Atlas of Oceanographic Conditions in the Strait of Georgia (2015-2019) based on the Pacific Salmon Foundation's Citizen Science Dataset

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Abstract

Pawlowicz, R., Suzuki, T., Chappell, R., Ta, A., and Esenkulova, S., 2020. Atlas of Oceanographic Conditions in the Strait of Georgia (2015–2019) based on the Pacific Salmon Foundation's Citizen Science Dataset. Can. Tech. Rep. Fish. Aquat. Sci. 3374: vii + 116 p.

Although the general characteristics of conditions in the Strait of Georgia, Canada, are reasonably well known, the precise details of how and when oceanographic conditions vary from place to place within the entire strait have been largely undescribed, because of the difficulties and cost of sustained data acquisition in the ocean. The Pacific Salmon Foundation (PSF) Citizen Science program addressed this lack of data during the Salish Sea Marine Survival Program by taking advantage of the time, interest, and experience of local residents around the strait to gather a comprehensive set of data about oceanographic conditions over a multi-year timescale. As many as ten patrols have sampled 80 stations about 20 times a year for a variety of parameters since 2015.

This atlas uses the first five years of this dataset to characterize conditions in the strait and its various subregions, from the spring through the fall, over the years 2015-2019. Average conditions, as well as regional and interannual variations in temperature, salinity, dissolved oxygen, chlorophyll biomass, nutrients, and the presence and absence of a variety of harmful algae, are discussed.

Résumé

Pawlowicz, R., Suzuki, T., Chappell, R., Ta, A., and Esenkulova, S., 2020. Atlas of Oceanographic Conditions in the Strait of Georgia (2015–2019) based on the Pacific Salmon Foundation's Citizen Science Dataset. Can. Tech. Rep. Fish. Aquat. Sci. 3374 : vii + 116 p.

Bien que les caractéristiques générales des conditions dans le détroit de Géorgie, au Canada, sont assez bien connues, les détails précis de quand et comment les conditions océanographiques varient d'un lieu à l'autre dans le détroit restent encore en grande partie indéterminés, à cause des difficultés et du coût associés à l'acquisition prolongée des données dans l'océan. Le programme Citizen Science, dirigé par le Pacific Salmon Foundation (PSF) durant le Salish Sea Marine Survival Project, a répondu à ce manque d'information en profitant du temps, de l'intérêt, et de l'expérience des résidents locaux pour recueillir un ensemble de données compréhensives des conditions océanographiques à l'échelon pluriannuel. Dix patrouilles ont prélevé des échantillons à 80 positions environ 20 fois par année pour plusieurs paramètres depuis 2015.

Cet atlas utilise les premières cinq années de cet ensemble de données pour caractériser les conditions dans le détroit et ses nombreuses sous-régions, dès le printemps jusqu'à l'automne, pour les années 2015 à 2019. Les conditions moyennes, ainsi que les variations régionales et interannuelles en température, salinité, oxygène dissous, biomasse de chlorophylle, et nutriments, ainsi que la présence et l'absence d'une variété d'algues nuisibles, sont discutés.

1 Introduction

This document provides an overview of marine conditions in the Strait of Georgia, British Columbia (Fig. 1) for the years 2015 to 2019. The Strait of Georgia, part of the Salish Sea which extends into both the U.S. and Canada, is one of the most biologically productive marine ecosystems in the world, supporting a variety of important fishing and aquaculture industries. Aquatic life in the strait takes advantage of the wide variety of marine habitats that are present, from the tidally-exposed shallow mudflats at the mouth of the Fraser River to regions where depths are more than 400 m, and from the sheltered waters around the Gulf Islands and in the different mainland inlets to the open waters of the central strait. However, this variety causes problems for scientific investigations and policy matters, because marine conditions in different locations in the strait may also differ.

A recent issue of concern in this region is that Chinook, coho, and steelhead stocks, resident in the Salish Sea, have experienced tenfold declines in their survival during the marine phase of their lives, relative to conditions 30 years ago. A large coordinated research program (the Salish Sea Marine Survival Project, SSMSP, marinesurvivalproject.com) has recently been carried out over 2014–2019 to better understand the reasons for these declines. Under so-called "bottom-up control" hypotheses about the factors that govern ecosystem operation, these changes would be linked to changes in marine conditions.

The most basic definition of marine or oceanographic conditions involves the temperature and salinity of the water, at different depths, as well as the concentrations of dissolved oxygen within the water and the amount of planktonic plant life residing near the surface. One basic purpose of this atlas is then to provide an overview of such conditions in different regions of the strait during the field years of the SSMSP. Details about these conditions may also be critical to understanding the life cycle of a variety of marine species, in addition to resident salmon, which concentrate in different areas. A second purpose of this atlas is then to characterize typical conditions, and their variability, in different regions of the strait to support future research questions.

This atlas is possible because of the flood of data now available from a Citizen Science Oceanography Program funded by the Pacific Salmon Foundation. After giving some background about the program itself, the atlas is divided into three parts. First, we detail the methods used. Second, we describe the seasonal cycle of the strait itself, concentrating on measurements from 2017. Third, we highlight interannual variations over the period 2015-2019, especially near the surface, in a series of figures in which the entire dataset, at a particular depth, is presented. Since the Pacific marine heatwave of 2014-216 ("the Blob") overlaps with the collection period for our dataset the results provided here may not be completely representative of long-term interannual variability, but addressing this issue is beyond the scope of this report. Finally, for quantitative comparisons that may be useful for other purposes, we provide in an Appendix a set of summary figures, in which data are presented by region and year.

1.1 The PSF CitSci program

Currently the general features of marine conditions in the Strait of Georgia are reasonably well known, although the only recent review (Beamish and McFarlane, 2014) has been written for a general rather than a scientific audience. However, there are a number of recent and/or ongoing sources of observational data, many of which are summarized annually in a report series (e.g., Boldt et al., 2019).

For example, surface temperature and salinity are monitored daily at several B.C. lightstations in the strait, as are meteorological conditions at more than a dozen locations and surface wave characteristics at two (Gemmrich and Pawlowicz, 2020). Water column temperature and salinity profiles (but not dissolved oxygen, chlorophyll, or nutrients) in a subregion of the central strait are recorded weekly since 1969 in the course of operations at the Canadian Forces Maritime Experimental and Test Ranges (CFMETR) facility (Masson and Cummins, 2007). Since 1999, surveys of oceanographic conditions in the Salish Sea have been carried out 3 or 4 times a year by government scientists in Fisheries and Oceans Canada at the Institute of Ocean Sciences (IOS), providing seasonal snapshots of a variety of parameters. Hydrographic profiles from this dataset cover the entire water column; within the Strait of Georgia they occupy about 30 regular stations and another 12 with enhanced sampling (this data is available at waterproperties.ca and has been analyzed in a number of publications, e.g., Masson, 2006; Johannessen et al., 2008; Masson and Peña, 2009). IOS scientists have also carried out a number of mooring programs for deep-water conditions over the years. In the past decade, continuous measurements of a variety of parameters, from ferries in the southern strait (Wang et al., 2019) and from a small number of locations on the sea floor, have been provided by Ocean Networks Canada (ONC, oceannetworks.ca). Recently, a sustained monitoring program in the far northern strait has been developed by the Hakai Institute (hakai.org). University scientists also contribute irregularly sampled data. They seasonally monitored the southern strait with high spatial and temporal resolution over 2003–2005 in the STRATOGEM program (Pawlowicz et al., 2007), and have recently developed a 3-dimensional numerical modelling system for the Salish Sea to provide daily now-casts, as well as hindcasts for recent years, of physical (and some biological) conditions (salishsea.eos.ubc.ca).

However, in spite of the availability of this data, the precise details of how and when marine conditions vary from place to place within the entire strait over the whole year, which requires sampling over many depths at high temporal resolution, remain mostly undescribed, largely because of the difficulties and cost of sustained data acquisition in the ocean. This is especially true in the central and northern strait, which are furthest from the various scientific and academic institutions that have traditionally studied this area. A coordinated program to sample different regions of the entire strait for the marine conditions important for fisheries, at monthly intervals, was last attempted in the late 1960s (Stephens et al., 1969). Unfortunately, many aspects of this dataset are virtually unusable today.

Some years ago, E. Carmack, a government scientist at IOS, envisioned a 'mosquito fleet' of small boats to overcome this problem, supplementing the existing datasets at high spatial and temporal resolution. Operated by citizen scientists under some central coordination, this fleet would provide a coordinated set of observations over a wide region. The Pacific Salmon Foundation (PSF, psf.ca) decided to fund such a program as part of the SSMSP and it was first implemented in the Strait of Georgia in 2015 for a 3-year period. This was extended to a 4th year, and then, in 2019, it underwent a transition into what is hoped to be a long-term monitoring program. At present the operation of the PSF CitSci program involves personnel from PSF, ONC, IOS, and the Universities of Victoria and of British Columbia, as well as approximately 7–10 boats and upwards of 30 citizen scientists. The dataset itself should be a standard reference for many years, and is archived by ONC (oceannetworks.ca) and the Strait of Georgia Data Centre (sogdatacentre.ca).

1.2 Standard Regions

To highlight regional variations, the Strait of Georgia is subdivided into a number of different regions. Previous studies of fish populations, and of the smaller zooplankton on which they feed, have similarly been based on a division of the strait into subregions, each of which are assumed to represent a particular habitat. Unfortunately, the two groups of researchers involved have divided the Salish Sea slightly differently.

Rather than choosing either, we have decided to create a third subdivision into 11 regions (Fig. 2), which can be mapped reasonably consistently onto either of the two existing classifications. Note that the actual location of CitSci stations within each region sometimes changes from year to year as the sampling plan changes.

1.3 Environmental Limits

Strait of Georgia water which is fully in equilibrium with the atmosphere will have dissolved oxygen concentrations of 8–15 ppm, depending on temperature and salinity, because colder and fresher water can hold more dissolved oxygen (Garcia and Gordon, 1992). However, seawater in B.C. coastal waters can be significantly undersaturated, and since a lack of oxygen is detrimental to the life of most organisms it is important to quantify the amount of oxygen present.

A variety of lower limits are used to describe the conditions in which oceanic organisms can live (Hofmann et al., 2011). For example, 2 ppm of O_2 (a concentration of about 63 μM) is often taken as a hypoxic limit, below which many organisms will die, but a more realistic general limit for oxygen concentrations, below which the growth of actively swimming fish is affected, is around 6 ppm. For salmonids in particular, studies find avoidance behaviors at concentrations of 4.5 to 6 ppm (BCMECCS, 1997b), with B.C. Water Quality Guidelines suggesting an acceptable instantaneous oxygen threshold of 5 ppm to prevent harm to all life stages of aquatic life (BCMECCS, 1997a). Based on expert recommendations we highlight a slightly more conservative upper limit of 6 ppm (or 187 μM) in our figures.

Warm temperatures may also affect fish, and temperatures above 17-18°C are thought to cause physiological stress in salmonids (US EPA, 2003). Expert recommendations suggest that highlighting a limit of 17°C in our figures would be most useful, and we have done so.

Finally, oceanic fish are also sensitive to salinity, but the typical transition between freshwater and saltwater species occurs at a salinity of about 5 g/kg (Whitfield et al., 2012). Water fresher than this limit is found in the Fraser and other rivers, but, except during ebb tides at the height of the freshet, when it can be briefly found offshore of the Fraser's mouth at Sand Heads, Strait of Georgia waters are always above this limit.

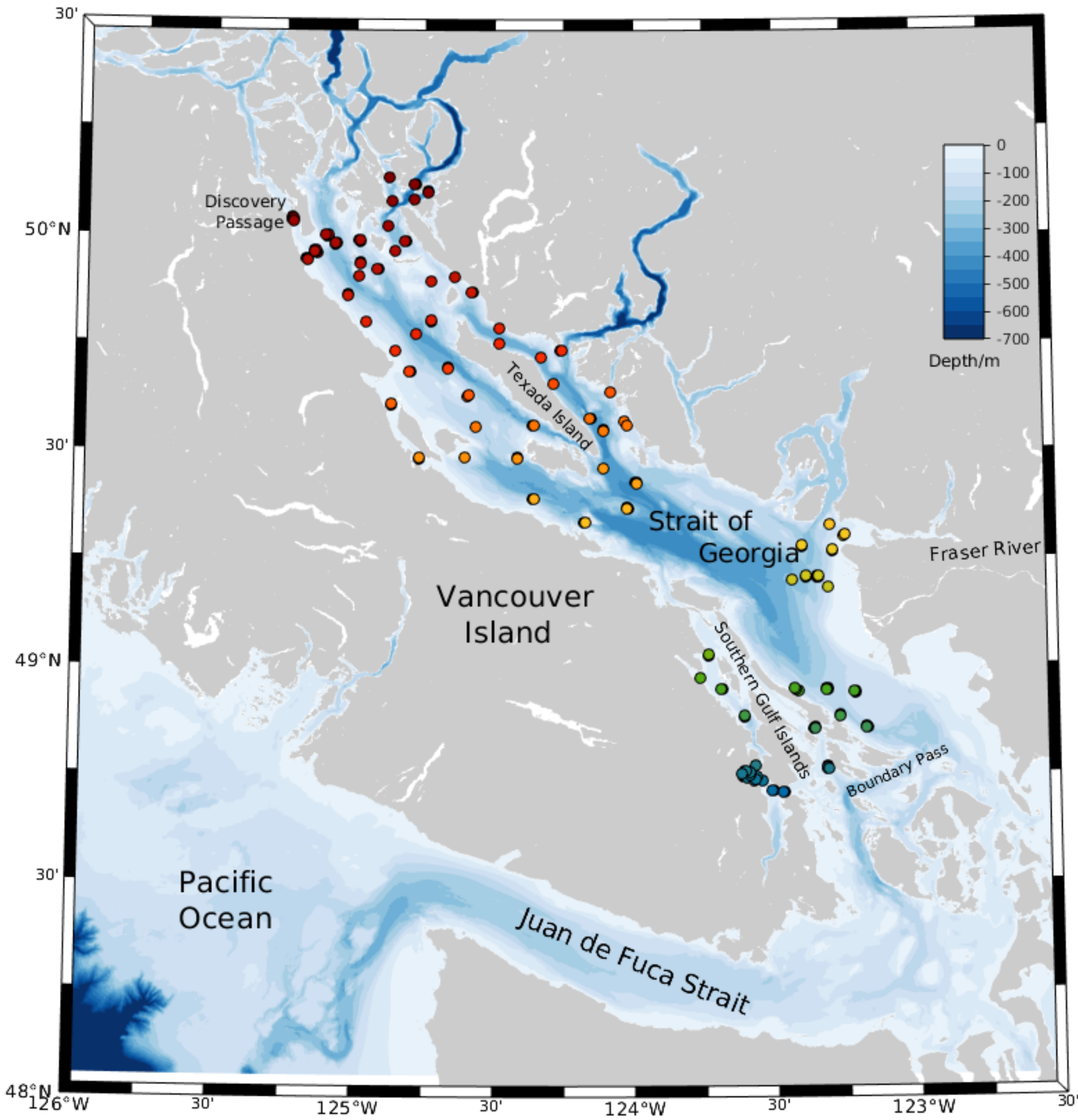

Figure 1: The Strait of Georgia is part of the Salish Sea region. Stations from the PSF Citizen Science program in 2017 and 2018 are shown, overlaid on the bathymetry of the region.

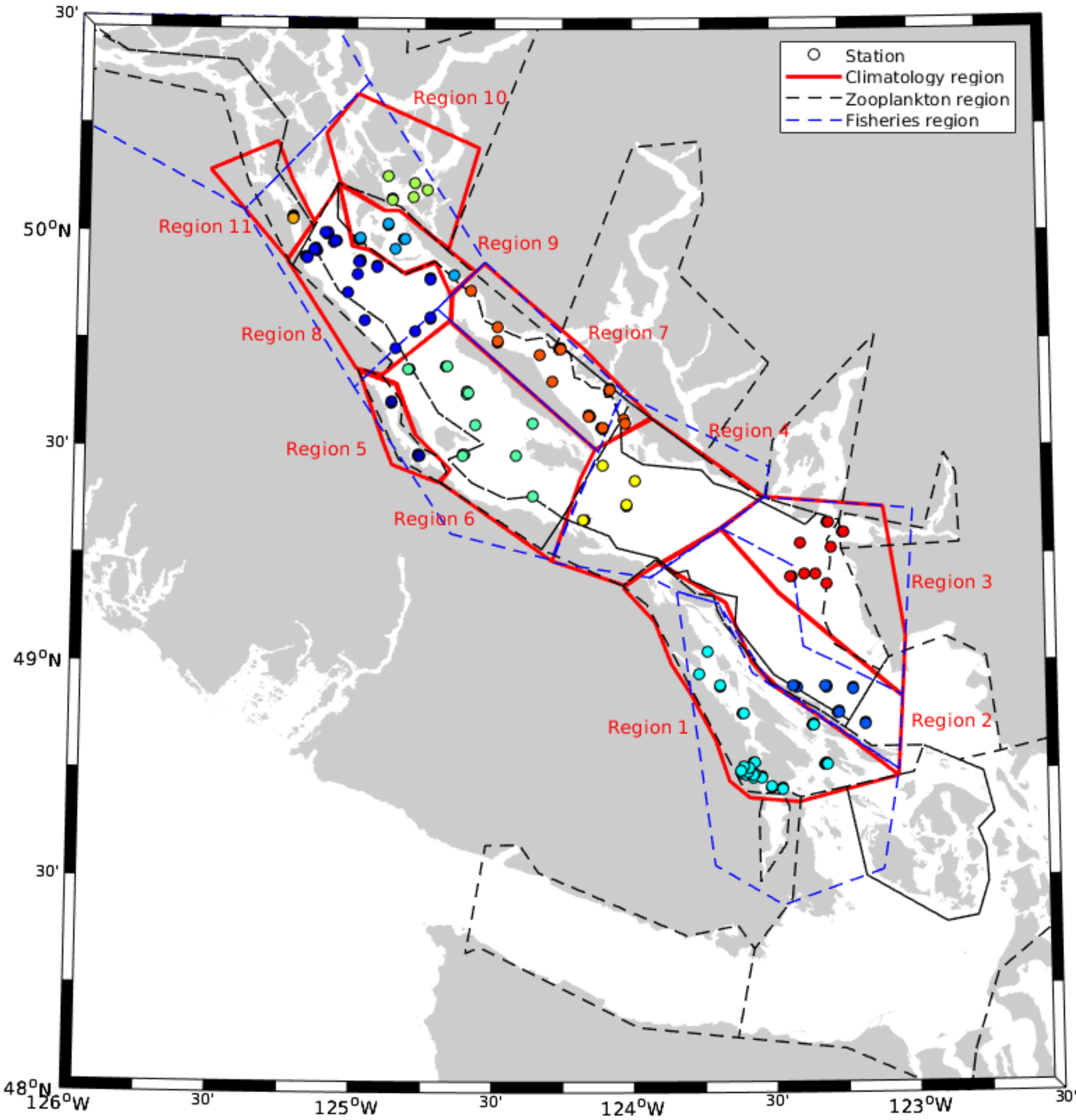

Figure 2: Map of fisheries and zooplankton regions, as well as the climatology regions defined for this atlas. Station colouring by region corresponds to colours used in Figs. 5–9.

2 Methods

2.1 Sampling Plan

The PSF CitSci program is composed of up to 10 "patrols", geographically spread over the entire strait (Fig. 4). The number and location of patrols have changed over the years in response to emerging science needs and funding availability. A Victoria patrol was in operation only in 2015, and a widespread reorganization took place for 2019 with the elimination and merging of several northern strait patrols and the creation of a new patrol on the Sunshine Coast. The Ladysmith patrol is community-driven with sampling carried out by members of the Stz'uminus First Nation along with a trained technician, and Institute of Ocean Sciences technicians sampled the Cowichan Bay stations until July of 2016.

In general, each patrol consists of a specially equipped vessel and a team of 2–5 "citizen scientists" (Fig. 3). Vessels have a small downrigger boom mounted on their side with a hand-cranked reel holding 150 m of wire to assist in sampling. All patrols are provided with sampling equipment and protocols. A PSF technician provides training in the use of the equipment, as well as logistical support for all patrols during the field season, monitoring their procedures, collecting log sheets, and sending frozen water samples to various laboratories for further analysis.

The sampling plan for each patrol consists of a set of sampling locations or stations to be revisited in each survey, and a schedule of about 21 sampling dates from March through to October (a winter sampling date, meant to provide a baseline for comparison with the summer conditions, began in the 2018/2019 winter). Sampling for all patrols is meant to be carried out nearly simultaneously, within a day of the scheduled times, so that "synoptic" snapshots of the strait can be generated from each survey.

Sampling dates (Figs. 5, 6, 7, 8 9 for years 2015 to 2019 respectively) were chosen according to the fortnightly cycle of tidal strength in the strait, with sampling occurring at times of both the strongest and weakest tides in the cycle. This results in a roughly weekly interval between surveys (more often in spring starting in 2019 to catch the spring bloom). However, weekends and holidays are removed from the pattern, giving rise to larger gaps. Other gaps arise from weather problems, broken equipment, start-up delays in spring, and other issues that arise in any field program. In spite of these problems, the final result is remarkably close to the original vision. Approximately 1100 stations are sampled in every year over 2015-2018, with only about 700 in 2019.

2.2 Temperature and Salinity

At each station, an electronic CTD (for conductivity - temperature - depth) probe is lowered to the bottom or a depth of 150 m, whichever is less, using the hand-cranked reel. 10 RBR-Concerto® CTDs were initially purchased, of which 7 are currently operational in the CitSci program (thus, there is some sharing of CTDs between patrols). These probes measure water temperature, water salinity (using the electrical conductivity of the water which arises from the presence of dissolved sea salt), and pressure, from which depth can be determined, continuously through the whole vertical profile. Temperature and salinity are important factors regulating the physiology of marine organisms; they can also be used as "tracers" to distinguish different water masses and their evolution in time and space.

The CTD instrument pool is managed by personnel at Ocean Networks Canada (ONC), who handle the logistics of annually returning these instruments to the vendor for service and calibration. ONC has also developed a tablet app which allows the raw profile data, along with GPS position data, to be transmitted electronically to their archive. Staff at ONC then carry out a set of quality control (Q/C) procedures, adjust the different sensor signals for sensor time delays, add and correct metadata (including station names), and also divide the data into "casts" with data provided at a uniform set of depths for each station. The resulting dataset still contains a number of problems (e.g., casts without positions, profiles which appear to be erroneous when compared with nearby data because of sensor malfunction, spurious "spikes" in salinity, and so on) and so an additional manual edit of the dataset was carried out by an experienced oceanographer before this atlas was generated. Typically, corrections are made to less than 5% of the 700–1500 profiles observed in any year.

In this dataset, temperatures are in °C on the ITS-90 scale (with a nominal accuracy of about ±0.01°C) and salinities are shown as mass fractions (grams of sea salt per kilogram of seawater) on the TEOS-10 Reference Composition Salinity Scale (IOC et al., 2010) with a nominal accuracy of ±0.01 g/kg. Salinities on the older Practical Salinity Scale 1978 (PSS78) are numerically smaller than Reference Salinities by a factor of about 0.9953; the difference is usually indistinguishable in figures.

2.3 Dissolved Oxygen and Chlorophyll

The CTD profilers are also equipped with extra sensors to measure the concentration of dissolved oxygen (necessary for sustain life for many organisms), and a fluorescence signal arising from concentrations of chlorophyll in the water column. Chlorophyll concentrations characterize the biomass of marine phytoplankton, the microscopic plant life in the ocean that is the base of all food webs.

Dissolved oxygen measurements are measured as a factor relative to atmospheric saturation. By using a standard equation that provides the actual concentration, when in equilibrium with the atmosphere at different temperatures, salinities, and pressures (Garcia and Gordon, 1992), these measurements can be converted into molar units of O_2, which we use here. Although no in-situ calibrations are carried out, the estimated static accuracy is around ±10 μM. However, the sensor response time is generally longer than for temperature and salinity so that profiles show a smoothed version of the actual variations.

Chlorophyll concentrations in units of micrograms of chlorophyll per liter of seawater, obtained from in-situ fluorescence measurements by CTD profilers, are nominal and based on factory calibrations only. However, each patrol also filters particulate matter from duplicate water samples obtained from a depth of 5 m at one station in each survey. Water samples are obtained as for nutrients, described in Section 2.5. A fixed volume of sample water is then passed through a glass-fibre filter with a nominal pore size of 1.2 μm, so that all larger particles, which include phytoplankton containing chlorophyll, are retained. Residue on the filters is subsequently analyzed in a laboratory for the actual chlorophyll content. The residues are extracted in acetone and chlorophyll amounts determined using a Turner 10AU fluorometer calibrated annually with a pure chlorophyll-a standard (Sigma) using standard procedures (Holm-Hansen et al., 1965).

Annual comparisons between the in-situ CTD fluorescence signal at 5 m with these water samples (Fig. 10) show a great deal of scatter, perhaps a little more than can be expected from the accuracy of the laboratory analysis itself, which can be judged from analysis of the duplicates (Table 1) and is about ±0.5 μg/L. However, there is significant uncertainty in actually matching CTD profiles against water samples taken many minutes earlier, especially when vertical gradients in concentration are large.

In addition, the relationship between insitu fluorescence and chlorophyll content can be affected by physiological factors in phytoplankton, including non-photochemical quenching. Non-photochemical quenching results in a light-dependent reduction of the fluorescence signal, relative to measurements made in darkness. The apparent chlorophyll concentration at highest light levels in the Strait of Georgia (i.e. for surface waters in summer), based on in-situ fluorescence measurements, was previously estimated by Halverson and Pawlowicz (2013) to be as little as 56% of a dark value due to this effect. However, corrections are complicated, since they depend on ambient light conditions and therefore on season, weather, depth, and water clarity, and attempting them is beyond the scope of this report.

In spite of these problems, the CTD and water sample chlorophyll measurements are clearly correlated ($r^2 \approx 0.6$), and least squares fits for each year suggest that actual chlorophyll concentrations are smaller than nominal by a factor of about 0.6. We shall use this factor to calibrate all CTD-derived chlorophyll measurements in this report.

Vertical profiles of chlorophyll are often quite variable. In many cases it is more useful to discuss the total plant biomass in the ocean per unit area, assuming that animals that feed on phytoplankton can find them wherever they are in the water column. This total can be found by integrating depth profiles from the surface to a depth below which chlorophyll concentrations are zero; the depth-integrated biomass is then presented in units of milligrams of chlorophyll per square meter of area.

2.4 Secchi Depths

Secchi depth measurements of water clarity are also made at each station, essentially by lowering a white "Secchi disk" into the water until it cannot be seen by an observer on the surface; the depth at which this occurs is recorded. The Secchi depth is a measure of the penetration into the water column of light that can drive photosynthesis, and is affected by the amount of particulate matter in the water column. Particulate matter can either be living (i.e., phytoplankton), or nonliving, mostly clays and fine sediments that enter the strait in the freshwater outflow of Fraser River. Because of its reliance on human perception, the resulting dataset is often very "noisy" but Secchi depths are a cheap and relatively simple measurement with a long history of use.

2.5 Nutrients at 0 and 20 m

At selected stations, water samples are collected at depths of 0 and 20 m for nutrient analysis. Water is obtained from a 'Niskin'-type sampling bottle, attached to a rope marked at various depths and kept vertical by both a weight at the bottom and maneuvering of the boat in the direction of any tilt. These bottles are lowered in an open position, and then closed to trap a water sample using a mechanism triggered by the descent of a weighted "messenger" on the sampling rope.

For nutrients, water from the Niskin is subsampled and (from 2016 onwards) filtered through a glass-fibre filter of nominal pore size 0.7 μm to remove all organic matter. The filtered water samples are frozen for storage, and then thawed and analyzed for the concentration of dissolved macronutrients in a laboratory. Dissolved macronutrients include: nitrate NO_3^- (actually nitrate plus nitrite is measured, although nitrite concentrations are generally much lower than those for nitrate in the ocean), phosphate PO_4^{3-}, and silicic acid $Si(OH)_4$ (sometimes assumed to have the chemical form of silicate or silica, a solid with formula SiO_2), all required for the growth of phytoplankton. Several different laboratories (and different analysts) have been used over the years to analyze samples in the CitSci program. For 2015 all three nutrients were analyzed using a 3 channel SEAL Autoanalyzer with the AACE data acquisition program following the methods described by SEAL analytical. In 2016 and 2017, nitrate and phosphate were analyzed on a Lachet autoanalyzer using Quickchem methods 31-107-04-1-G and 31-115-01-1H, and silicate on an Ultrapsec 2000 using a method from Strickland and Parsons (1968). In 2018 and 2019 all nutrients were analyzed using an Astoria autoanalyzer following methods described in Barwell-Clarke and Whitney (1996). Salinity corrections were not applied to fresh samples but the resulting bias is only a few percent even when salinities are zero.

In general, errors in any nutrient dataset can arise from handling problems (including mislabelling of samples, problems in filtering, and problems arising from not freezing rapidly enough and/or subsequent thaw/freeze cycles), as well as analytical problems in the laboratory, and it is important to consider the effects of these errors.

A standard quality-control practice is to examine correlations between the different nutrients in property/property plots. Nutrient concentrations in the ocean generally co-vary in relatively fixed ratios with each other (so-called "Redfield" ratios, for which NO_3^-:Si:PO_4^{3-} are in proportions of 16:15:1) because their concentrations are controlled by phytoplankton uptake and remineralization processes, and phytoplankton contain nitrogen, silicon, and phosphorus in these ratios. These relationships also appear in the CitSci dataset in the Strait of Georgia; when measurements are presented in property/property plots they can be seen to be clearly correlated along lines with slopes that approximate the Redfield ratios (Fig. 11). Offsets from curves with these slopes that pass through the origin are often used to infer the effects of denitrification, a microbial process that converts nitrate into nitrogen gas. This is probably not an important part of the Strait of Georgia ocean ecosystem, but may be important in the open ocean regions from which the Strait of Georgia waters are sourced.

Although the scatter in nitrate/silicate comparisons is larger than in nitrate/phosphate comparisons, this effect is also seen in property/property plots for the high-quality data gathered by government scientists during their much more limited sampling program in the strait (Fig. 12) over the same years. An increased scatter is a reflection of variations in the type of phytoplankton that grow in the strait, as some species use more silica than others.

Because of these tight correlations, the scatter in property/property plots can often be used to judge data quality. Note that samples in these scatter plots fall mostly within a dense core of points, but that a number of outliers far from this dense core are also seen. These outliers are quite numerous in 2015 for the CitSci data, but are relatively rare in 2018 and 2019. Large outliers in these scatter plots may indicate sample handling problems. This suggests that sample handling has improved over the years and is now of relatively good quality. Changes in sample handling procedures have included filtering after sampling, more consistent freezing protocols, and purchase of single-use sample containers. As a comparison, property/property plots for the high-quality data gathered by government scientists in the strait (Fig. 12) show very few outliers and are consistent in appearance across all years.

Ignoring the outliers, the scatter in the dense core of the property/property plots is probably more representative of analytical errors in the laboratory procedures. By examining duplicate samples (two subsamples of the same water sample) in the CitSci dataset, which were obtained for this purpose, we estimate that these analytical errors are around ± 0.3 μM for nitrate, ± 1 μM for silicic acid, and ± 0.05 μM for phosphate (Table 1).

However, note that the scatter pattern in the 2016 and especially the 2017 CitSci dataset looks qualitatively different than the pattern in other years, with a lower and rounder shape. Deep concentrations are also lower. The reason for this is not clear, however the analytical procedures used in those years were different than in the other years. A difference in data quality for those years is also suggested by comparison with the more limited high-quality data collected by government scientists (Fig. 12), which does not show a qualitative difference in the appearance of the scatter over all years. Thus, we suspect that the 2017 measurements especially are also affected by procedural biases. These biases will not affect comparisons within that year, but make year-to-year comparisons more uncertain.

Not shown in Fig. 11 are the effects of mislabelling the 0 m and 20 m samples from the same station. Generally, one expects the surface samples to have lower concentrations than those at 20 m (especially in summer) and on the order of 20 pairs in each year are transposed so that this occurs, under the assumption that a labelling problem occurred.

2.6 Harmful Algae

Surface seawater samples for phytoplankton analysis are collected with a Niskin bottle mounted on a pole (or directly by submerging the sample container) at each station, with additional water samples from 5, 10, and 20 m depths being collected at one station per patrol in the same manner as the nutrient samples. Once collected, samples are immediately preserved by adding Lugol's iodine solution (final concentration in the sample ∼1–2%). Samples are then visually examined by an analyst using a compound light microscope to characterize the types of phytoplankton present; the limitations of optical methods limit this to species larger than about 10 μm in size. This includes both the dominant types (not discussed here), as well as all species that are known or suspected to have a negative effect on finfish and shellfish in B.C. (Haigh et al., 2004), including *Alexandrium* spp., *Chaetoceros convolutus*, *C. concavicorne*, *Cochlodinium fulvescens*, *Dictyocha* spp., *Dinophysis* spp., *Heterosigma akashiwo*, and *Rhizosolenia setigera*. Harmful species of a known concern in BC coastal waters that were not encountered in the strait during this study included *Chattonella* cf. *marina*, *Gymnodinium mikimotoi*, and *Pseudochattonella* cf. *verruculosa*.

Duplicate Water Sample Analysis Results S_p (Num. Pairs)					
	Year				
	2015	2016	2017	2018	2019
Nitrate	0.2737 (336)	N/A	N/A	0.7594 (304)	0.1286 (155)
Silicate	0.7029 (290)	N/A	N/A	2.0675 (307)	0.6404 (176)
Phosphate	0.0553 (349)	N/A	N/A	0.0775 (309)	0.0378 (159)
Chlorophyll	0.1758 (38)	0.5032 (117)	0.3018 (147)	0.3305 (127)	0.3760 (63)

Table 1: At many stations (typically one station per patrol per survey), duplicate water samples were taken. Shown here are the pooled standard deviations of duplicate samples after outliers were removed, and the number of pairs of duplicates included in the calculations.

Figure 3: A typical patrol, with team members on the rear deck of their vessel displaying the equipment used. Note the downrigger at right, the CTD profiler being shown by the patrol member at center, and the tablet held by the patrol member on the left.

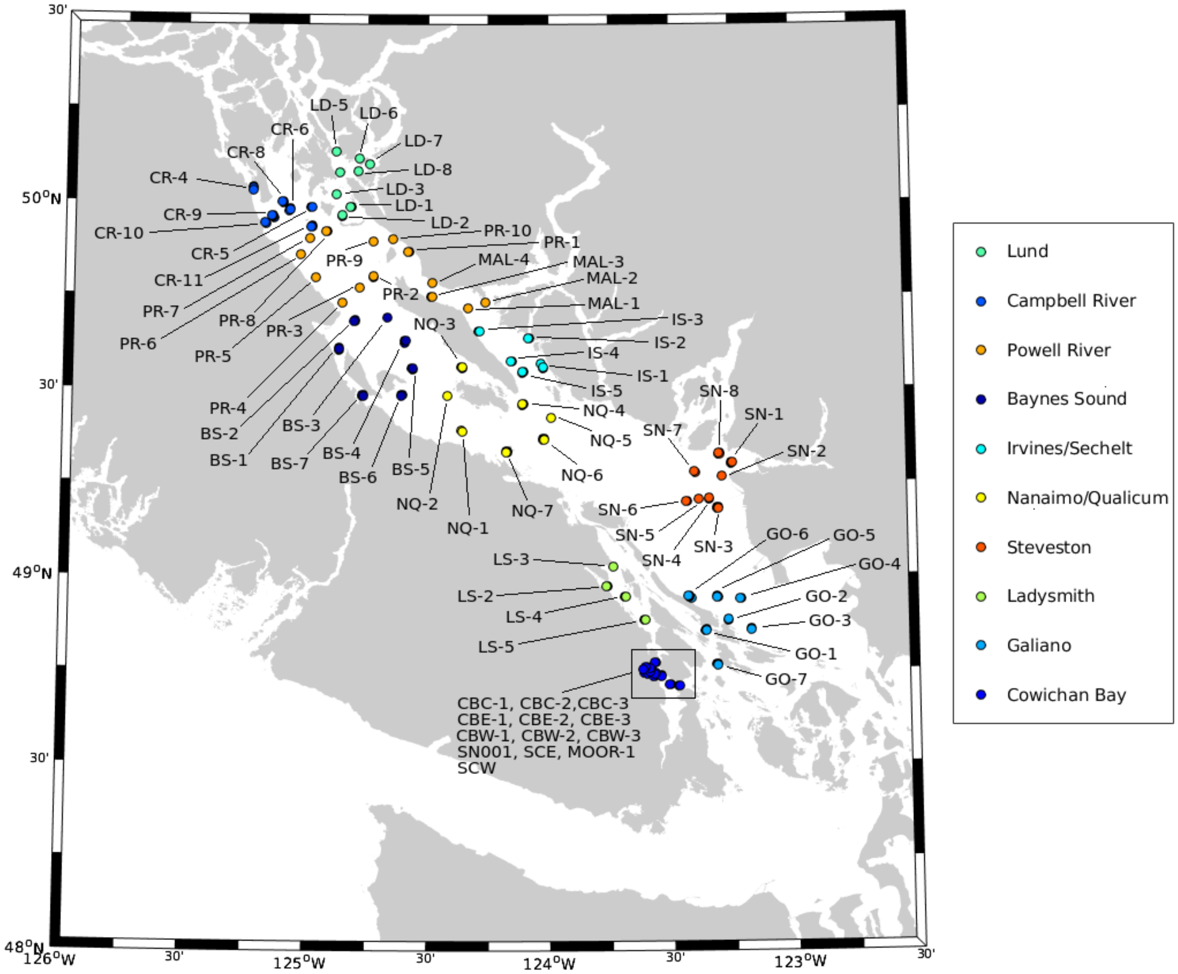

Figure 4: Map of all stations in 2016 and 2017 (in 2015 the Galiano Patrol was stationed in Victoria, and the Steveston stations were located further south; in 2019 new stations SS-1–8 on the Sunshine Coast were occupied). Station markers are coloured by patrol.

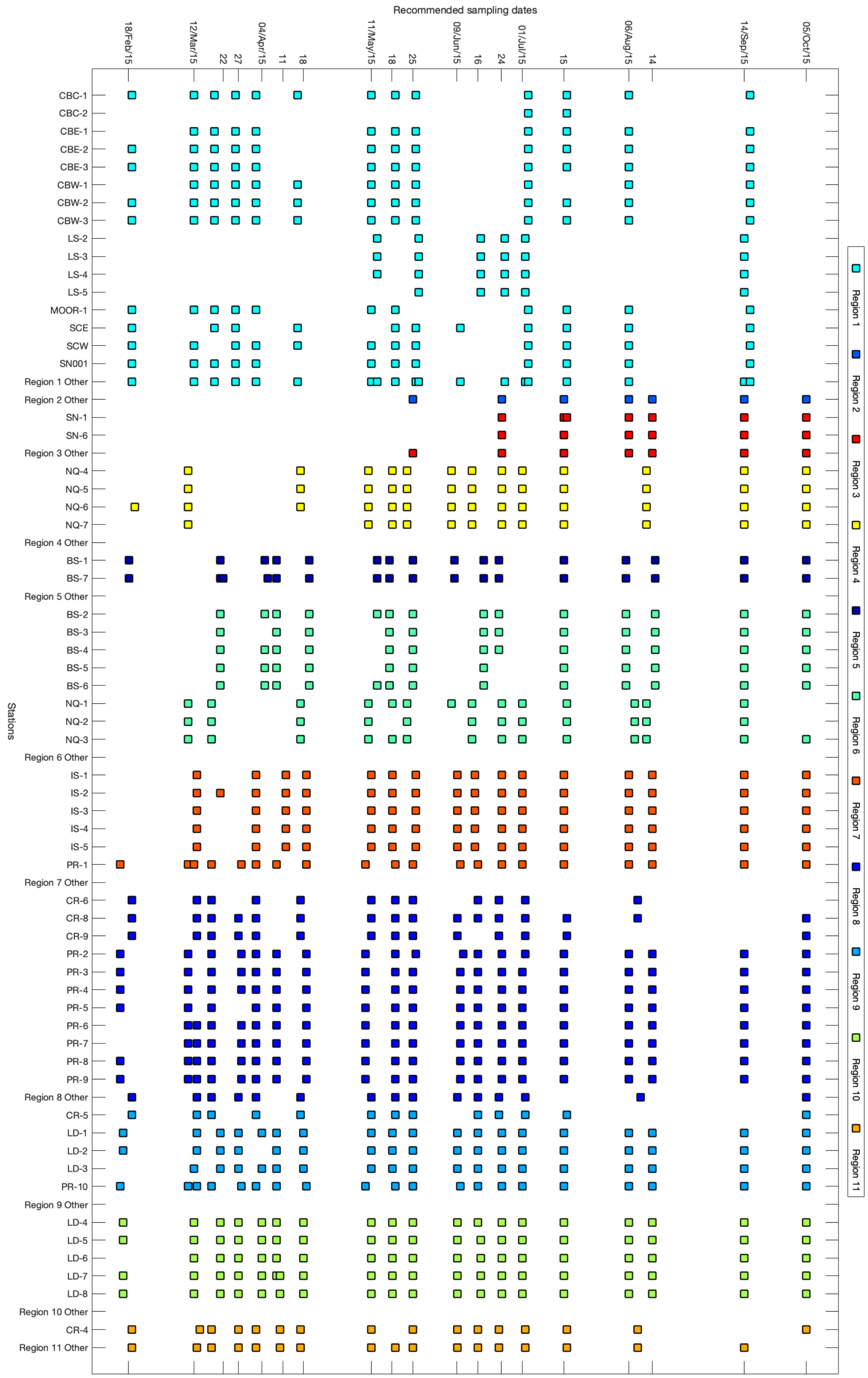

Figure 5: Sampling days for each station in 2015. Stations are grouped by region. Some casts fall within a region, but cannot be matched to a station. These casts are indicated by "Region X Other".

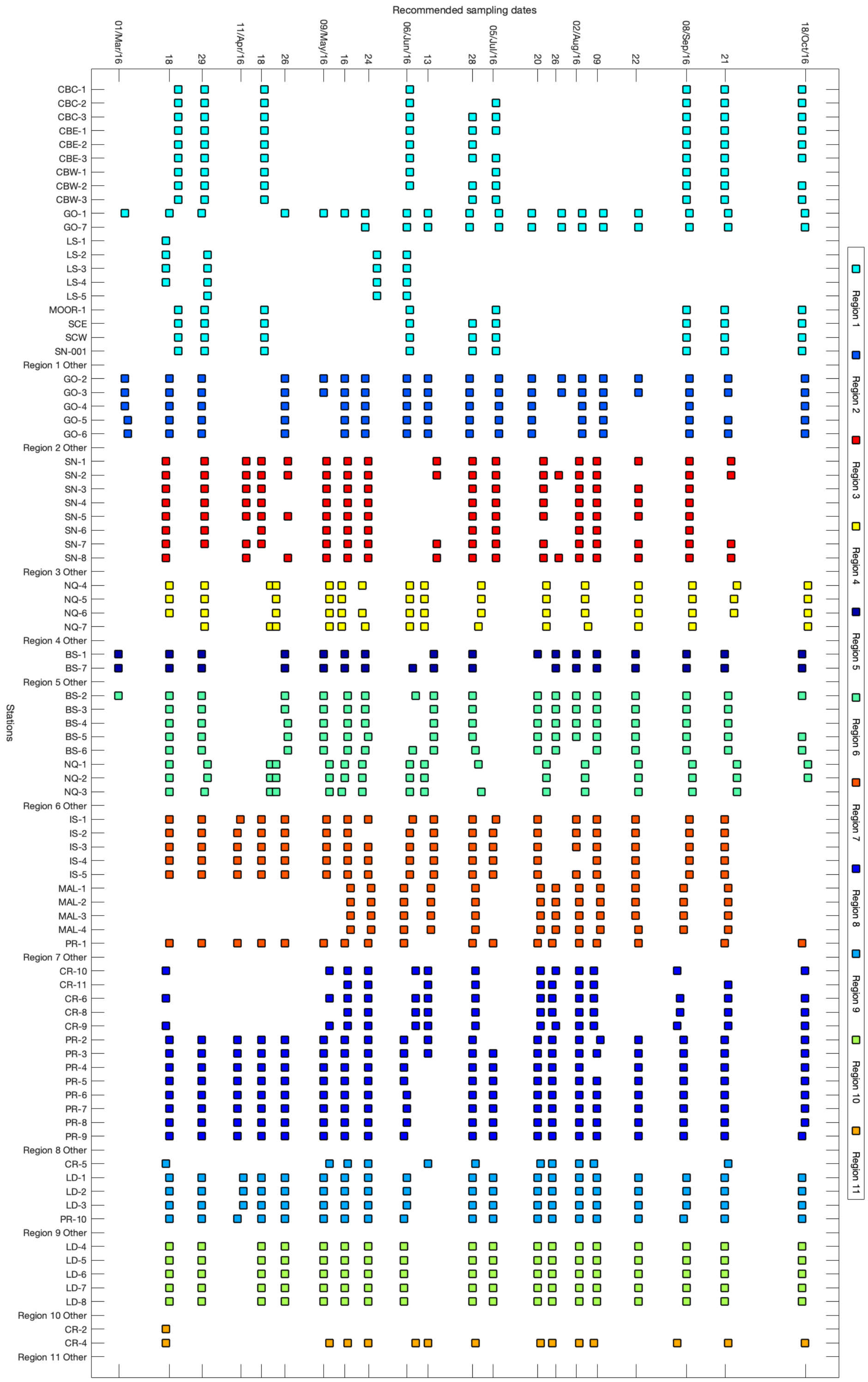

Figure 6: Sampling days for each station in 2016. Stations are grouped by region. Some casts fall within a region, but cannot be matched to a station. These casts are indicated by "Region X Other".

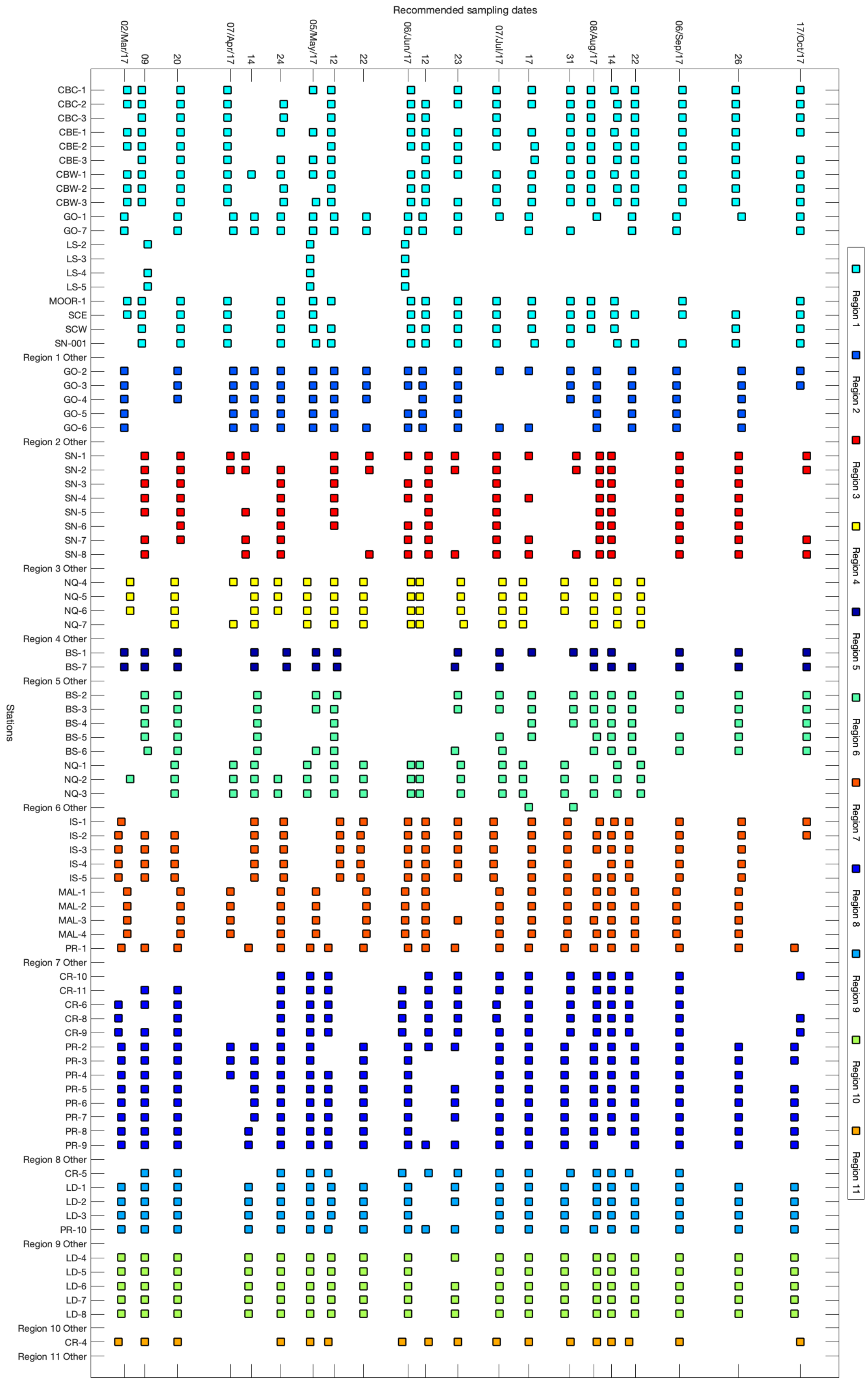

Figure 7: Sampling days for each station in 2017. Stations are grouped by region. Some casts fall within a region, but cannot be matched to a station. These casts are indicated by “Region X Other”.

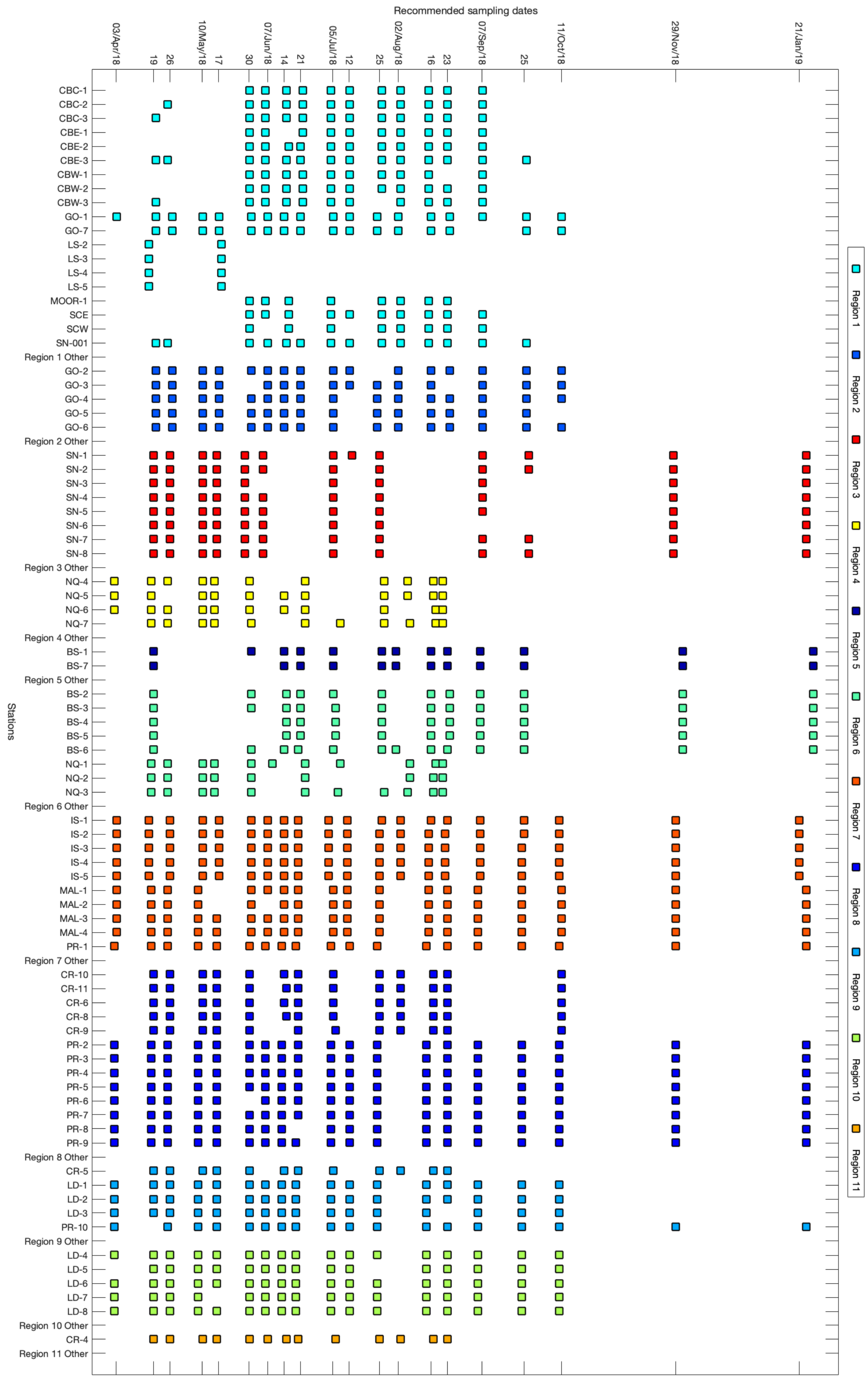

Figure 8: Sampling days for each station in 2018. Stations are grouped by region. Some casts fall within a region, but cannot be matched to a station. These casts are indicated by “Region X Other”.

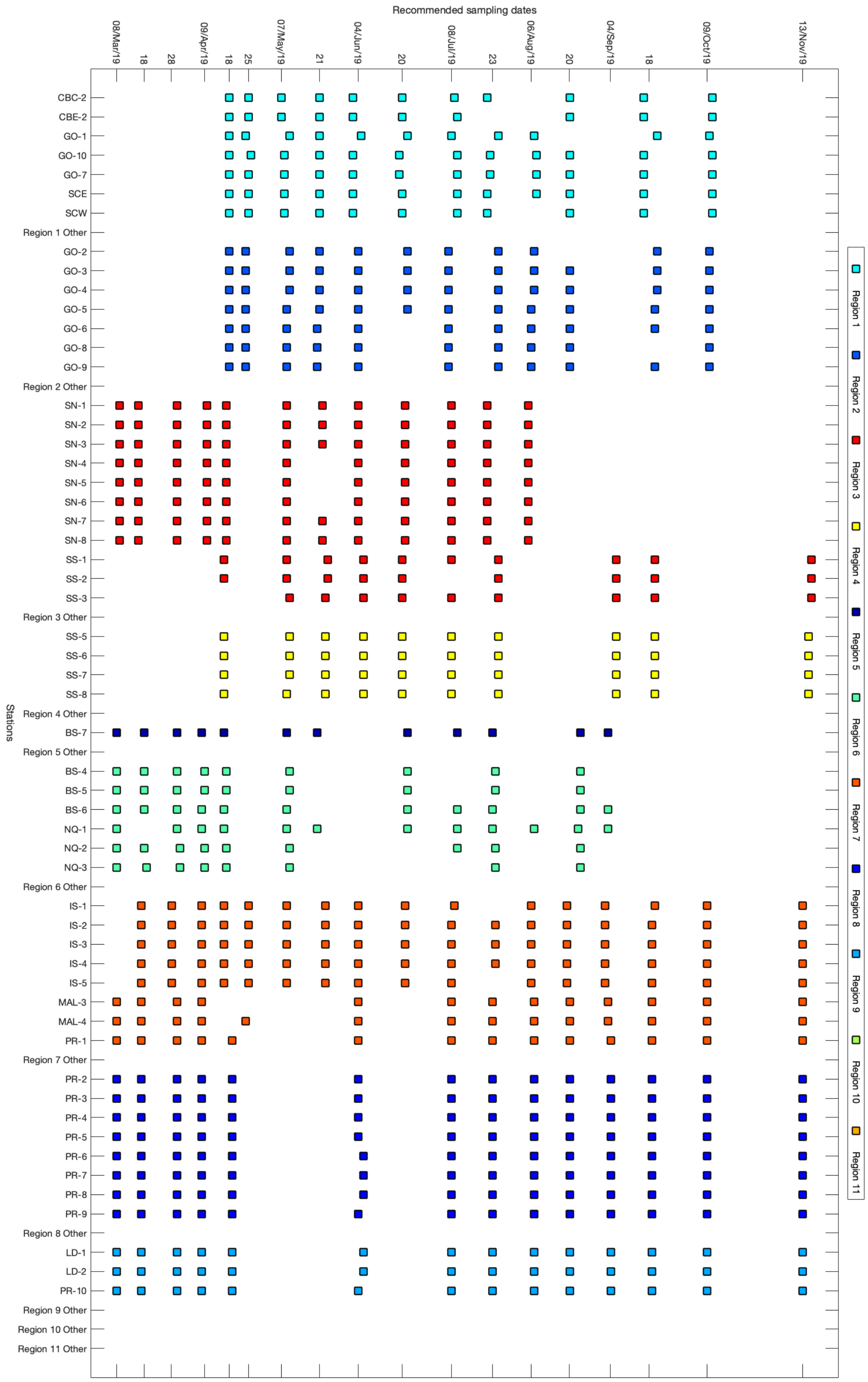

Figure 9: Sampling days for each station in 2019. Stations are grouped by region. Some casts fall within a region, but cannot be matched to a station. These casts are indicated by "Region X Other".

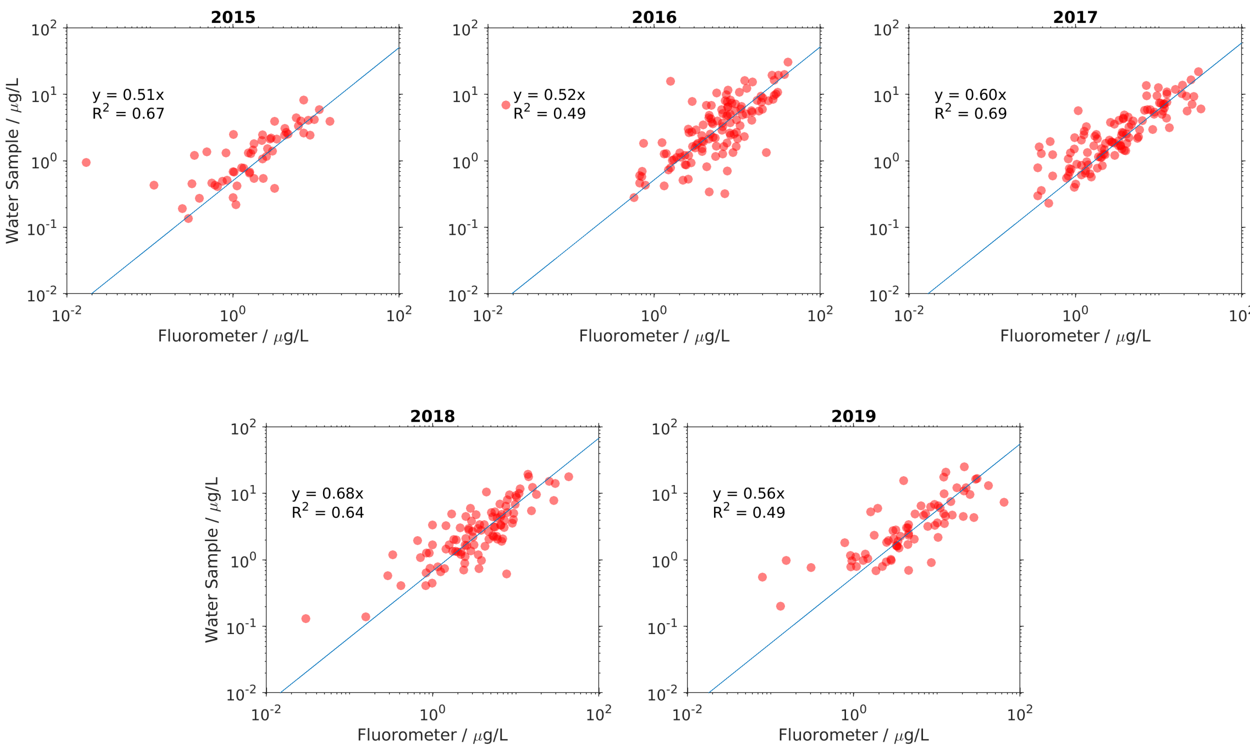

Figure 10: Scatter plots comparing two independent measurements of chlorophyll concentrations. CTD fluorometer reading is plotted on the x-axis, and laboratory analysis of water samples at the same depth and location on the y-axis. The line is a least squares fit to a one-parameter line through the origin, with data weighted using an assumed error that is a constant percentage of the measured value.

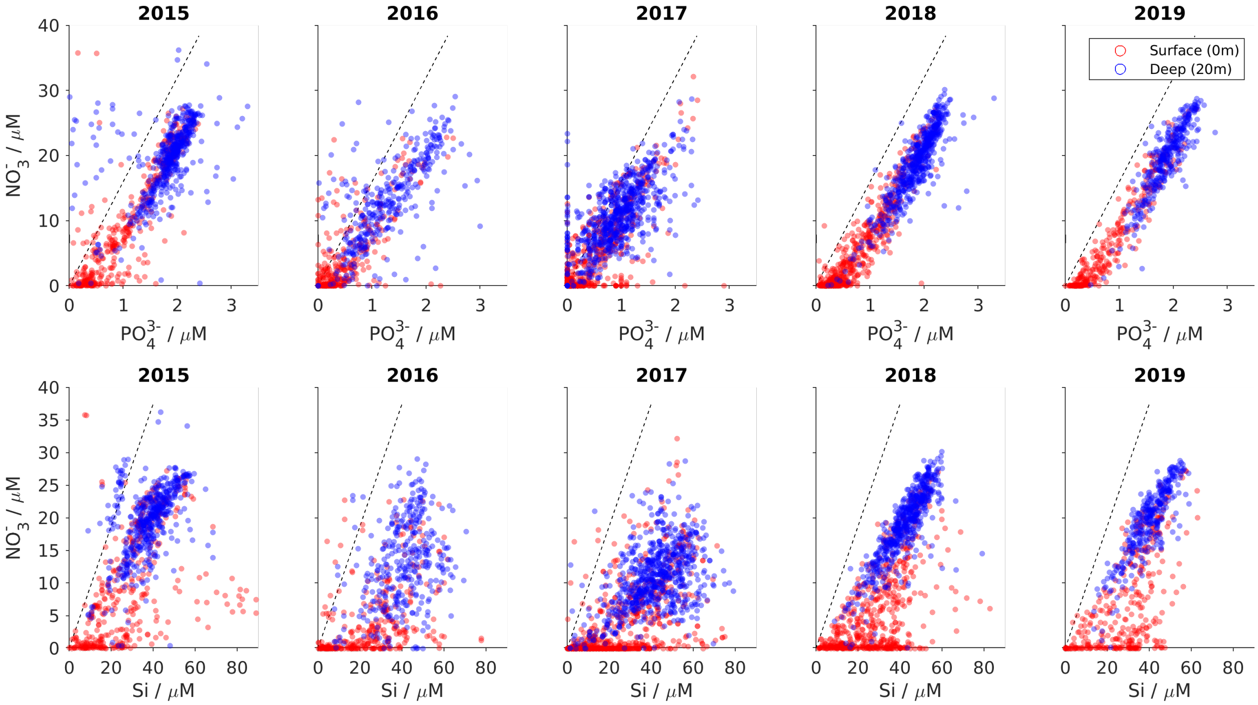

Figure 11: Nutrient ratios for CitSci data, by year. Upper row are nitrate/phosphate correlations, lower row are nitrate/silicic acid correlations. The dashed lines indicate Redfield ratios.

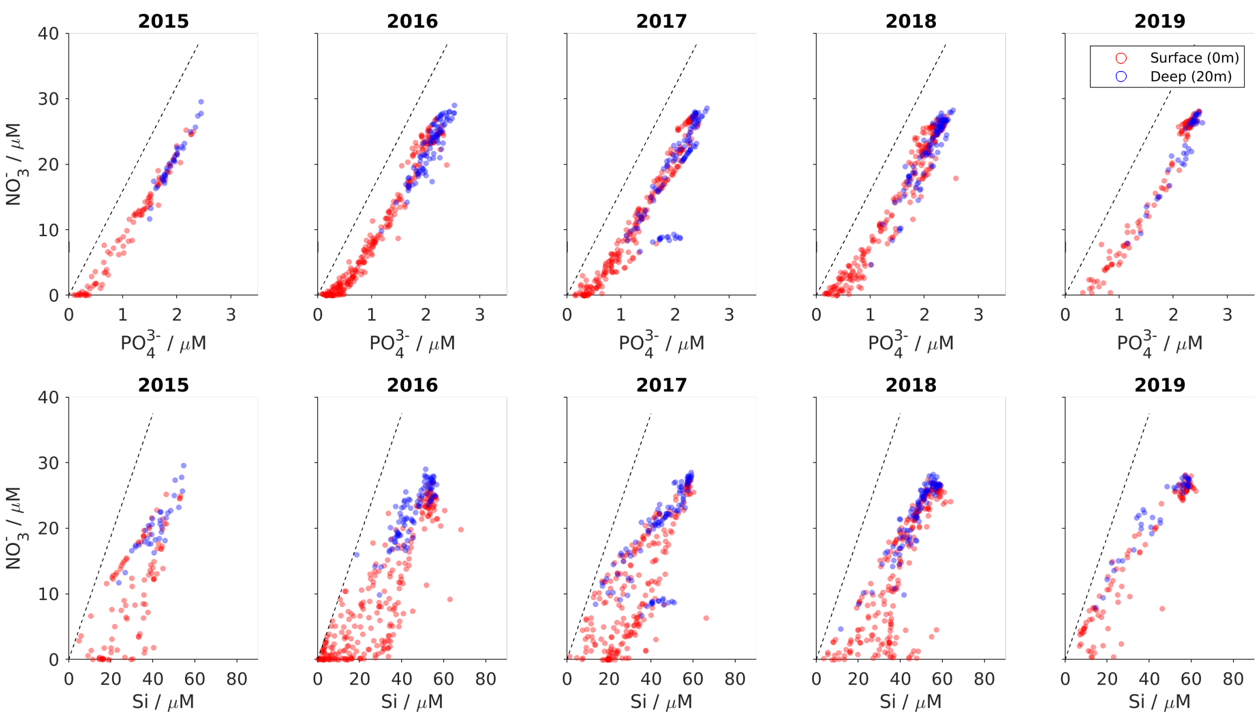

Figure 12: Nutrient ratios for Strait of Georgia measurements in the IOS data archive. Format as in previous figure.

3 The Seasonal Cycle (2017)

The largest changes in the strait are seasonal, but over longer periods there are noticeable changes from year to year as well. In this section we begin by discussing the seasonal cycle in 2017. This will provide a background for later discussion of the changes from year to year.

3.1 Strait-wide Average Properties

3.1.1 Temperature and Salinity

Averaging over all regions within the Strait of Georgia itself (i.e., not including the Gulf Islands, Desolation Sound, or Discovery Passage regions), we see that surface temperatures, which are usually coldest in January, are around 7°C in March and rise to 18°C in July and August (Fig. 13a). A seasonal cycle with the same timing can be seen down to depths of more than 25 m, although the summer maximum is lower at greater depth, reaching only 13°C at 10 m in late summer (Fig. 14b). On average, only waters shallower than about 3 m reach temperatures above 17°C in summer.

Below 50 m, however, the seasonal cycle has a different pattern. The minimum temperature of about 8°C appears in early May, and temperatures continue to rise until mid-October, when they reach nearly 11°C. The water column is thus divided into a surface water directly affected by solar heating and an intermediate water below that, separated by a mixture region. The delayed seasonal cycle in the intermediate water reflects the time required to fill the strait from waters that originate in either Discovery Passage to the north or Boundary Pass to the south, which can take many months (Pawlowicz et al., 2007). As a result of these differences in the timing of the seasonal cycle, the water column is almost isothermal in April as the surface warms and the deeper water cools, and, although this is not observed in the CitSci dataset, is likely almost isothermal in November as well as the surface cools and the lower waters warm.

The salinity also has a seasonal cycle (Fig. 13b), which is marked by a strong surface stratification from May to July, with surface salinities down to about 20 g/kg when diluted by the freshet inflow from the Fraser and other rivers (Fig. 14a,c), but as high as 28 g/kg in March and November. This freshening is only apparent near the surface, and is difficult to see even at a depth of only 10 m.

In the intermediate water, salinities are lowest in May or June, but thereafter increase. Salinities increase due to the inflow of even more saline water into the strait from May onwards, which pushes upwards previously deep water. Salinities decrease over the winter as freshwater is slowly mixed downwards from the surface.

3.1.2 Dissolved Oxygen and Chlorophyll

The dissolved oxygen content (Fig. 13c) at the surface is highest in April. This is partly due to the colder water which is present at that time (since oxygen is more soluble in cold water than in warm water), but also due to increased primary productivity (i.e., chlorophyll growth) in the spring (Wang et al., 2019). Effects of this growth are more easily seen when we consider oxygen levels as a percentage of saturation. Surface oxygen saturation levels rise to more than 110% in May (Fig. 14d) and even at 10 m are more than 100% in late April, and the surface remains supersaturated until September. Winter oxygen levels near the surface, not shown here, are usually significantly undersaturated.

In the intermediate water, oxygen content is highest when waters are coldest in early May, but thereafter decrease. Note that the oxygen content in waters deeper than about 20 m drops below 6 ppm (around 187 μM of O_2) in June and July, and reaches concentrations of 4 ppm (130 μM) in mid-October. The 6 ppm level is a lower limit for the preferred habitat of fish, below which they have decreased growth, and taking this limit as a boundary implies that large portions of the deeper parts of the water column are not good habitat for these fish for much of the year.

Finally, the chlorophyll content of the strait (Fig. 13d) has a peak of about 6 μg/L in April (the spring bloom in this year), with another smaller peak of about half that size in August, before returning to low winter values.

Maximum chlorophyll concentrations occur at a depth of about 5 m in both the early and late peaks, but at a depth of about 10 m during the intervening summer. Surface concentrations are less than half of the maximum concentrations, although some of that reduction may result from non-photochemical quenching of the fluorescence signal in summer (Sec. 2.3). Chlorophyll concentrations are less than 1 μg/L below depths of about 30 m, although the amount decays roughly exponentially with depth and a small fluorescence signal is still present at depths of 70 m (this is not visible in our plot).

The depth-integrated chlorophyll biomass (Fig. 14e) peaks at about 110 mg/m^2 in the spring bloom, but is only about 50 mg/m^2 for the remainder of the summer, dropping to about 25 mg/m^2 in September/October. Unlike peak levels, the depth-integrated biomass does not show a peak in late summer. Although we have no winter measurements, in other years the "winter" biomass levels are in the range of 4–20 mg/m^2.

3.1.3 Nutrients

Surface nutrient concentrations are high in winter. Averaged over the strait, they decrease steadily in March and April (Fig. 14f–h) as biomass and dissolved oxygen saturation levels increase. Nitrate concentrations decrease to near-zero and remain there over the summer. Silicates reach a minimum in late April at the end of the diatom-dominated spring bloom. Thereafter surface silicate levels rise to well above zero for the remainder of the summer. Phosphate concentrations, although they also decrease during the spring and increase during the fall, and they do so in a Redfield-ratio proportion with nitrate, do not fall to zero during the summer.

The fall in nutrient levels in the spring occurs while biomass values are high, and hence primary productivity is also likely high. The rise in nutrient concentrations starting in September, coupled with the end of oxygen supersaturation, indicates that productivity at this time is low.

Summer nitrate depletion likely occurs below the surface to at least the depth of the chlorophyll maximum (5–10 m). Below this level nutrient concentrations may not be depleted in summer, but small decreases are seen in our observations even at depths of 20 m (not shown here, but see Sections 3.2.3 and 4.3).

3.2 Regional Variations

3.2.1 Temperature and Salinity

Although the above discussion described average characteristics over the whole strait, there are systematic regional variations. Even though surface temperatures are warmest and coldest at about the same time everywhere, in the intermediate water (Fig.15a) southern temperatures are colder and northern temperatures generally warmer than average in March, but after June southern temperatures are warmer and northern temperatures are colder than the strait-wide average.

In contrast, spatial variations in salinity are relatively small in the intermediate water, but are quite large in surface waters (Fig. 15b). Southern strait surface salinities are generally always significantly lower than northern strait surface salinities. However, salinity values in Gulf Island waters are often much greater than those at the same depths within the strait.

More insight can be obtained by presenting the data in the same form as in Fig. 13, only with the data divided by the regions defined in Fig. 2. Surface temperatures are uniformly coldest in March, and warmest in late summer (Fig. 16), but although the warm surface waters are seen for several months, well into September in most areas, surface temperature drop below 17°C in August in regions 5 and 6, and to some extent in region 8, on the western side of the northern strait. Surface temperatures remain cold in Discovery Passage (region 11), and in the Gulf Islands (region 1).

In the intermediate water, most areas show a temperature minimum in the first half of the year, but the time of this minimum becomes later as we move northwards, and the depth of the minimum is less in regions 7, 9, and 10 on the eastern side of the strait.

Surface salinities are lowest in the southern strait, especially in region 3 near the mouth of the Fraser River (Fig. 17). Deeper salinities tend to be greatest in the southern strait, and even in the Gulf Islands (region 1) but the spatial variation is not as marked as it is for temperature and surface waters are always stratified. The most obvious exception is in Discovery Passage (region 11), where waters are relatively well-mixed.

3.2.2 Dissolved Oxygen, Chlorophyll and Secchi Depth

Chlorophyll profiles are also quite different, with southern profiles showing significantly larger surface values (Fig. 18a) in the first half of the year. In 2017, highest chlorophyll levels were found in May at depths of 5-15 m in the central strait. More typically, summer chlorophyll concentrations peak at no more than about 10 μg/L, somewhere in the upper 30 m. Chlorophyll concentrations are generally small below about 50 m.

Dissolved oxygen levels (Figs. 18b, 19) are quite high in surface waters in regions 3 and 4, and lower in the northern strait. They are particularly low in the Gulf Islands, southern strait, and Baynes Sound (regions 1, 2 and 5 respectively). In the intermediate water, a maximum in O_2 appears in the first half of the year, and, like the minimum for temperature, appears slightly later in more northern regions. There is a decline in deeper O_2 concentrations later in the year, with oxygen levels becoming lowest in the most northern regions (especially 9 and 10) and the 6 ppm limit (187 μM) starts to surface rapidly in late summer, reaching depths of about 20 m almost everywhere.

However, breaking down the chlorophyll fluorescence data by region does not reveal many systematic trends (Fig. 20). Highest values of 20–30 μg/L tend to occur in spring, with the depth of maximum concentrations at the surface near the Fraser River (regions 2 and 3), and to some extent in the Gulf Islands (region 1), but deeper in other areas. Little chlorophyll is seen in the well-mixed waters of Discovery Passage (region 11).

Depth-integrated chlorophyll shows that the initial stages of the bloom in March are concentrated around the edges of the strait, but are not seen in regions 4 and the southern part of region 6 in the central strait (Fig. 21). During the summer, biomass levels are high everywhere (except in the northern part of region 6). There is no significant difference between the southern and northern strait. During the fall, however, biomass levels drop everywhere, but are not as small in the northern strait.

Secchi depths, on the other hand, are always larger in the northern strait than in the southern strait, and are consistently largest in the Discovery Passage area (regions 11 and the northern part of region 8), and smallest near the Fraser River (region 3).

3.2.3 Nutrients

The growth of phytoplankton (through photosynthesis) requires the uptake of inorganic nutrients. These inorganic nutrient concentrations (Figs. 22 – 24) vary highly at the surface. From around April to September, when an abundance of light favours phytoplankton production, surface nitrate (Fig. 22) and phosphate (Fig. 23) are often at or near zero within the strait. Surface nitrate levels are somewhat higher in and near Discovery Passage, at the northern entrance to the strait, as well in the Cowichan Bay and in the southern strait (region 1). The abundance of nutrients is probably the reason why surface chlorophyll concentrations are so high there; conversely, the depletion of surface nutrients in central strait regions may explain the relative lack of near-surface chlorophyll there over the summer.

Below the surface at 20 m, the water is generally less favourable for algae production because there is little light. There is an influx of nutrients through upwelling and mixing with the nutrient-rich deep water, but little uptake. Because of this, concentrations remain relatively high (usually 10 to 20 μM for nitrate) throughout the year.

As nitrate and phosphate concentrations are well correlated (Fig.11), we see that the pattern of phosphate variations (Fig. 23) are similar to those for nitrate, although there is a slight deficit of nitrate relative to phosphate, so that when nitrate is zero there remains a slightly non-zero amount of phosphate. Surface phosphate levels are lowest only in regions 4–8, but remain high in the northern strait regions 8 and 9, as well as the southern strait regions 1 and 2. One difference is in region 3, where nitrate concentrations are near zero all summer, but phosphate concentrations are often significant. This may reflect the effect of nutrient inputs from the Fraser River, where nutrients are not linked though Redfield ratios. At 20 m, concentrations of phosphate are around 1 μM all year and are well correlated with nitrate (Fig. 11).

Silicic acid levels at the surface (Fig. 24) decrease in early summer along with a decrease in nitrate and phosphate, but are well above zero later in the summer. Silicate is a primary component of the frustules of diatoms, a particular class of fast-growing phytoplankton that tends to dominate the spring bloom. However, later the in the year diatoms are a less important part of the phytoplankton community and so silicic acid levels can increase to significantly non-zero concentrations. Silicic acid concentrations at 20 m, again, well correlated with nitrate (Fig.11) are about 40 to 60 μM throughout the year.

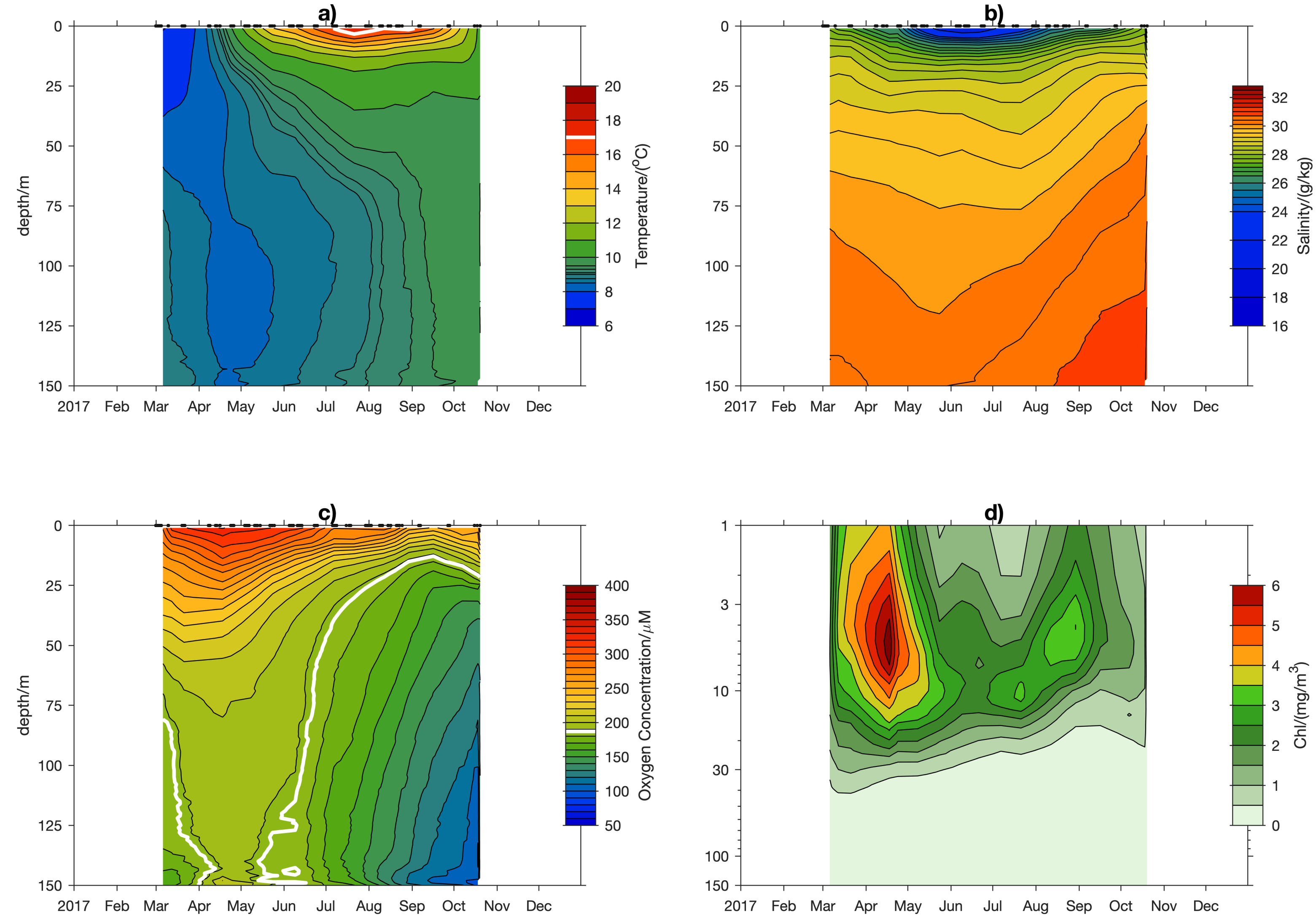

Figure 13: Mean 2017 conditions for the Strait of Georgia (averaged over regions 2/3/4/6/7/8/9) for a) temperature, b) salinity, c) dissolved oxygen content, and d) chlorophyll. White lines indicate 17 °C and 187 μM (6ppm) O_2. Note that the depth axis is logarithmically scaled in d) to highlight near-surface details.

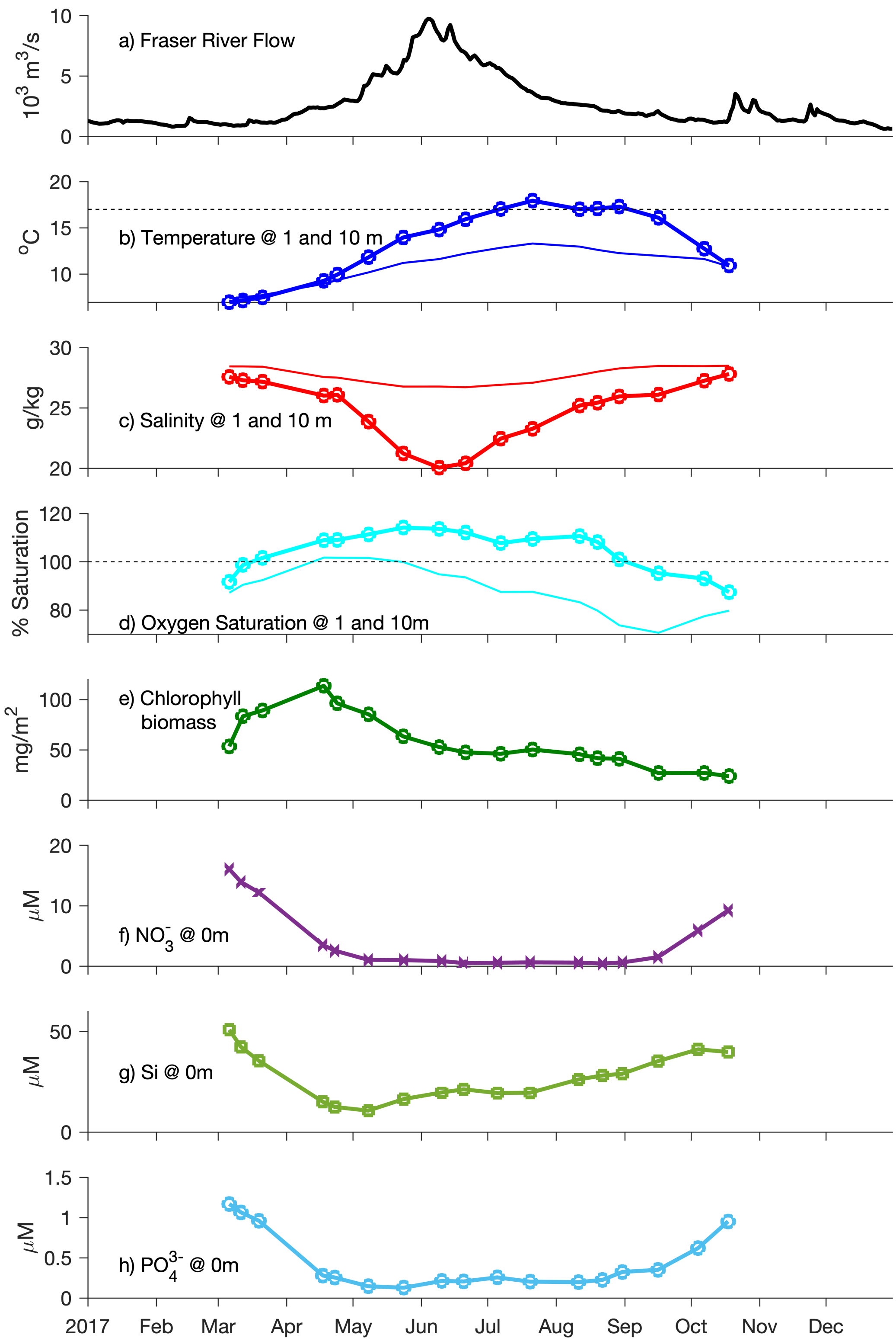

Figure 14: Mean 2017 conditions for the Strait of Georgia (averaged over regions 2/3/4/6/7/8/9) for a) Fraser River flow, b) Temperature at 1 m and (as a thin line) at 10 m, c) salinity at 1 m and (as a thin line) at 10 m, d) Oxygen Saturation at 1 m and (as a thin line) at 10 m, e) Depth-integrated chlorophyll biomass, f) Surface nitrate, g) surface silicate, h) surface phosphate.

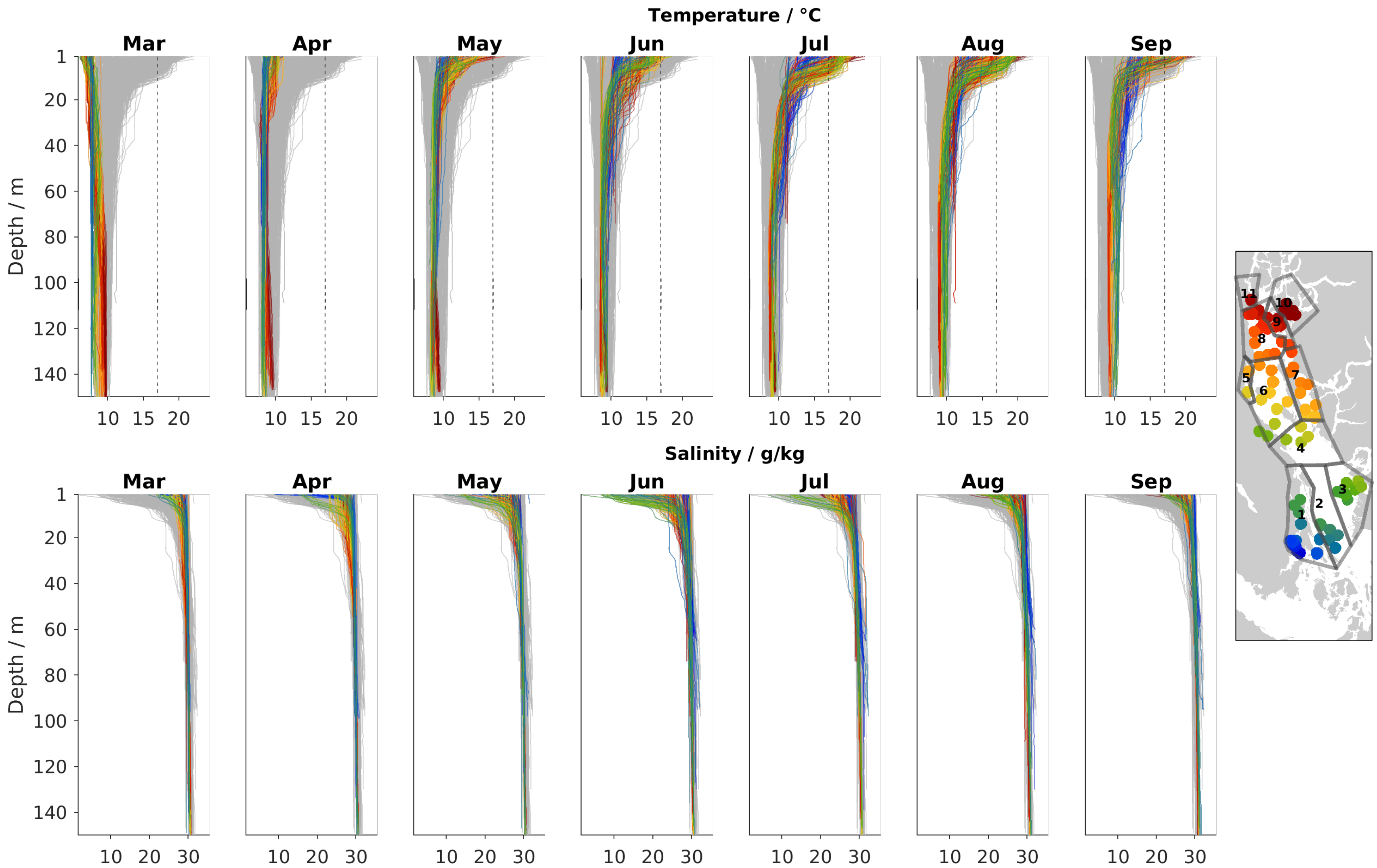

Figure 15: Overview for all temperature and salinity data for 2017. Profiles are binned by month, with colours indicating distance from the south end of the Georgia Strait, as in the map. Dashed lines indicate 17 °C. The gray background lines show all profiles for the whole year.

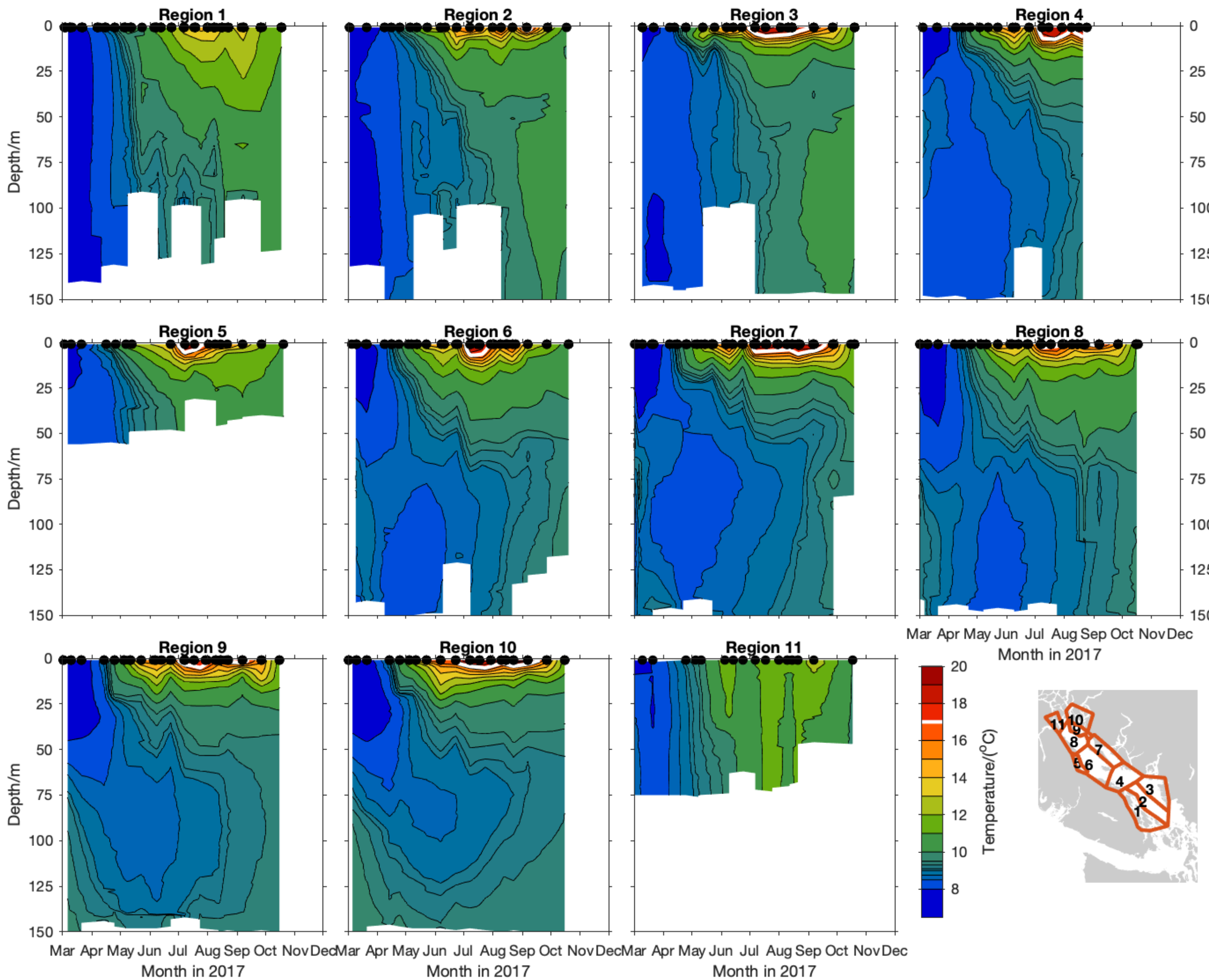

Figure 16: Contour plot for temperature in each region in 2017. Black dots at the top of each plot indicate sampling days for that region. The white line indicates 17 °C.

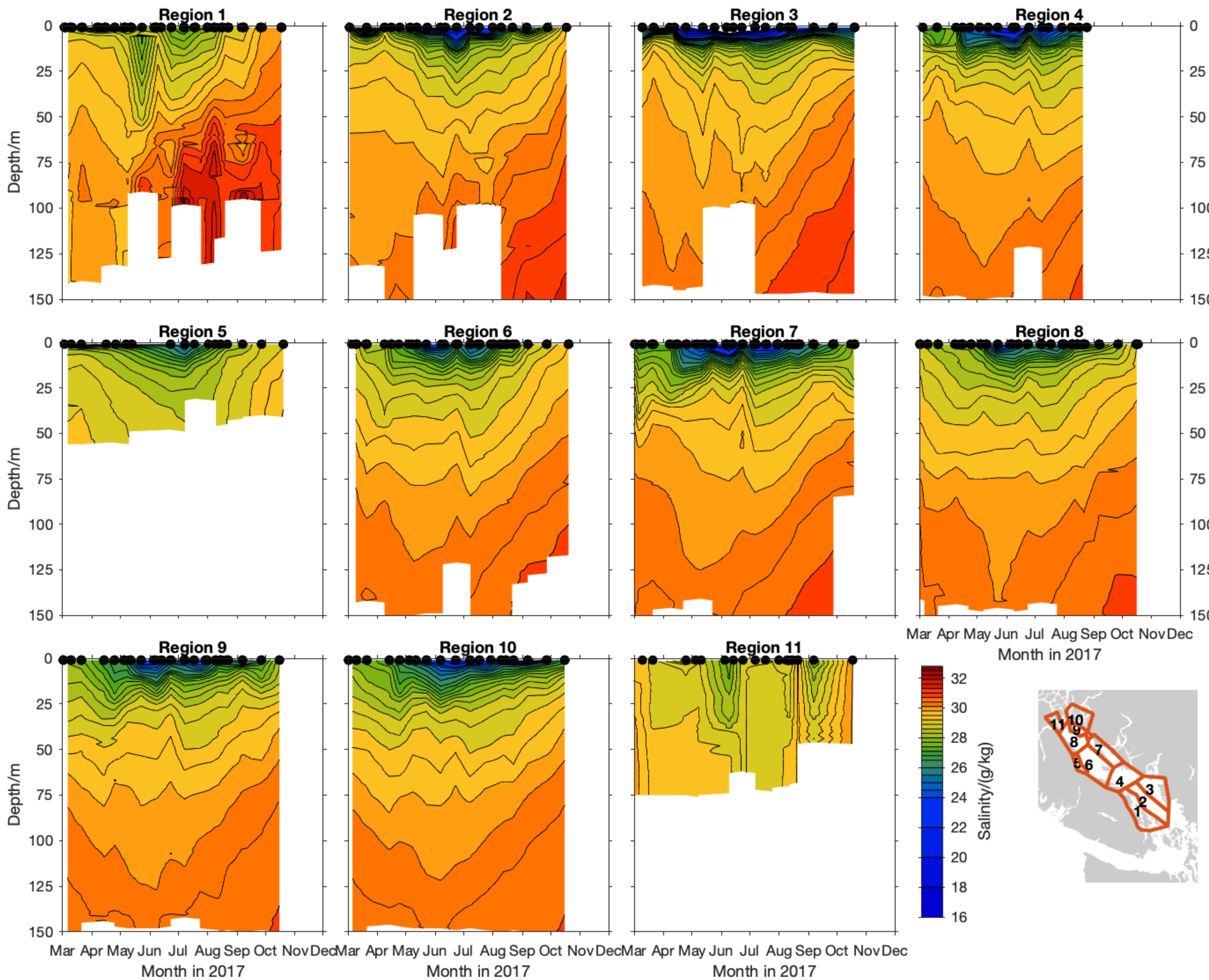

Figure 17: Contour plot for salinity in each region in 2017. Black dots at the top of each plot indicate sampling days for that region.

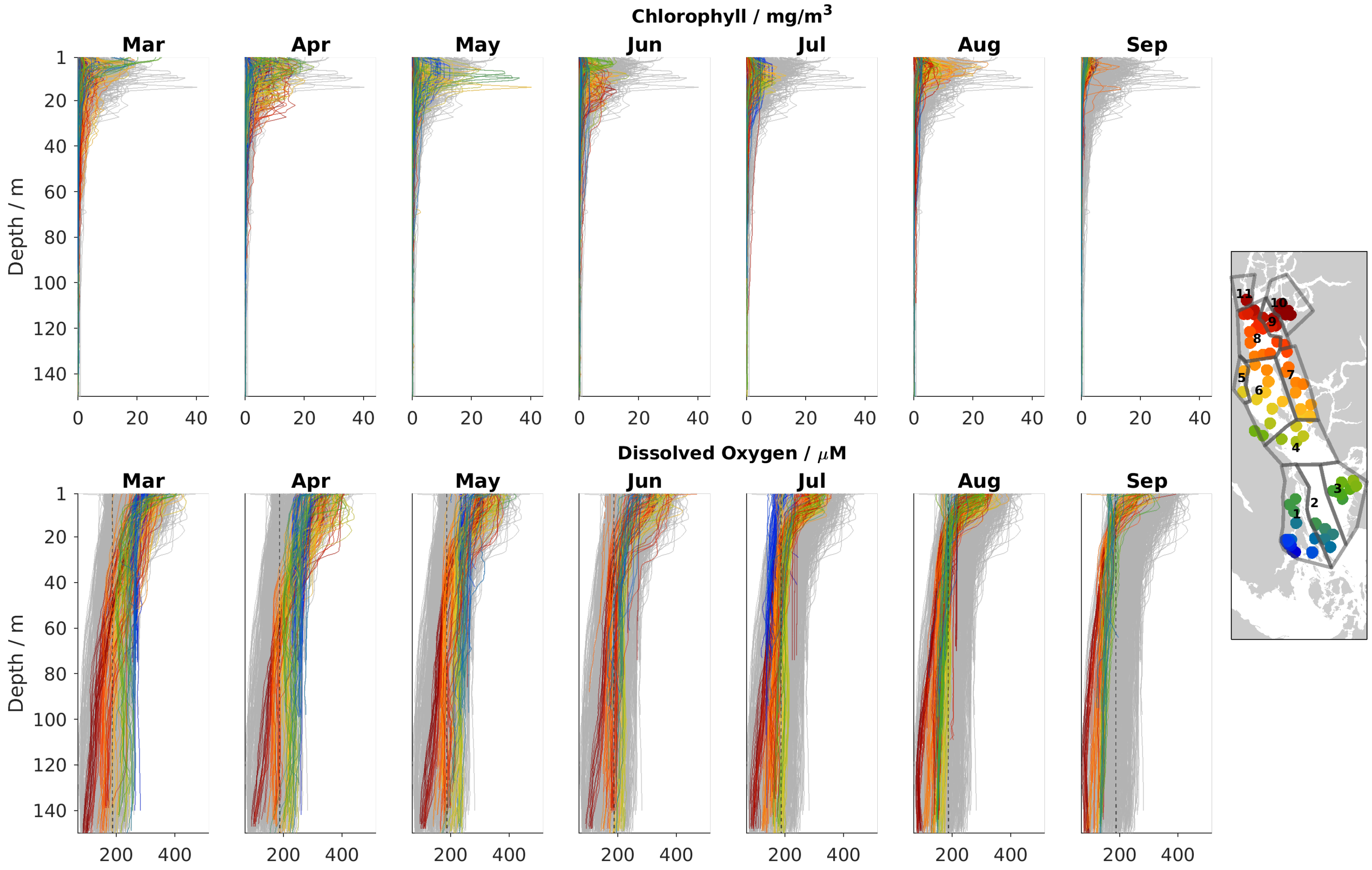

Figure 18: Overview for all chlorophyll fluorescence and dissolved oxygen data for 2017. Profiles are binned by month, with colours indicating distance from the south end of the Georgia Strait, as in the map. Dashed lines indicate 187 μM (6ppm) O_2. The gray background lines show all profiles for the whole year.

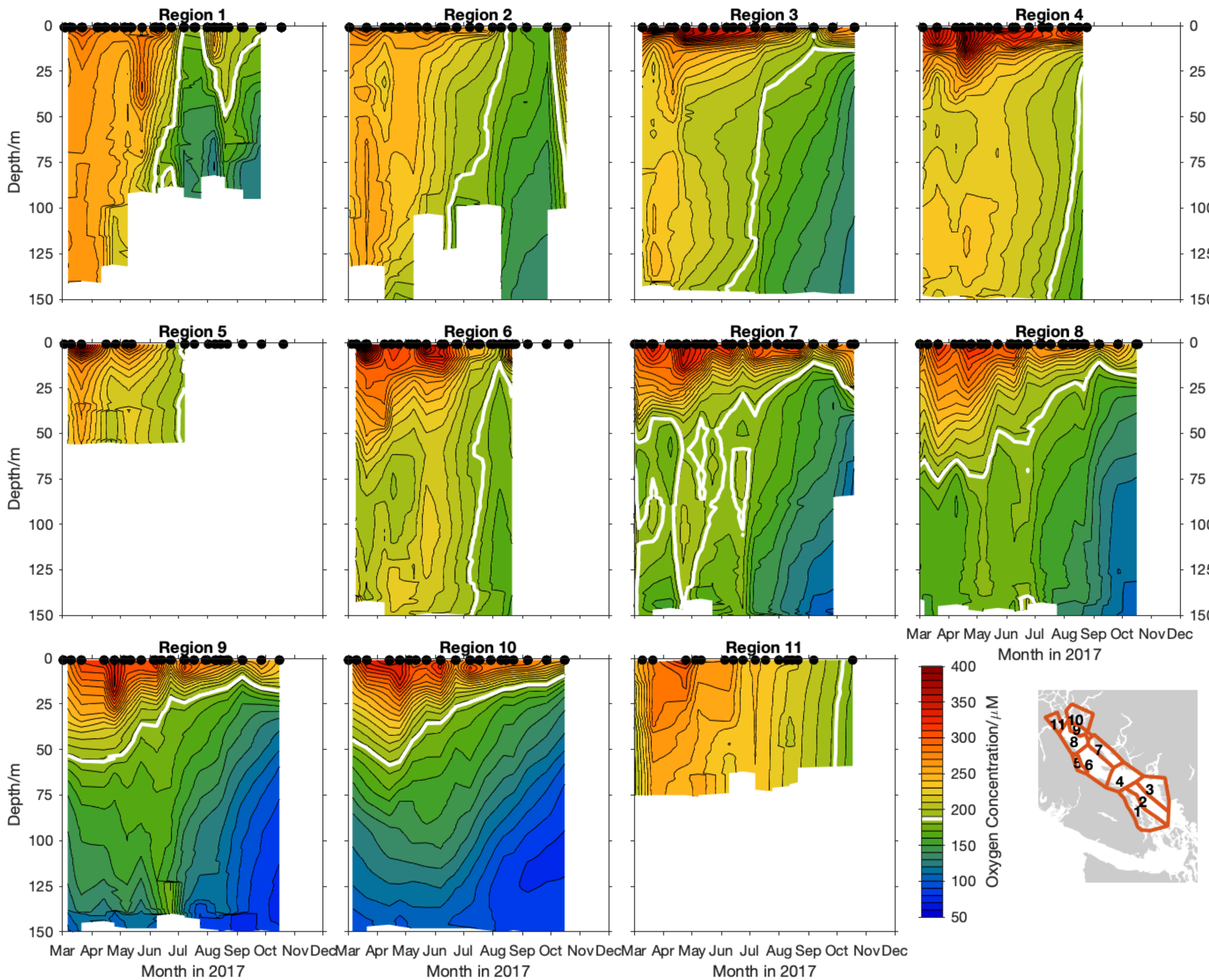

Figure 19: Contour plot for oxygen in each region in 2017. Black dots at the top of each plot indicate sampling days for that region. The white line indicates 187 μM or 6 ppm.

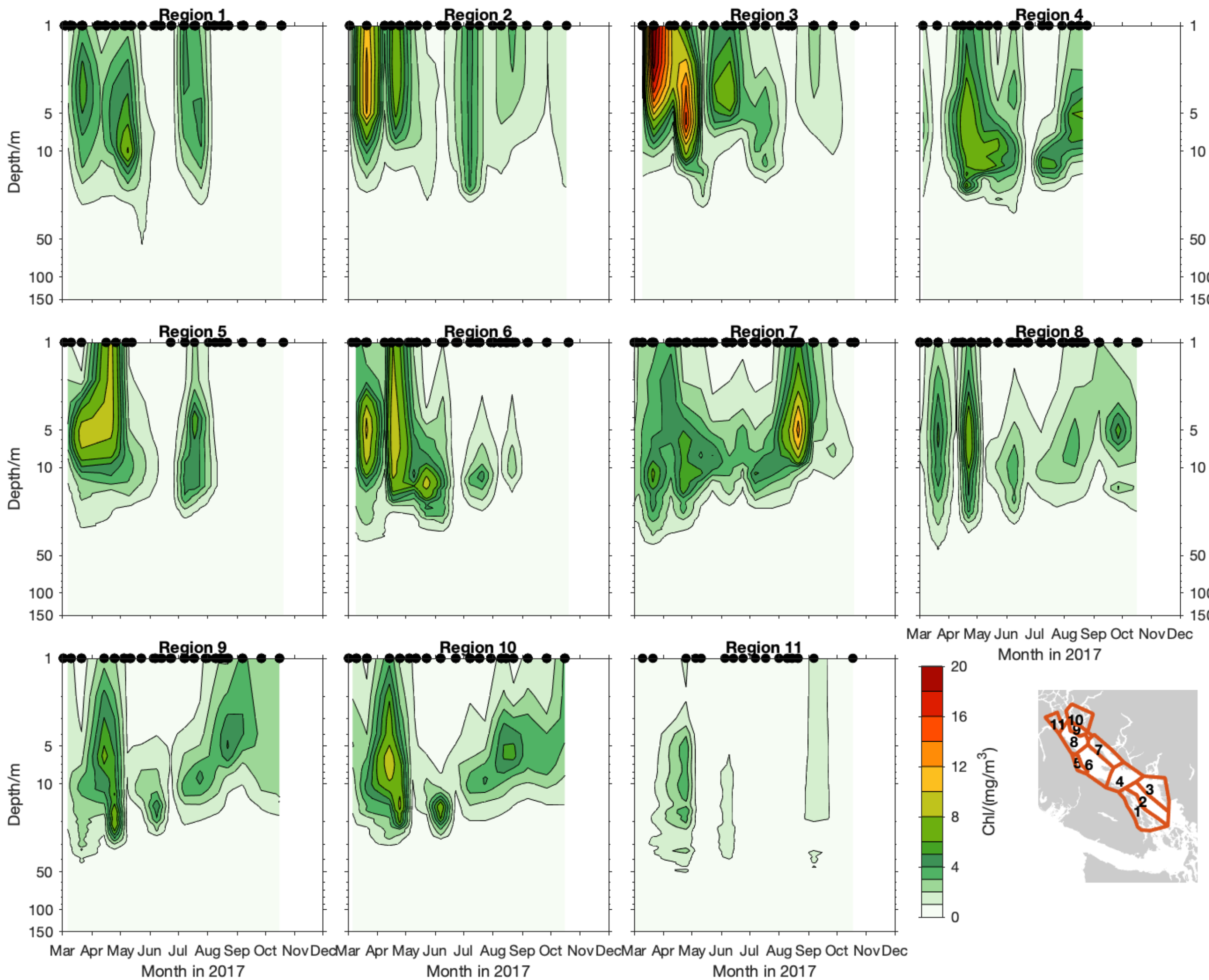

Figure 20: Contour plot for chlorophyll in each region in 2017, with depth on a log scale. Black dots at the top of each plot indicate sampling days for that region.

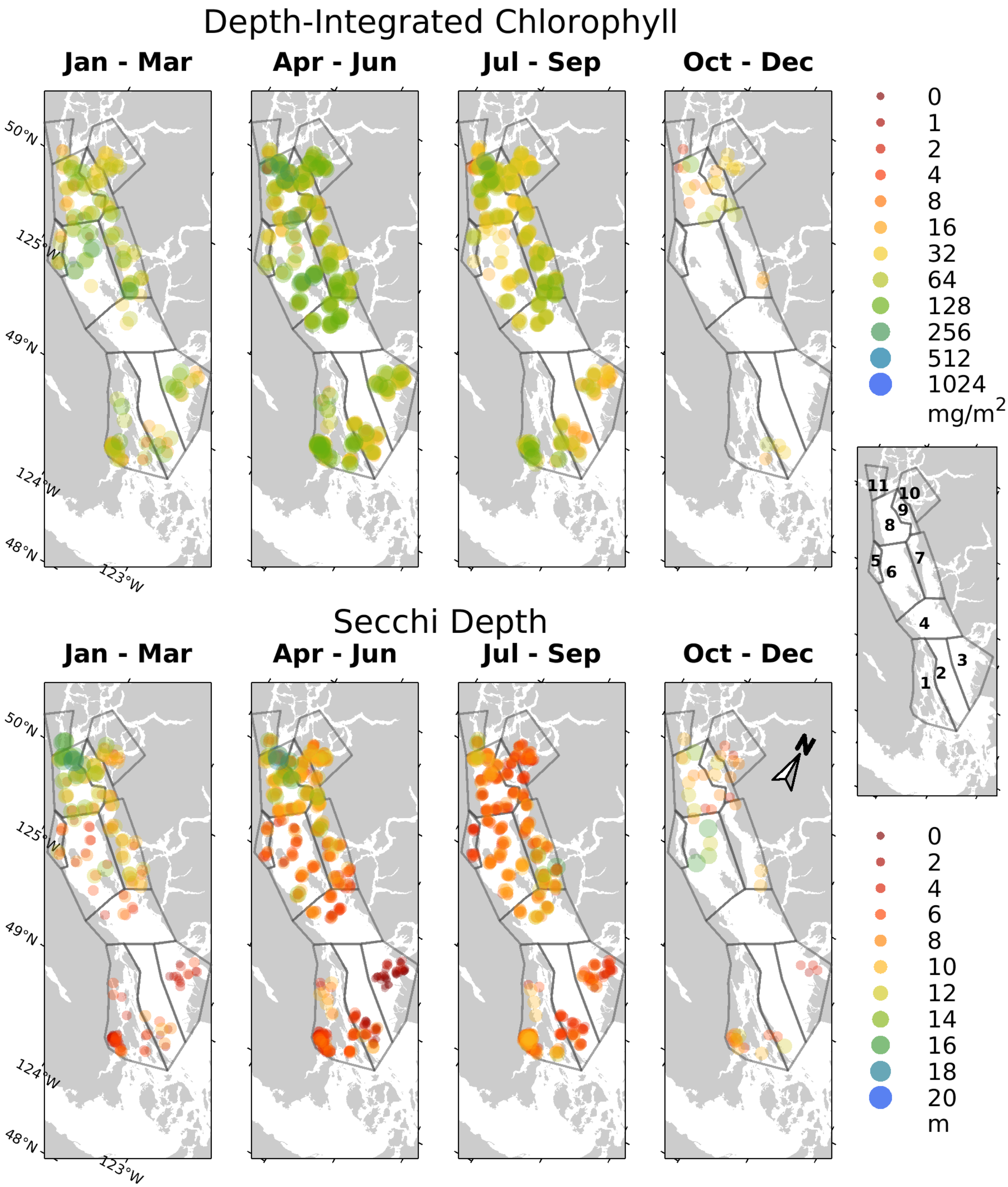

Figure 21: Depth-integrated chlorophyll (upper row) and Secchi depths (lower row) plotted at the location of the measurement, separated into 3 months intervals, for 2017.

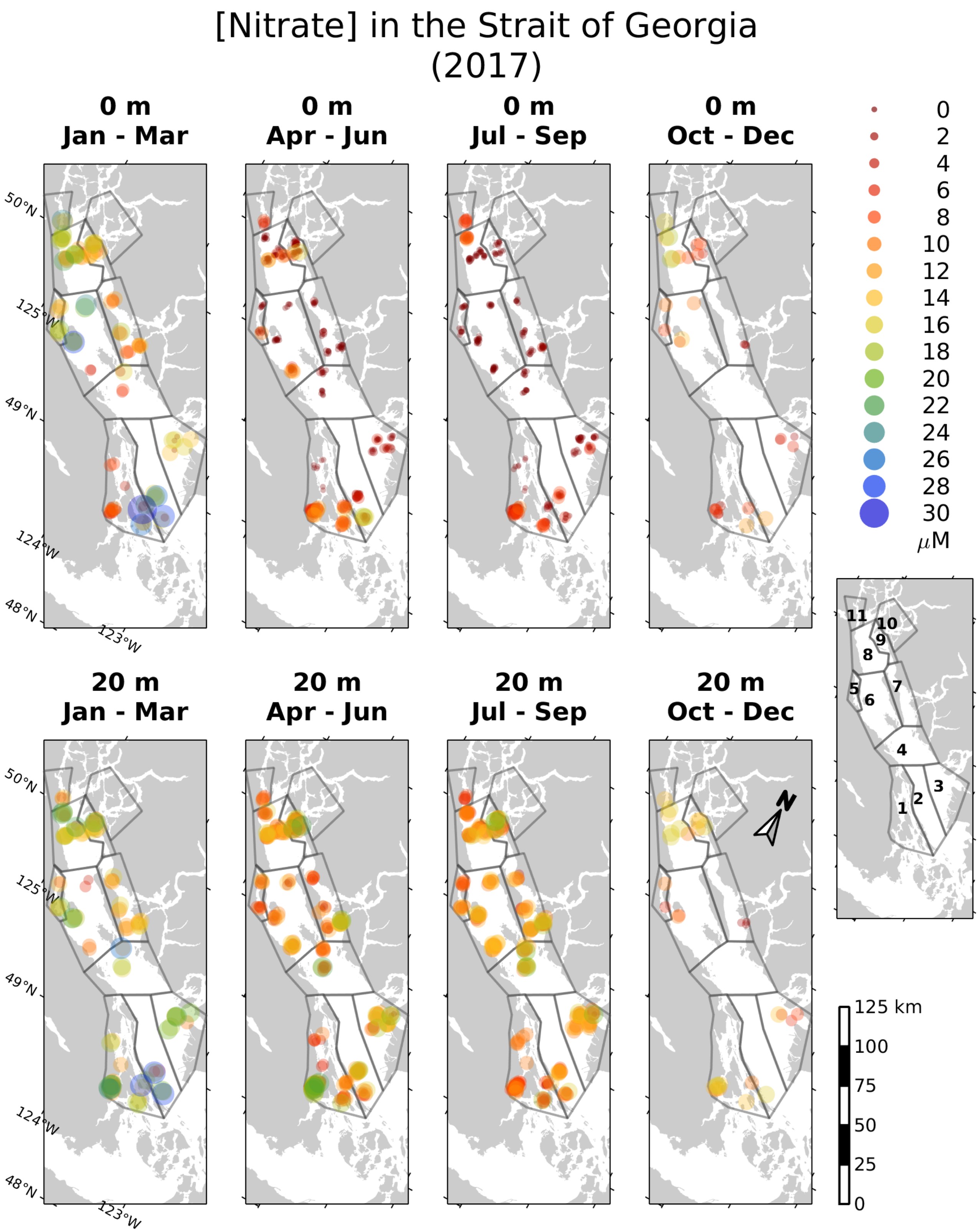

Figure 22: Nitrate levels for 2017 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

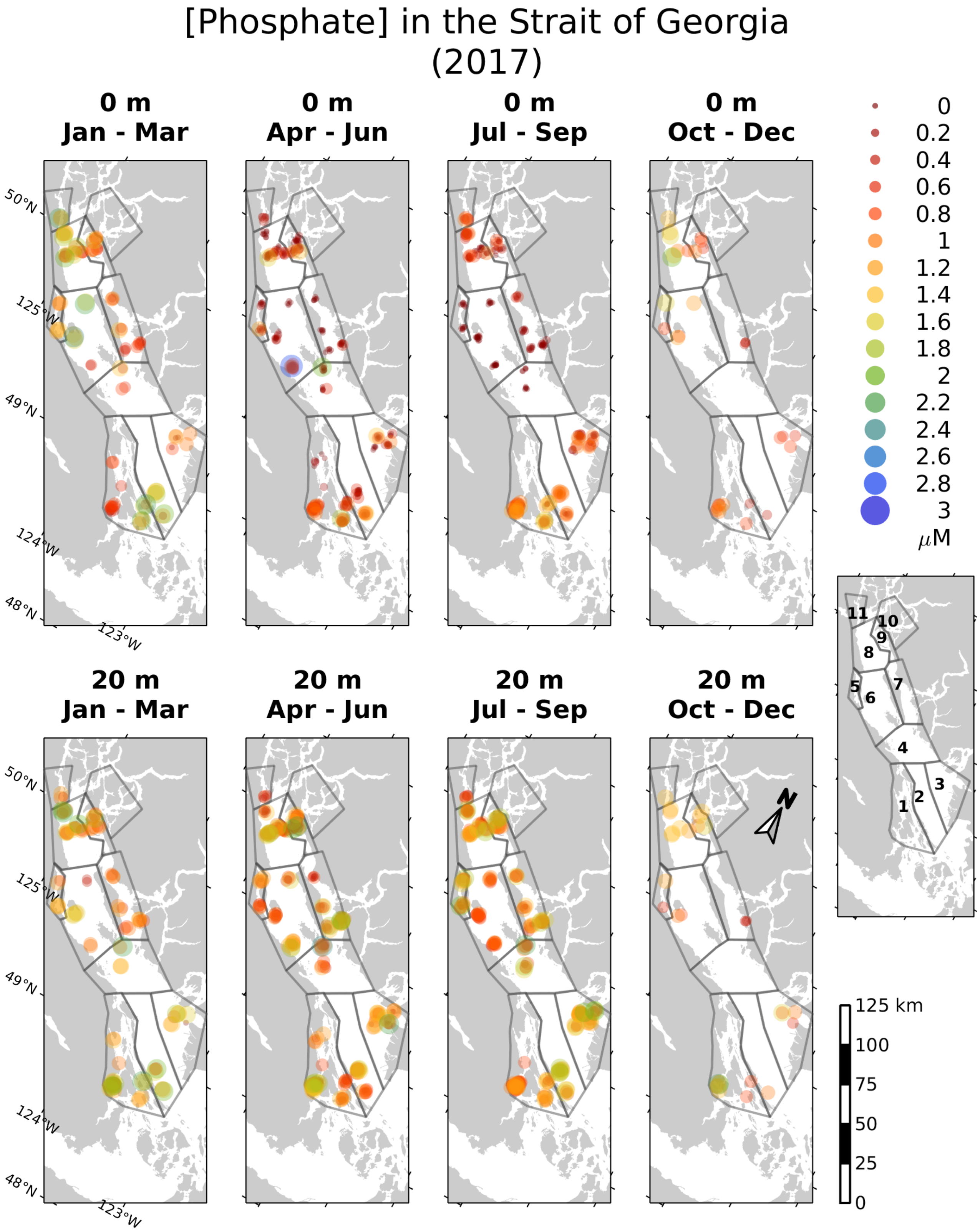

Figure 23: Phosphate levels for 2017 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

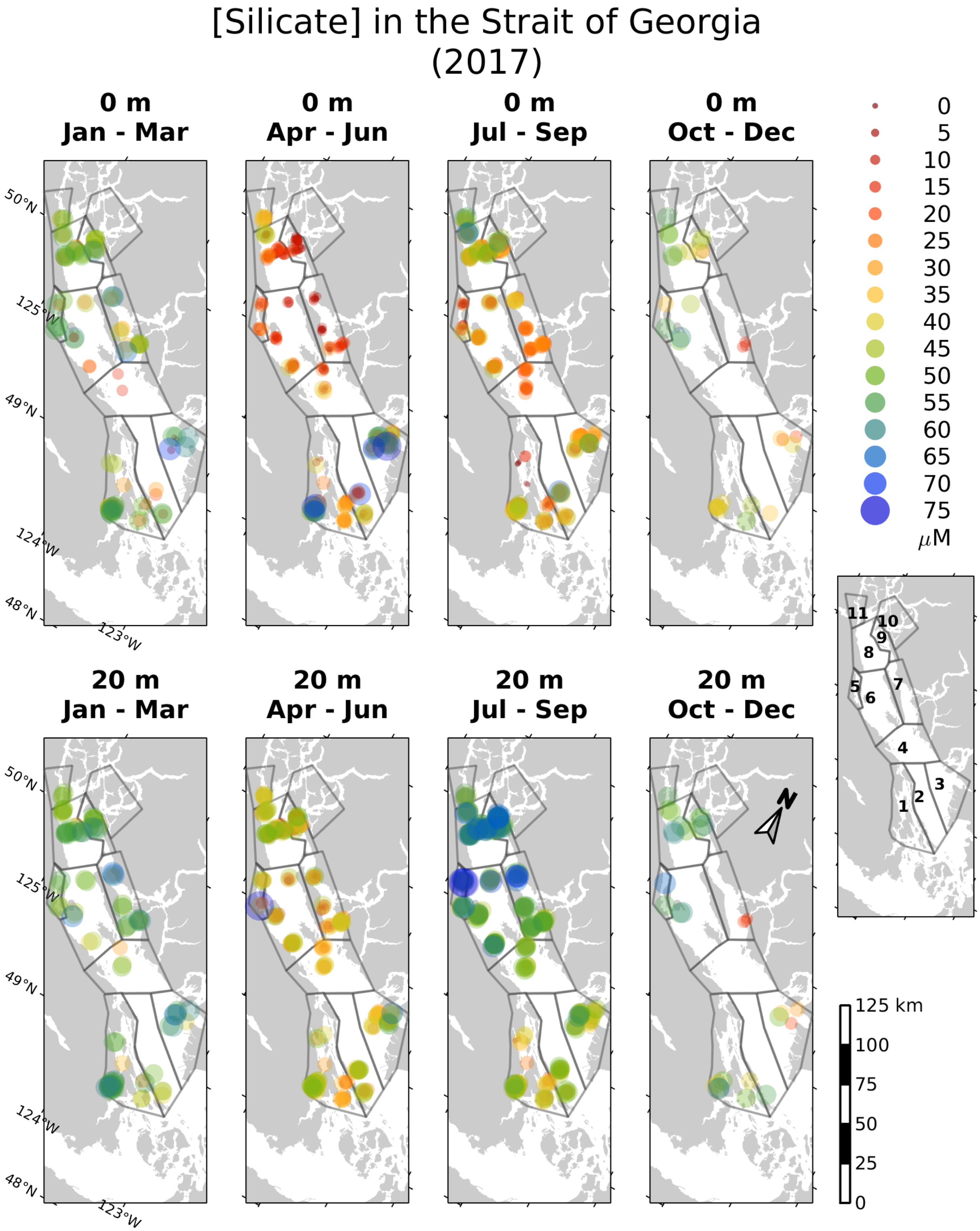

Figure 24: Silicate levels for 2017 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

4 Interannual Changes Near the Surface (2015–2019)

Although the strait has a well-defined annual cycle in its marine characteristics, it can be seen in the figures above that this cycle is slightly modified in different regions within the strait. In addition, there are also year-to-year changes. These changes arise because of interannual variations in local weather, in the timing and magnitude of freshwater inflow during the summer, in the timing and magnitude of wind reversals on the outer coast, and in changes to the characteristics of inflowing Pacific Ocean water. However, these variations in the forcing factors affect different marine characteristics in different ways.

In this section we will present changes over the full 5 years of our dataset. An overview plot (Fig. 25) will summarize all near-surface characteristics, averaged over all regions within the strait itself (i.e., not including the Gulf Islands, Discovery Passage, and Desolation Sound areas). Following this we show interannual variability at each station in a series of plots. In each of these plots, we show the sample locations on a map at left (as in, e.g., Fig. 26), and at right, the time-series data with time shown on the horizontal axis. The data is plotted at the same vertical level as the map marker of the station at which it was collected. Note however that the Cowichan Bay stations are moved downward slightly so as not to overlap with the southern strait stations, as are region 9 stations in the nutrient plots. The values of specific observations are colour and size-encoded according to a legend on the right hand side.

Freshwater inflow is a major factor affecting the strait. Just over half of this inflow is provided by the Fraser River (Pawlowicz et al., 2007; Morrison et al., 2012). Although there are no direct measurements of the flow of this river at its mouth due to the complications of tides, the continuously monitored gauge at Hope, B.C. , above winter tidal influences (Water Survey of Canada station 08MF005) accounts for about 90% of the total Fraser inflow. Thus, we show the flow of the Fraser River at Hope over the same time period in all plots.

The annual cycle of the Fraser River flow is marked by a strong freshet during the summer as a result of snowmelt in the B.C. interior (Fig. 25a). The 2017 and especially 2018 freshets are marked by a brief period of very high flows in late May and early June. In contrast, the 2016 freshet began earlier, but peak flows were only half as large as those in the two following years and well below a climatological mean. Note however that these freshet peaks reflect the rapidity of snowmelt, although not necessarily its amount. The total annual discharges for the years 2015–2018 (not shown) are quite similar, but somewhat larger than the discharge for 2019.

4.1 Temperature and Salinity

Temperatures at a depth of 1 m (Fig. 25a and 26), essentially the same as surface temperature, are cold in the winter and warm in late summer. A similar cycle in amplitude and timing is seen virtually everywhere in the strait, except perhaps at the southernmost stations in the strait itself (the southern end of region 2). There is little difference between surface temperatures in the southern, central, and northern straits, nor are there large differences in the cycle from year to year.

However, surface temperatures in Discovery Passage at the northern boundary of the strait remain far colder than strait waters in summertime, with maximum temperatures of only about 13°C, whereas maximum strait surface temperatures peak at around 21°C (Fig. 26). Summer surface temperatures are even colder off Victoria (observed only in 2015), reaching only 12 °C. Then, within the Gulf Islands, surface temperatures in Cowichan Bay are also colder than in the Strait of Georgia (although warmer than Victoria), reaching only about 16°C.

Wintertime temperatures are less well known from this dataset. However, on the basis of a few measurements over the winter of 2018/2019, we estimate that surface temperatures in the strait can drop to as low as 5°C (minimum strait-wide average about 6.5°C).

Salinities near the surface also have a prominent seasonal signal, clearly related to the freshet (Fig. 25c), with the mean over the entire strait dropping to as low as 20 g/kg. However, salinities are very different in different regions. They are significantly lower in the southern strait than in the northern strait, affected by the freshwater inflow from the Fraser River (Fig. 27). In the northern strait, salinities are in the high 20s (g/kg) over the early and late part of the year, dropping into the low 20s in summer, although the seasonal cycle is not well-defined. In the southern strait, however, salinities are clearly lowest during the peak of the freshet, and also reach much lower values in years when the freshet peak flows are highest (2017 and 2018), compared to years with lower freshet flows like 2016 and 2019. Salinities in areas offshore from the Fraser River can fall below 6 g/kg in these high-flow periods, but only as low as 10 g/kg in low-flow years. As we move northwards away from the Fraser River mouth into the central strait, our 2019 measurements show lower salinities in stations nearest the Sunshine Coast, relative to those offshore; freshet-related decreases in salinity are also seen in most years extending as far as Texada Island.

The colder waters off Victoria are also significantly saltier than strait waters, with salinities of around 30 g/kg year-round in 2015. Gulf Islands waters are also salty, although not a salty as Victoria surface waters, in the range of 27 g/kg, with no obvious seasonal trend.

4.2 Dissolved Oxygen, Chlorophyll Biomass, and Secchi Depth

The chlorophyll biomass, calculated by depth-integrating chlorophyll fluorescence profiles (Fig. 25e and 28), is quite different from year to year. Winter values are only in the range of 4–20 mg/m^2, but are in the range of 30–80 mg/m^2 during the summer, and 200–300 mg/m^2 in May 2016 and March 2019. These extremely high spring bloom values tend to occur only in the northern and central strait, with values south of the Fraser River peaking at somewhat lower values of around 100 mg/m^2, while values in Discovery Passage and off Victoria tend to peak at no more than 60 mg/m^2.

During the summer, spatially coherent increases and decreases in biomass can be seen on an approximately monthly cycle, especially in the northern strait in 2017 and 2018, but these do not appear in strait-wide averages (Fig. 25e). The integrated biomass is not noticeably less in the waters near the Fraser River relative to those elsewhere in the strait, even though (as we shall see next) the Secchi depths are quite different. However, recall that the chlorophyll biomass tends to have a maximum near the surface even in summer in the southern strait, while this maximum is at a depth of 5–10 m in the northern strait (Fig. 20).

Somewhat hidden in Fig. 28 is the fact that region 5 (Baynes Sound) integrated chlorophyll levels are somewhat higher than those in other years, in all years except 2015. This is more easily seen in Fig. 48 in Appendix A.

Dissolved oxygen levels near the surface are well above saturation all summer (Fig. 25d), and this supersaturation appears even down to 10 m in most years during the spring (2015 is an exception). The degree of supersaturation is not clearly linked to the amount of biomass, although both are largest in 2016, suggesting that other factors, such as advective export or air-sea gas transfer might also play a role in setting these concentrations (Wang et al., 2019).

Water clarity, as measured by the Secchi depth (Fig. 29), is strongly seasonal. Winter values are ≈ 15 m, and values of 10 m are typical for Discovery Passage. Victoria stations have depths of around 8 m, while in the southern strait, the turbid Fraser plume waters (Pawlowicz et al., 2017) result in depths of less than (and sometimes much less than) 1 m. Over the central and northern strait values range from 1 to 10 m, and are typically inversely correlated with the depth-integrated chlorophyll measurements (Fig. 28), with large biomass resulting in a smaller Secchi depth.

4.3 Nutrients

Surface nitrate values (Fig. 30) tend to be around 22 μM year-round off Victoria, and during the winter in the strait. At these times this nutrient is mixed upwards from deeper waters and is not depleted by the growth of phytoplankton. However, during the summer, nitrate values are essentially zero near the surface within the strait (Fig. 25f); nitrate is presumably the factor limiting phytoplankton growth. Nitrate levels in Cowichan Bay, on the other hand, are around 6–10 μM, somewhere between those of the strait and those off Victoria. Note also that non-zero nitrate concentrations are also regularly observed in region 8, just south of Discovery Passage (region 11). This may represent occasional surface outflows (perhaps related to the stage of the tide) from Discovery Passage itself.

Nitrate values at 20 m (Fig. 31) are generally high, although 20 m is not quite deep enough to get below the near-surface chlorophyll biomass so that a slight summer decrease is seen in most years. More obvious are the generally lower concentrations at this depth in 2016 and (especially) in 2017. The source of this decrease is probably a bias arising from the different analytical procedures used in that year (see Section 2.5)

Phosphate values at 0 m (Fig. 25h and 32) and 20 m (Fig. 33) are closely correlated with those of nitrate (see Fig. 11), but when nitrate decreases to zero phosphate does not. Thus, surface levels of phosphate in the strait are slightly non-zero during the summer (about 0.3 μM but this varies from year to year), although are still much smaller than winter values of about 2 μM, as well as those in Cowichan Bay.

Silicate is occasionally depleted in summertime surface waters (Fig. 34), but although average summertime levels of around 20 μM are significantly lower than wintertime levels of 50 μM they are well above zero (Fig. 25g). They tend to be lowest around May, likely due to the dominant presence of diatoms in the phytoplankton community, but a second minimum also appears in late summer of 2018.

4.4 Harmful Algae

Harmful algae were identified in many samples, although with little consistency from year to year (Figs. 36–41), note that 2019 samples had not yet been enumerated at the time of writing. The most abundant taxa of harmful algae (present in >5% of the samples) included *Alexandrium* spp., *Dictyocha* spp., *Heterosigma akashiwo*, and *Rhizosolenia setigera*. All of these except *H. akashiwo* were almost always present in low concentrations in a subset of samples at any particular time outside of winter, but all except *Alexandrinium* also had some noticeable "blooms" with high concentrations that covered large portions of the strait at some times in the summer.

Alexandrium (Fig. 36), which produces toxins causing paralytic shellfish poisoning or PSP in humans and other mammals, was consistently present at levels high enough to cause PSP closures (i.e., >0.5 cells/mL; Hallegraeff et al., 2004) throughout spring and summer in all years. Although not obvious in Fig. 36, it generally appeared only at shallow (<100 m) sampling sites. Very high concentrations (>10 cells/mL) were recorded once or twice in each summer in Cowichan Bay; in 2015 this coincided with high values near Ladysmith.

The silicoflagellate *Dictyocha* (Fig. 37), toxic to fish, had blooms of >200 cells/mL in June 2016 and August 2017. These blooms were apparent almost everywhere, but were strongest in the northern strait, Malaspina Strait, and in Cowichan Bay.

The ichthyotoxic raphidophyte *H. akashiwo* (Fig. 38), which kills salmon, had maximum concentrations exceeding 5,000 cell/mL in some areas of the strait in June 2018. Its concentrations were approximately two orders of magnitude lower in the central strait in the late summer of 2016, but almost none were seen in 2015.

Finally, the centric diatom *Rhizosolenia setigera* (Fig. 39), harmful to fish gills, consistently bloomed around the beginning of August of all years. Concentrations at that time were many 100s of cell/mL in August of 2016, 2017, and 2018, but the bloom in August of 2015 was very much weaker.

Other harmful algae were also present on occasion. *Chaetocerus convolutus* and *C. concavicorne*, (Fig. 40), harmful to fish gills, was observed in the northern strait in the spring and summer of 2015, as well as in March and October 2017, but was otherwise not present in summer. *Dinophysis* (Fig. 41), a taxa that causes diarrhetic shellfish poisoning, was seen in 2018 in the central strait, and especially in Cowichan Bay, but was only occasionally observed otherwise.

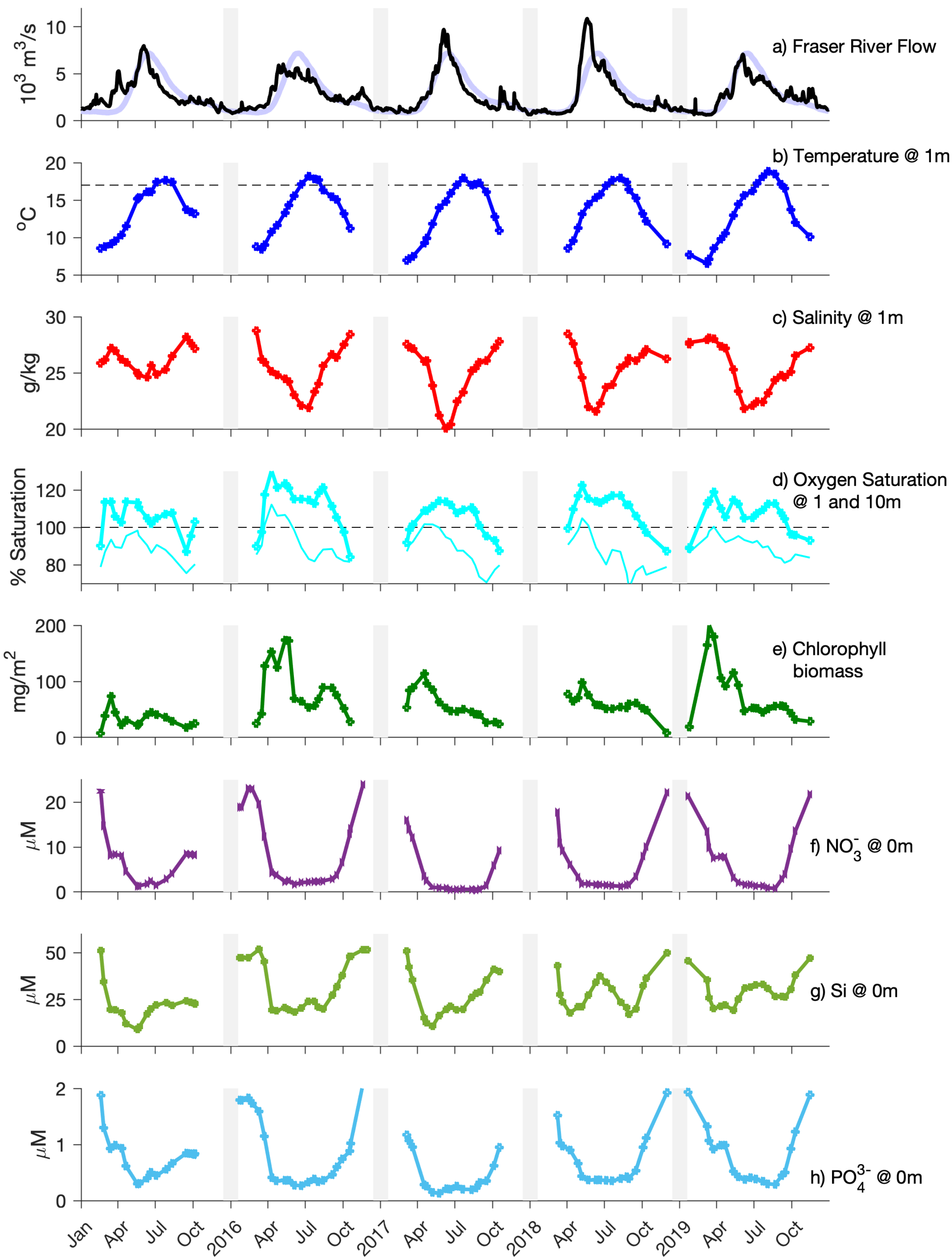

Figure 25: Mean conditions for the Strait of Georgia (averaged over regions 2/3/4/6/7/8/9) for a) Fraser River flow (light mauve line is a 108-year climatology), b) temperature at 1 m, c) salinity at 1 m, d) oxygen Saturation at 1 m and (as a thin line) at 10 m, e) depth-integrated chlorophyll biomass, f) surface nitrate, g) surface silicate, h) surface phosphate.

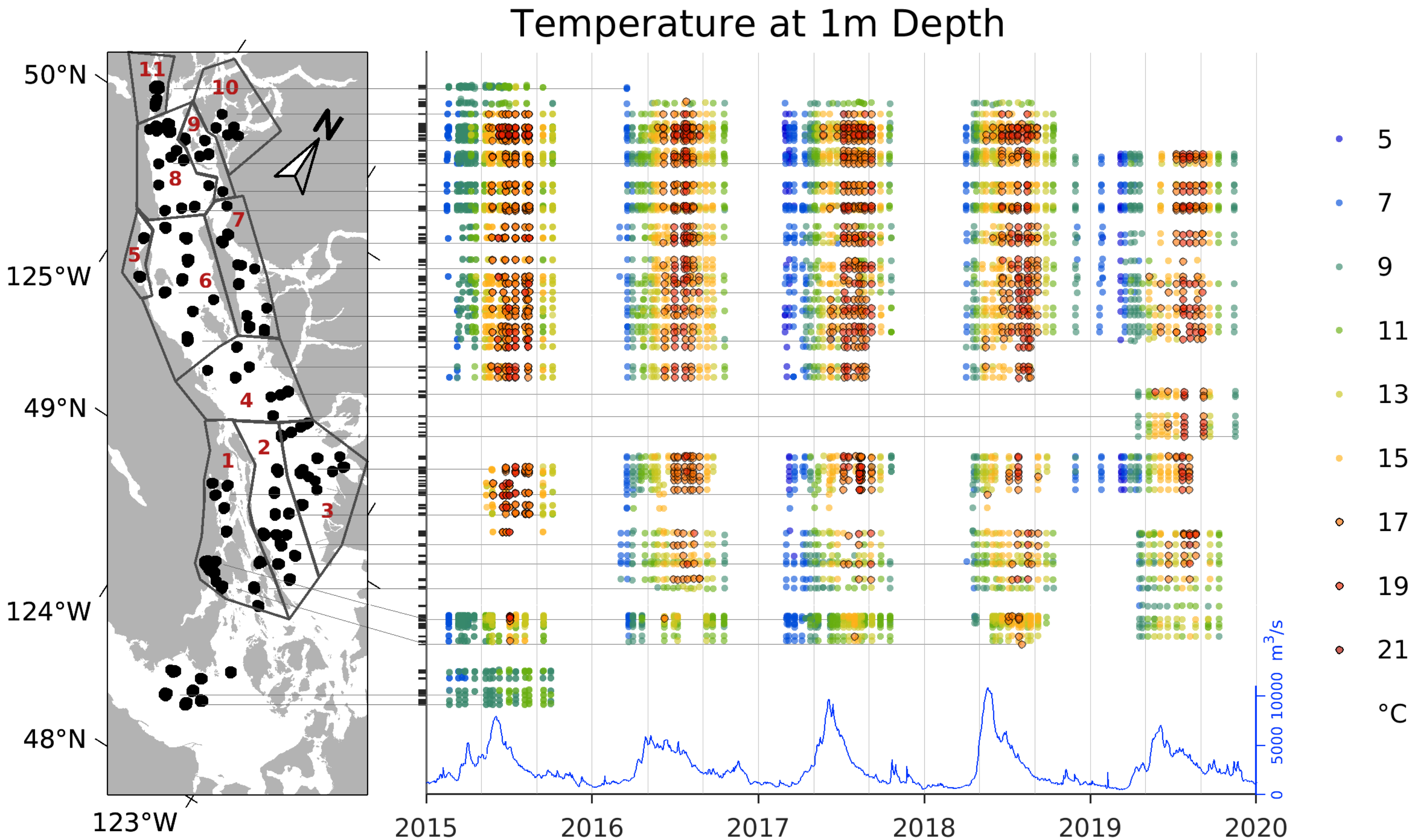

Figure 26: Temperature data for all years. Data for each station is plotted horizontally through time at a vertical location that coincides with its location in the map at left. Gray lines mark the beginnings of January, May and August in each year. The blue line indicates the flow of the Fraser River. Temperatures of 17 °C or above are shown with a black outline.

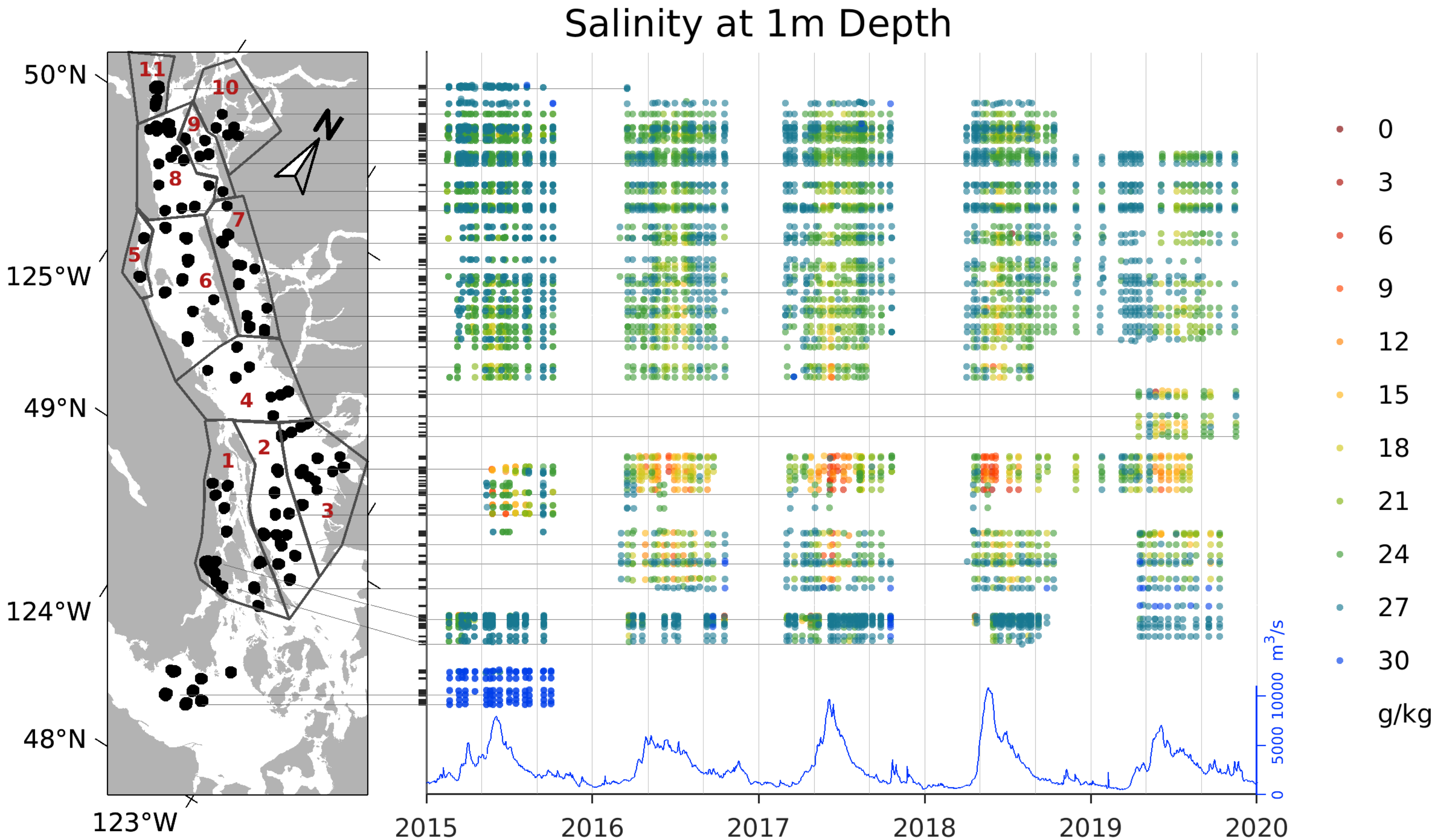

Figure 27: Salinity data for all years. Data for each station is plotted horizontally through time at a vertical location that coincides with its location in the map at left. Gray lines mark the beginnings of January, May and August in each year. The blue line indicates the flow of the Fraser River.

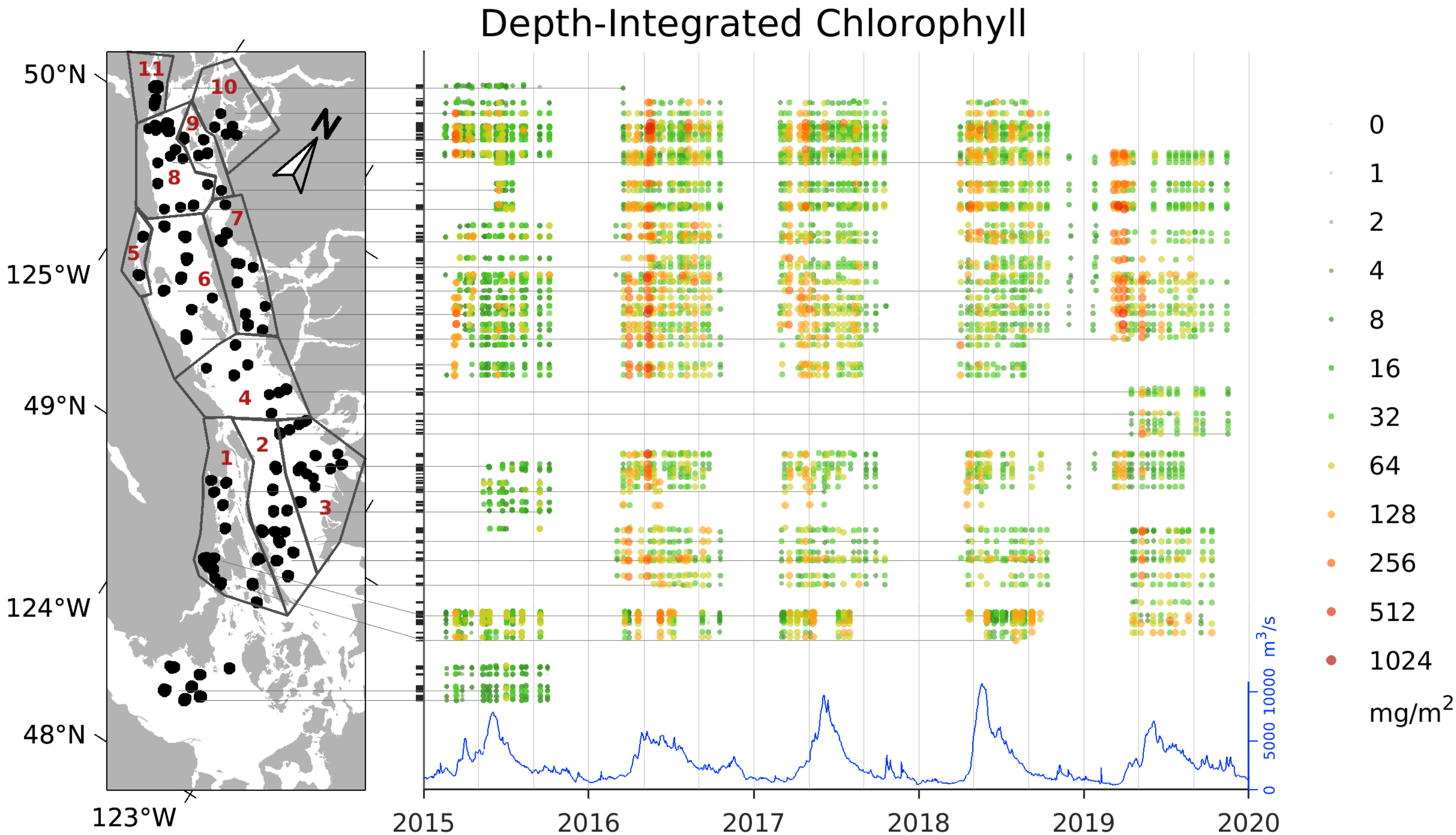

Figure 28: Depth-integrated chlorophyll data for all years. Data for each station is plotted horizontally through time at a vertical location that coincides with its location in the map at left. Gray lines mark the beginnings of January, May and August in each year. The blue line indicates the flow of the Fraser River.

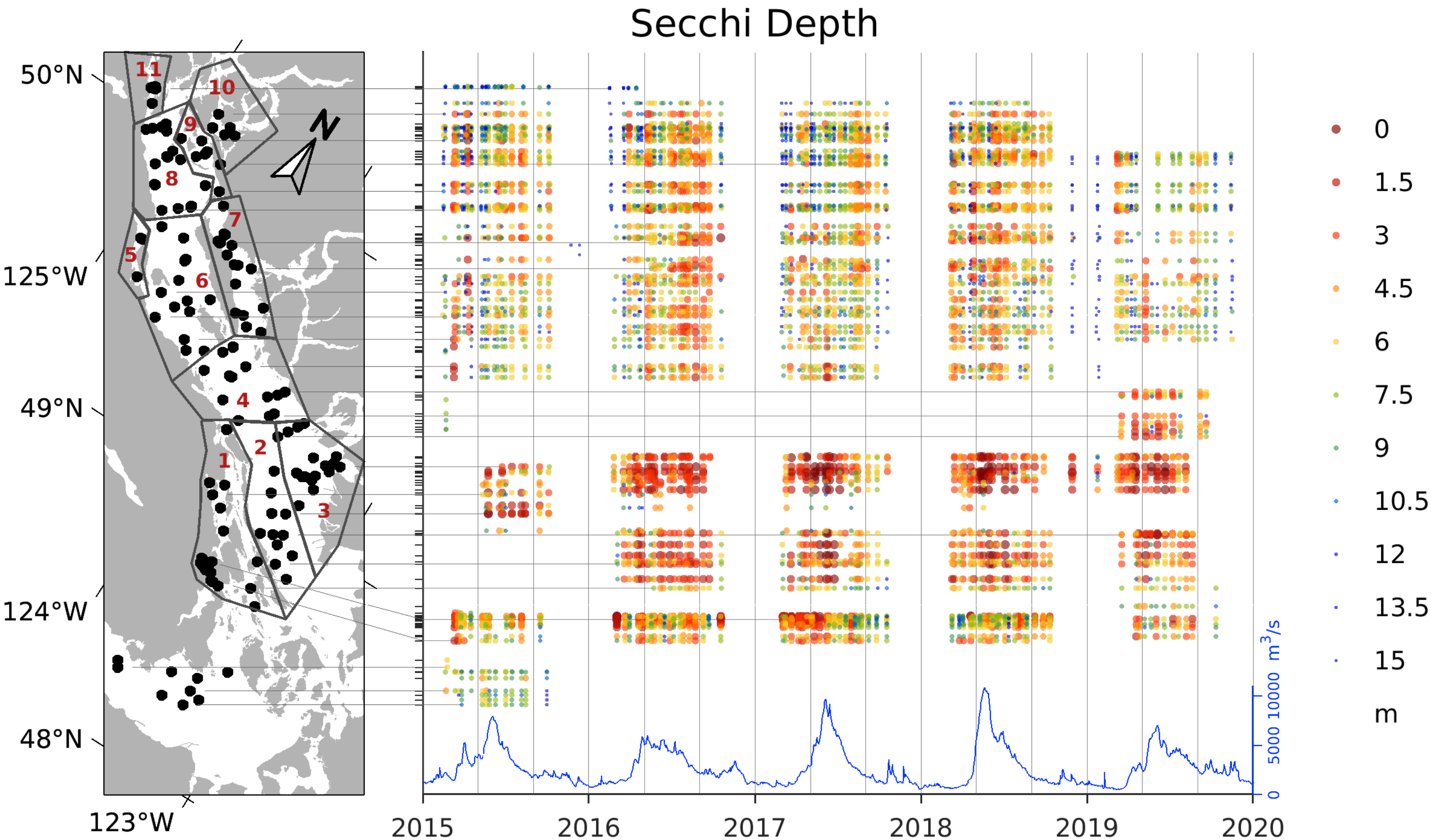

Figure 29: Secchi depth data for all years. Data for each station is plotted horizontally through time at a vertical location that coincides with its location in the map at left. Gray lines mark the beginnings of January, May and August in each year. The blue line indicates the flow of the Fraser River.

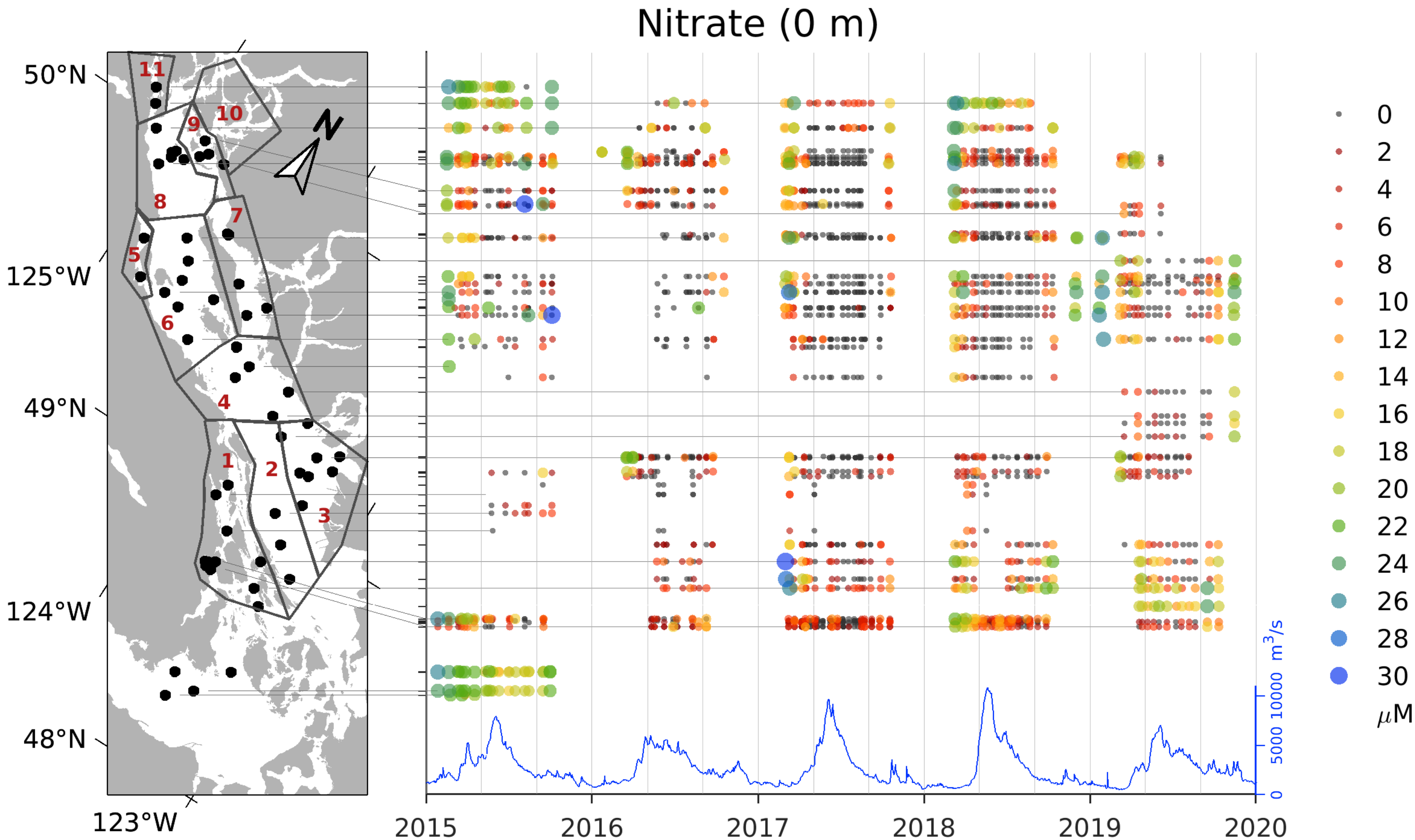

Figure 30: Nitrate data at 0 m for all years. Data for each station is plotted horizontally through time.

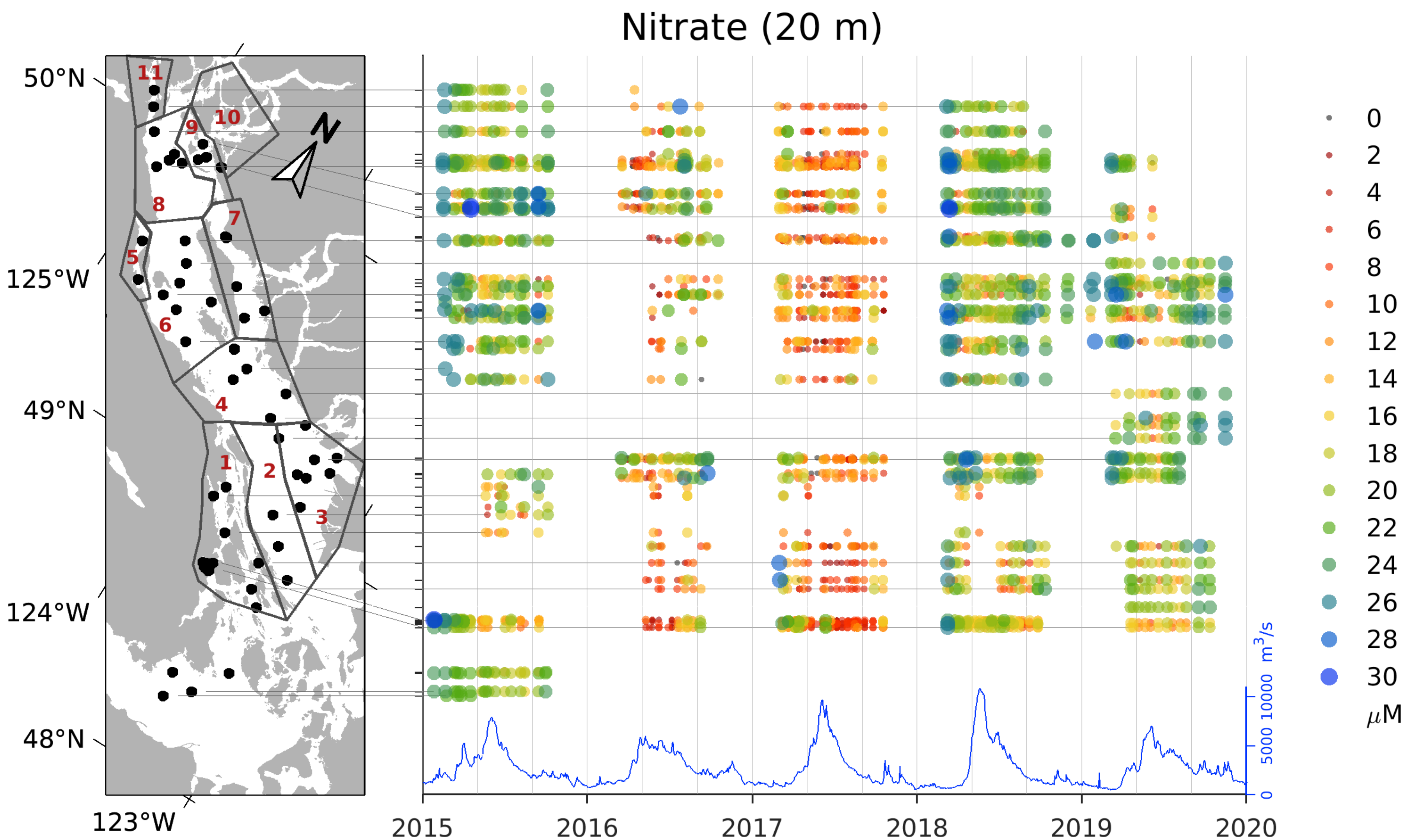

Figure 31: Nitrate data at 20 m for all years. Data for each station is plotted horizontally through time.

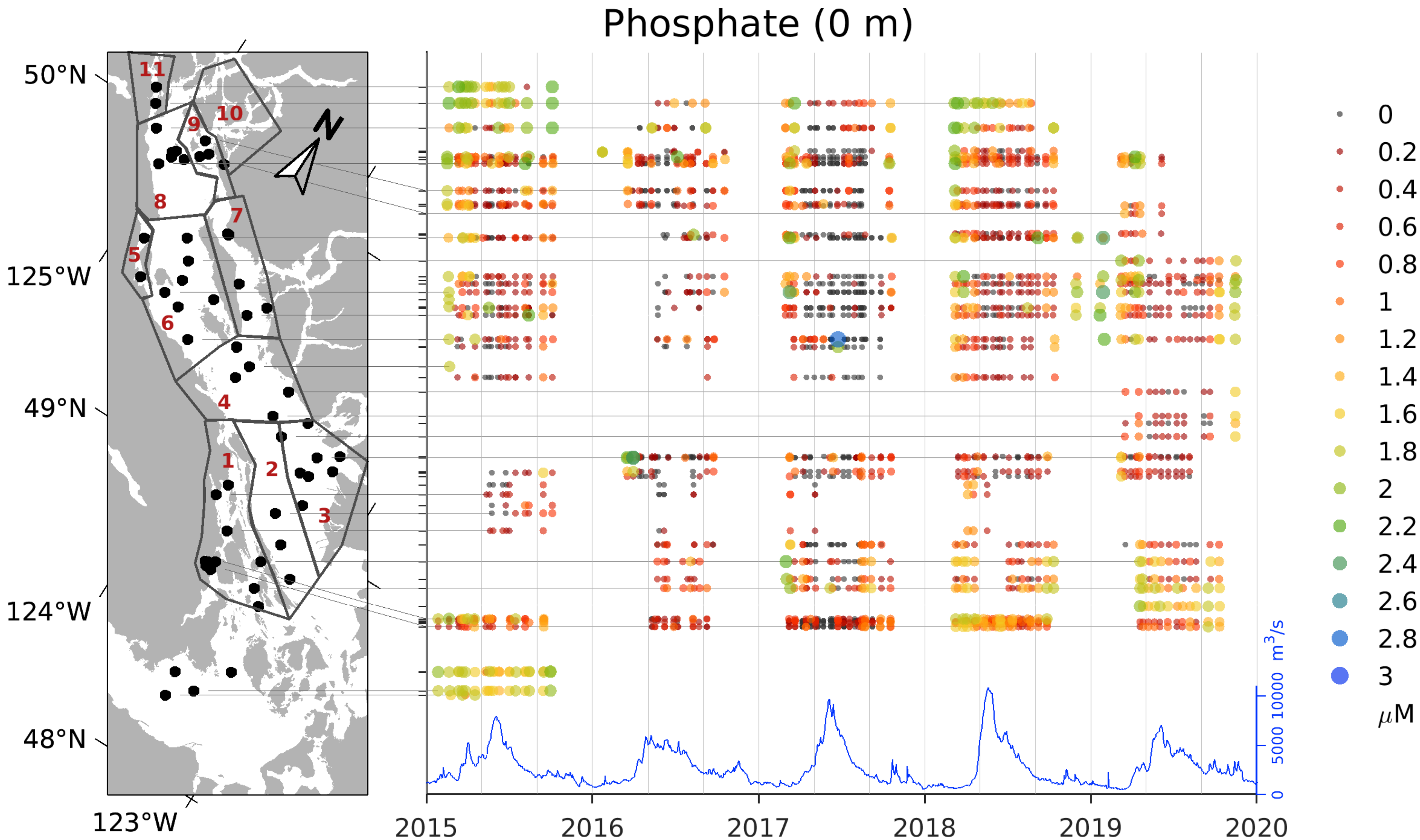

Figure 32: Phosphate data at 0 m for all years. Data for each station is plotted horizontally through time.

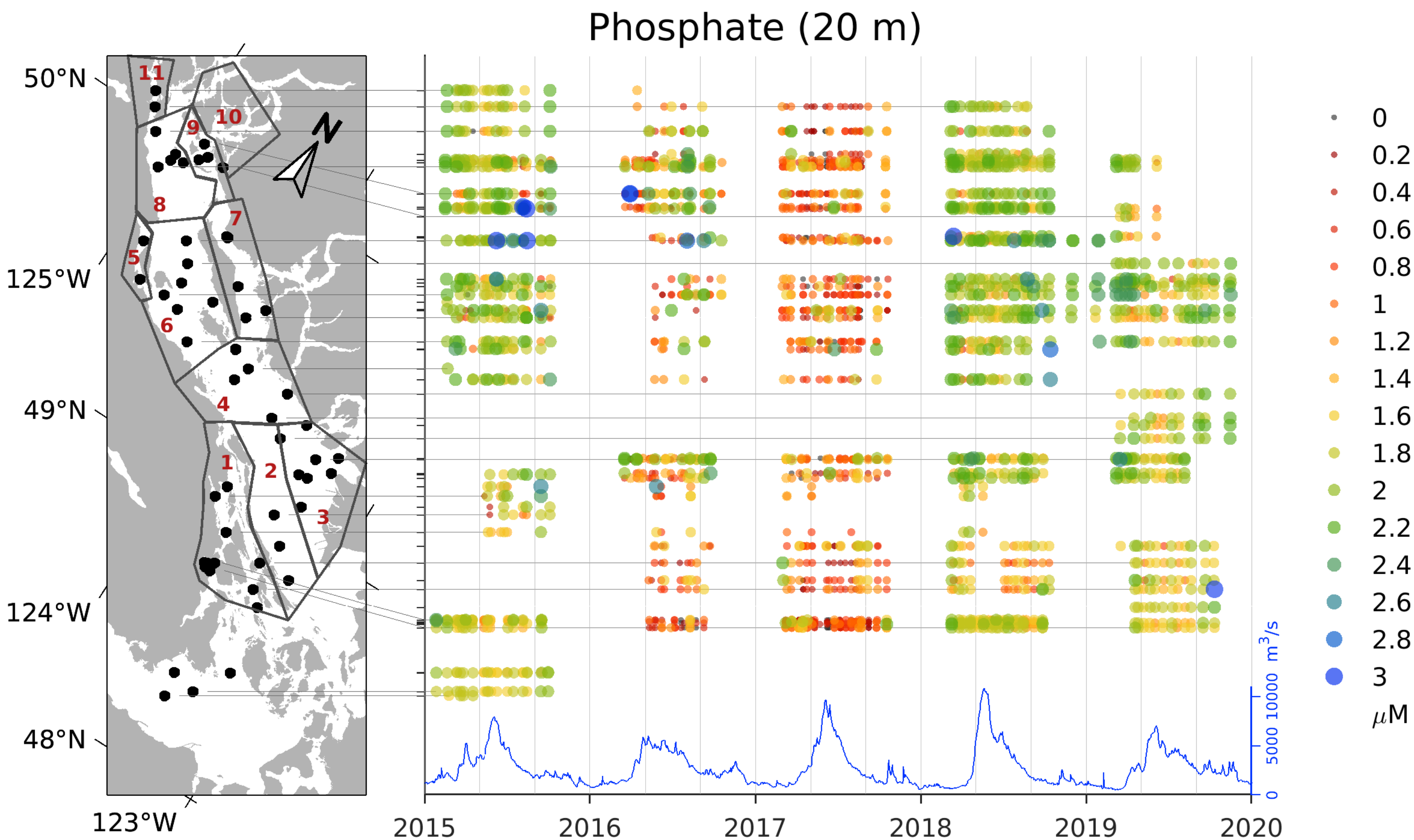

Figure 33: Phosphate data at 20 m for all years. Data for each station is plotted horizontally through time.

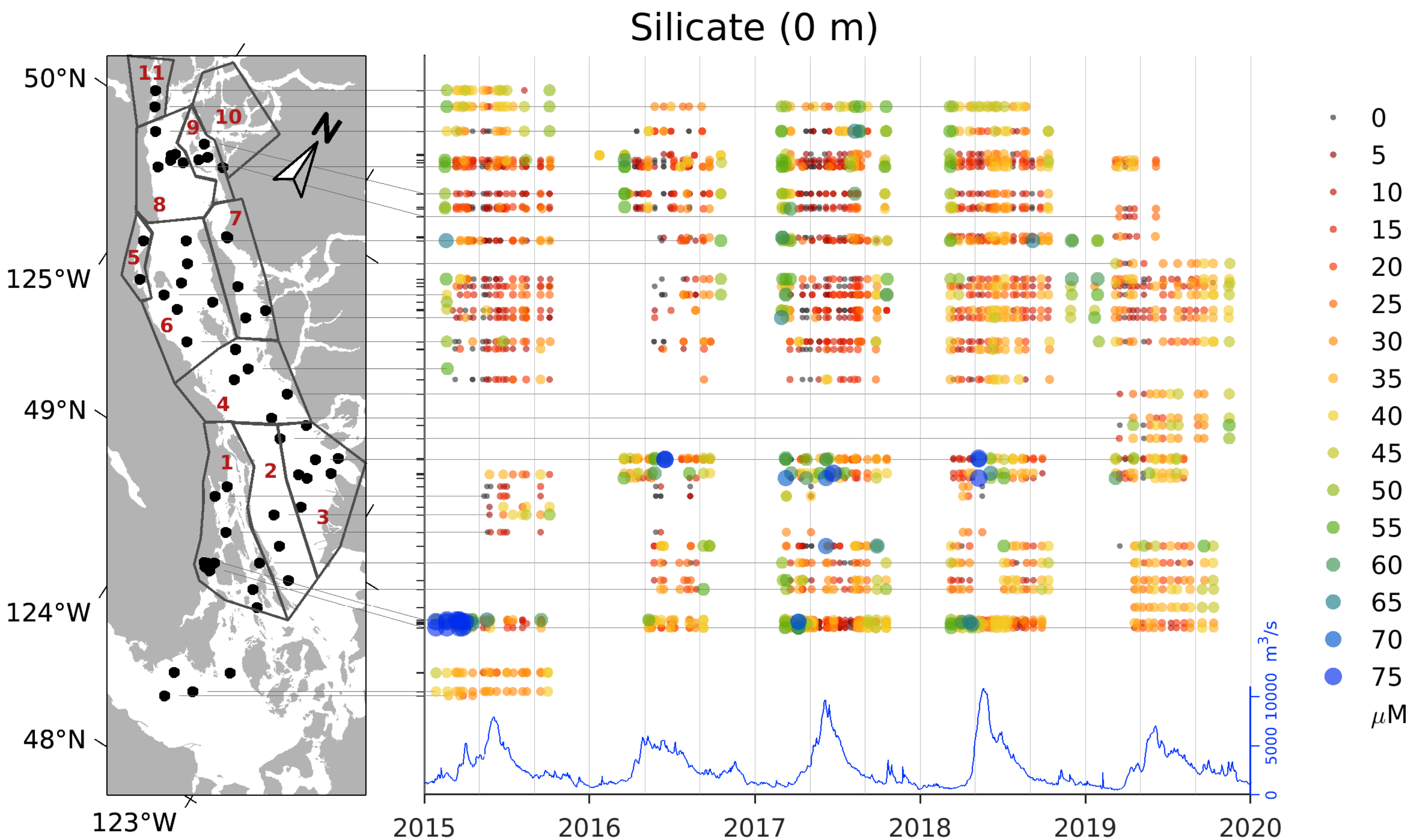

Figure 34: Silicate data at 0 m for all years. Data for each station is plotted horizontally through time.

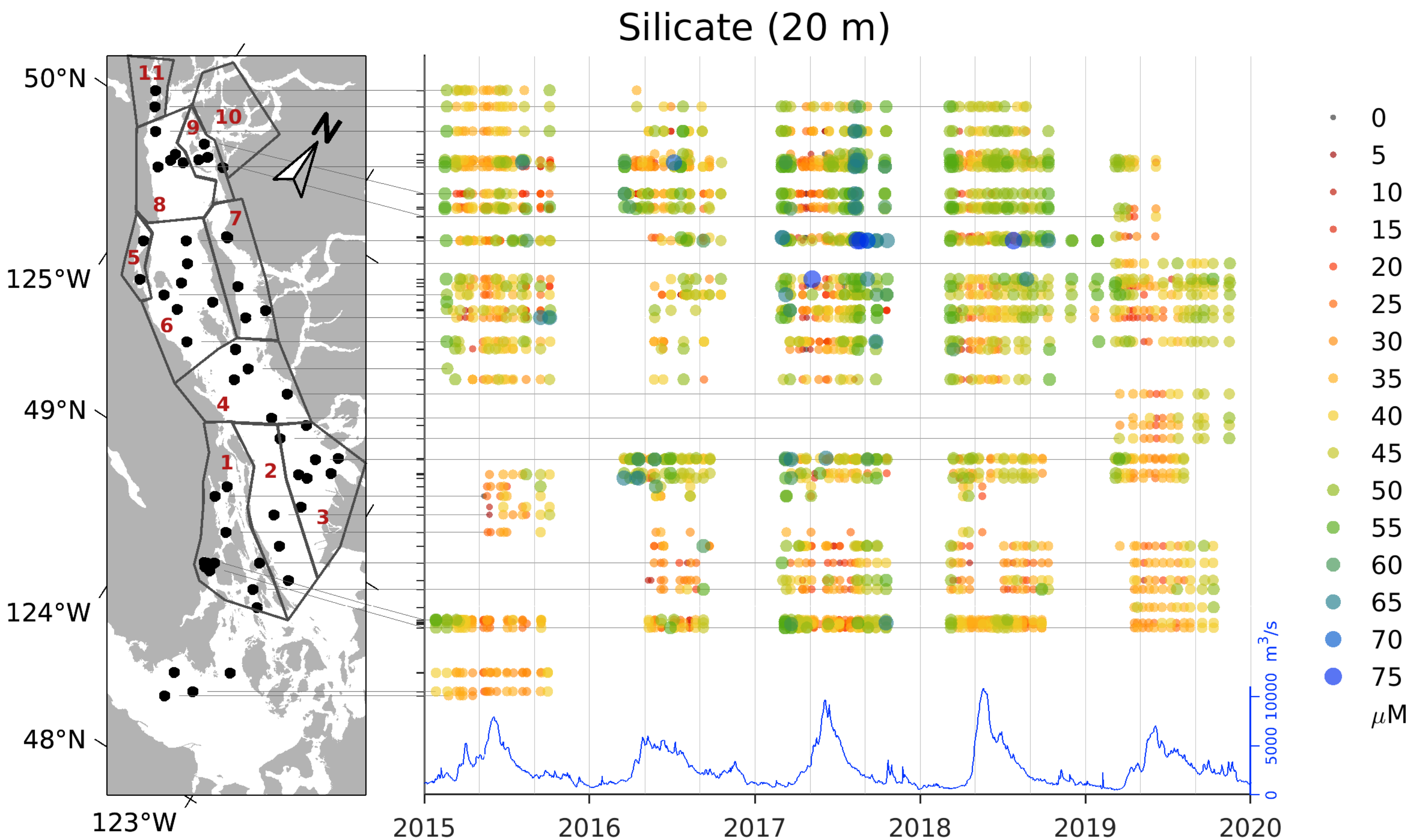

Figure 35: Silicate data at 20 m for all years. Data for each station is plotted horizontally through time.

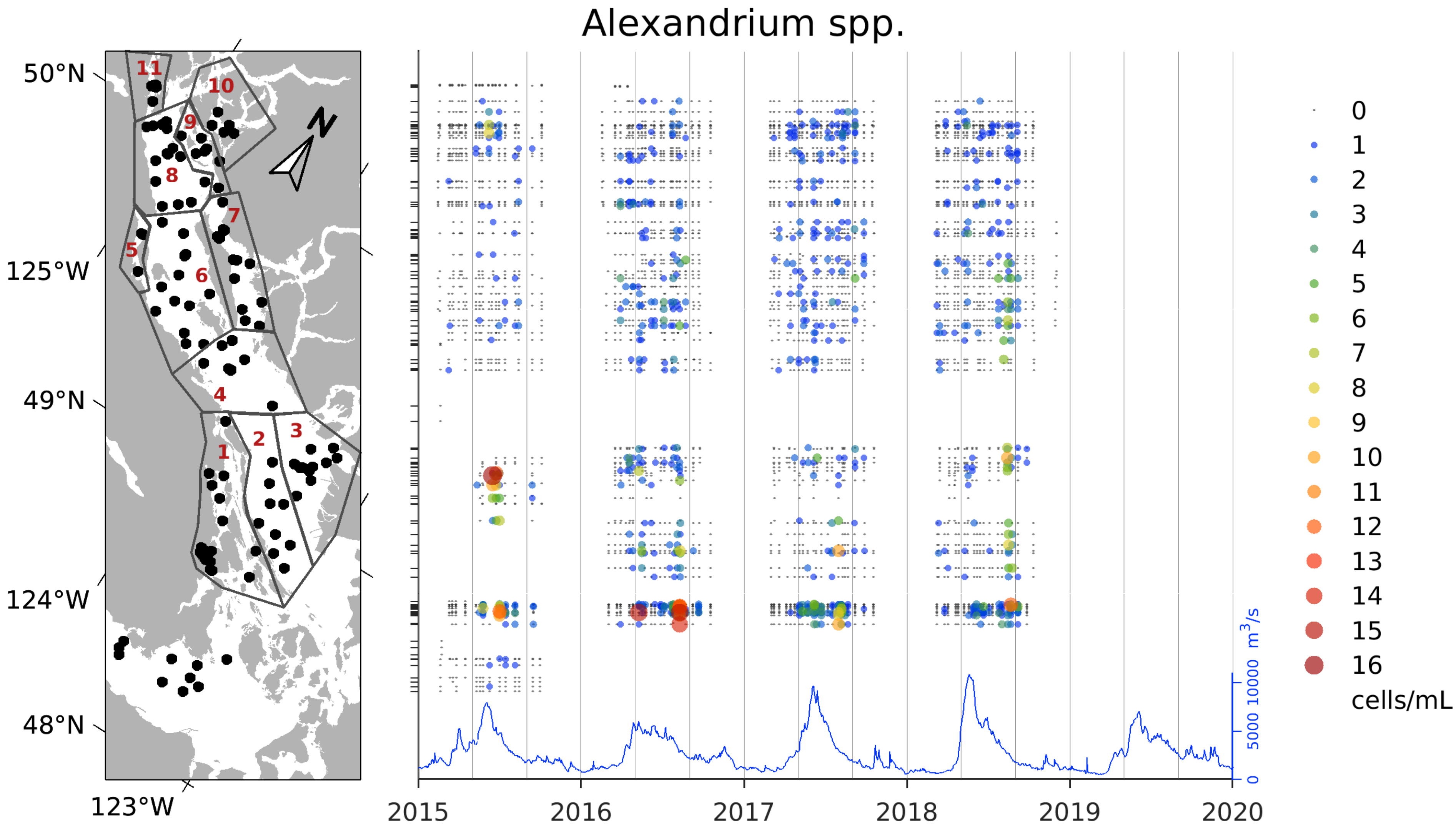

Figure 36: Dinoflagellate *Alexandrium* spp., which produces toxins causing paralytic shellfish poisoning in humans and other mammals.

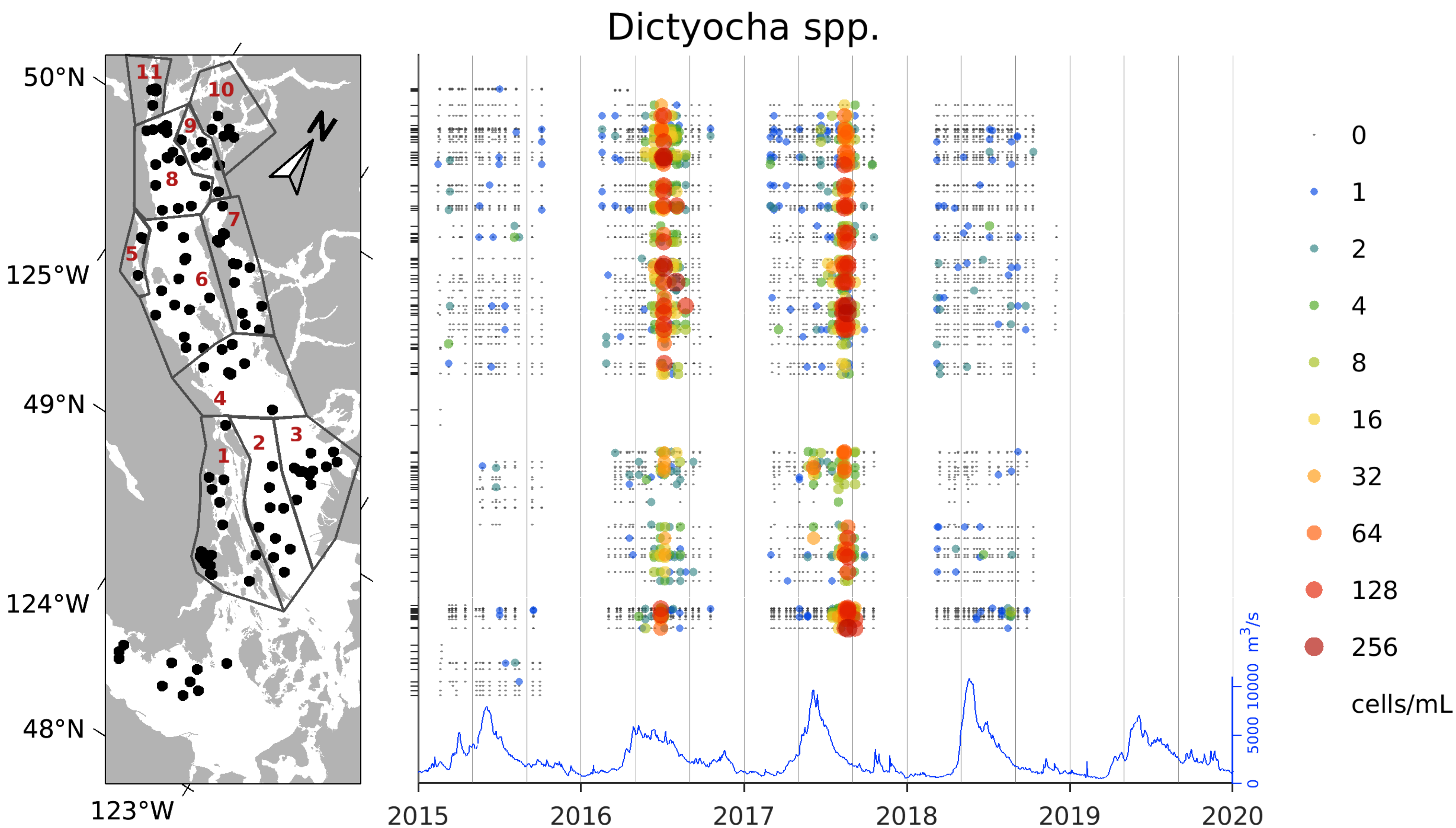

Figure 37: Silicoflagellate *Dictyocha* spp., toxic to fish.

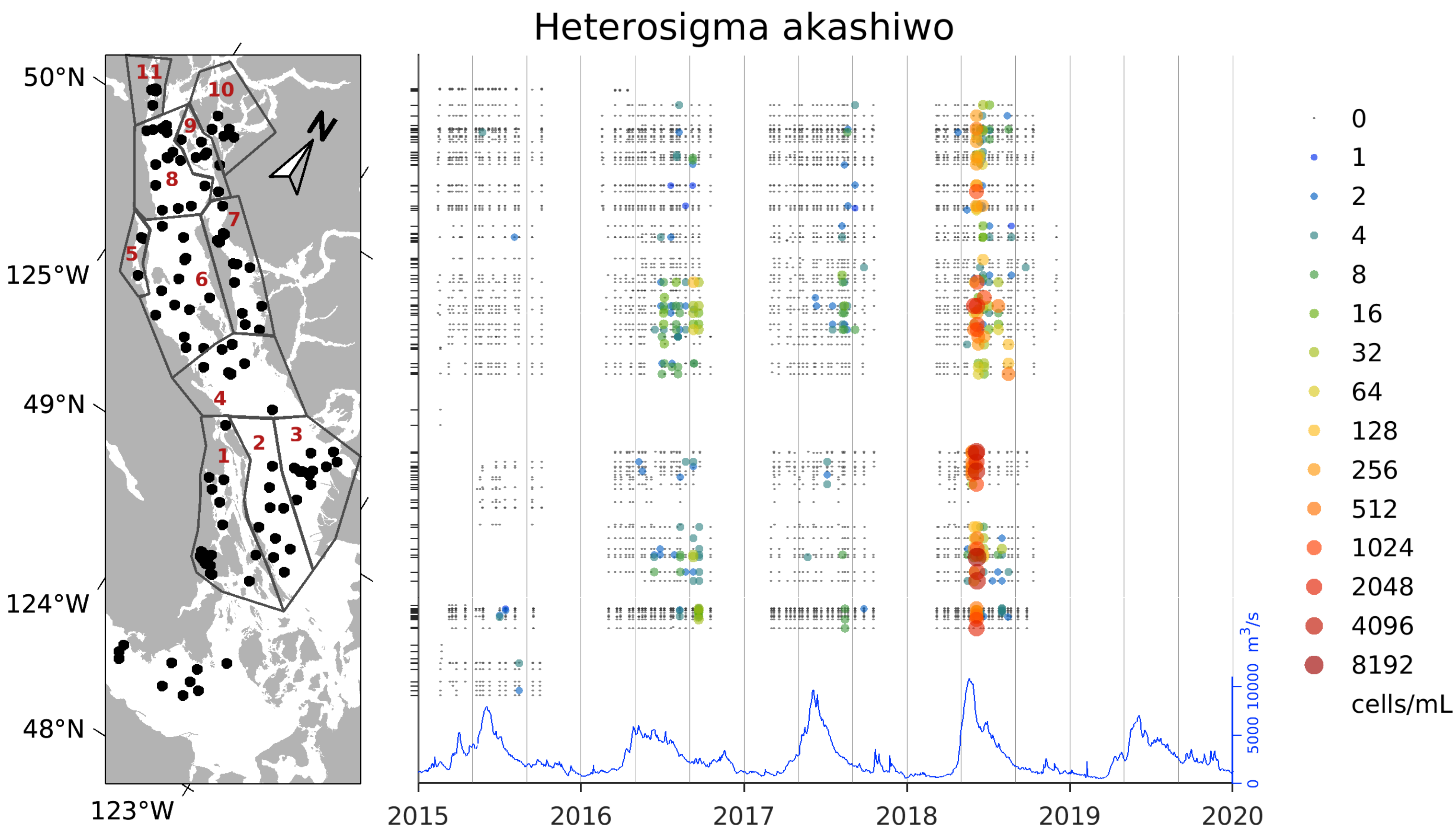

Figure 38: The mixotrophic rapidophyte *Heterosigma akashiwo*, which kills salmon.

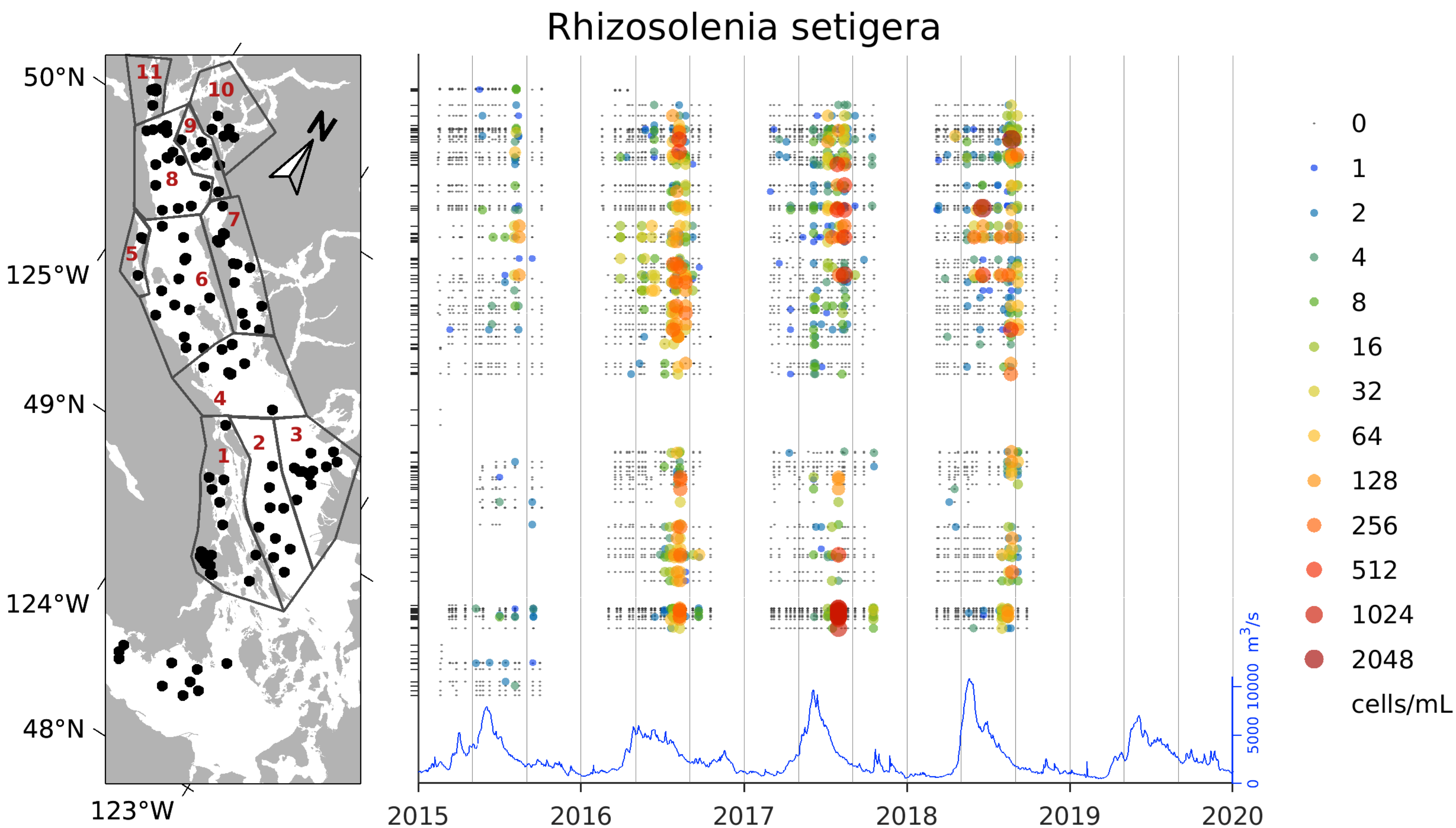

Figure 39: Centric diatom *Rhizosolenia setigera*, harmful to fish gills.

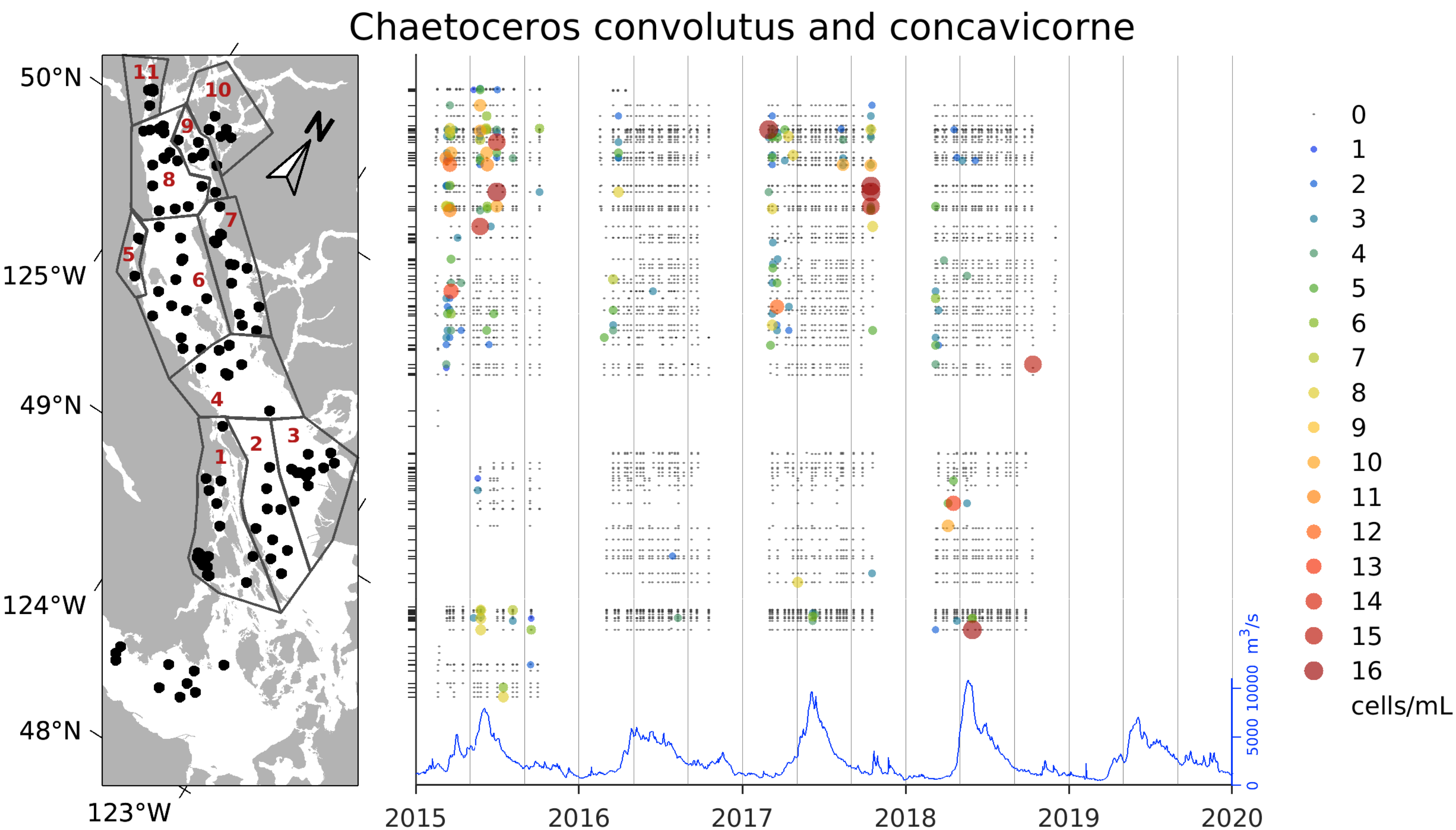

Figure 40: The centric diatom *Chaetocerus convolutus* and *C. concavicorne*, harmful to fish gills.

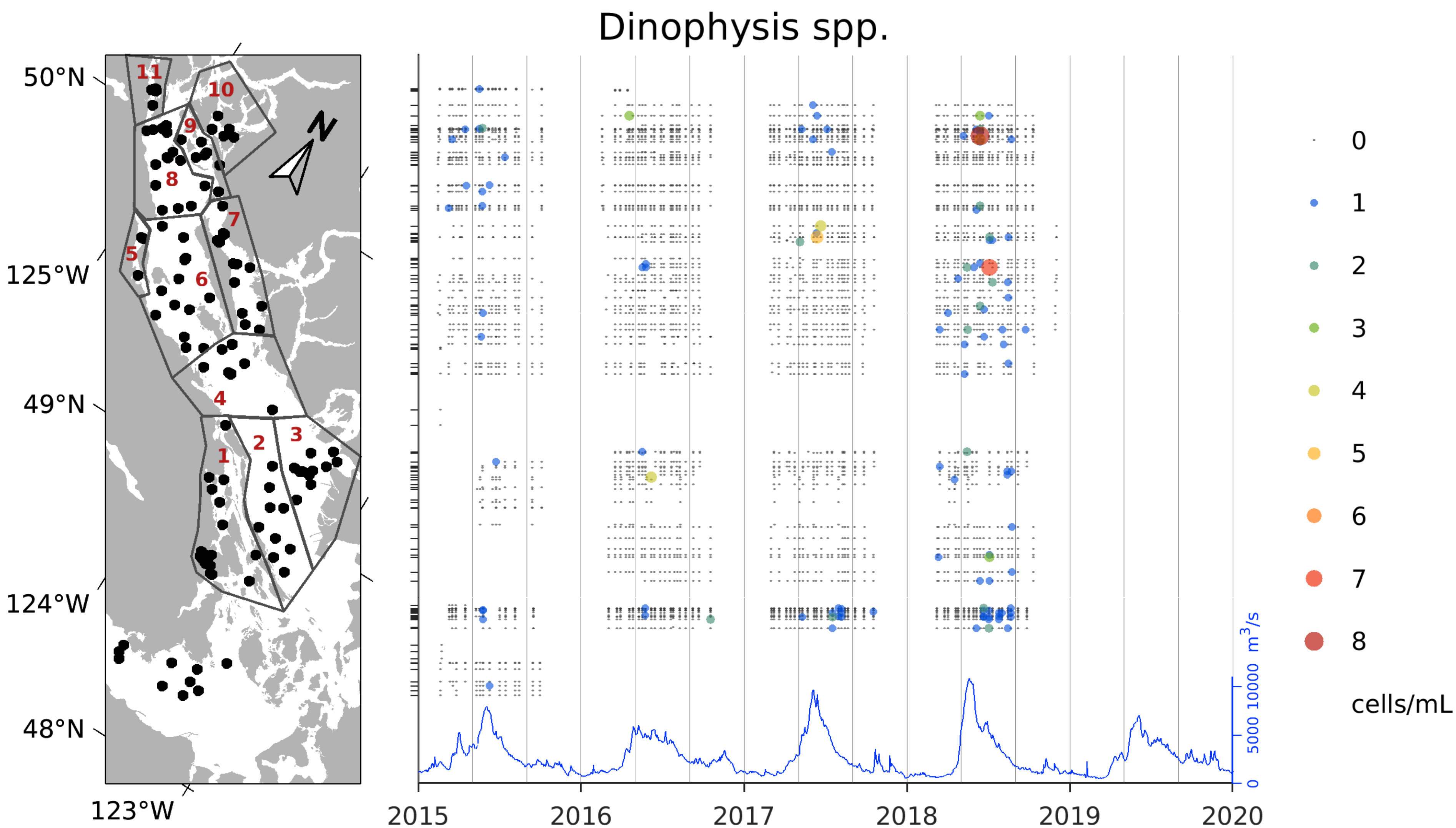

Figure 41: Dinoflagellate *Dinophysis* spp., a cause of diarrhetic shellfish poisoning.

Appendix A: Full Regional and Interannual Variability

After subdividing the dataset into different regions, the profiles were further subdivided into one-month blocks. Mean profiles for each block were calculated, as was the mean time for all profiles within a block. The mean time is not necessarily at the middle of each month due to the sampling plan. Note that the maximum depth of profiles within each block can vary, due to changes in bathymetry. Thus, the number of profiles in each average will decrease with depth. In some blocks (e.g., Region 1) this average may sometimes include only a single profile at greatest depths.

4.5 Contoured information

Once this smoothed set of profiles is computed, we produce a series of contour plots for each measured parameter and each year. These figures show how vertical profiles change with time in each region, and provide more detailed regional information than the summary plots in the previous sections. Many region-specific trends can be discerned.

4.5.1 Temperature and Salinity

Regional temperature plots for all years all show the same general trends, with warmest waters near the surface in summer and coldest waters near the surface in March, as previously discussed in Section 3. The surface warming is much less pronounced in regions 1 and 11 than in other regions (Figs. 42). Region 11 especially is almost isothermal at all times, relative to other regions, with highest temperatures of no more than 15°C. However, within the strait, surface waters are warmer than the critical 17°C in July and August almost everywhere, in all years, although the length of time for which this is true is noticeably smaller in 2017 relative to other years.

This summer warming is still present, but less noticeable, as depth increases, and at depths below about 50 m the coldest waters appear in April or May, as discussed earlier (Figs. 43). Although the annual cycle is similar in all years, there are changes from year to year in the actual temperatures. Waters below about 25 m were noticeably colder in 2017 than they were in 2015 and 2016, with 2018 and 2019 in between.

In contrast to the interannual changes in temperature, salinity levels and their annual cycle are almost the same over all years. Near the surface, freshest water is seen in region 3 in the summer, within the Fraser River plume (Figs. 44). Fresher surface waters are also seen in regions 2 and 4. Least fresh surface waters are on the western side of the northern strait (regions 5, 6, 8). However, even these north-western regions have surface waters fresher than those found in Region 11.

Below the surface, salinities increase with depth (Figs. 45). All regions show stratification except for region 11 which is relatively well-mixed down to 75 m. Region 11 salinities are broadly similar to the mean salinities over the upper 90 m of region 8.

Below 50 m, all areas within the strait show very similar variations in salinity. These waters become saltier and slightly more stratified later in the year; minimum salinities coincide with coldest temperatures in the April–June period. Most saline waters are seen in Region 1 later in the year. The deep waters are slightly more saline in 2018 and 2019 in regions 6-10.

4.5.2 Dissolved Oxygen and Chlorophyll

Dissolved oxygen variations differ greatly from region to region, and from year to year. Near the surface (Figs. 46), levels are always high, but at depth concentrations decrease over the year (Figs. 47). Deep water levels approach (but do not reach) a hypoxic limit of 60 μM near 100 m in regions 9 and 10 in September and October. Minimum values in the southern strait, which also occur in the fall, are much higher (around 150 μM). The depth of the critical 6 ppm (187 μM) contour is about 10 m in regions 9 and 10 at the end of the summer in 2015, but is at about 25 m in 4, 5, and 6. The same general pattern is seen in 2017, although oxygen levels and hence the depth of the critical contour is deeper. However, in 2016 the critical level does not continue to get shallower. Instead, it becomes noticeably deeper in October.

Finally, we discuss regional chlorophyll concentrations (Figs. 48). Even after averaging, chlorophyll concentrations remain highly variable in time and space. Generally, peak values, especially in the summer, occur at a depth of about 10 m, although this varies between 5 and 20 m. On the other hand, chlorophyll concentrations in the spring and fall are often significant near the surface. There is also a high degree of interannual variability, with concentrations in 2016 significantly greater than all other years, and 2015 values noticeably smaller. Region 5 (Baynes Sound) consistently has somewhat higher levels of chlorophyll than other regions, except in 2017.

4.6 Climatological Anomaly Time Series

Within each region, we may also want to consider whether particular years have conditions that are different than a climatological mean. In order to indicate this, we plot time series at specific depths of 1, 25, and 100 m. For each, we calculate the 5-year monthly means, and then use a blue or red shading to show whether the data for a particular time is above (red) or below (blue) this climatology. For temperature and salinity, we can also compare against the measurements made in the Nanoose Time Series (a set of data, obtained roughly weekly at the Canadian Forces Maritime Experimental and Test Ranges (CFMETR) facility, dating back to the late 1960s), and used for previous studies of long-term changes (Masson and Cummins, 2007).

4.6.1 Temperature and Salinity

In most regions, 2015 and 2016 temperatures are above the climatological mean but salinities are sometimes above and sometimes below (Figs.49-59). In 2017 temperatures and salinities are below the mean. In 2018 and 2019 are not so straightforward to characterize. In most areas, surface temperatures are above 17 °C for part of the summer. In general, the seasonal cycle in temperature is larger than any interannual variations at all depths. However, the interannual variability is of the same size as the seasonal cycle in salinity, except in the southern strait (especially region 3).

4.6.2 Dissolved Oxygen

Dissolved oxygen was often below the climatological mean in 2015, and (in most regions) above the mean in 2017 and in 2019 (Fig. 60-64). Although the CitSci program observations are usually between March and October, during which dissolved oxygen levels at most depths are monotonically decreasing, there must be an increase in dissolved oxygen levels over the winter. However, the timing of this increase is not easily determined. Surface oxygen levels are always above the 6 ppm (187 μM) level, but at 25 m most regions spend the late summer below this limit.

4.7 Maps

4.7.1 Chlorophyll Biomass and Secchi Depth

Mapping the depth-integrated chlorophyll biomass into 3-month bins highlights spatial variations (Figs. 65-69). However, there are no consistent patterns to the summertime (Apr-Sep) biomass. Again, 2015 biomass is lower than in later years. In some periods (Apr-Jun 2016, Fig. 66, or Apr-Jun 2018, Fig. 68) biomass in the northern strait appears to be greater than in the southern strait, but the differences are not large.

Secchi depths, however, are consistently greater in the northern strait in summer relative to southern strait values.

4.7.2 Nutrients

For reference and for comparison with the time series plots, we provide maps for the annual cycles in nitrate (Figs. 70-74), phosphate (Figs. 75-79), and silicic acid (Figs. 80-84). These make it clear that surface nitrate levels during the summer are usually close to zero in the Strait of Georgia itself, but that this is often not true in the Gulf Islands, nor is it true in the very northern end of the strait.

4.7.3 Harmful Algae

Our time series of harmful algae (Figs. 36-41) suggested that widespread blooms of various species often appear at irregular intervals in summer. However, the exact spatial extent of these blooms was not always easy to discern. Here we provide spatial maps in 3-month bins for all species (Figs. 85-96).

Cowichan Bay is very consistently a region of elevated *Alexandrium* counts (Figs. 85-88), although they are seen throughout the Strait in summer. *Dinophysis* consistently appears in Cowichan Bay as well, and very occasionally elsewhere.

The 3 summer blooms of *Rhizosolena setigera* (in 2016, 2017, and 2018) have somewhat different spatial extents (Figs. 89-92), being strongest on the mainland coast in 2016 but on the Vancouver Island coasts in 2017 and 2018. *Chaetocerus convolutus* and *C. concavicorne* appears in Cowichan Bay consistently, and occasionally around the edges of the northern Strait.

Weak blooms of *Heterosigma akashiwo* are seen in region 7 (Malaspina Strait) in the late summers of 2016 and 2017, but the very large bloom that occurs in 2018 appears most strongly in southern Strait (regions 1-3), is slightly weaker in Malaspina Strait, and then even weaker in the northern Strait (regions 8-10) (Figs. 93-96). Finally, the two *Dictyocha* blooms in 2016 and 2017 consistently appear in Malaspina Strait.

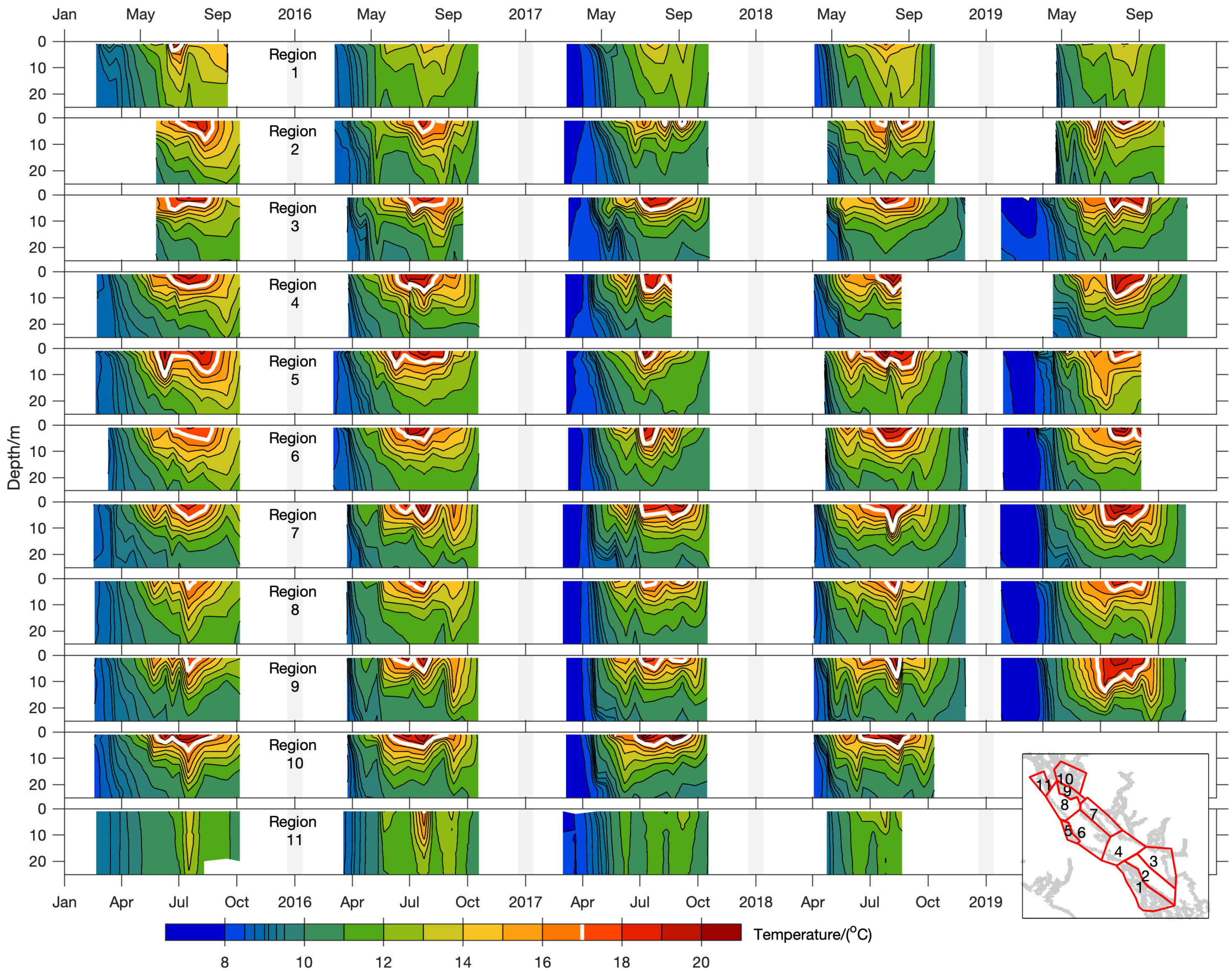

Figure 42: Contour plots for temperature in each region over all years. The white line indicates 17°C. Only the upper 25 m of the water column is shown.

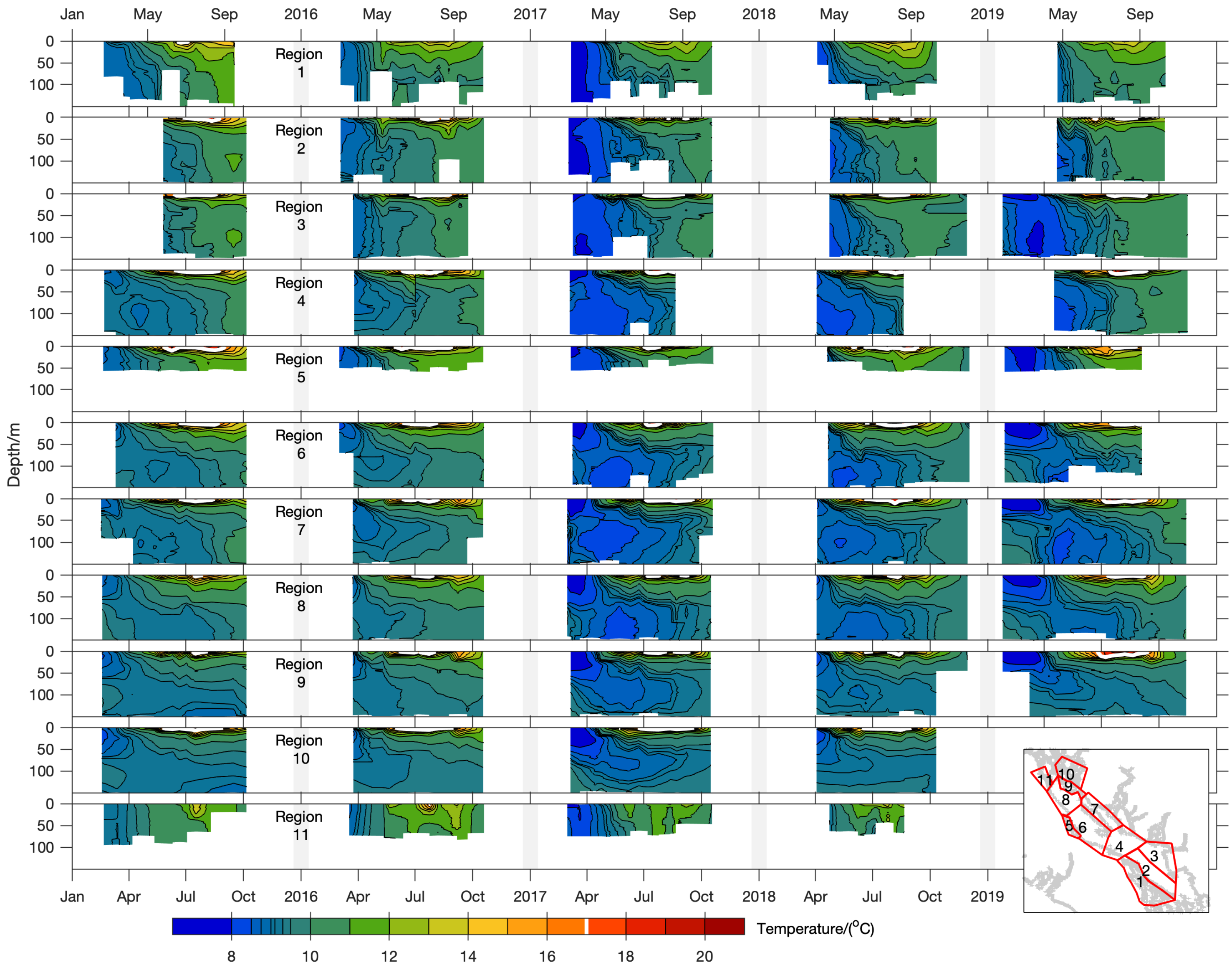

Figure 43: Contour plots for temperature in each region over all years. The white line indicates 17°C.

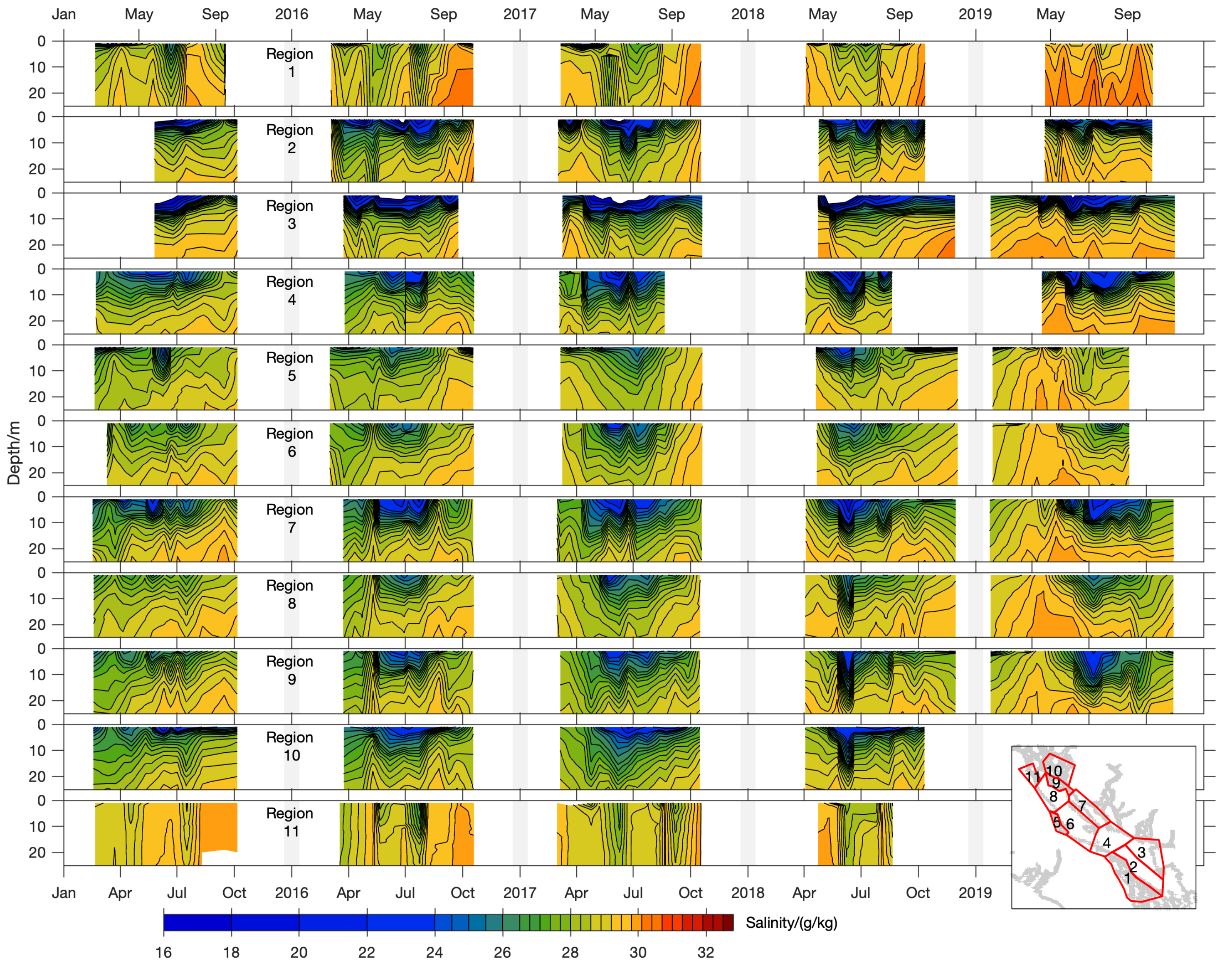

Figure 44: Contour plots for salinity in each region over all years. Only the upper 25 m of the water column is shown.

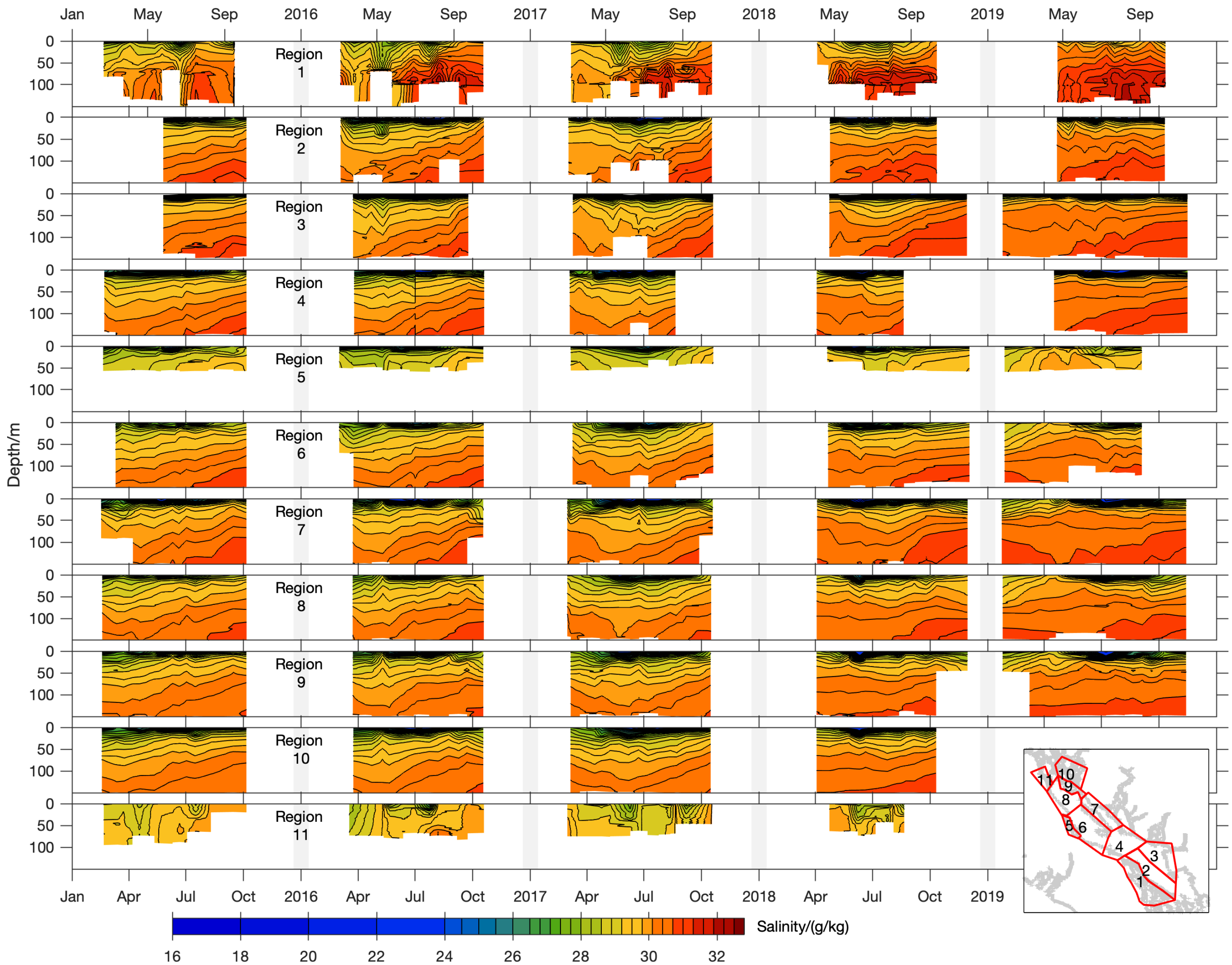

Figure 45: Contour plots for salinity in each region over all years.

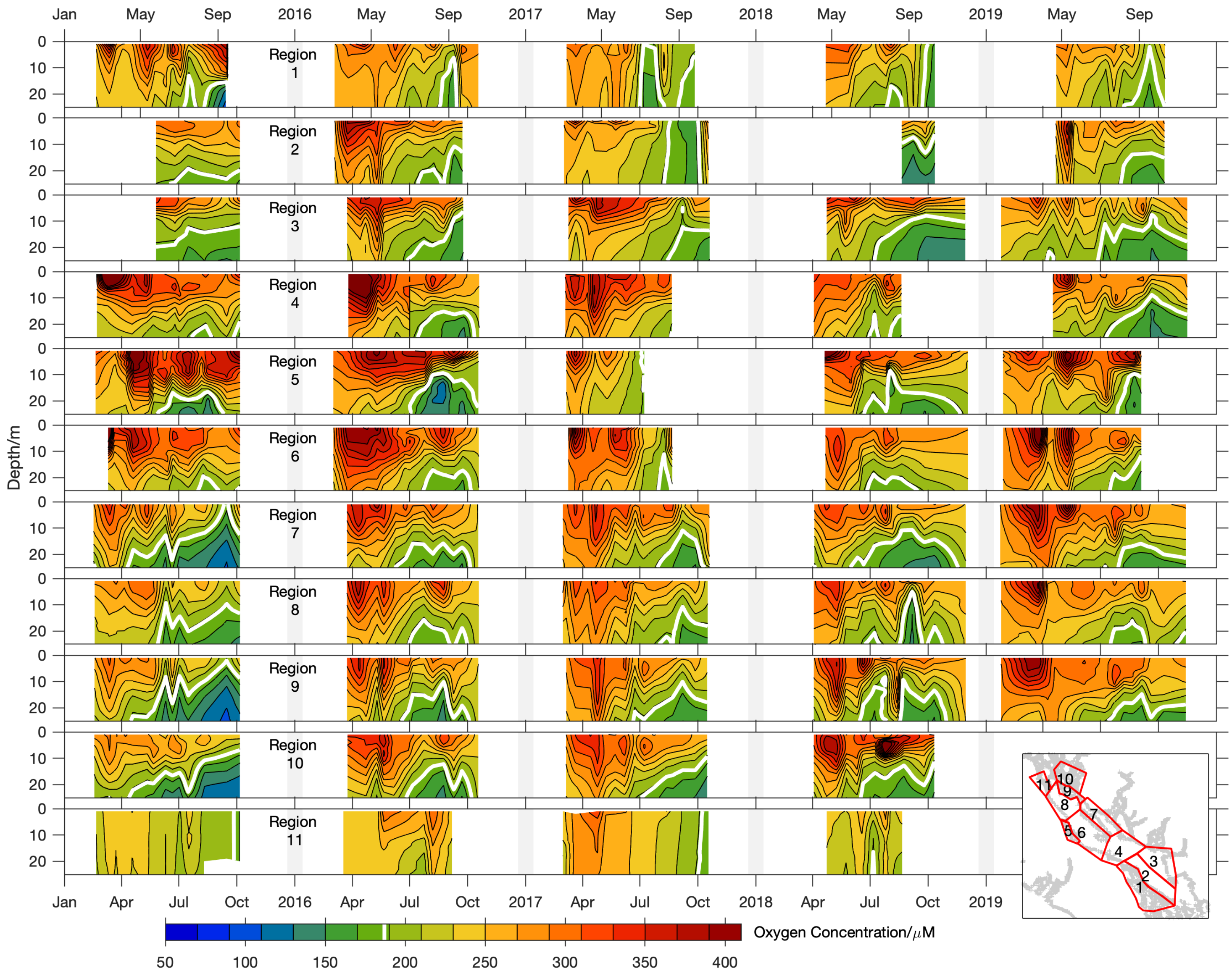

Figure 46: Contour plots for dissolved oxygen in each region over all years. The white line indicates 6 ppm or 187 μM. Only the upper 25 m of the water column is shown.

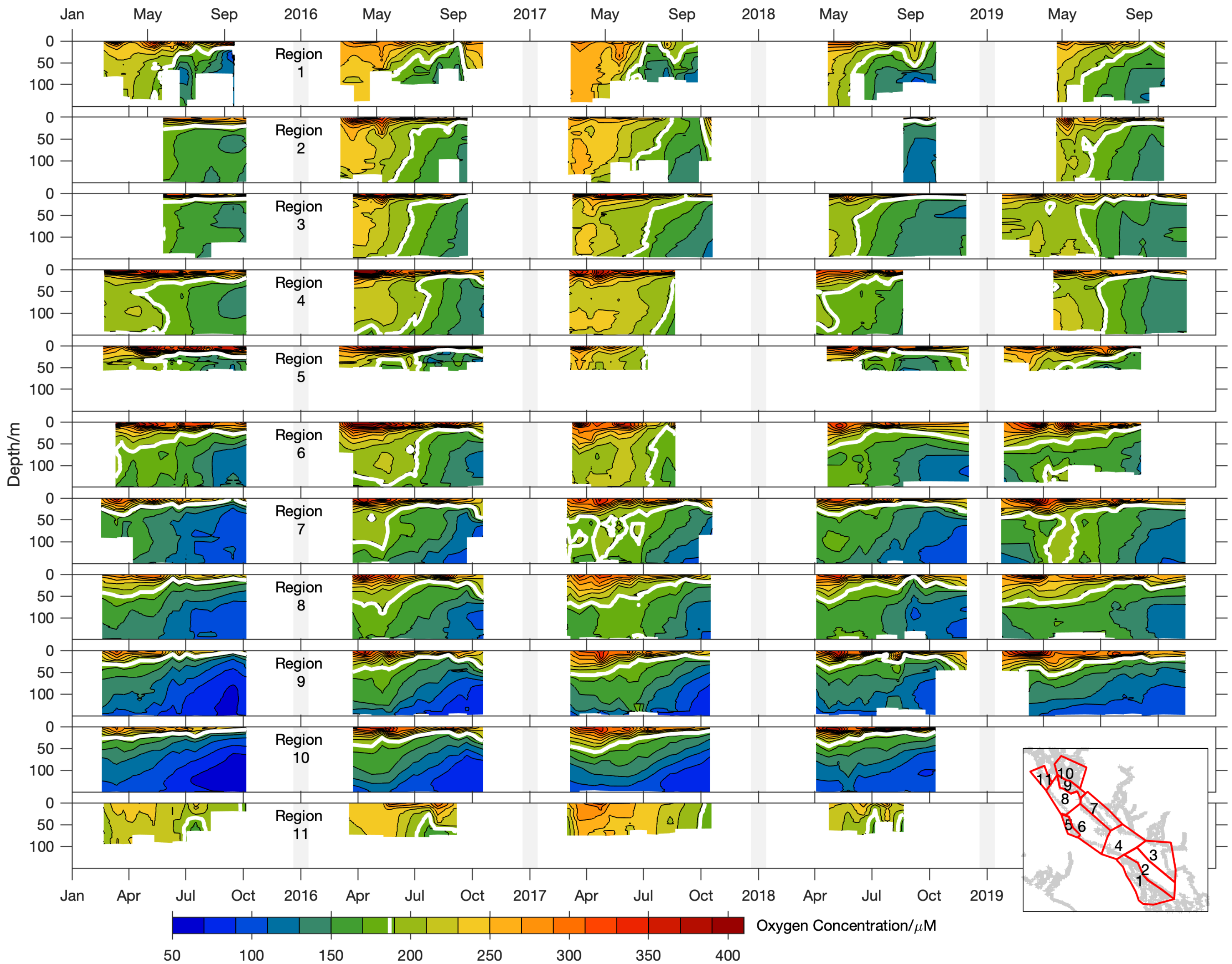

Figure 47: Contour plots for dissolved oxygen in each region over all years. The white line indicates 6 ppm or 187 μM.

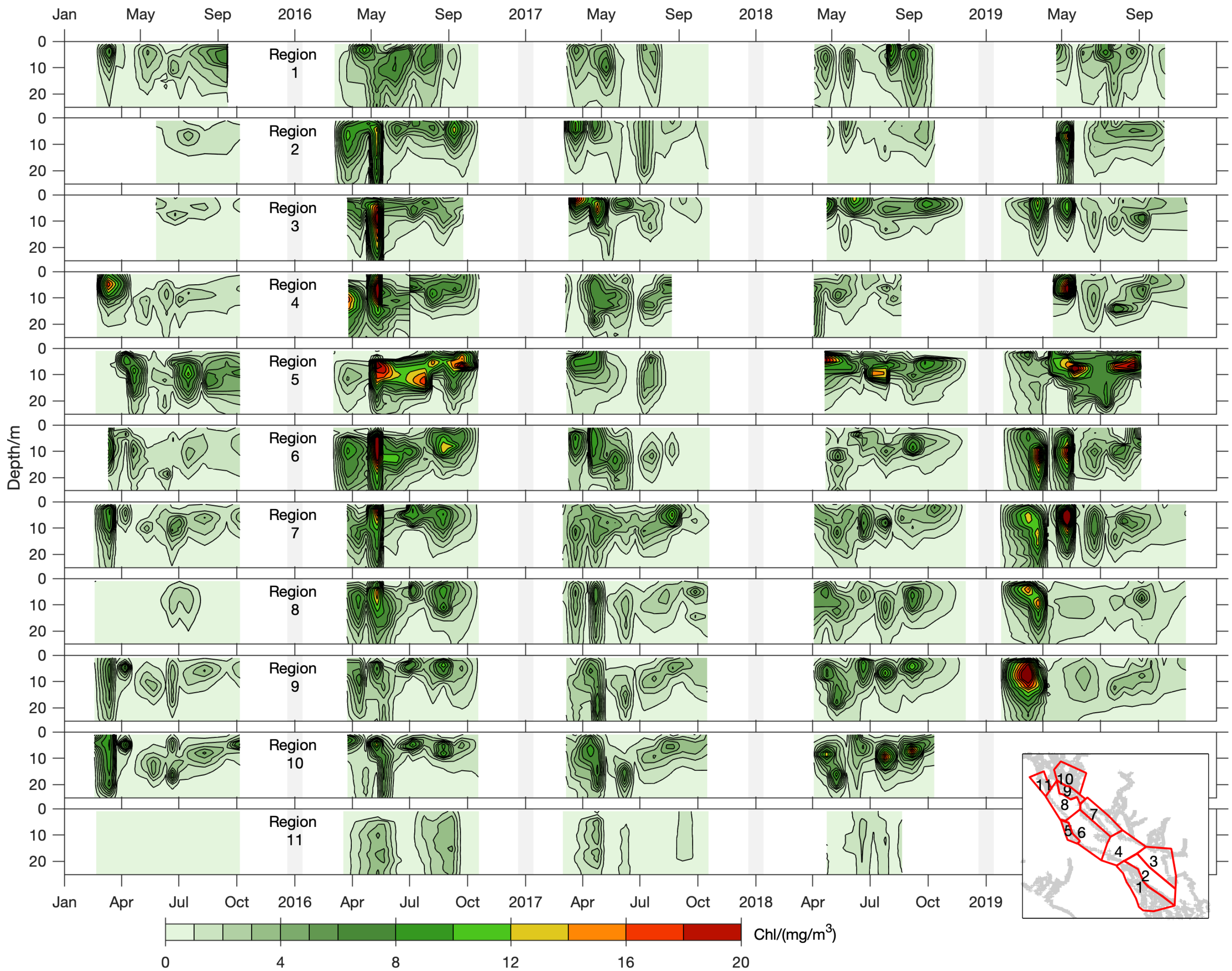

Figure 48: Contour plot for chlorophyll in each region over all years. Only the upper 25 m of the water column is shown.

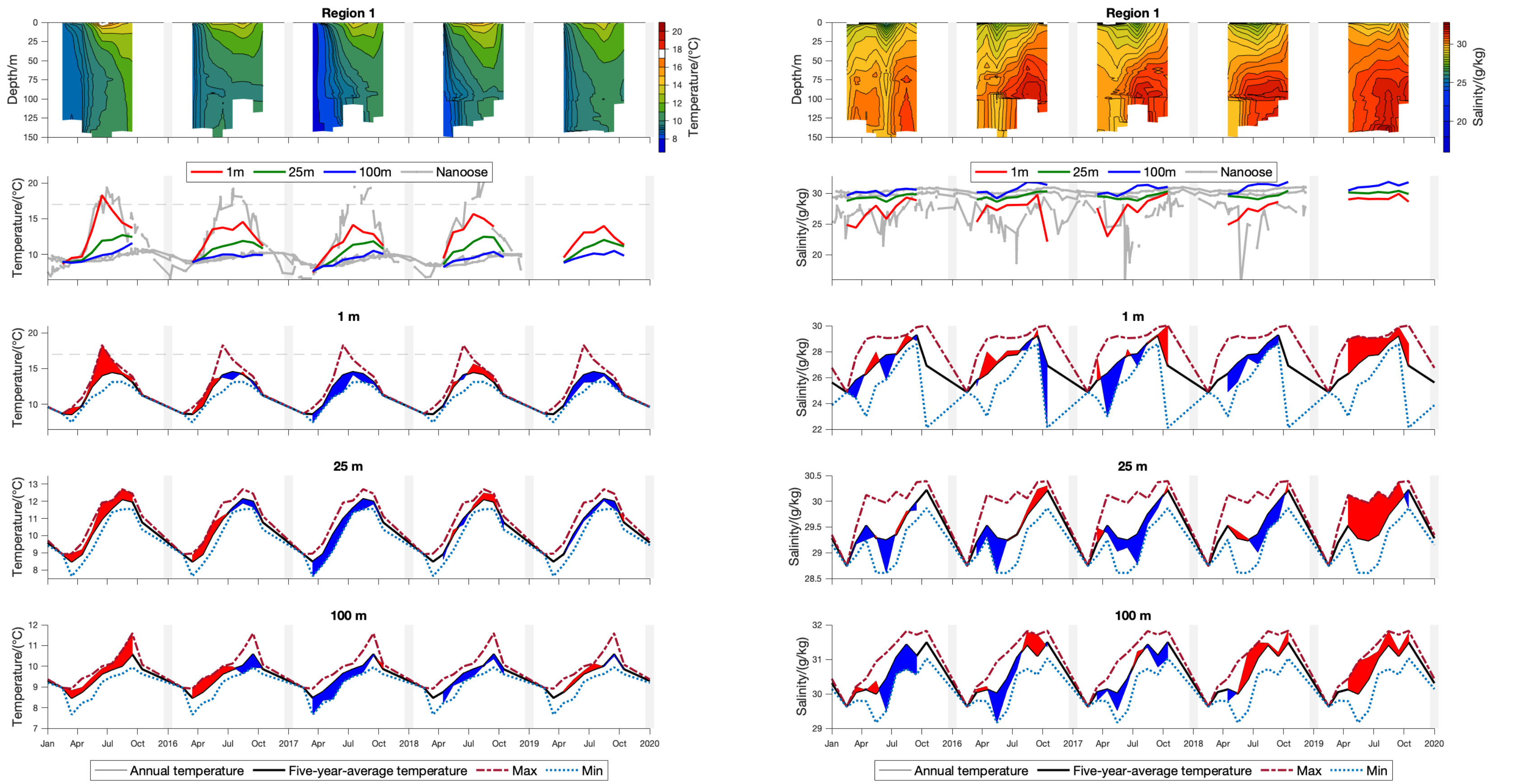

Figure 49: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 1. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

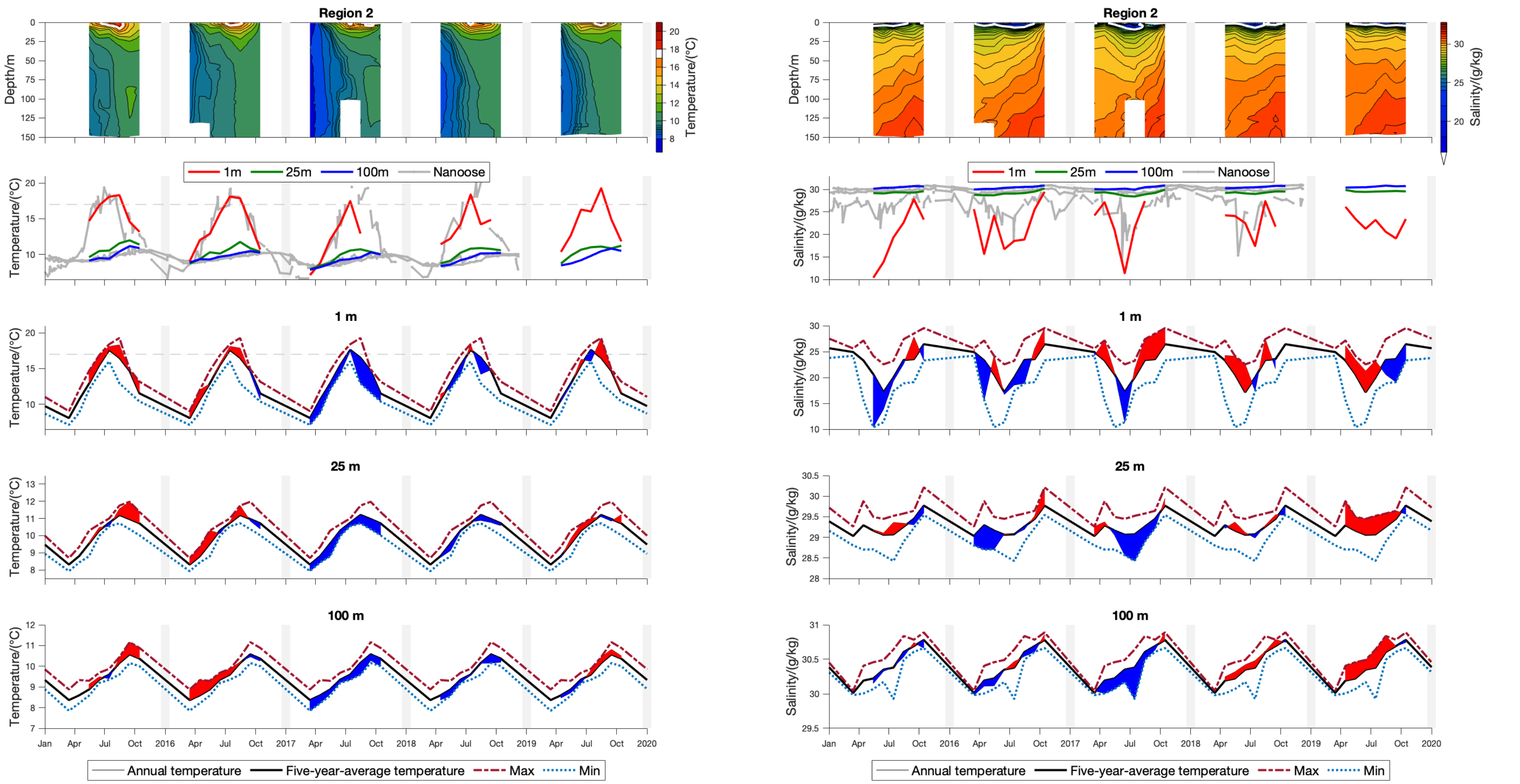

Figure 50: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 2. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

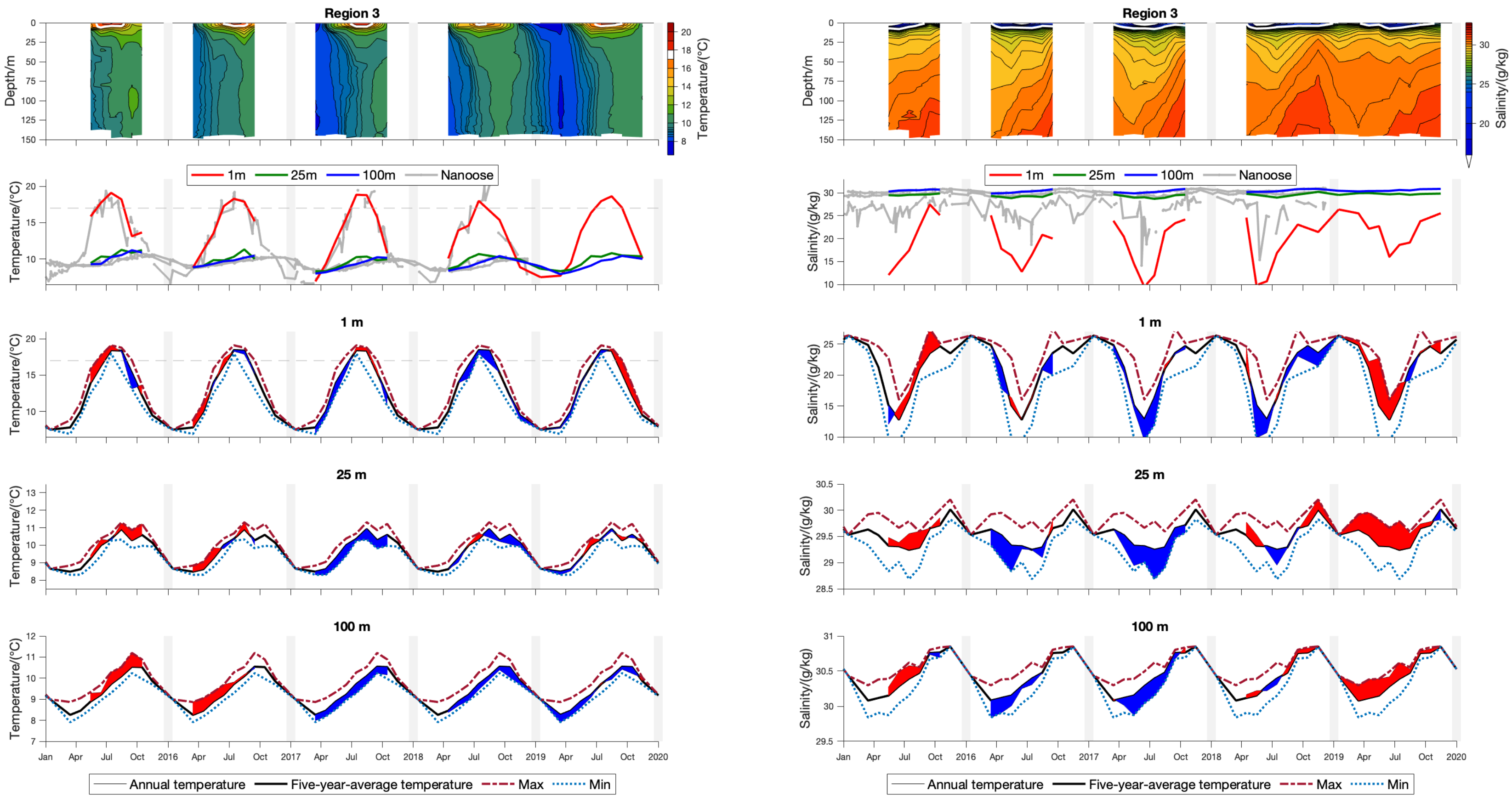

Figure 51: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 3. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

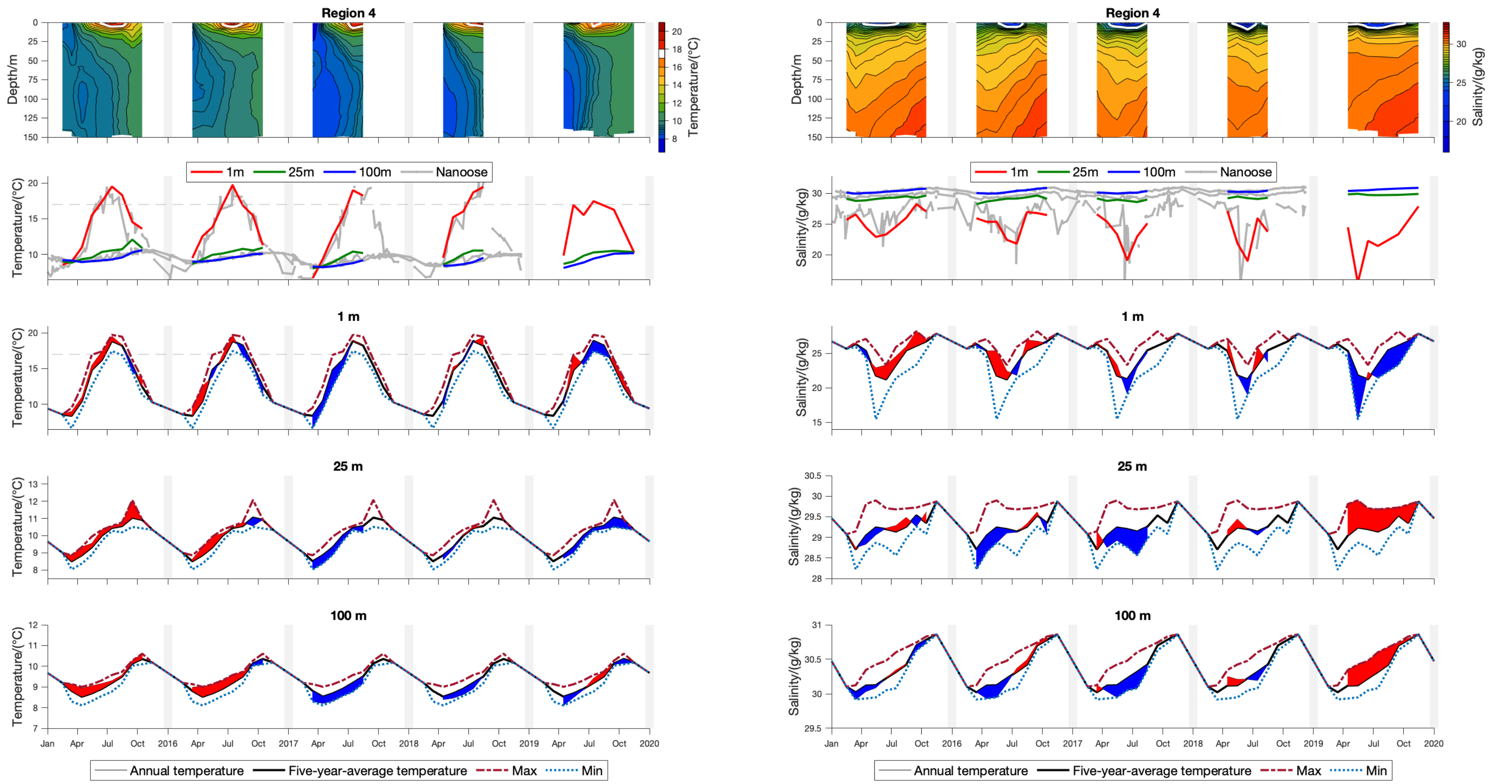

Figure 52: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 4. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

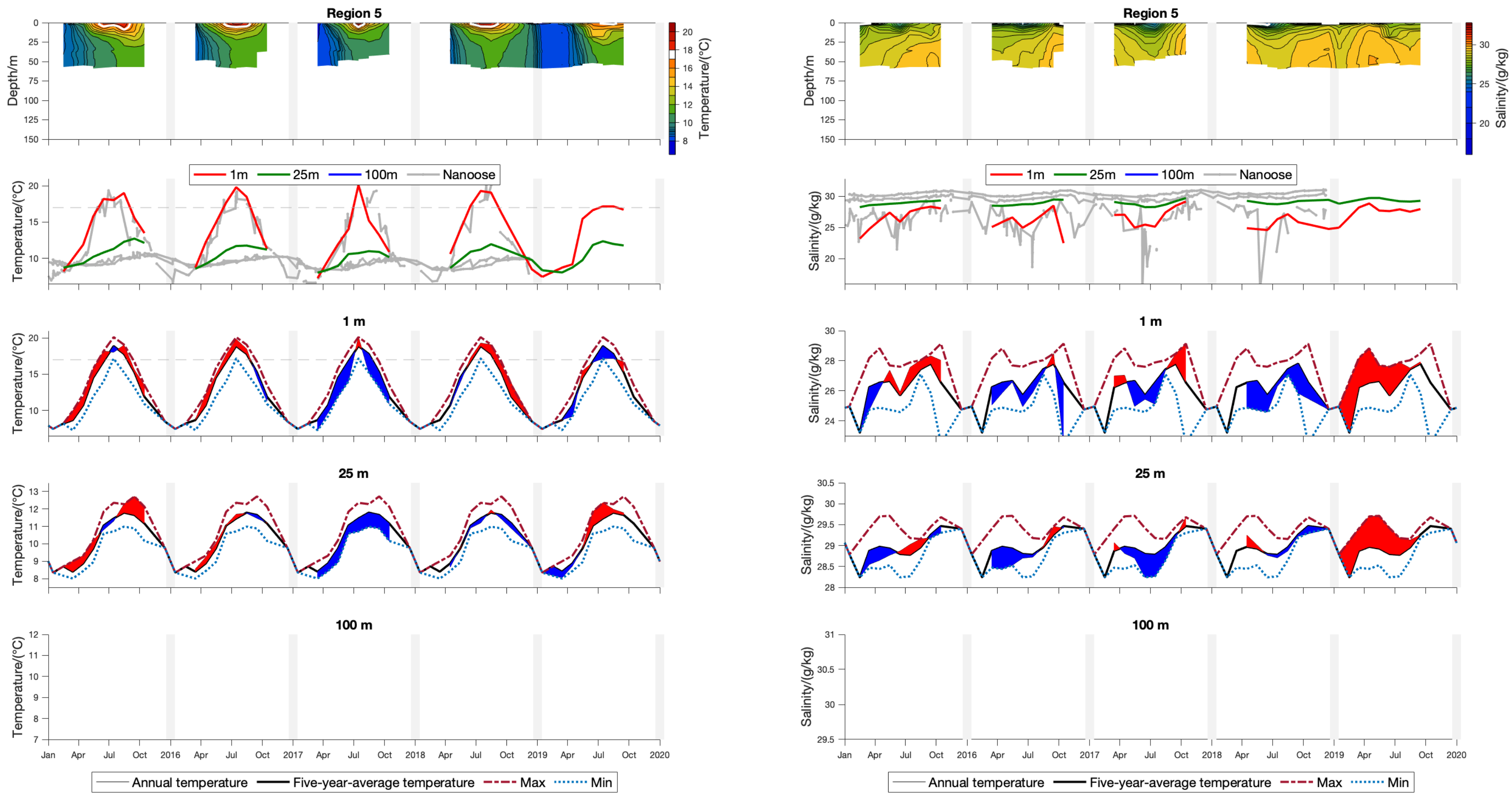

Figure 53: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 5. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

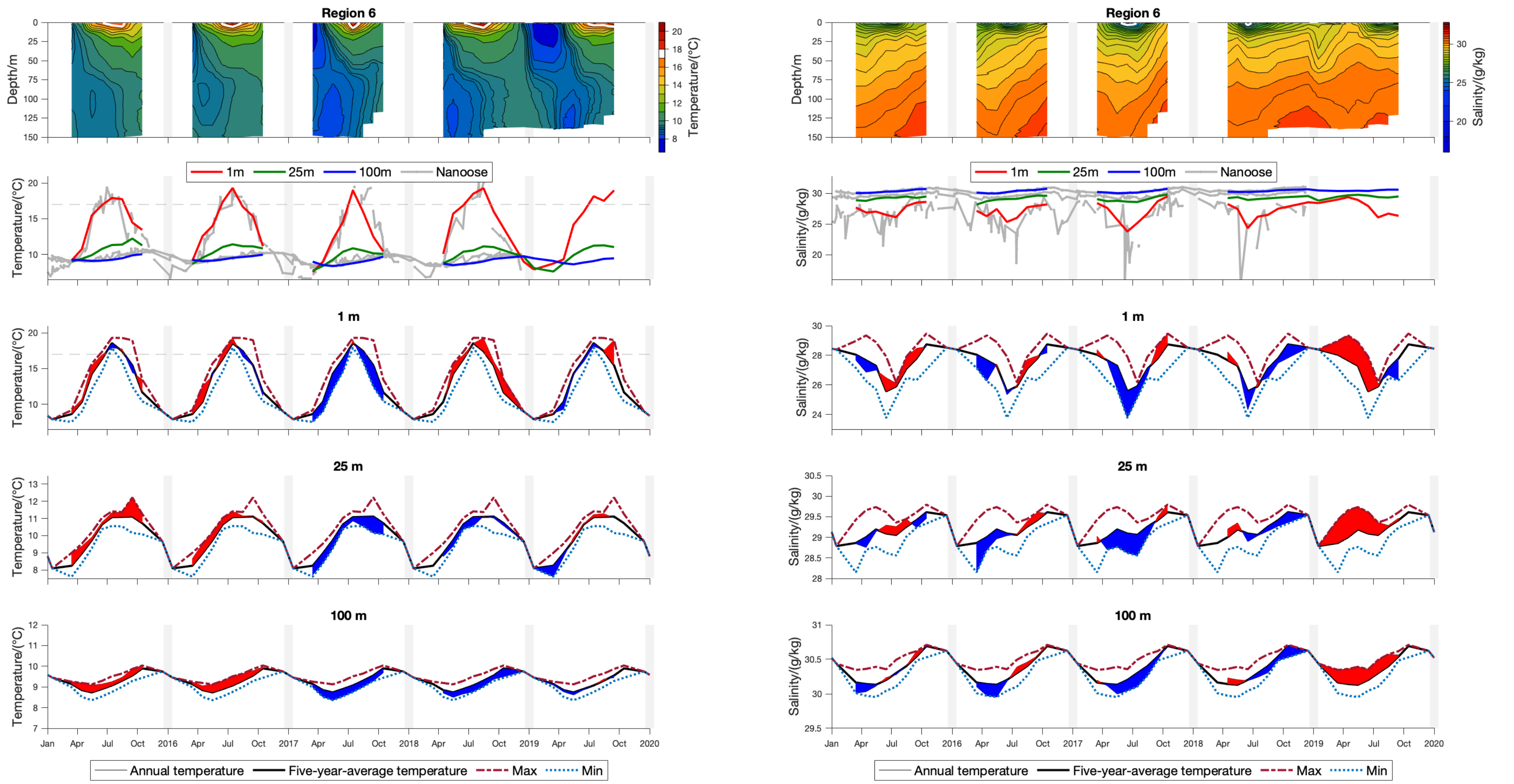

Figure 54: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 6. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

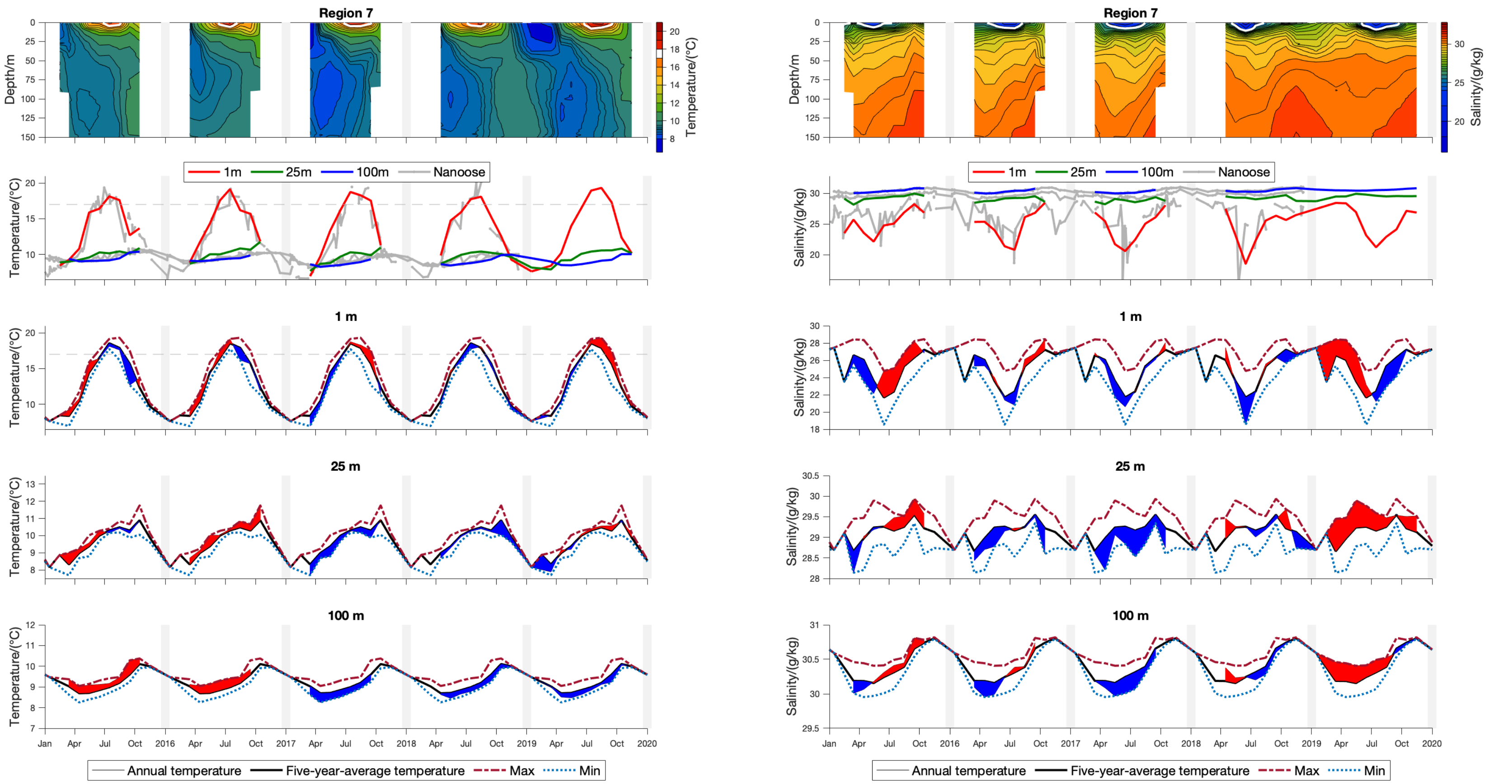

Figure 55: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 7. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

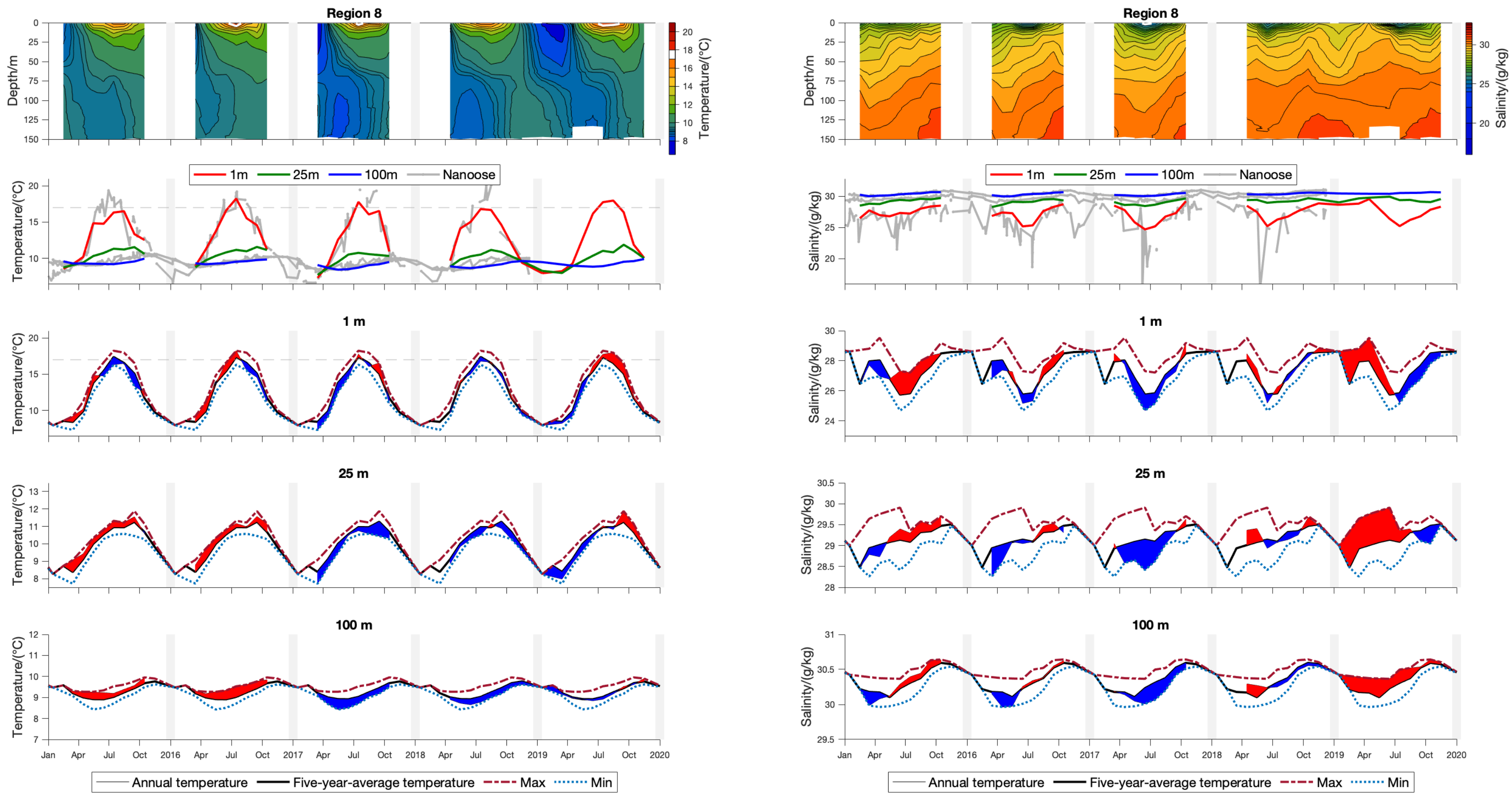

Figure 56: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 8. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

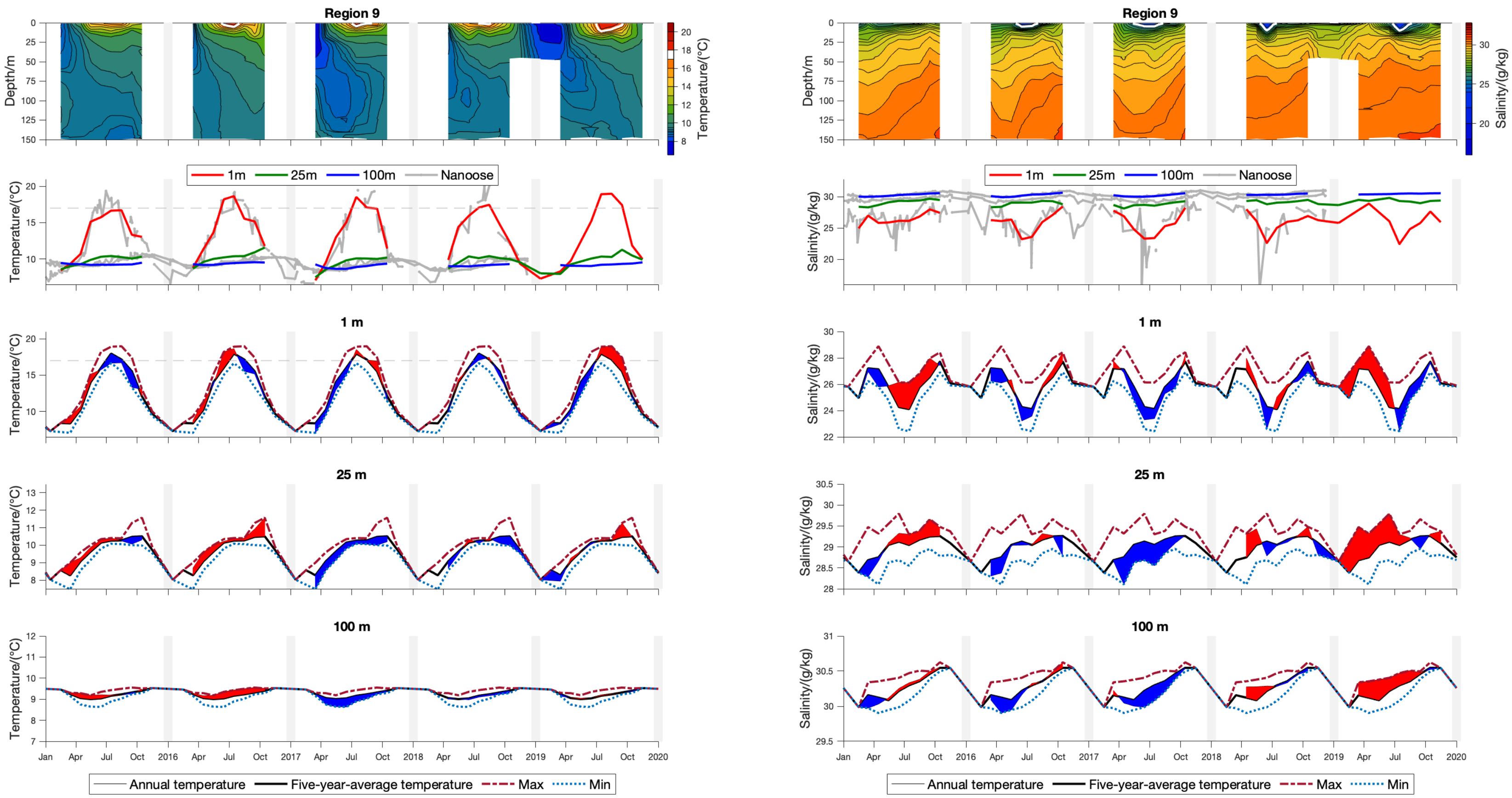

Figure 57: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 9. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

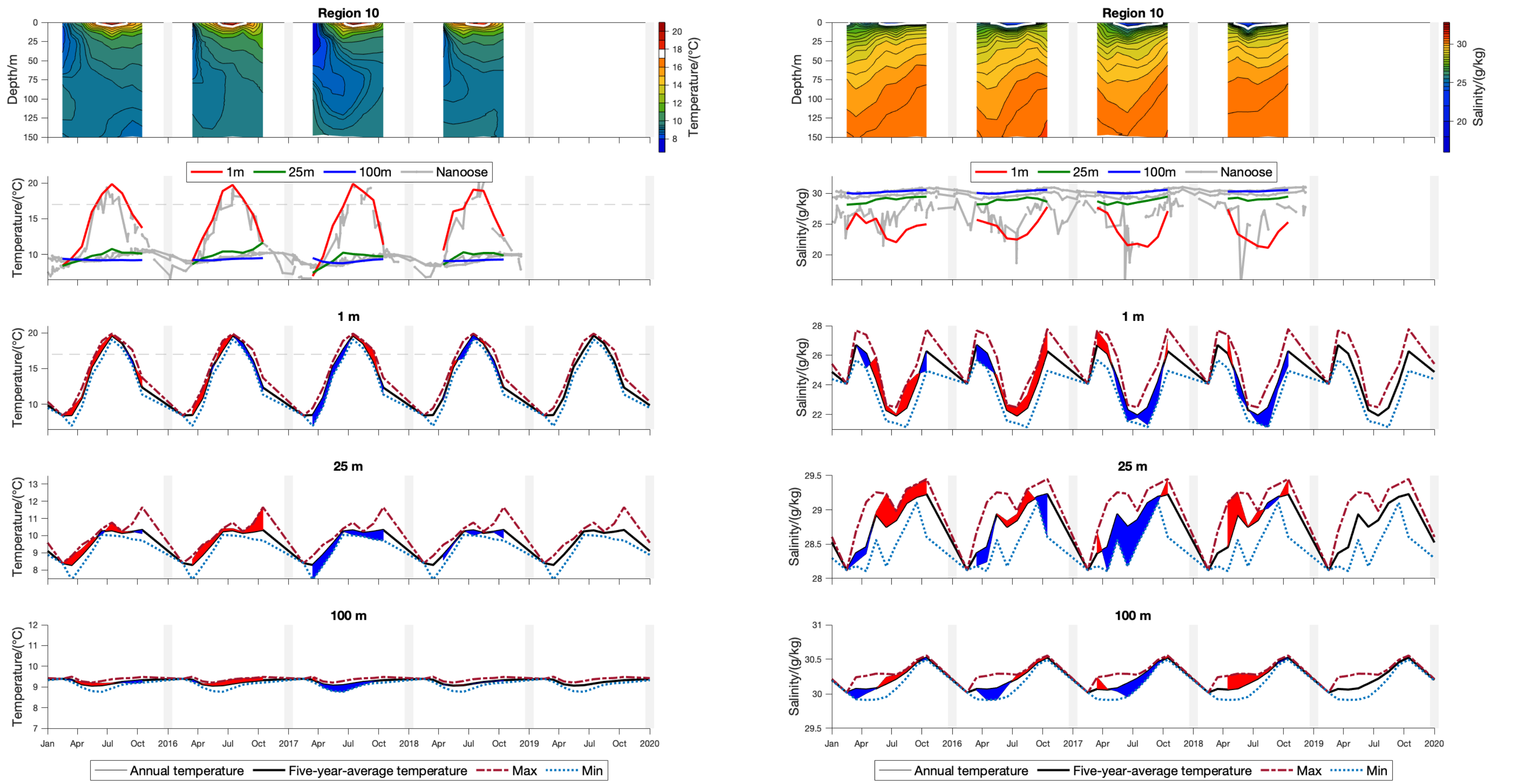

Figure 58: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 10. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

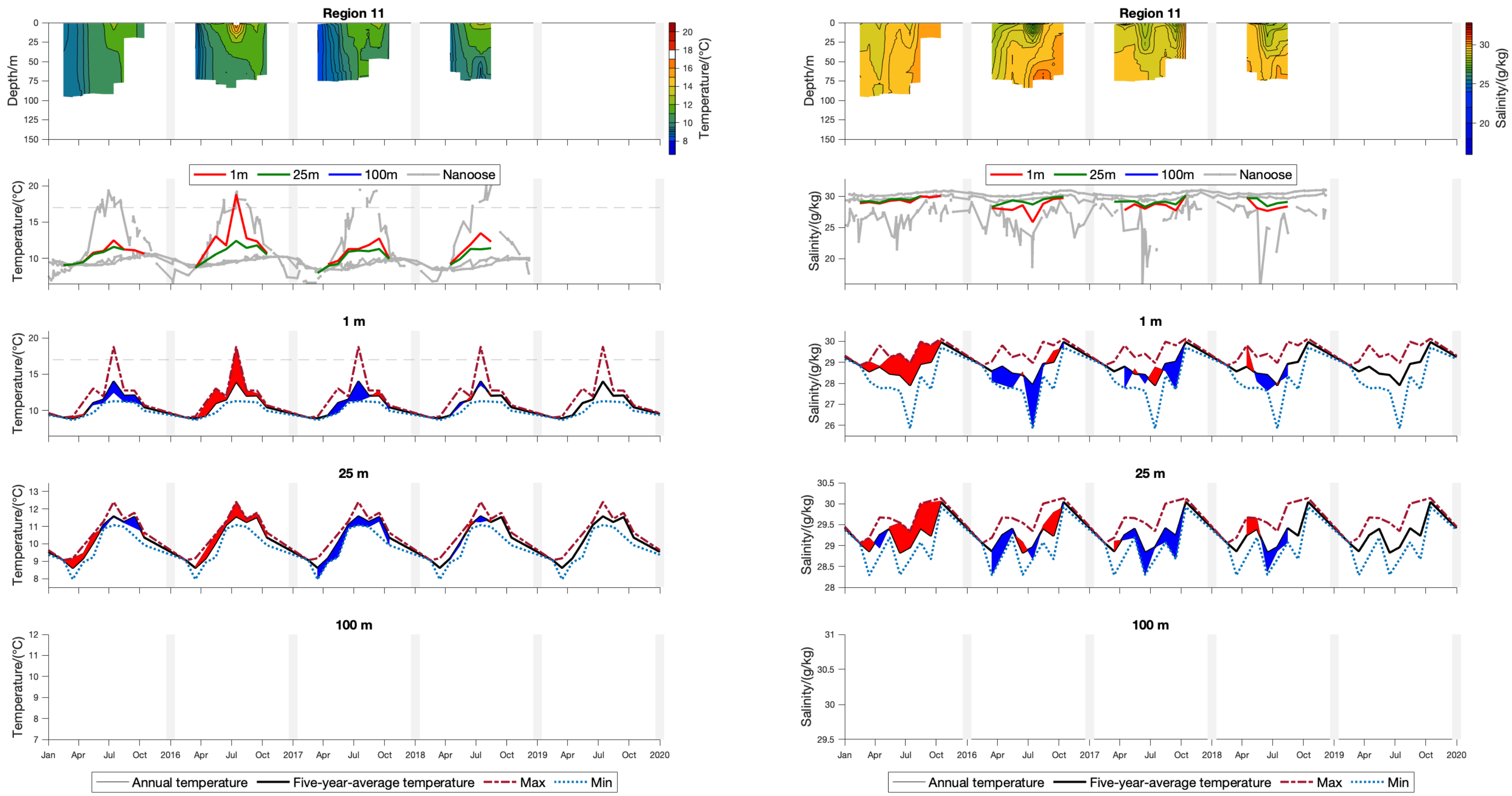

Figure 59: Variations about the climatological monthly means for (left) Temperature and (right) Salinity in Region 11. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

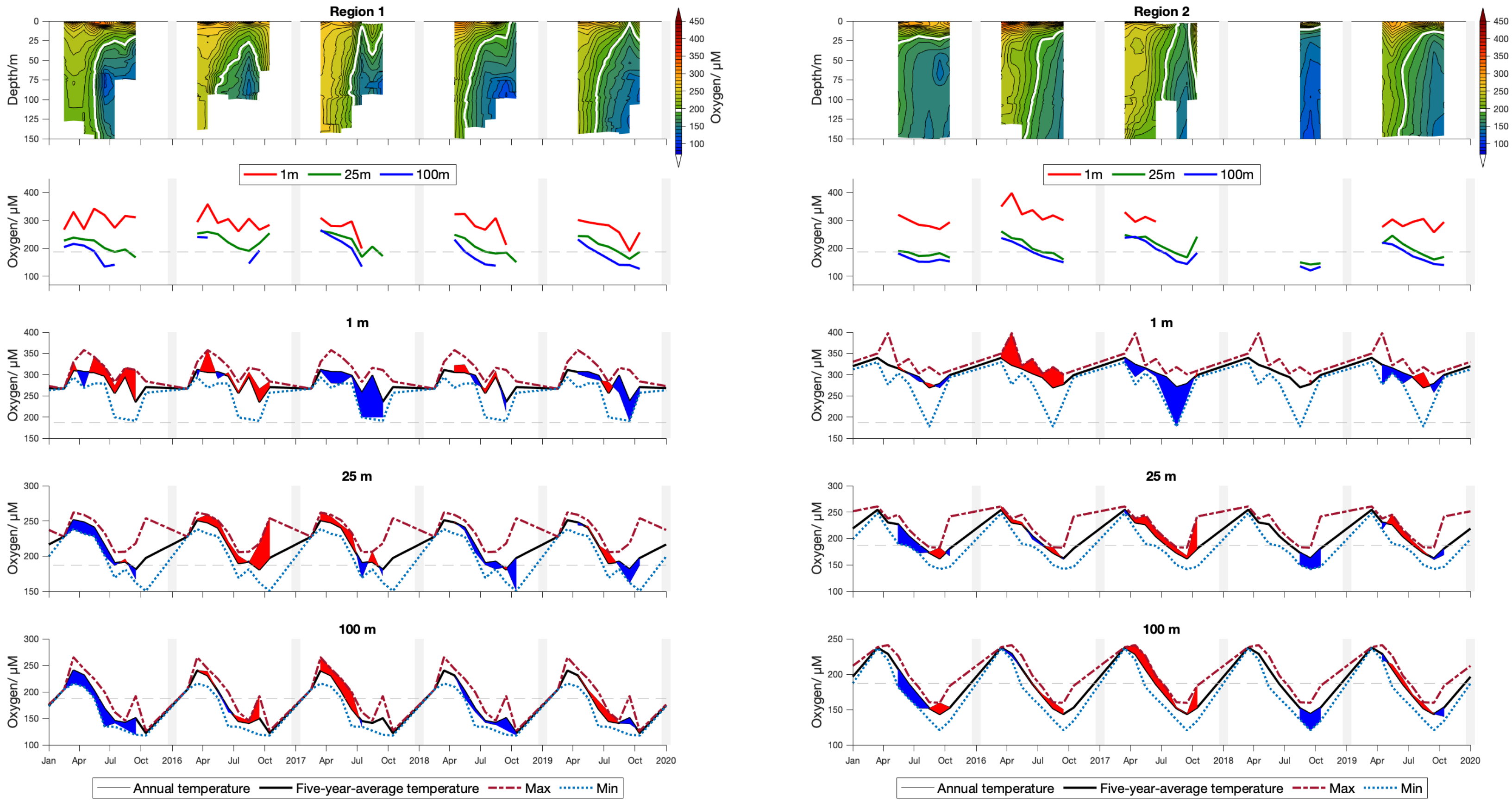

Figure 60: Variations about the climatological monthly means for Dissolved Oxygen in (left) Region 1 (right) Region 2. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

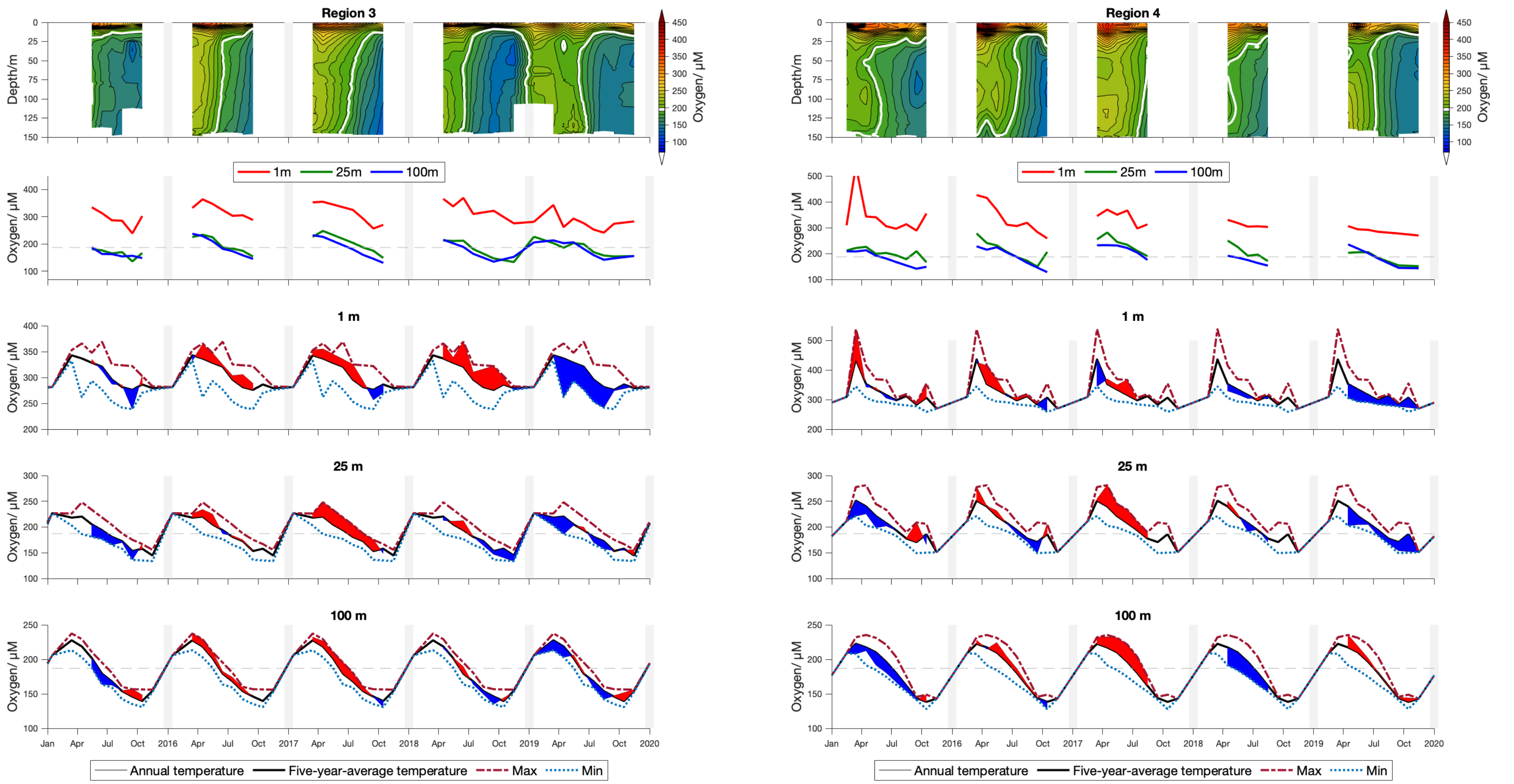

Figure 61: Variations about the climatological monthly means for Dissolved Oxygen in (left) Region 3 (right) Region 4. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

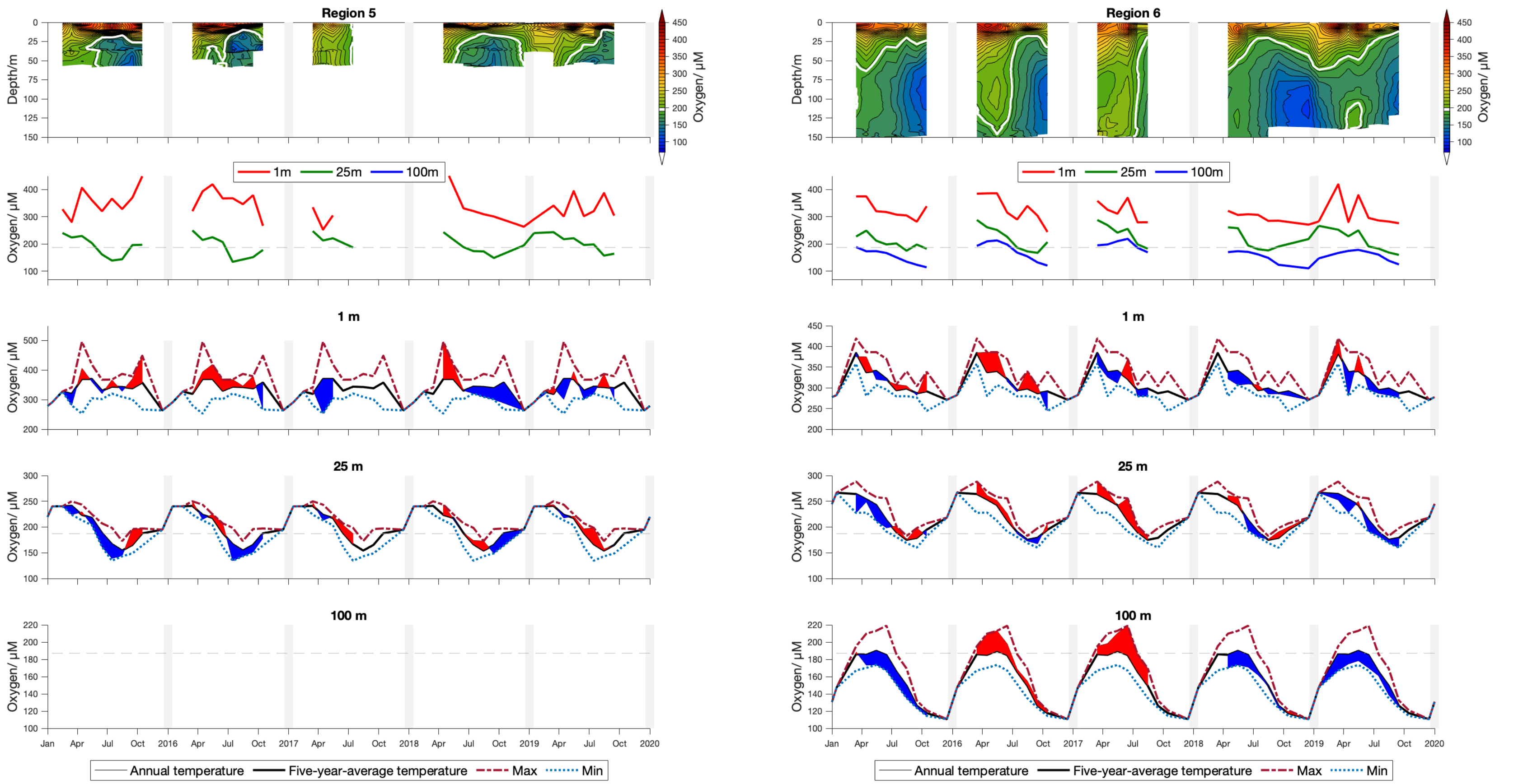

Figure 62: Variations about the climatological monthly means for Dissolved Oxygen in (left) Region 5 (right) Region 6. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

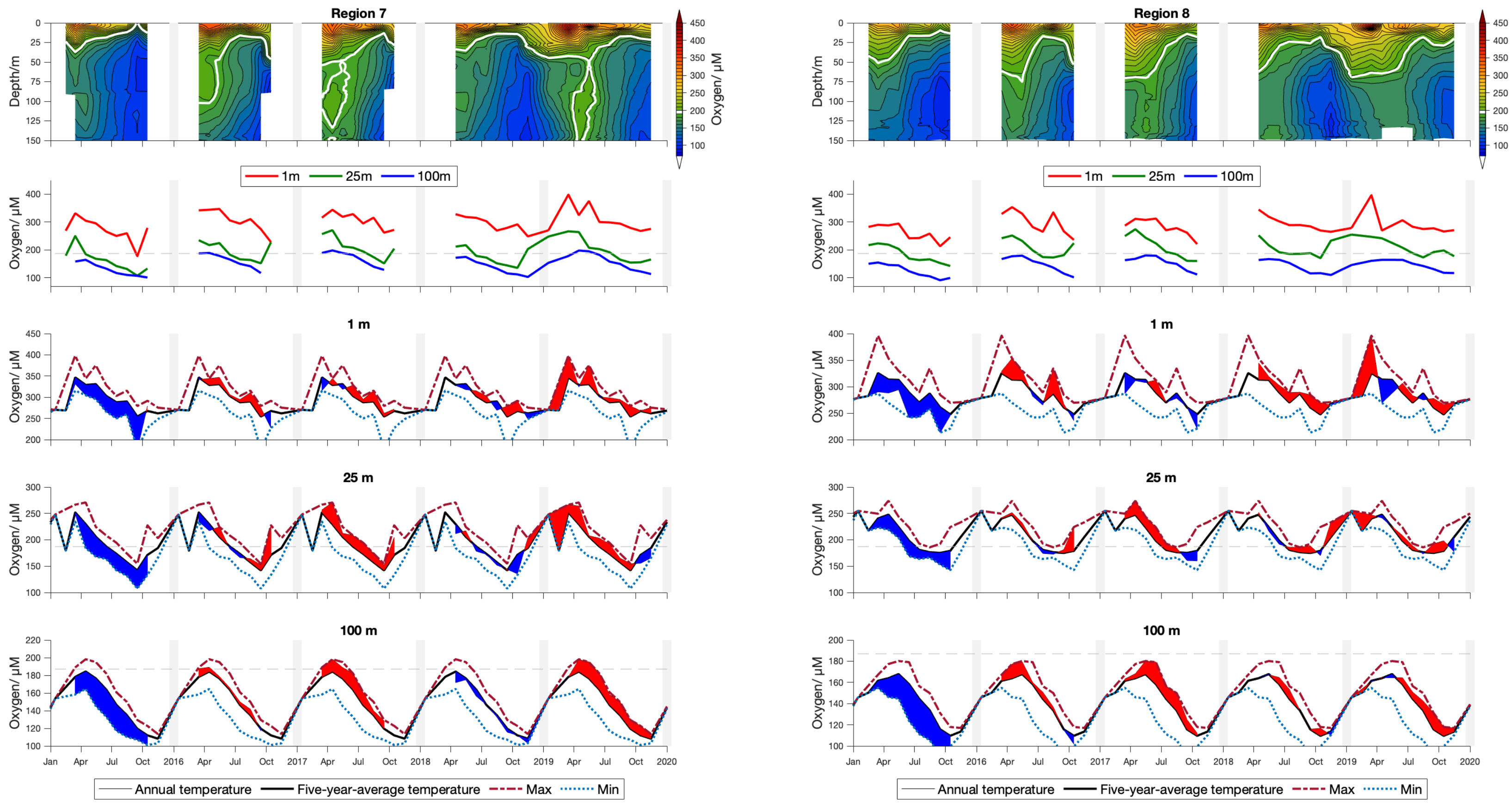

Figure 63: Variations about the climatological monthly means for Dissolved Oxygen in (left) Region 7 (right) Region 8. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

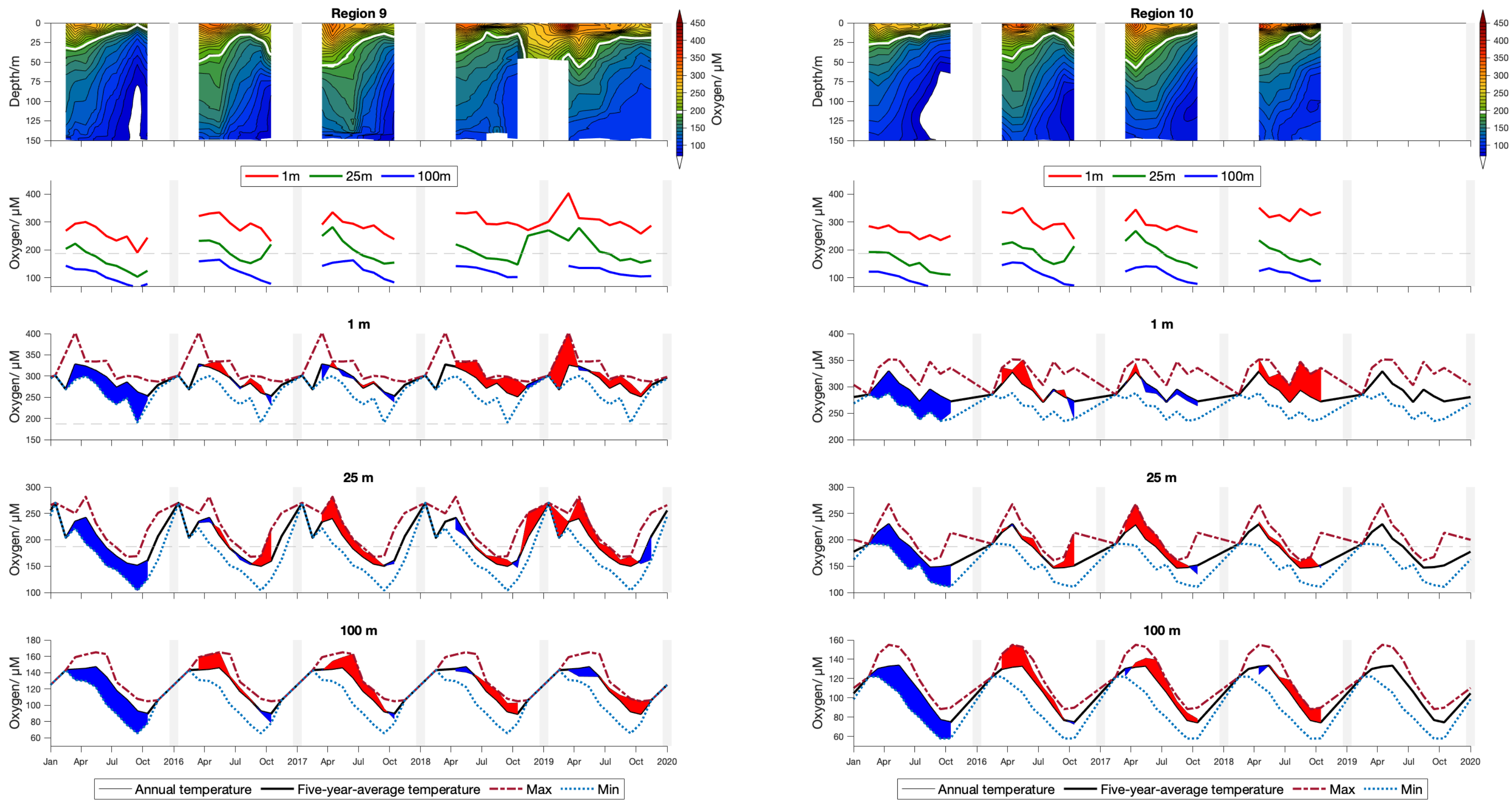

Figure 64: Variations about the climatological monthly means for Dissolved Oxygen in (left) Region 9 (right) Region 10. In lower panels, blue shading shows values below the climatological mean, and red shows values above this mean, at depths of 1, 25, and 100 m.

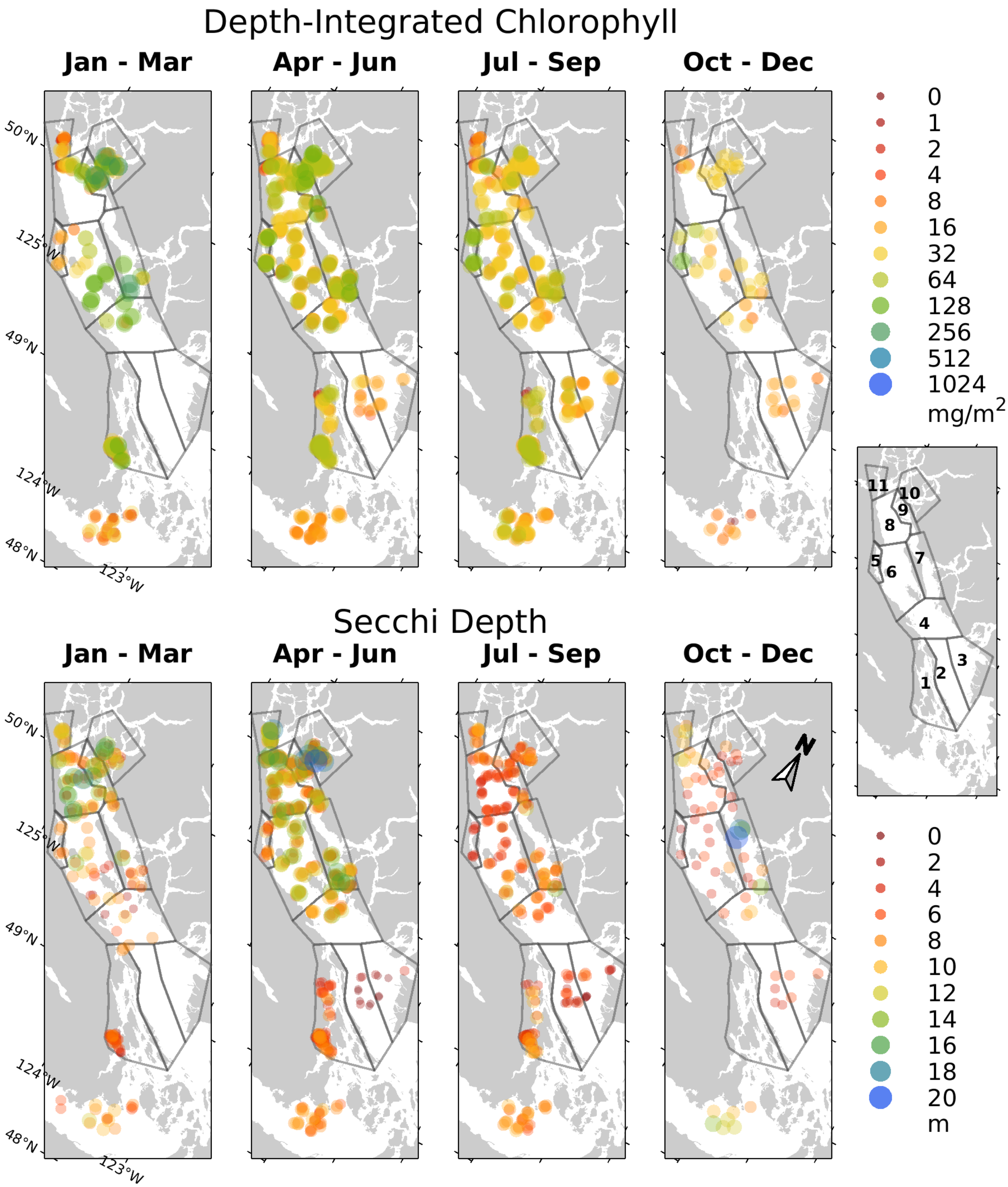

Figure 65: Depth integrated chlorophyll and Secchi depth for 2015 plotted at the location of the measurement, separated into three-month intervals.

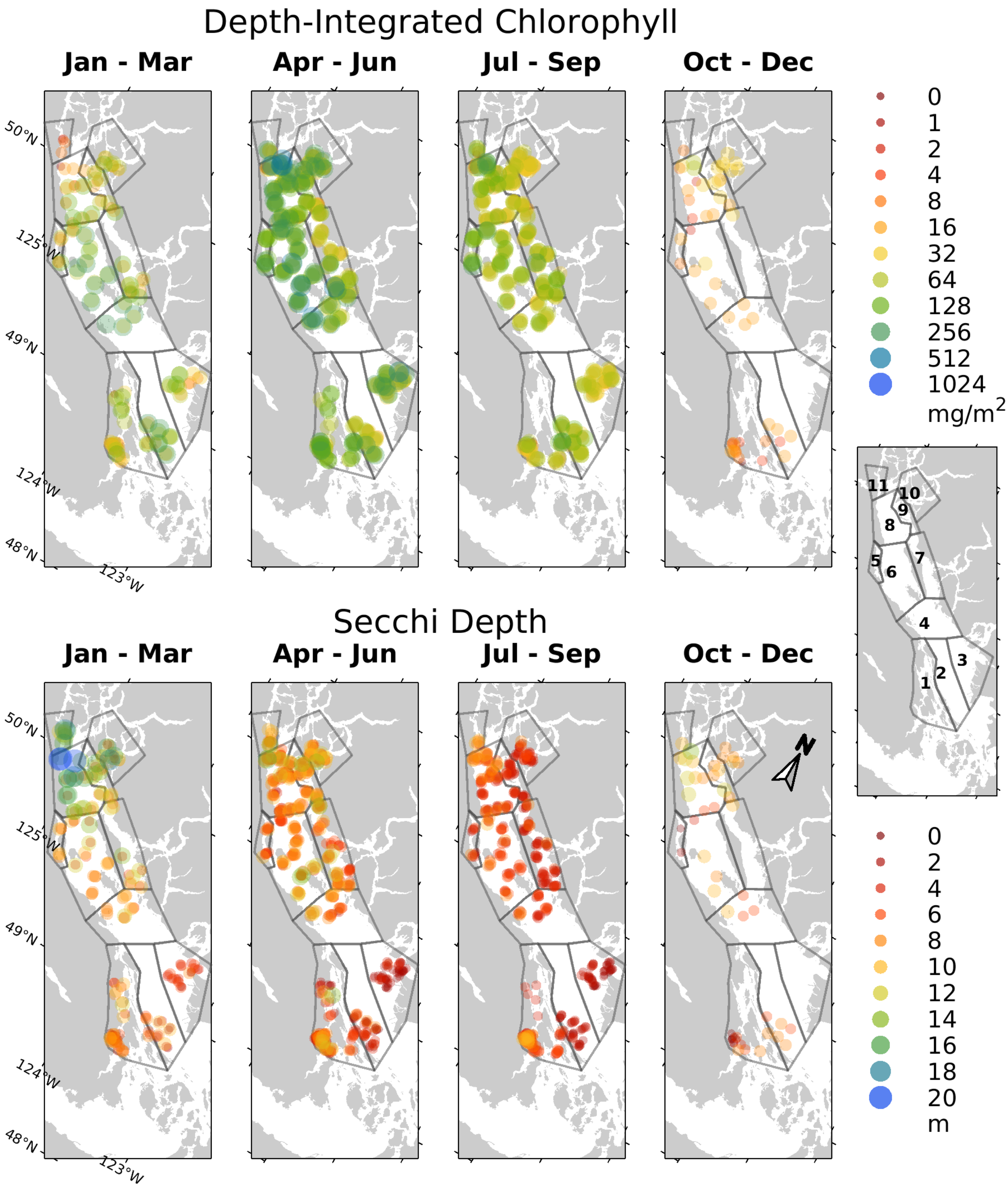

Figure 66: Depth integrated chlorophyll and Secchi depth for 2016 plotted at the location of the measurement, separated into three-month intervals.

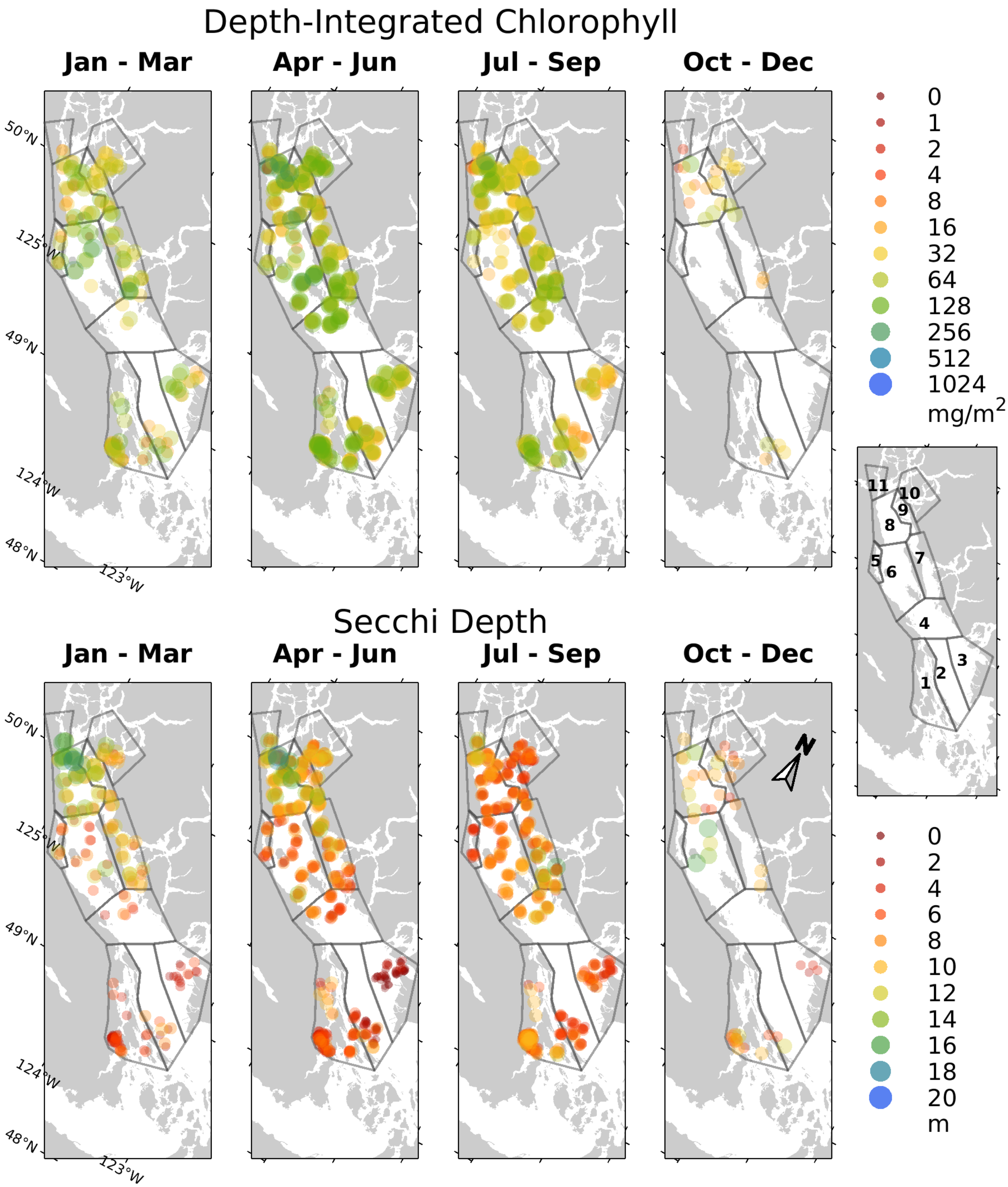

Figure 67: Depth integrated chlorophyll and Secchi depth for 2017 plotted at the location of the measurement, separated into three-month intervals.

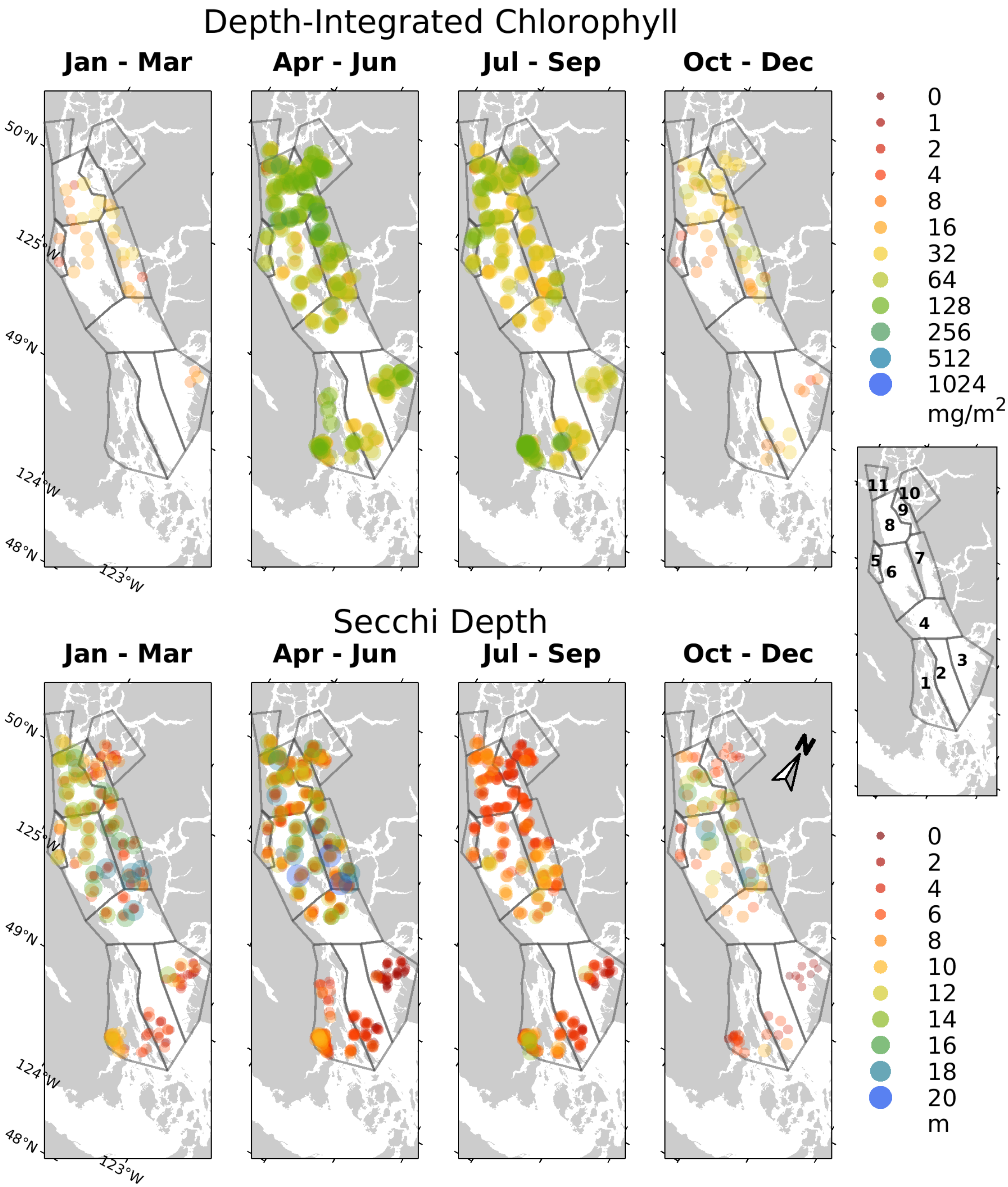

Figure 68: Depth integrated chlorophyll and Secchi depth for 2018 plotted at the location of the measurement, separated into three-month intervals.

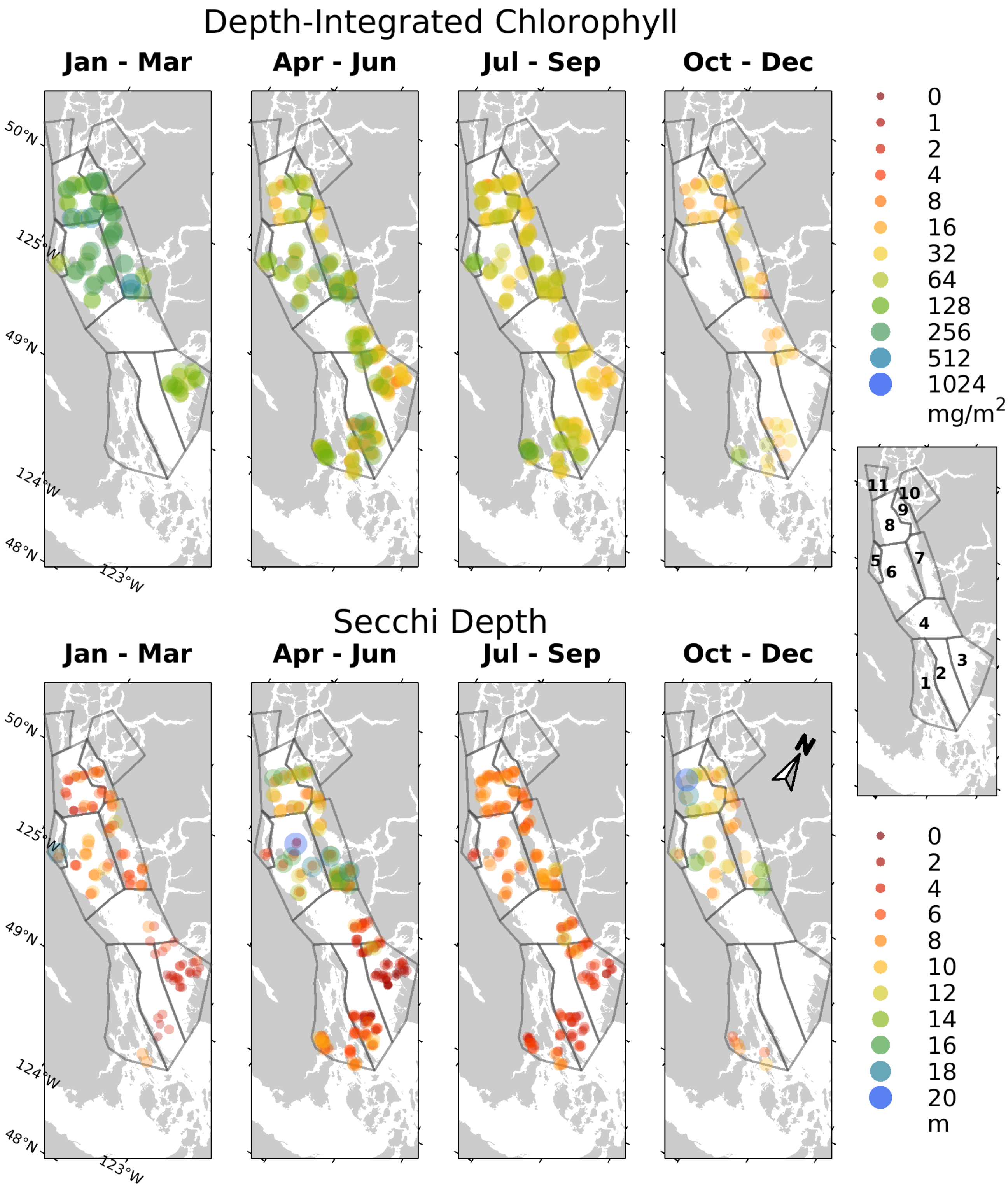

Figure 69: Depth integrated chlorophyll and Secchi depth for 2019 plotted at the location of the measurement, separated into three-month intervals.

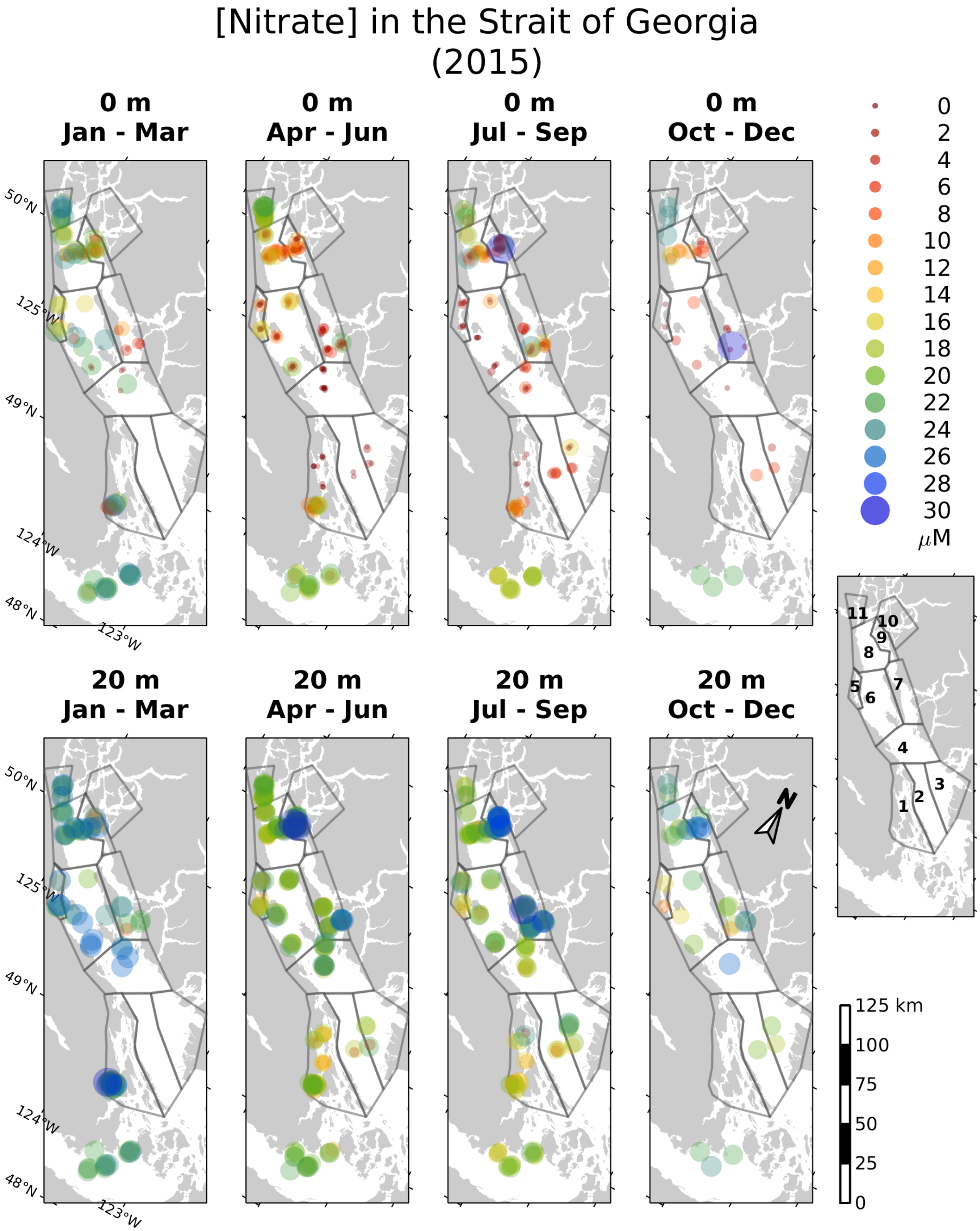

Figure 70: Nitrate levels for 2015 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

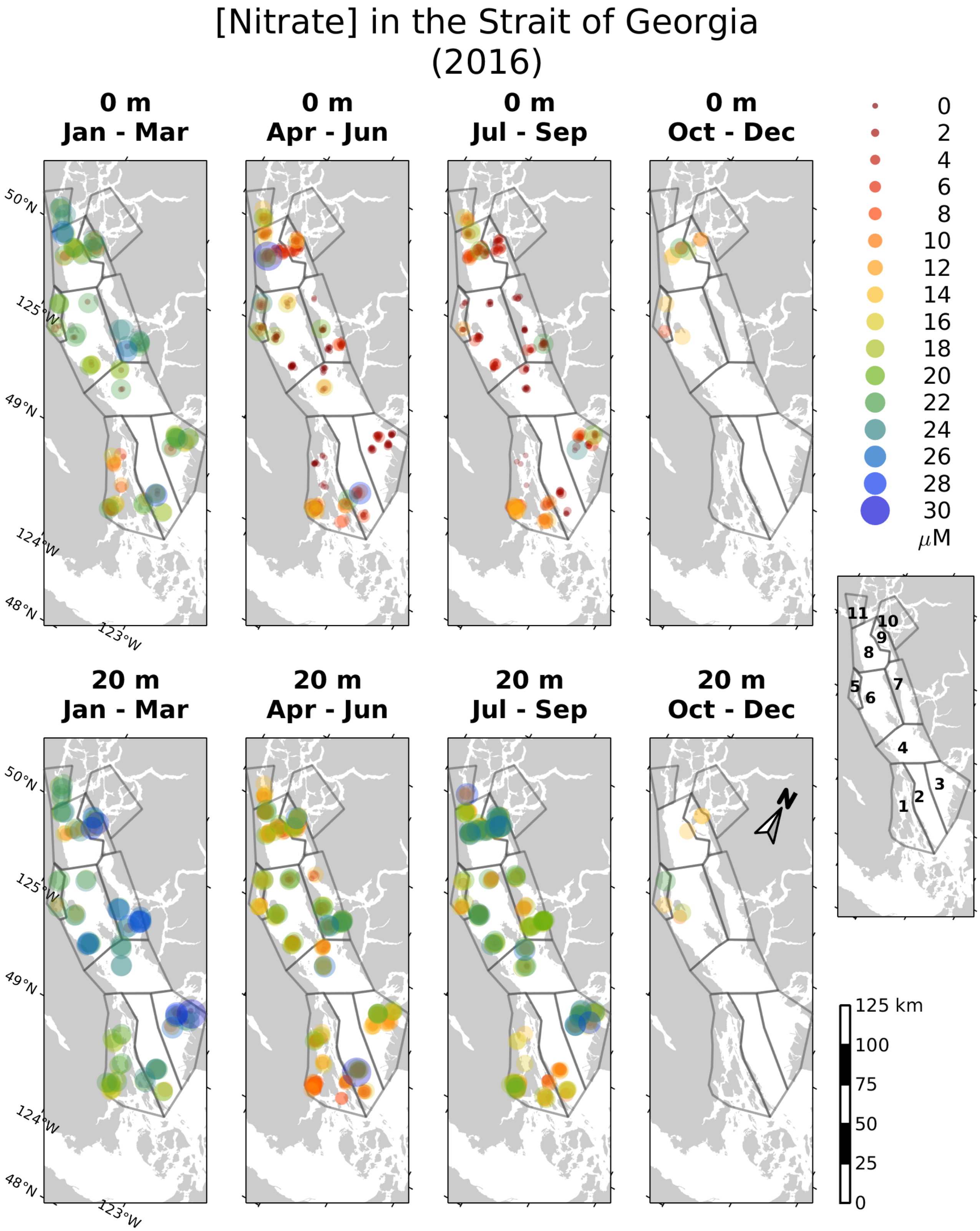

Figure 71: Nitrate levels for 2016 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

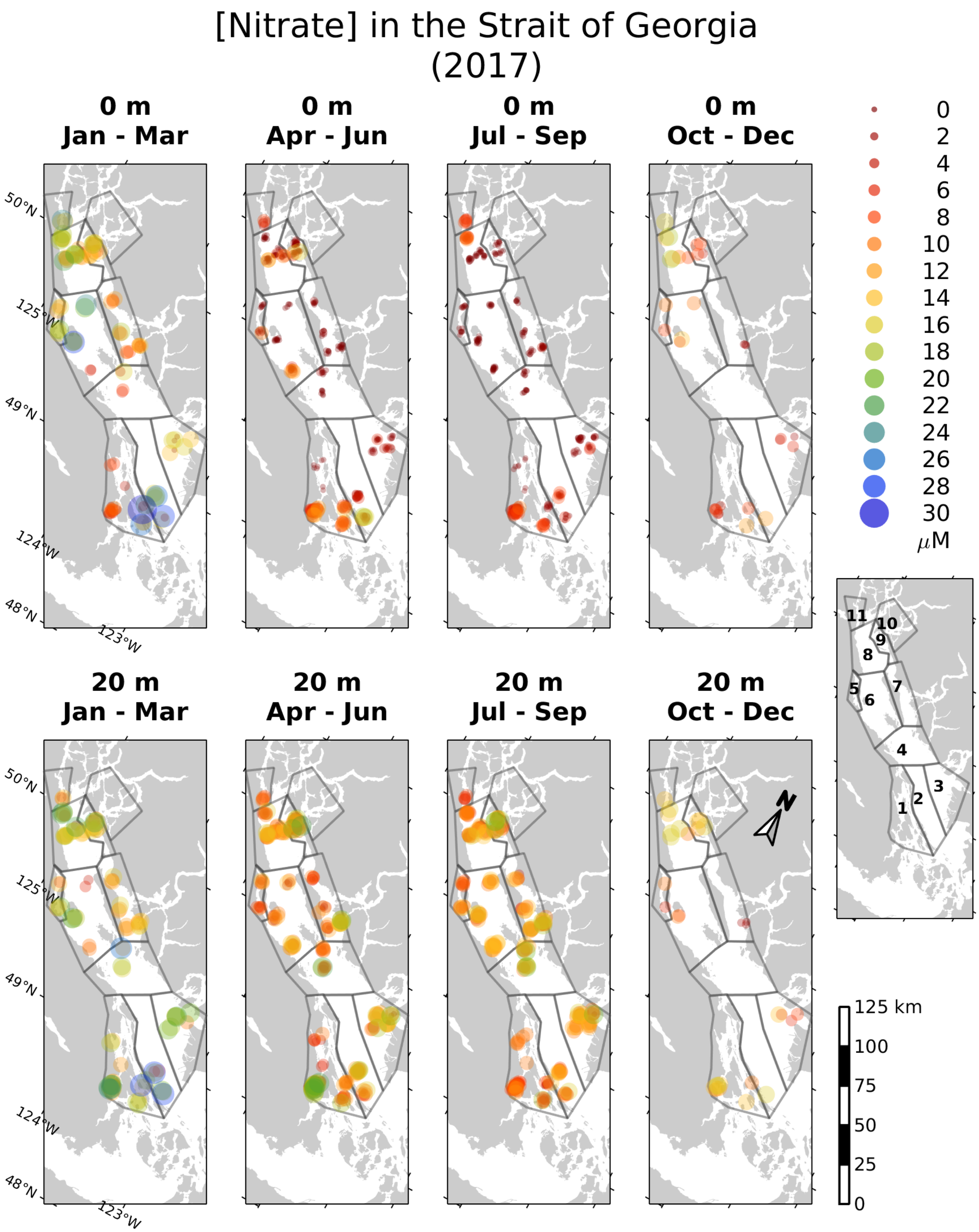

Figure 72: Nitrate levels for 2017 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

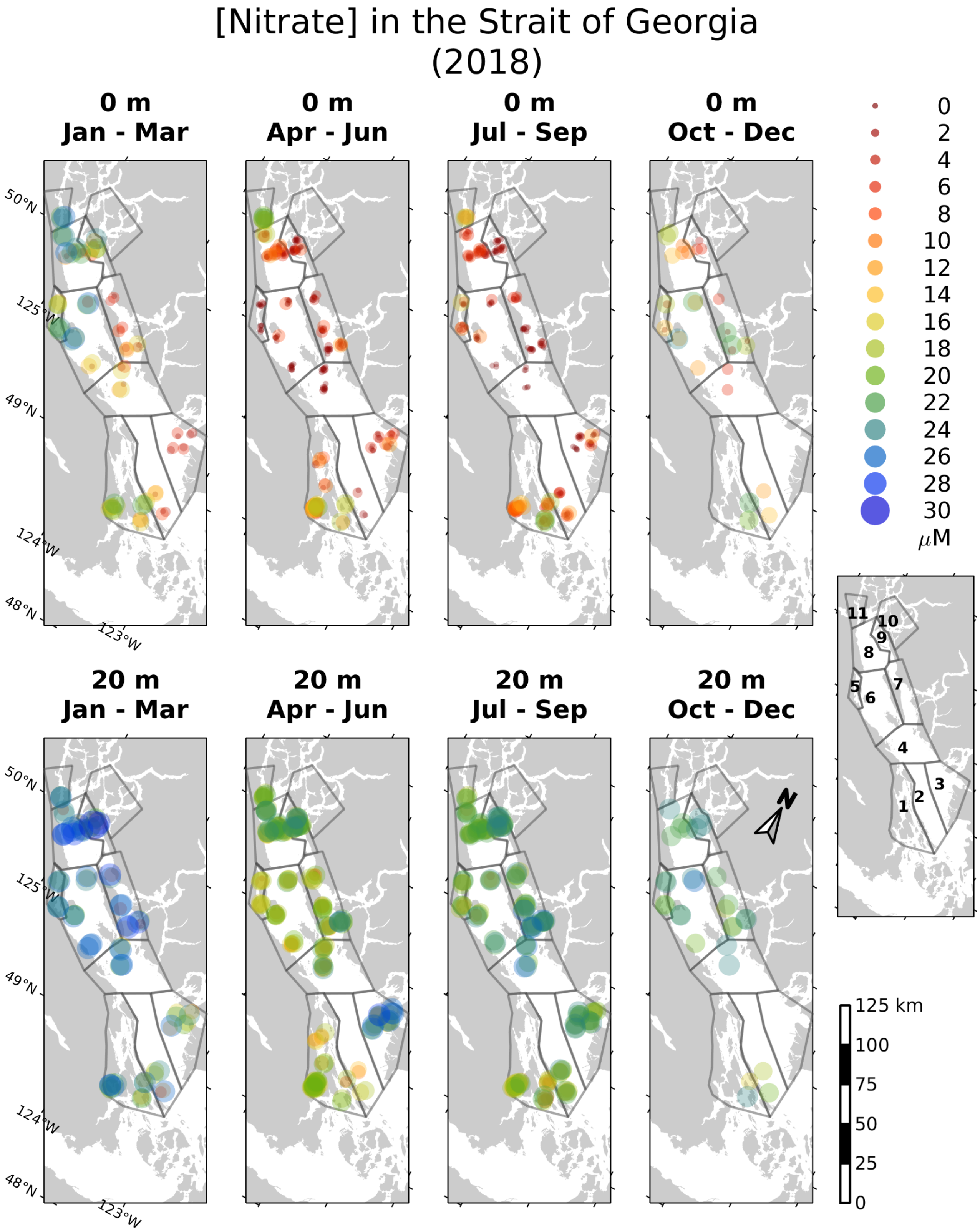

Figure 73: Nitrate levels for 2018 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

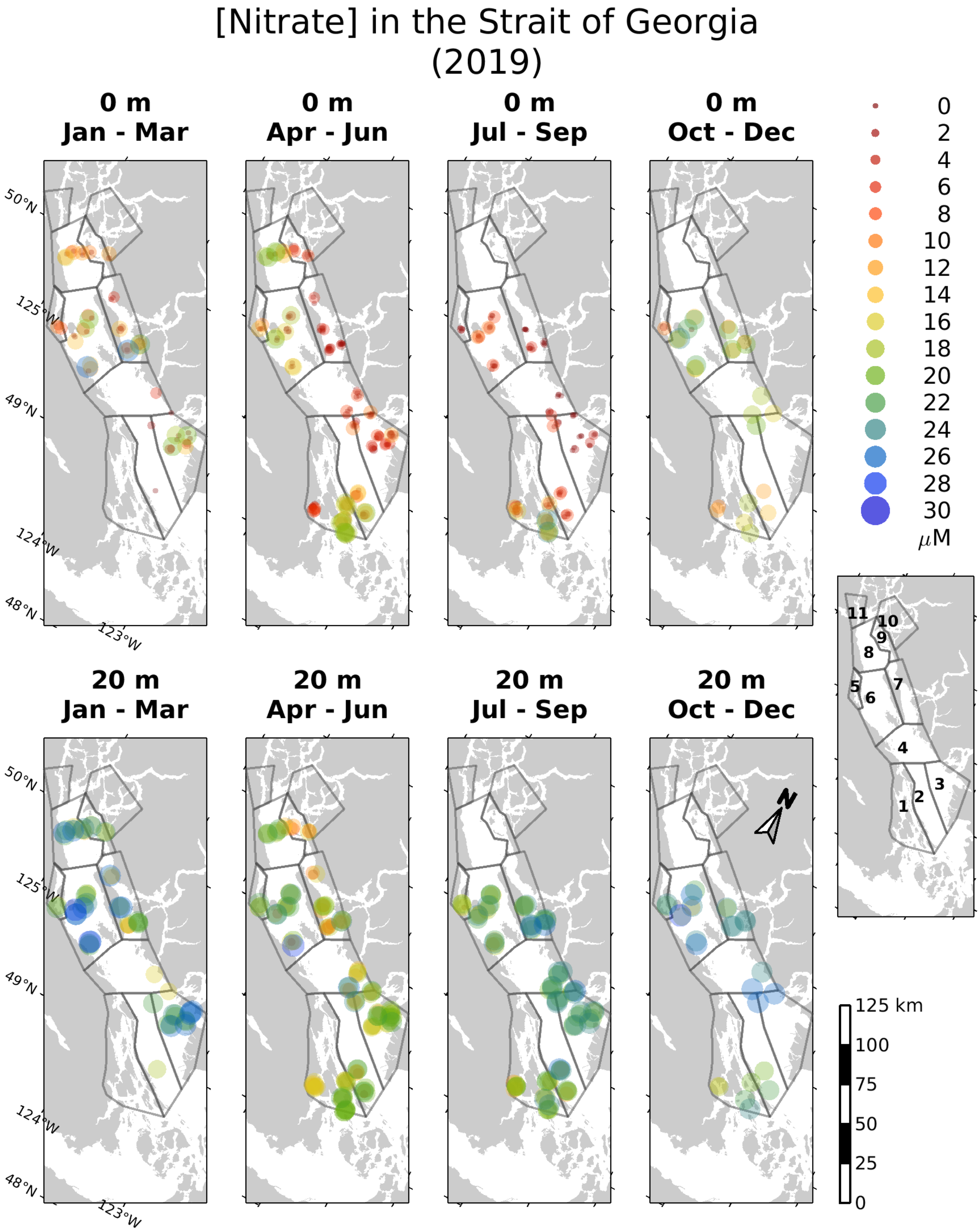

Figure 74: Nitrate levels for 2019 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

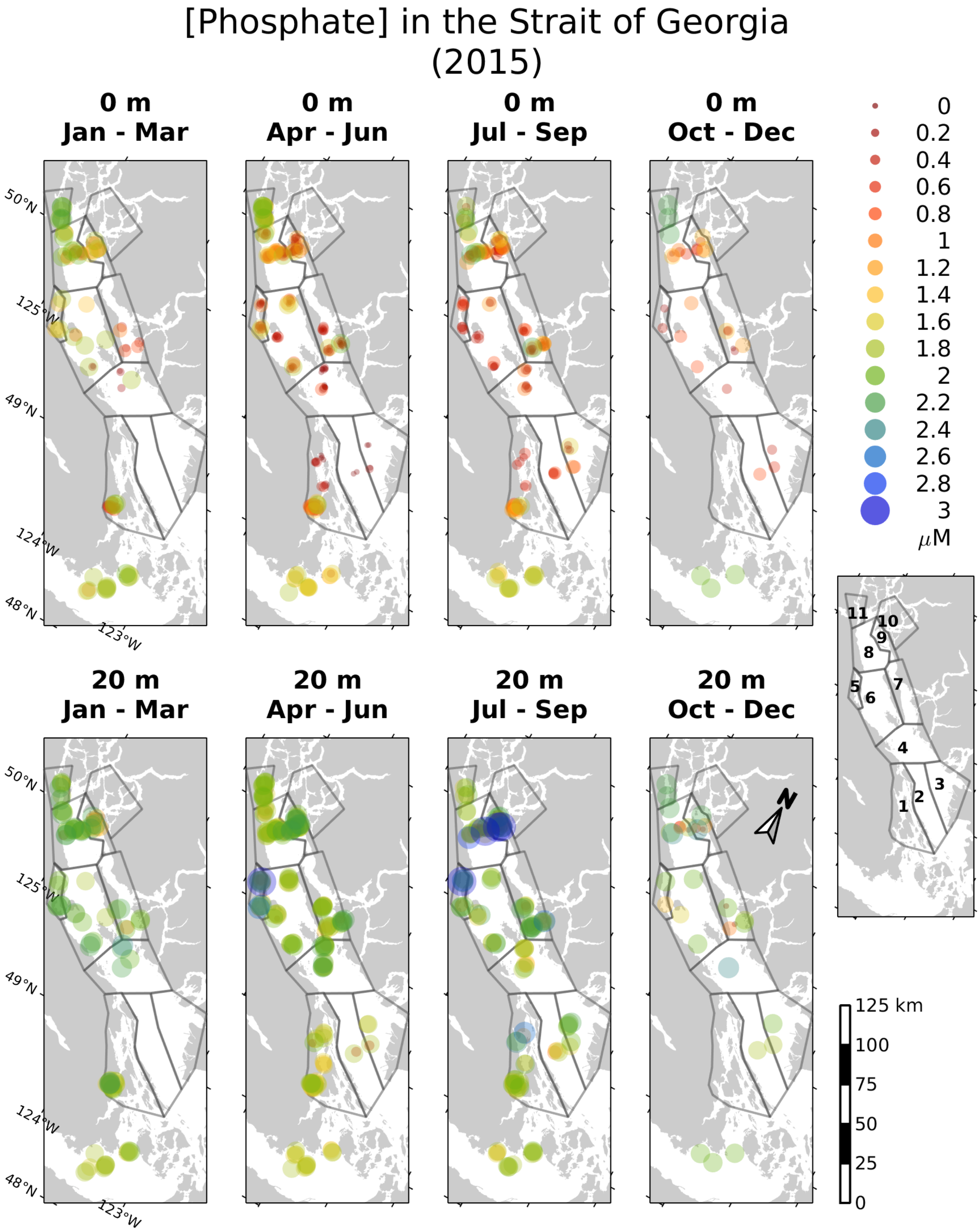

Figure 75: Phosphate levels for 2015 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

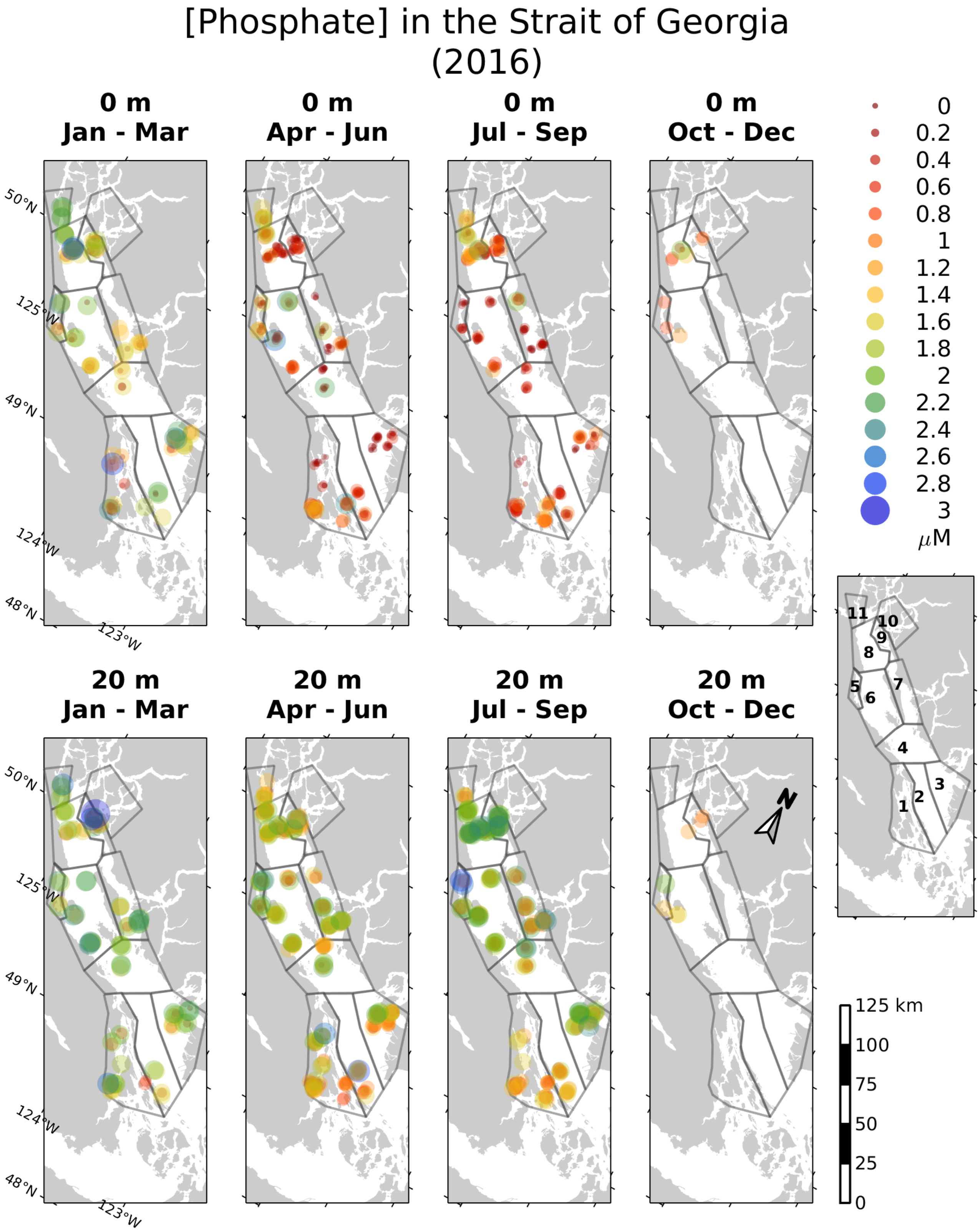

Figure 76: Phosphate levels for 2016 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

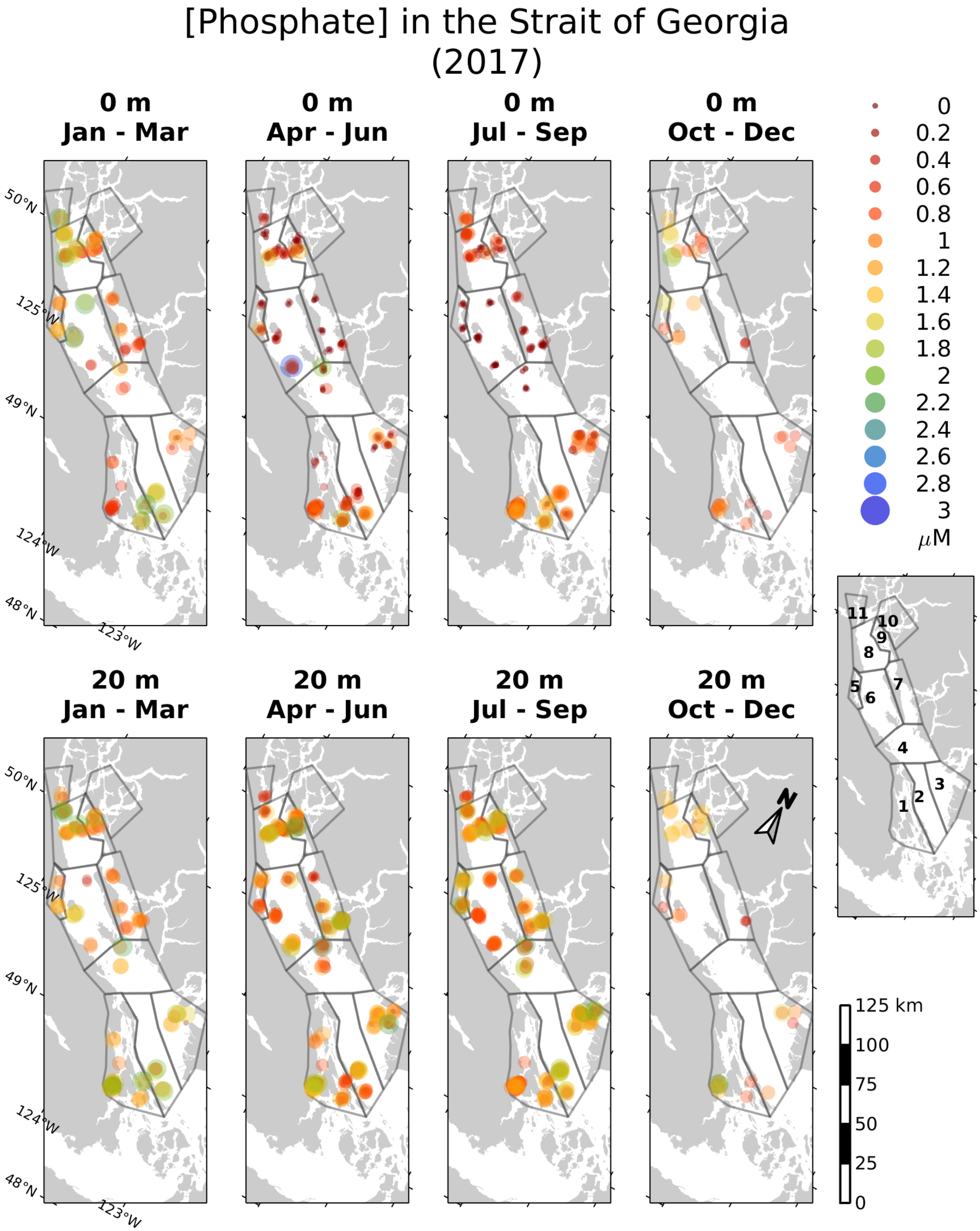

Figure 77: Phosphate levels for 2017 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

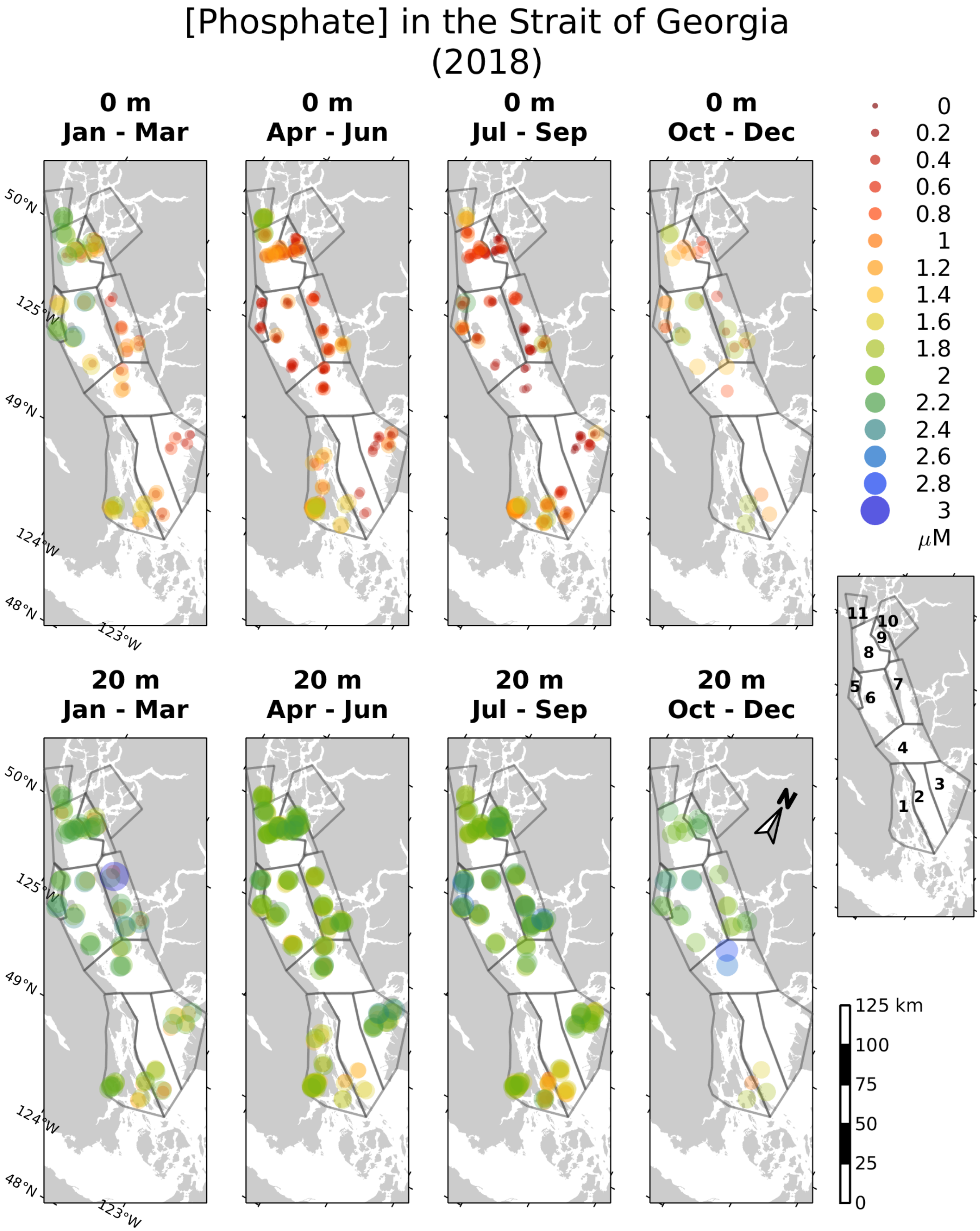

Figure 78: Phosphate levels for 2018 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

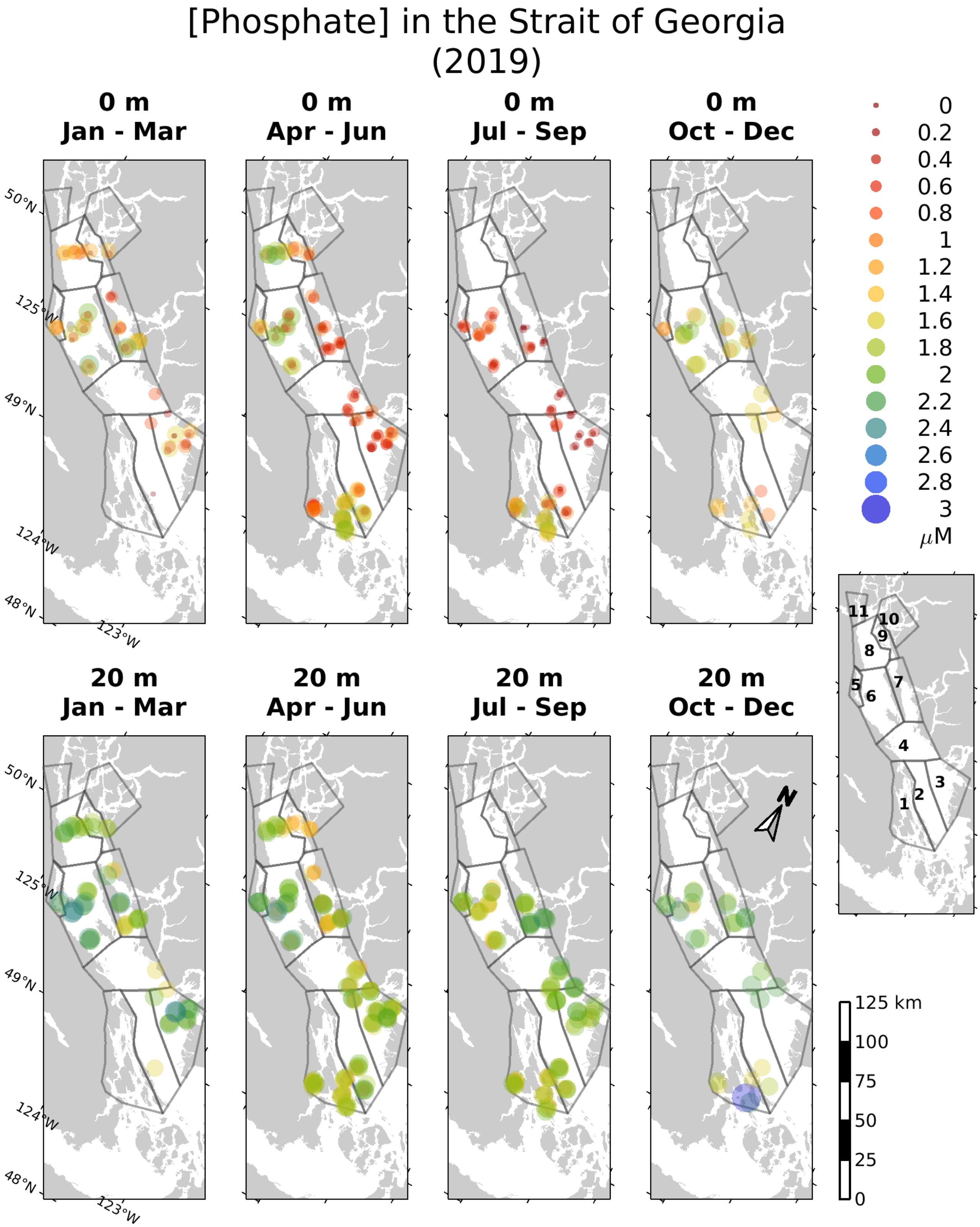

Figure 79: Phosphate levels for 2019 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

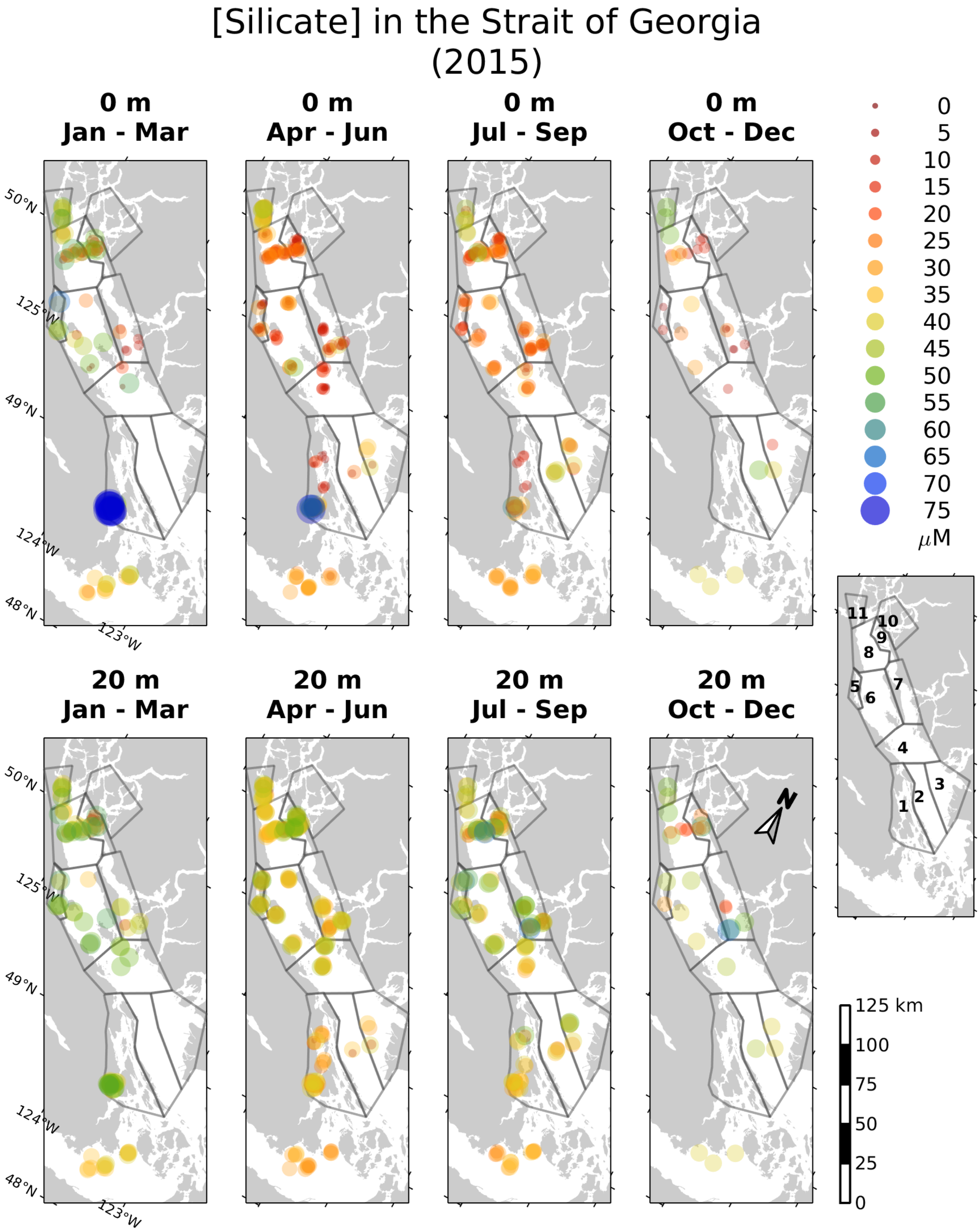

Figure 80: Silicate levels for 2015 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

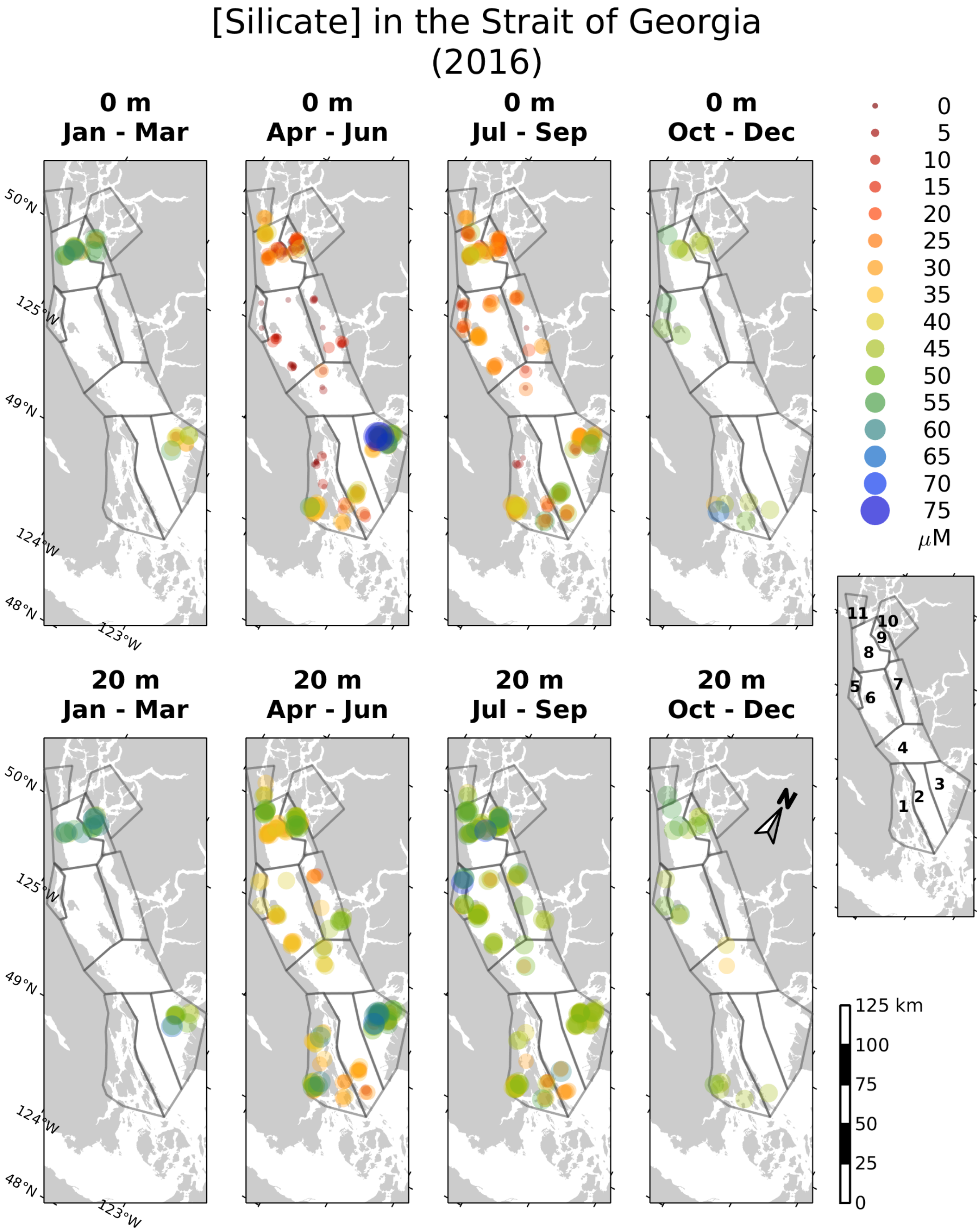

Figure 81: Silicate levels for 2016 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

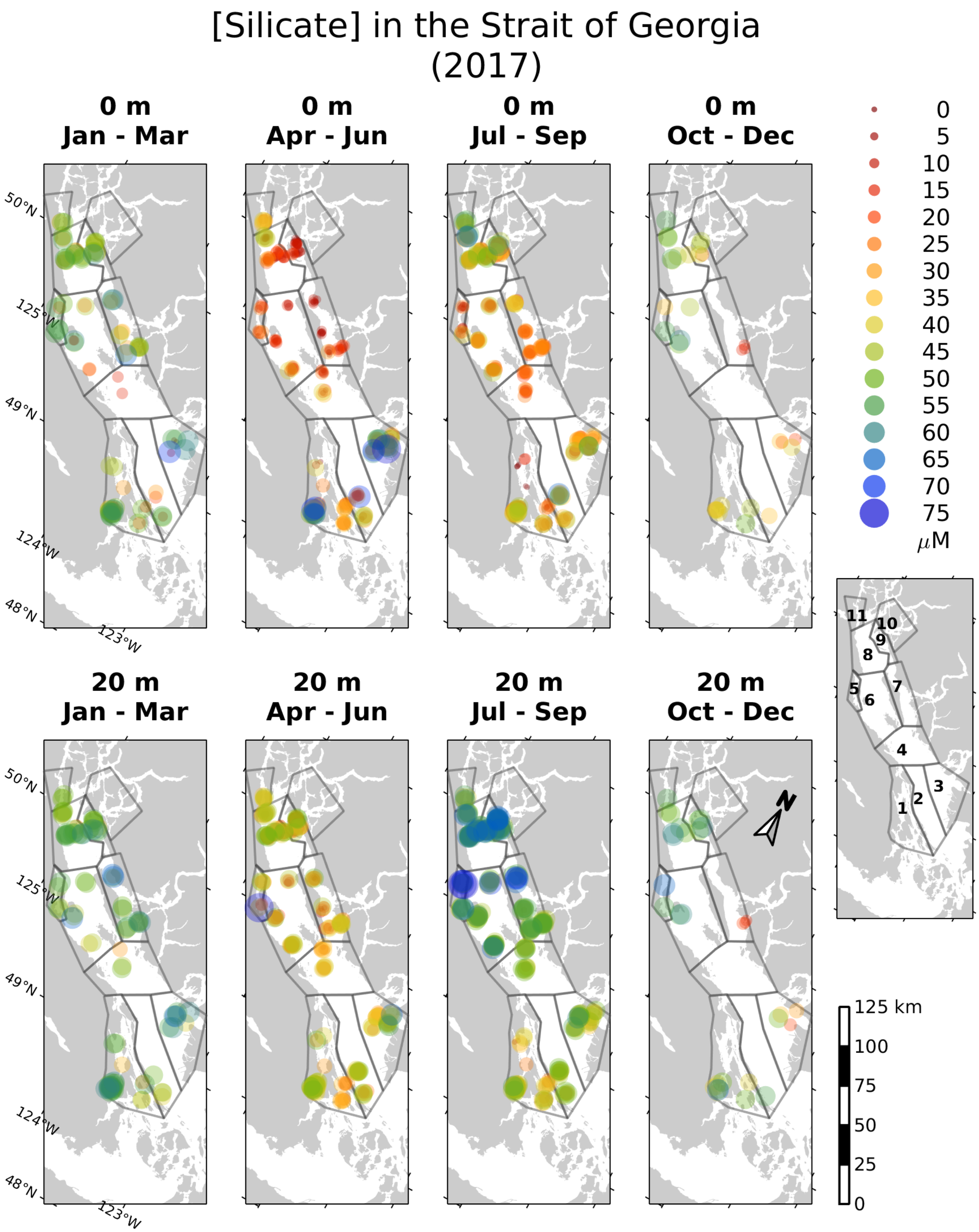

Figure 82: Silicate levels for 2017 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

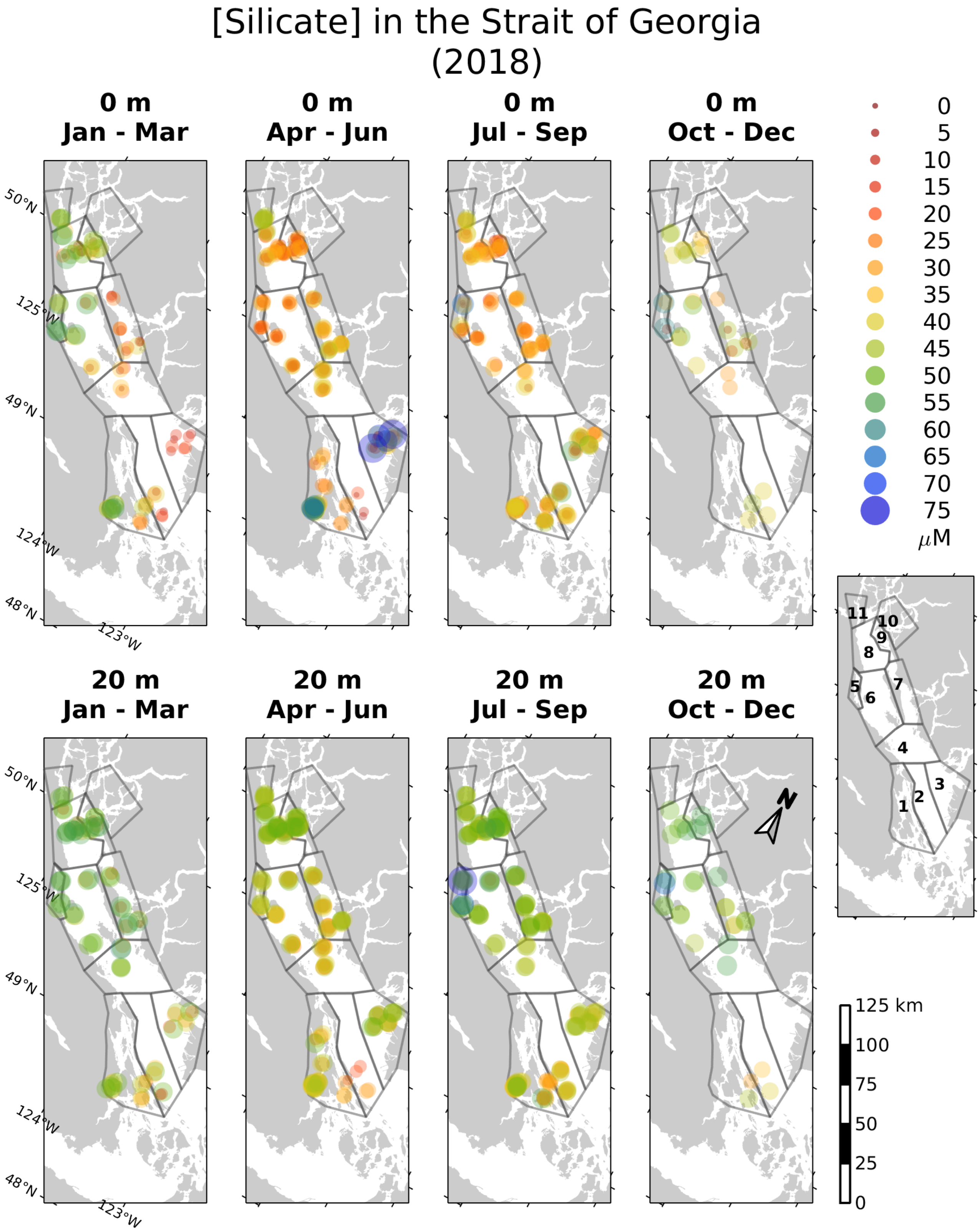

Figure 83: Silicate levels for 2018 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

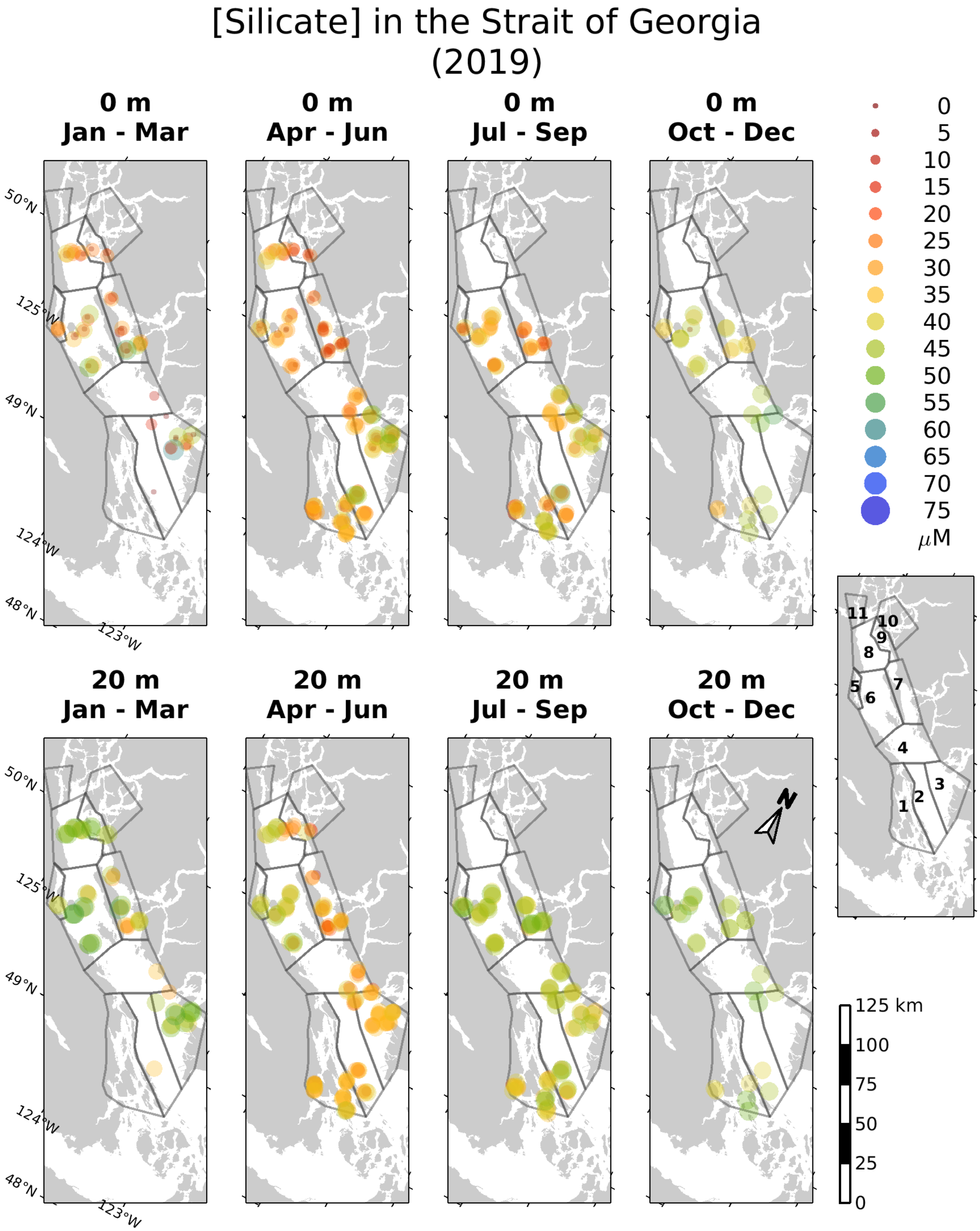

Figure 84: Silicate levels for 2019 plotted at the location of the measurement, separated into three-month intervals, for zero and 20 meters.

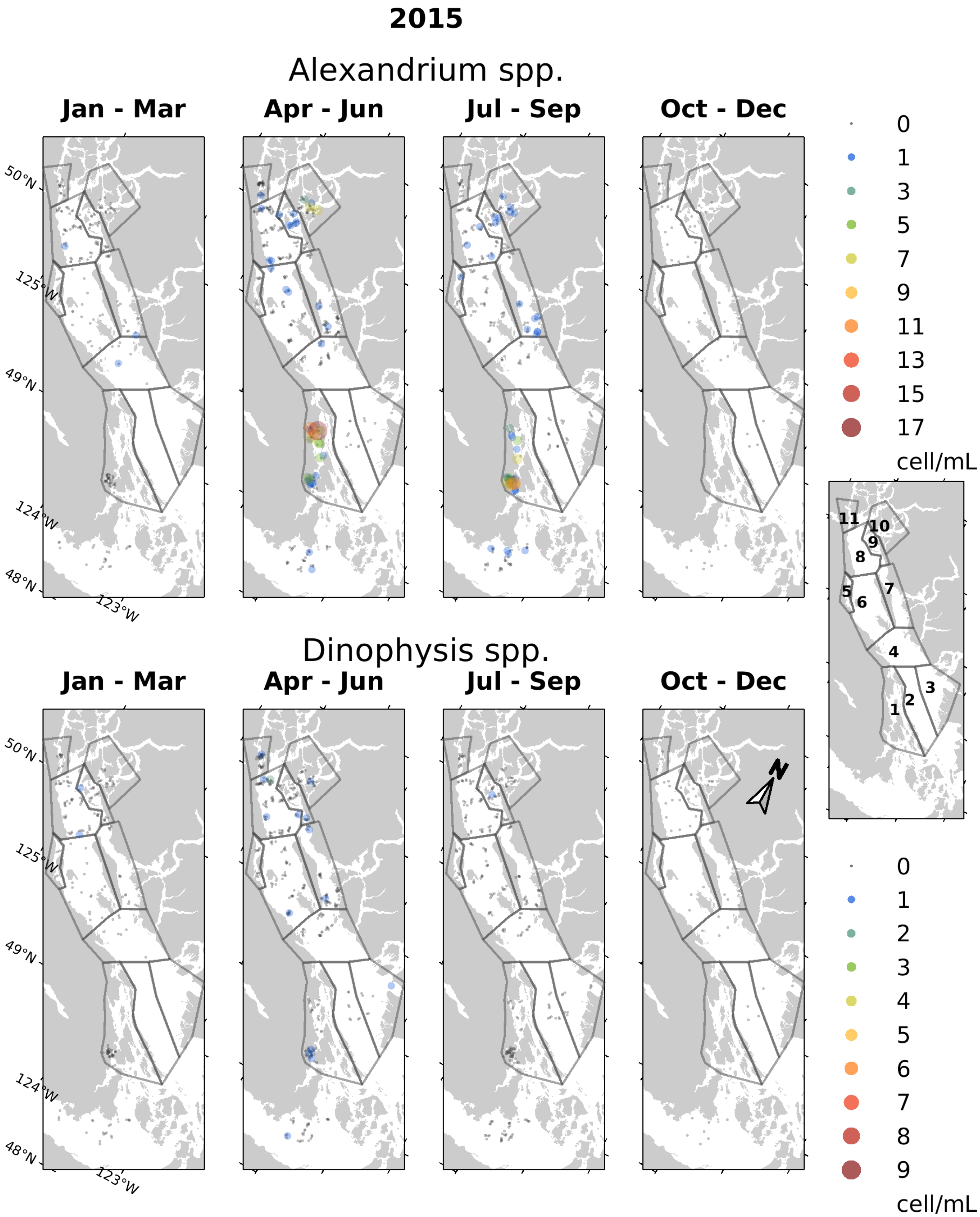

Figure 85: *Alexandrium* and *Dinophysis* concentrations for 2015, separated into 3-month intervals.

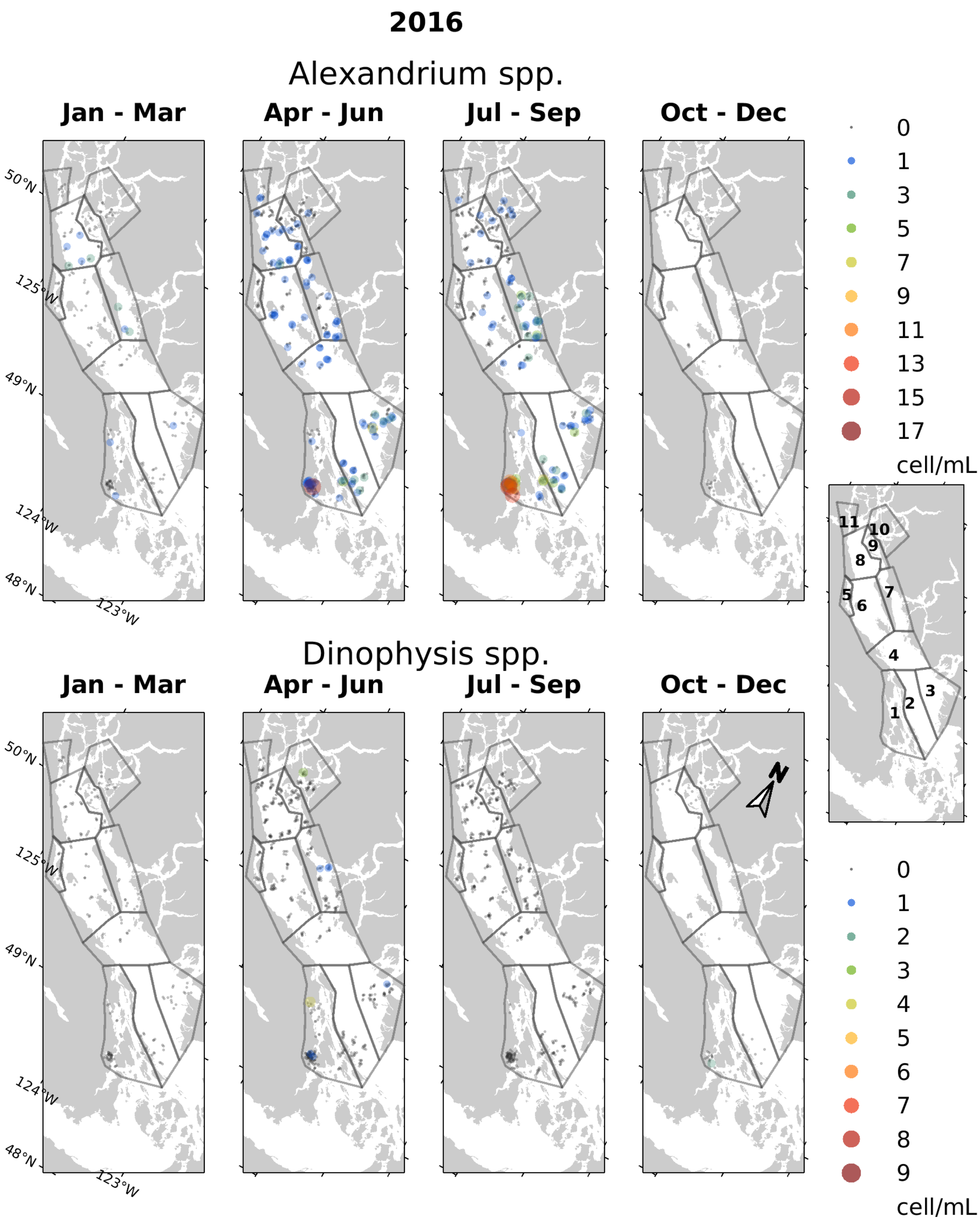

Figure 86: *Alexandrium* and *Dinophysis* concentrations for 2016, separated into 3-month intervals.

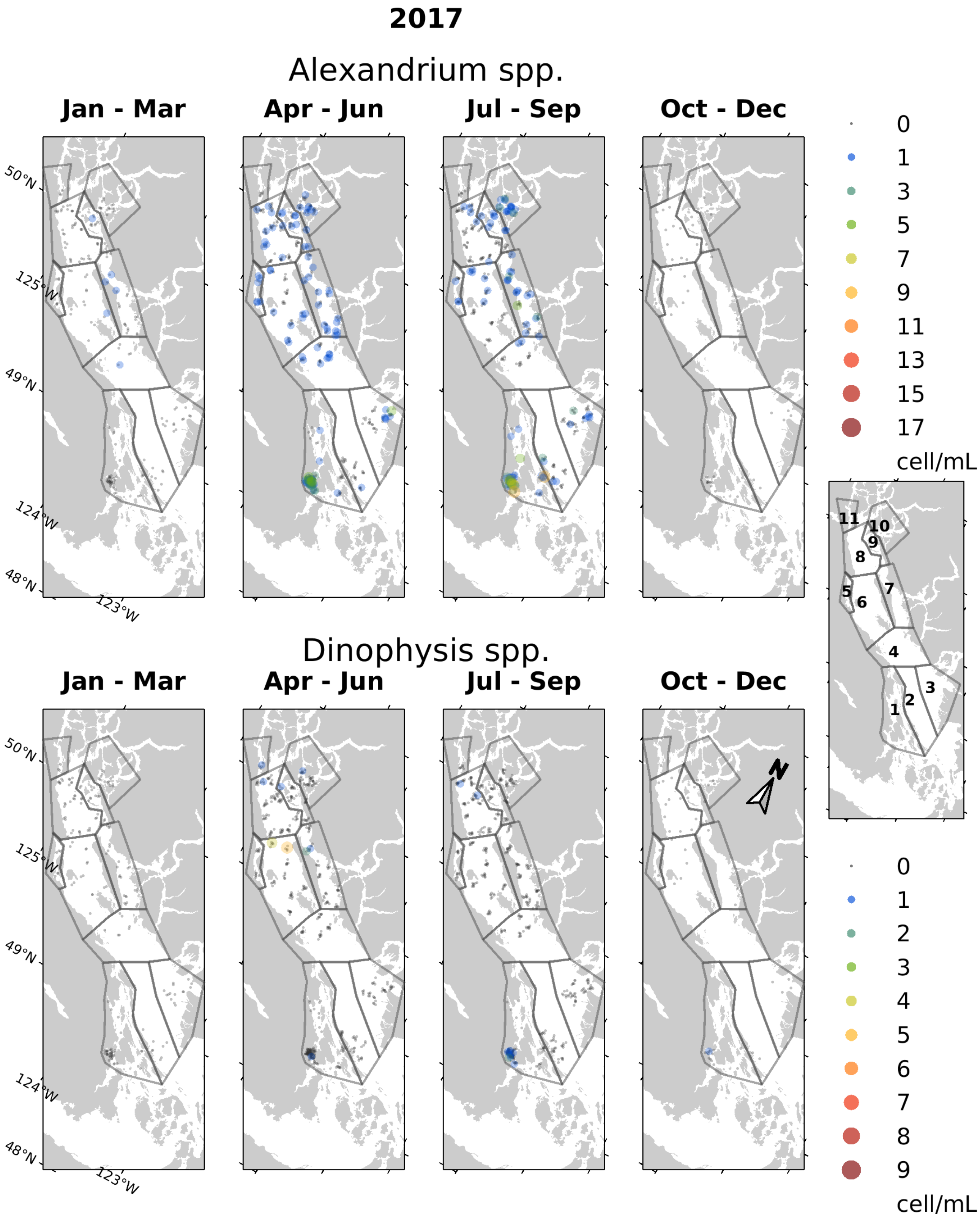

Figure 87: *Alexandrium* and *Dinophysis* concentrations for 2017, separated into 3-month intervals.

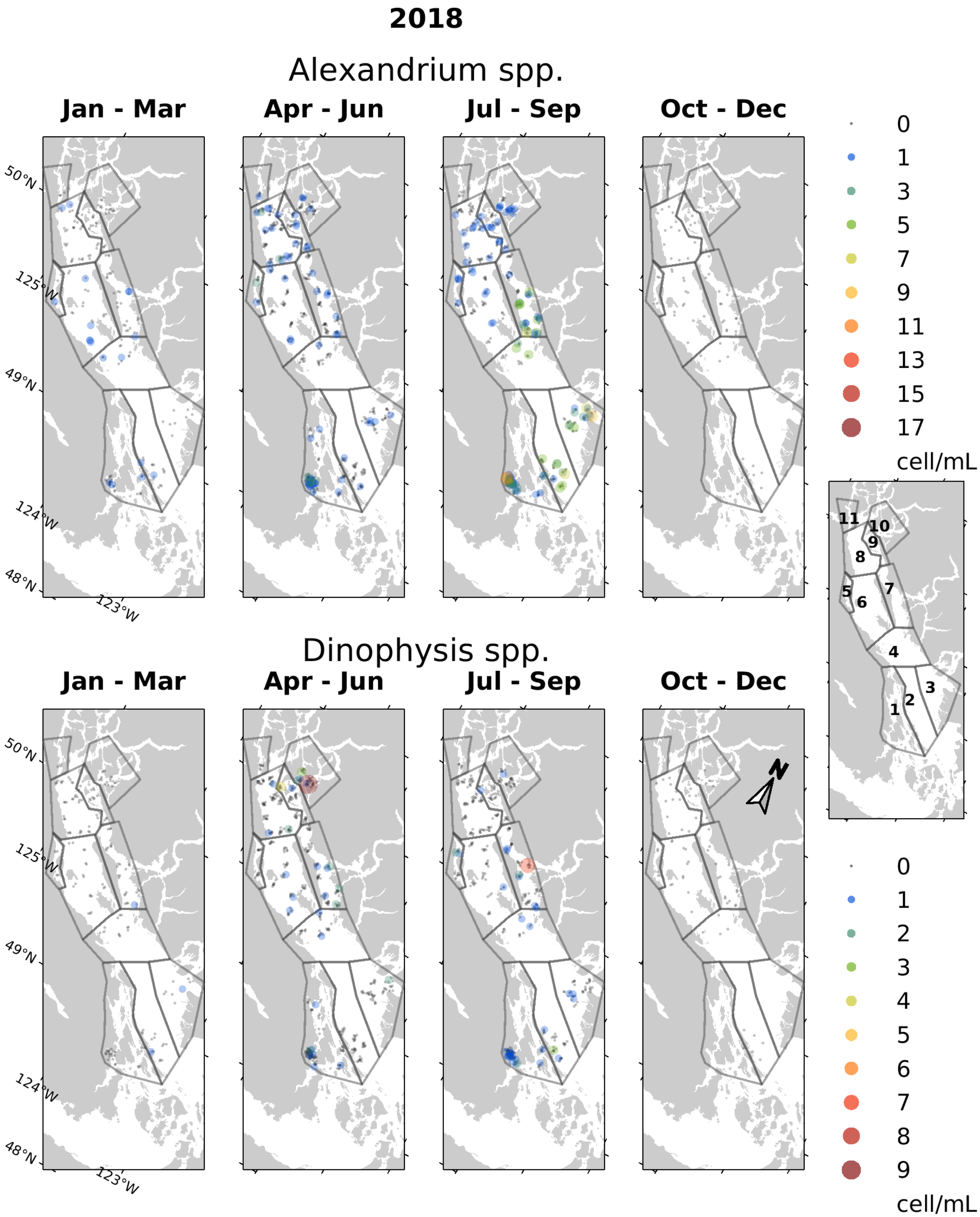

Figure 88: *Alexandrium* and *Dinophysis* concentrations for 2018, separated into 3-month intervals.

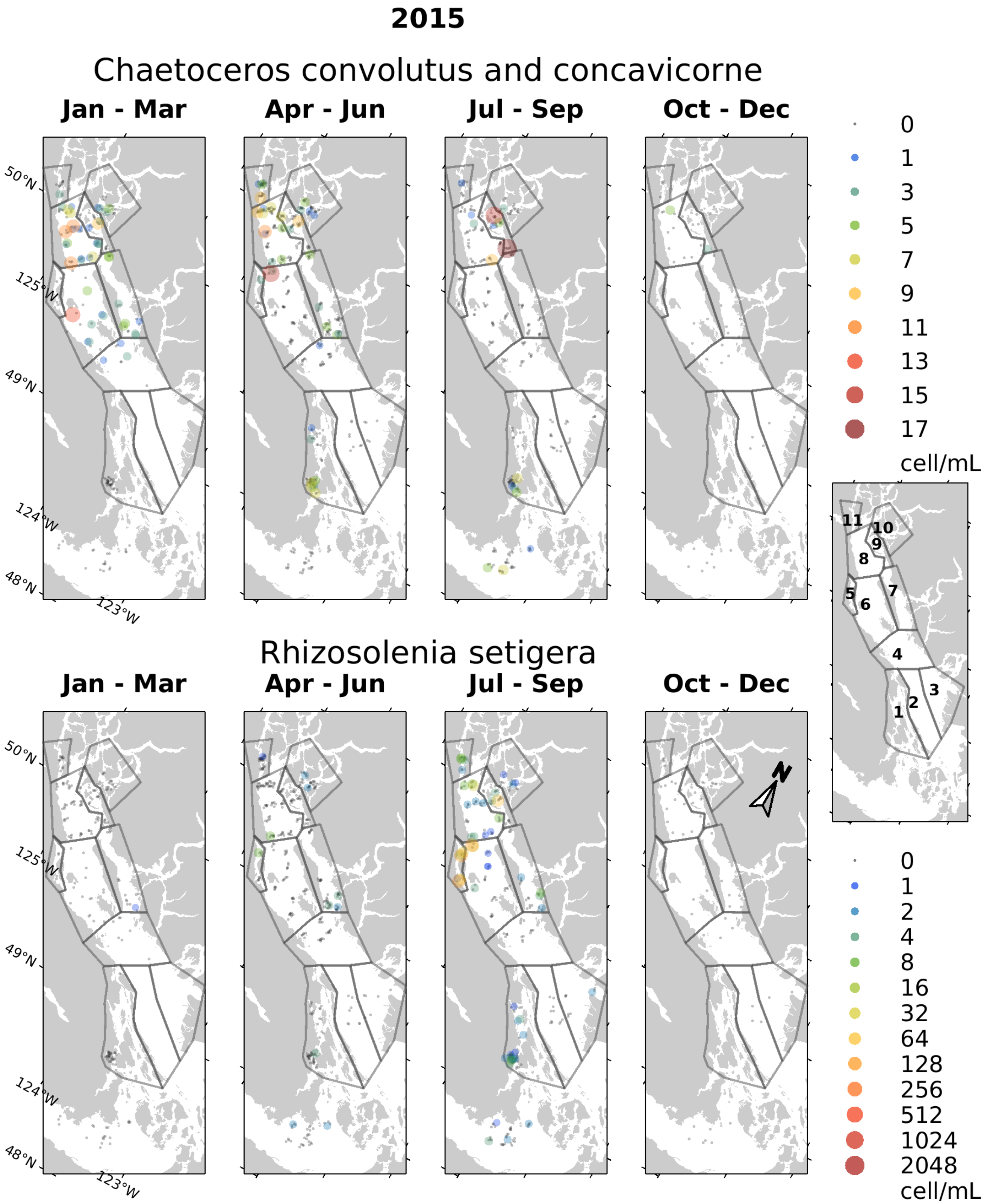

Figure 89: *Chaetocerus convolutus* and *C. concavicorne* , as well as *Rhizosolenia setigera* concentrations for 2015, separated into 3-month intervals.

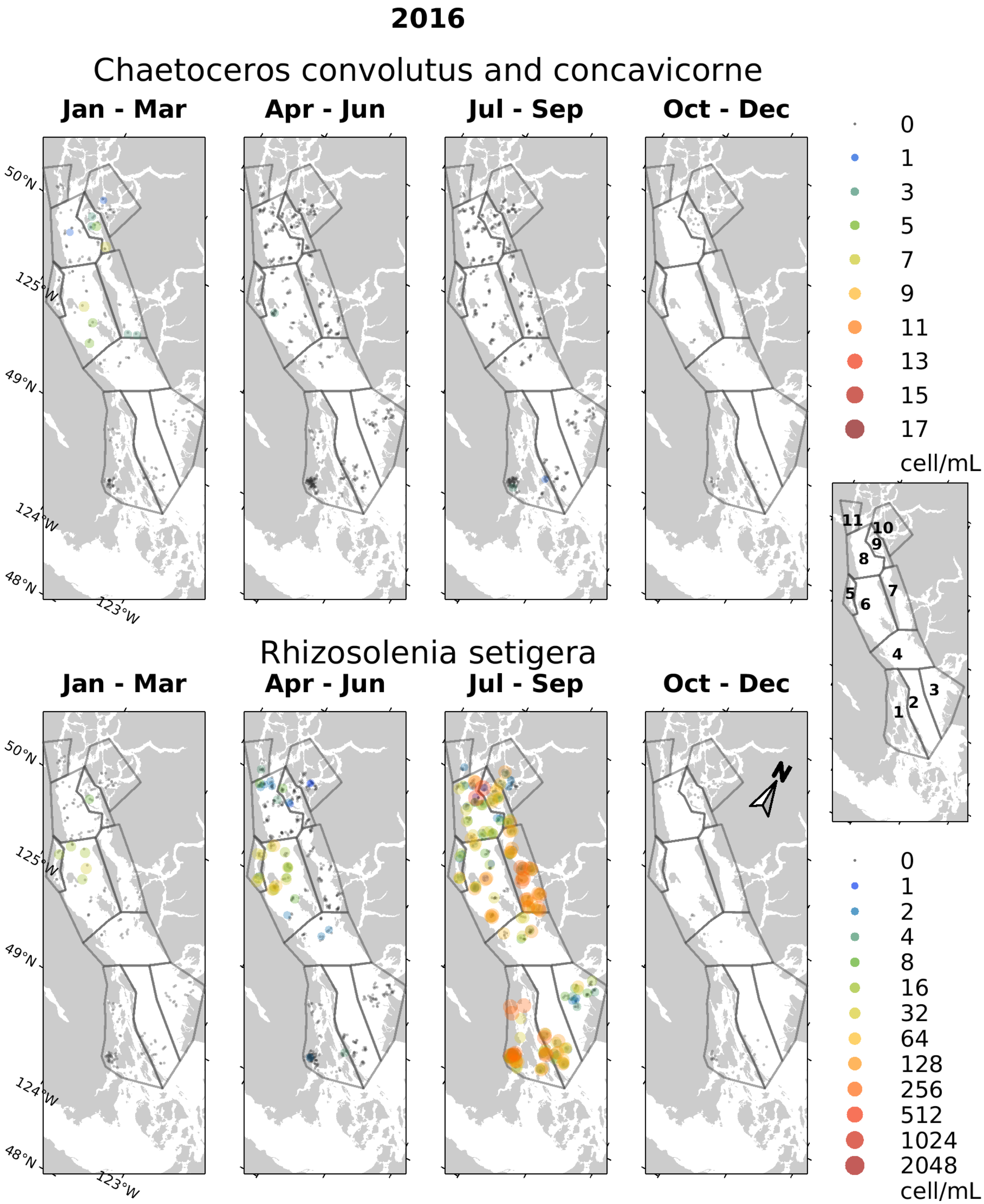

Figure 90: *Chaetocerus convolutus* and *C. concavicorne* , as well as *Rhizosolenia setigera* concentrations for 2016, separated into 3-month intervals.

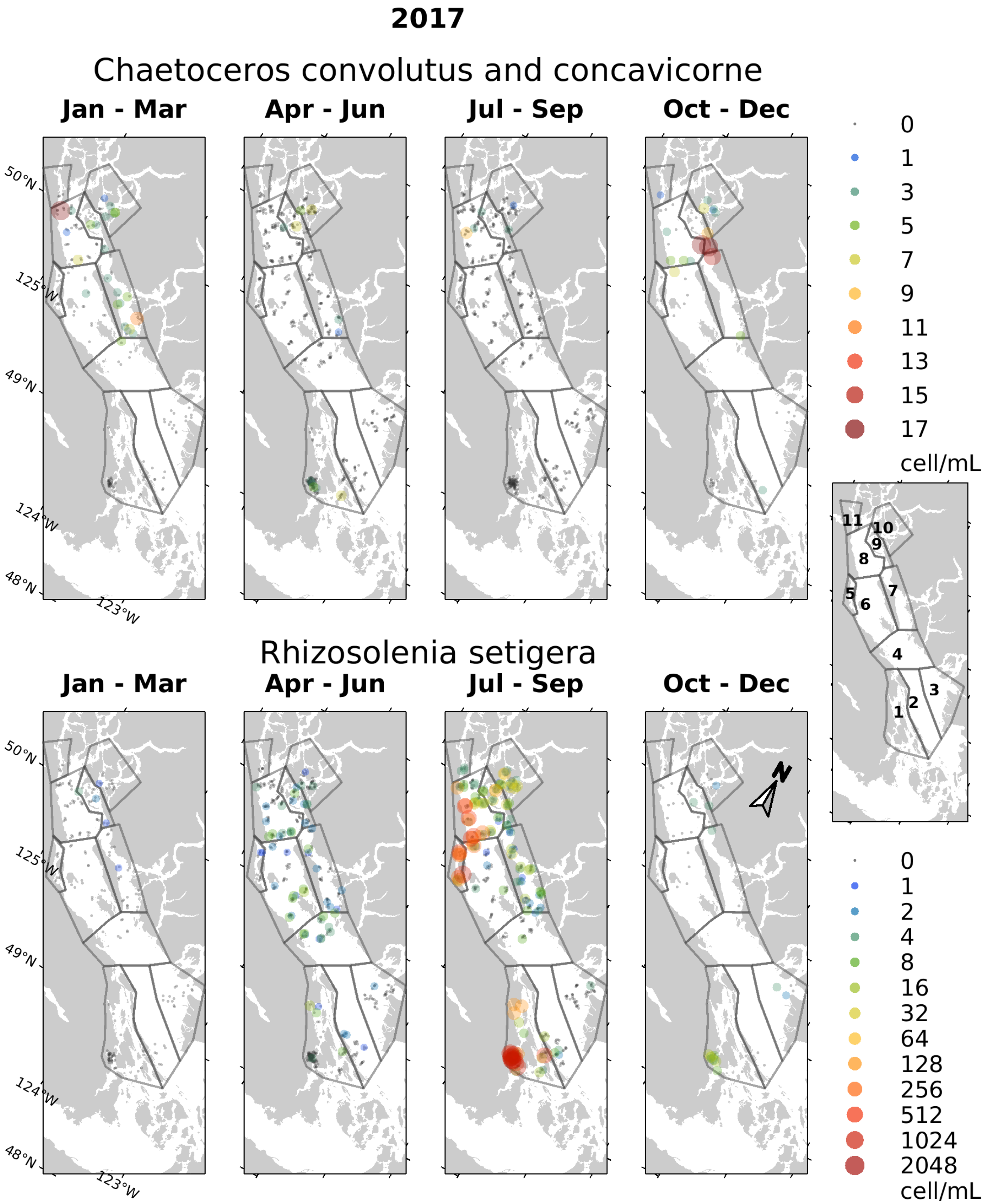

Figure 91: *Chaetocerus convolutus* and *C. concavicorne*, as well as *Rhizosolenia setigera* concentrations for 2017, separated into 3-month intervals.

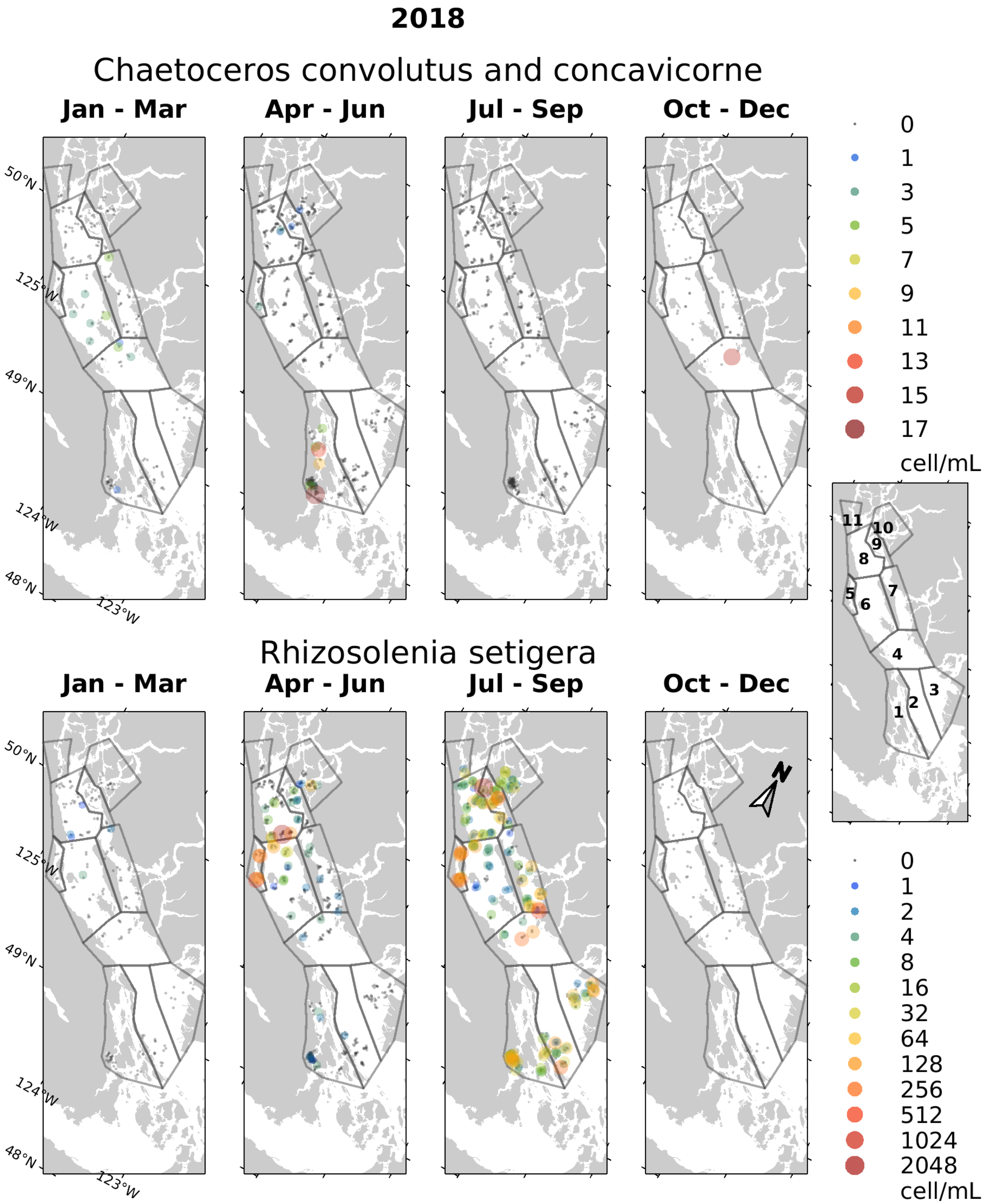

Figure 92: *Chaetocerus convolutus* and *C. concavicorne*, as well as *Rhizosolenia setigera* concentrations for 2018, separated into 3-month intervals.

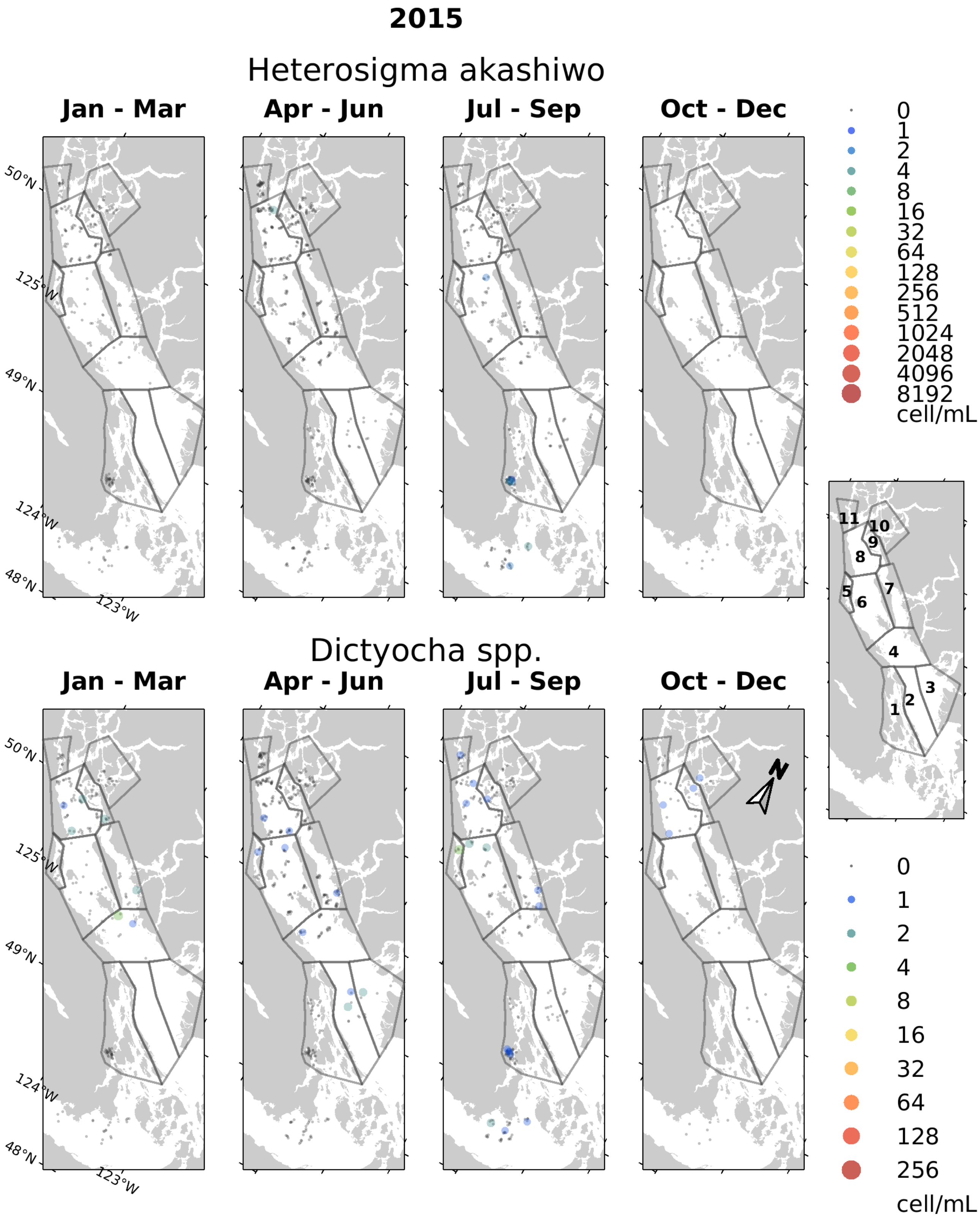

Figure 93: *Heterosigma akashiwo* and *Dictyocha* spp. concentrations for 2015, separated into 3-month intervals.

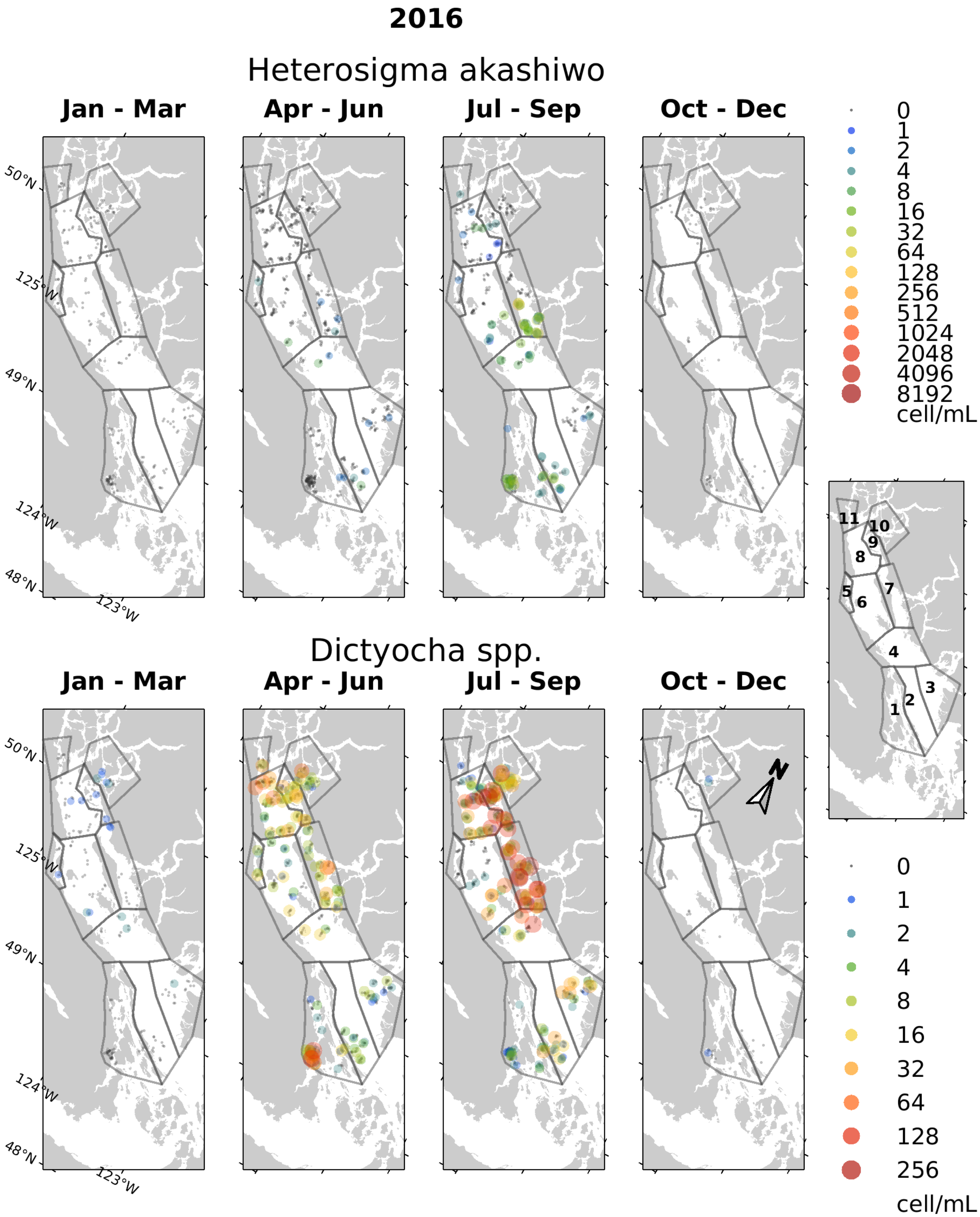

Figure 94: *Heterosigma akashiwo* and *Dictyocha* spp. concentrations for 2016, separated into 3-month intervals.

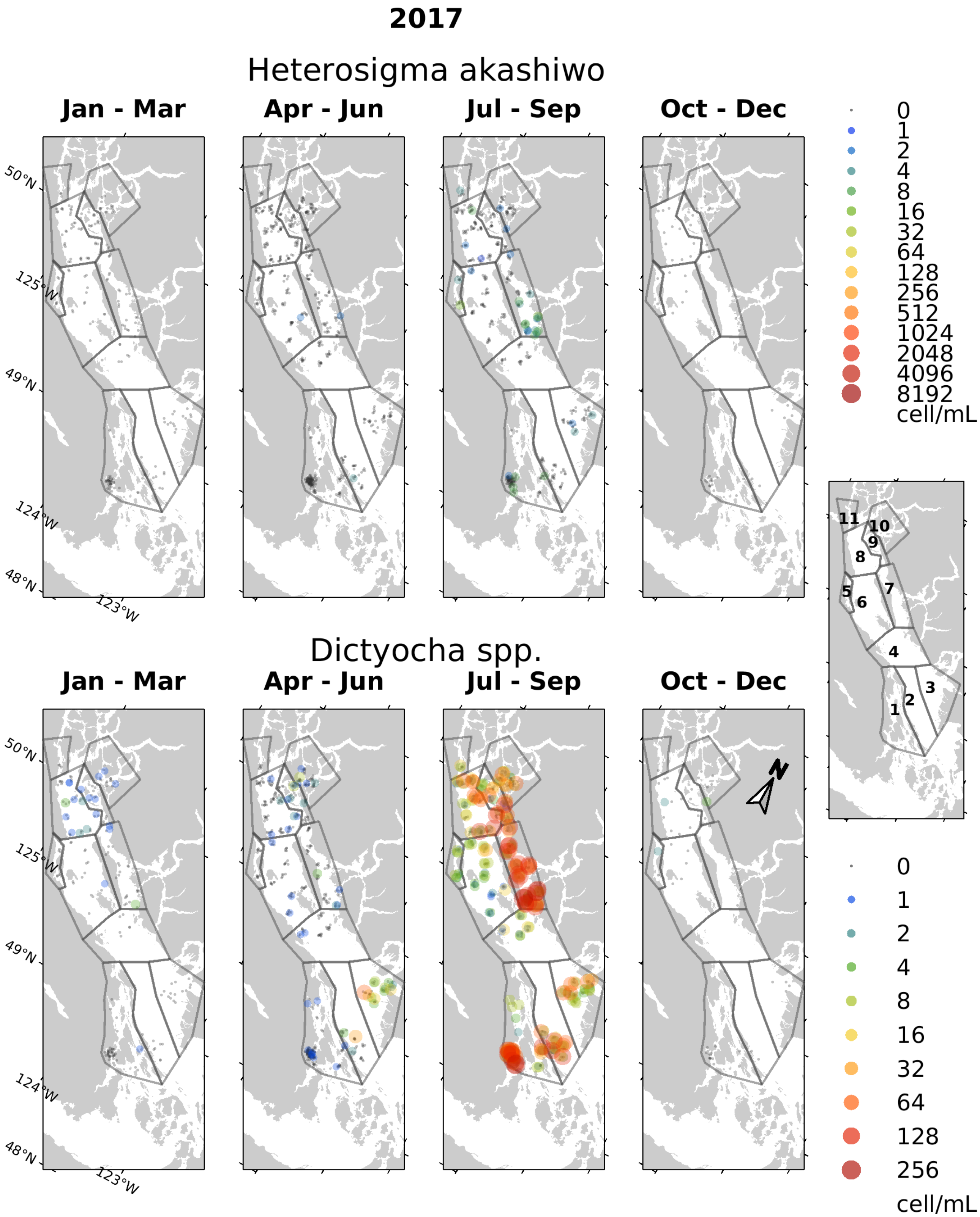

Figure 95: *Heterosigma akashiwo* and *Dictyocha* spp. concentrations for 2017, separated into 3-month intervals.

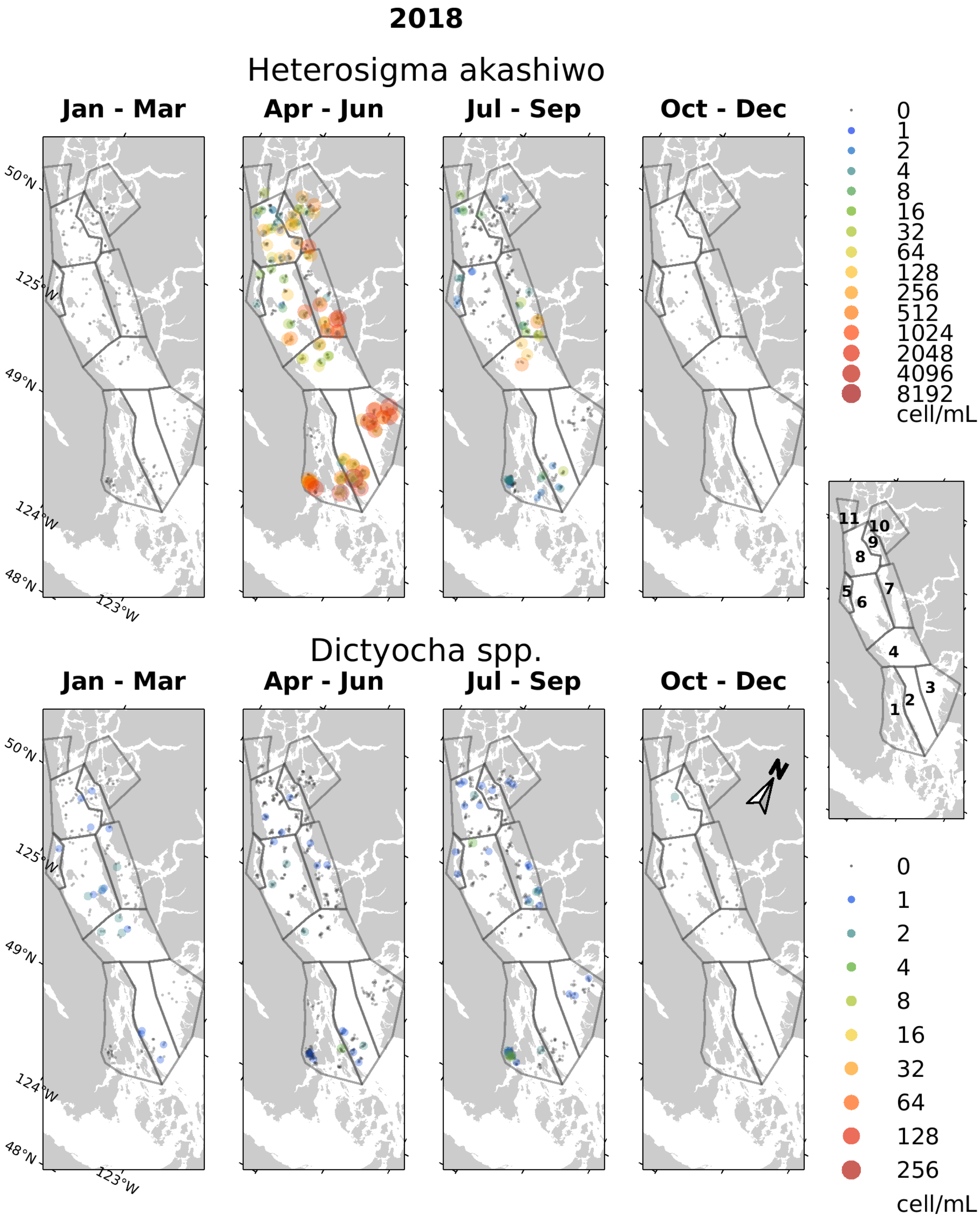

Figure 96: *Heterosigma akashiwo* and *Dictyocha* spp. concentrations for 2018, separated into 3-month intervals.

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