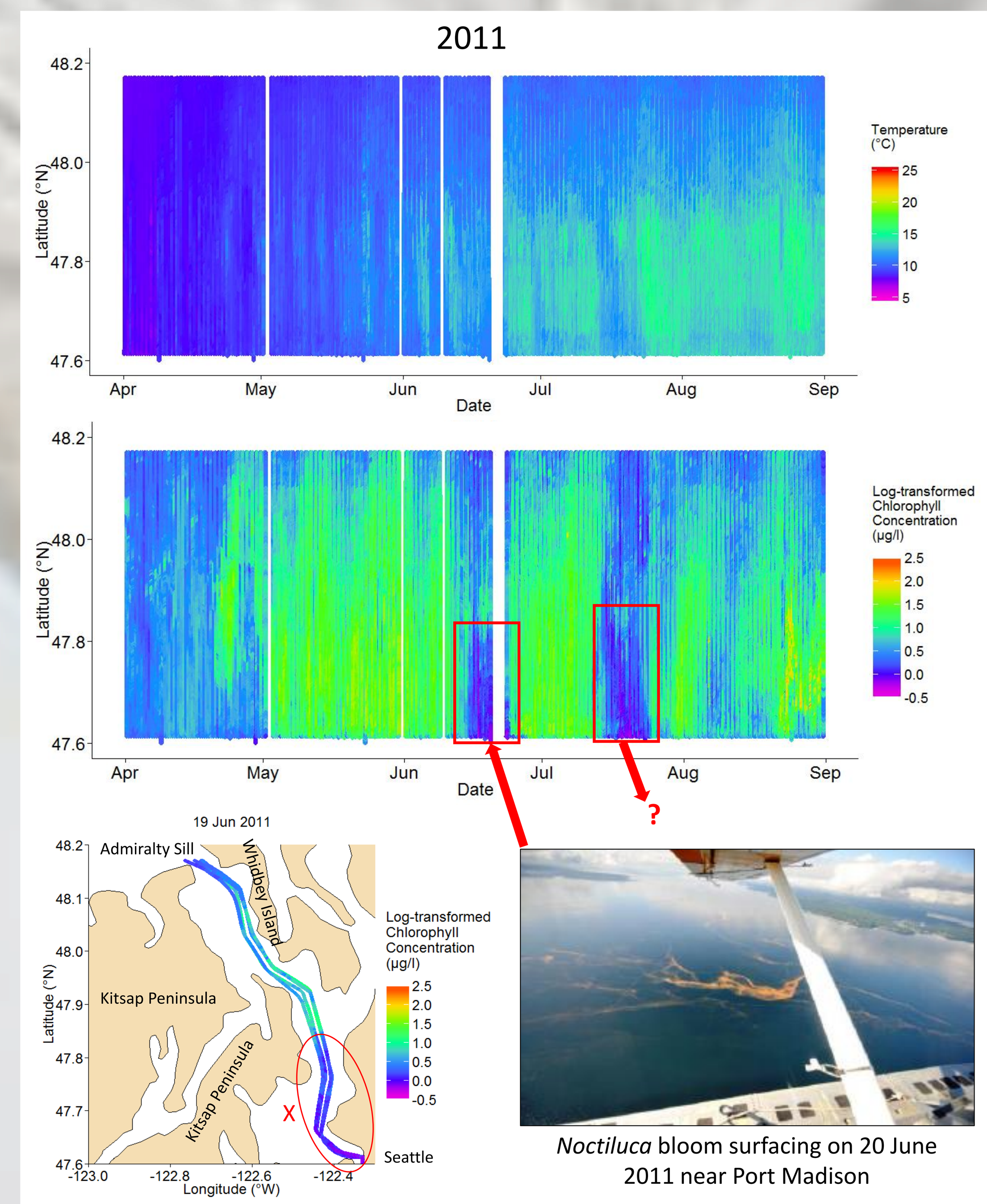

Figure 4. Cooling water temperature somewhat coincided with low chlorophyll in June and July. Low chlorophyll coincided with *Noctiluca* blooms in June as verified by photography. Low chlorophyll occurred again in late July, but could not be confirmed during the monthly aerial photography which occurred earlier on 6 July 11. X = location of *Noctiluca* bloom.

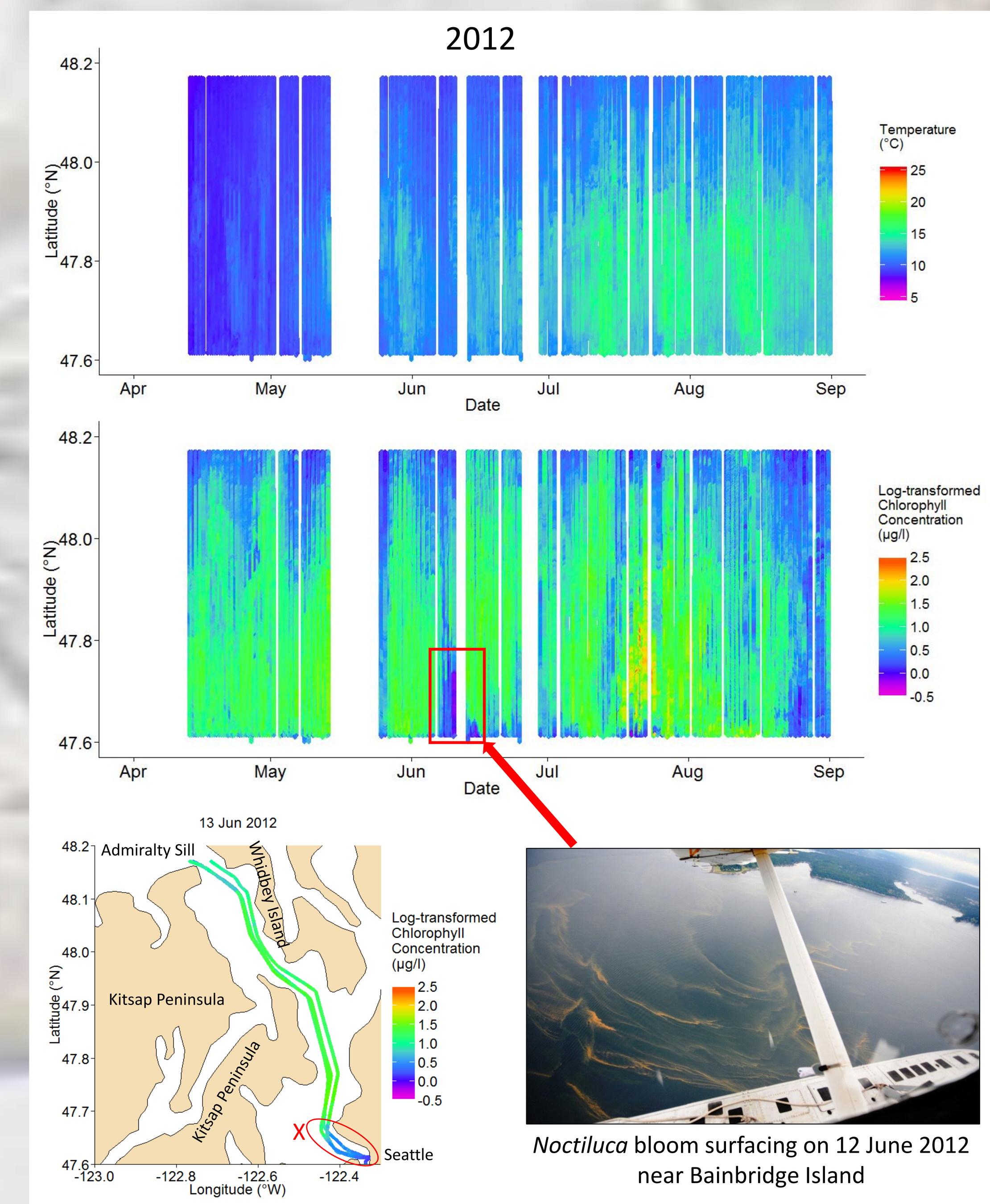

Figure 5. Cooling water temperature somewhat coincided with low chlorophyll in June. Low chlorophyll coincided with *Noctiluca* blooms in June as verified by photography. X = location of *Noctiluca* bloom.

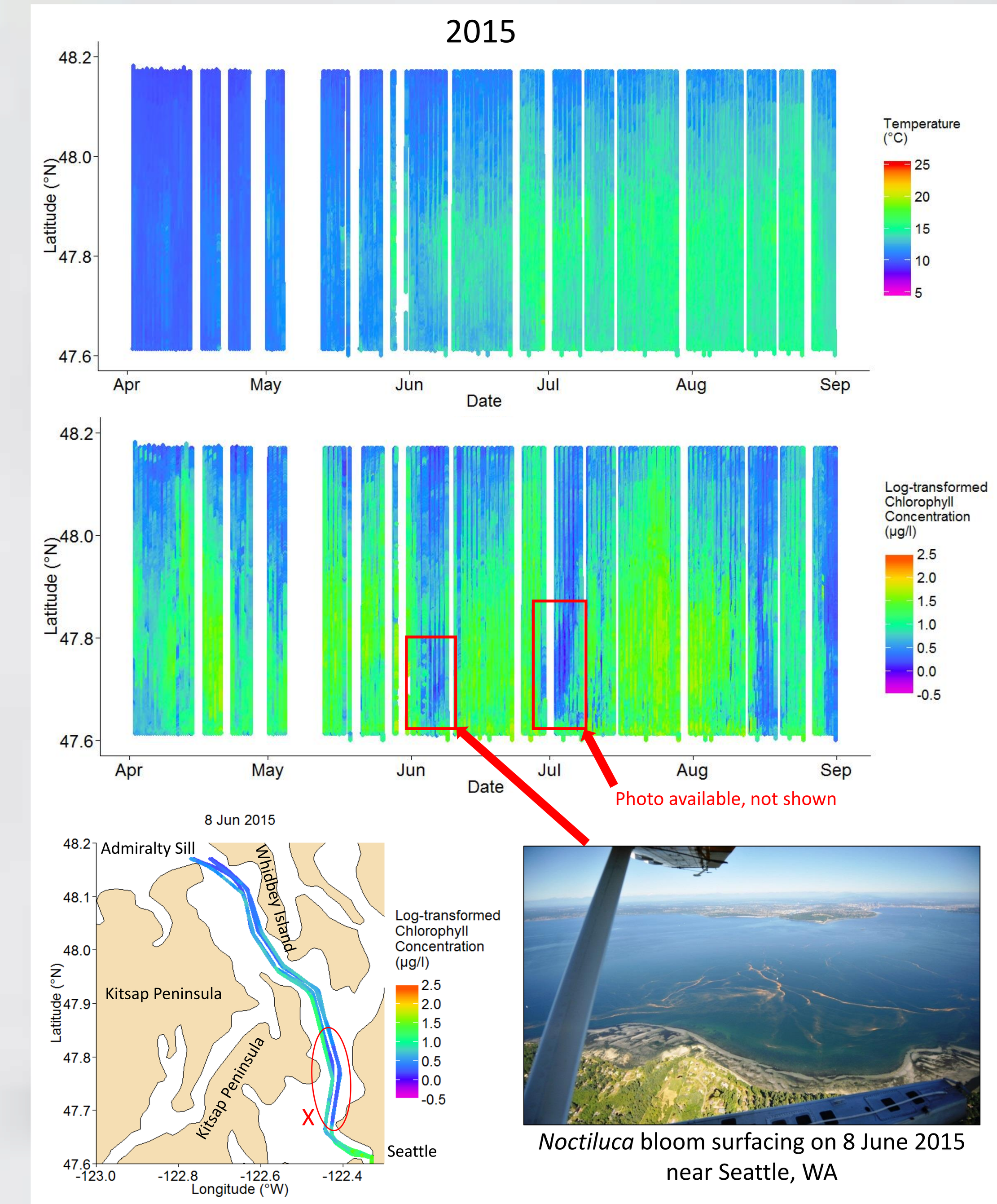

Figure 6. Unlike 2011 and 2012, cooling water temperature did not appear to coincide with low chlorophyll. Low chlorophyll coincided with *Noctiluca* blooms in June and early July as verified by photography; only June photograph is shown. X = location of *Noctiluca* bloom.

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Acknowledgments

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