

### **Anonymous Referee #1**

*The manuscript by Teel et al. present a dataset of T, S and chlorophyll-a obtained from glider crossings in the San Pedro Channel, in the Southern California Bight. The channel is home to the San Pedro Ocean Time Series (SPOT), a long running oceanographic station that is sampled about once a month. Teel et al. analysis of the glider dataset suggests that SPOT profiles are overall representative of the SPC, with conditions ranging from oligotrophic deep chlorophyll maxima similar to offshore waters (by far the dominant pattern), to post-upwelling surface blooms. Notably, the glider data shows very weak correlations with satellite-based estimates of the surface chlorophyll, raising doubts about reliability of satellite data in the region. Ocean time series have been fundamental in advancing our understanding of ocean physics and biogeochemistry. However, they are localized in space, and sampled at most at monthly frequencies, raising the question of how representative they may be for broader regions, and how much high-frequency variability they may miss. This is a critical question in a region like the SCB, where complex circulation patterns, including upwelling, mesoscale eddies, island wakes, sustain variability on a range of timescales. Thus the work by Teel et al., is a welcome attempt at characterizing variability at a time series in relation to larger scales. I am of two minds about the paper. The dataset presented is of good quality and potentially useful in elucidating physical and biogeochemical variability in the region. In fact, I encourage the Authors to make the data available for the community. The decomposition of this variability into representative modes is also a useful insight. However, some aspects of the methods, the presentation of the results, and some parts of the discussion are not very clear, and made for a difficult and often opaque read. I encourage the Authors to work on a better synthesis and explanation of their results.*

To address the overall concerns raised by the Reviewer, we have edited the text to clarify the methods, added additional analyses, and included a comparison between the glider data and ship-based SPOT measurements. Below we provide a detailed point-by-point response to each specific comment. We are fully committed to making this data available to the community and plan to upload the glider data used in this analysis to the BCO-DMO repository (<https://www.bco-dmo.org/>) upon publication of this work.

#### *General comments:*

*Footprint of SPOT data. The paper wants to make a broad claim about the variability at SPOT, but the glider dataset has itself quite a limited footprint, extending for one 28 km between the mainland and Catalina Island. This is scarcely representative of the broader Southern California Bight, and it would have been nicer to have a broader sampling, or comparison with a broader set of observations.*

We completely agree that additional data with a wider footprint would be fantastic and would help constrain variability within the Southern California Bight. Unfortunately, we were limited in the number of gliders we had access to and the time in which they could be in the water. That said, the cross-channel glider transects were strategically chosen in order to best sample the

region. As flow is primarily north-south through the San Pedro Channel, the largest gradients are expected east-west and so the gliders were focused on capturing these features (Hickey, 1992; Noble et al., 2002; Di Lorenzo, 2003; Hickey et al., 2003; Noble et al., 2009b). In addition, the deployment times were chosen to span the seasonal upwelling events, again with the aim to best capture variability within the San Pedro Channel (Hickey, 1992; Di Lorenzo, 2003; Hickey et al., 2003). We have edited the text to clarify the choice of the transect path and the deployment time and how these choices might impact estimates of variability in the San Pedro Channel. We have also added a discussion on the channel as a proxy for the larger Southern California Bight.

The primary aim of this work was to leverage high temporal and spatial scale data (e.g. glider data) to generate a framework for understanding datasets sampled with coarser temporal and spatial resolution (e.g. monthly time-series). We hope that this conceptual framework will be applied to other datasets for the region in order to compare variability across the larger California Current System.

*This is especially important in light of few of the main aims of the paper, e.g. addressing local vs. regional drivers of variability (abstract, line 19), and determining the spatial domain of a time series (abstract, line 28). I feel that more effort could have been made to discuss how the study resolves these questions, at least for the SPC. After reading the paper, I am not sure I have a clearer idea of the questions.*

We have edited the text to help clarify the primary conclusions of the paper. Specifically, our analysis of the glider-based high-resolution data shows that the SPOT time-series data are more reflective of the offshore stratified environment rather than the near-coastal upwelling environment where coastal discharge (outfalls and storm water) are a more significant factor. As such, we conclude that the SPOT site is more likely to be influenced by regional responses to climatic shifts than to local events (e.g. increased discharge into the port of Los Angeles). In addition, we show that the end-member PCA provides a useful framework for analyzing seasonal and interannual shifts in variability at a time-series site.

*Actual SPOT data. While the data discusses at depth the representativeness of the SPOT time series for the context of the SPC, actual profiles from SPOT dataset are not used, but only glider data that pass through the SPOT station. I think there is a missed opportunity to for a reanalysis of the SPOT data in light of the information provided by the new glider dataset. With ~monthly sampling, nearly 20 years of SPOT data should contain ~100 profiles (for March-July periods) that could be easily couched within the variability identified by the glider profiles. Do they all fall within the range of variability observed here? Are the frequencies of the different modes observed in the SPOT data in agreement with their frequencies from the glider data analysis? It would be interesting to know if there are outlier in the SPOT data, which may suggest perhaps importance of inter annual variability.*

We thank the Reviewer for this suggestion. We have added a comparison between both ship-based SPOT data from 2000-2011 and data from a set of Upwelling Regime In-Situ

Ecosystem Efficiency study (UpRISEE) cruises that occurred during the time of the glider deployments (2013-2014) (*Supplemental Figure S6 in the revised manuscript*). This allows us to both analyze interannual variability and seasonal differences in variability. Specifically, we find that the variability in water column profiles captured by the high-resolution gliders during the upwelling period (March-July) of 2013-2014 was comparable to the interannual and seasonal variability observed in monthly sampling at SPOT over a decade (*Figure 9 in the revised manuscript*). In addition, samples taken every two-weeks during the UpRISEE period also matched the glider profiles from SPOT (*Figure 3 in the revised manuscript*). We have modified the text to add a comparison between glider and ship-based SPOT measurements (*section 3.5 of the revised manuscript*), updated Figure 3 (formerly Figure 4), and added Figure 9 and Supplemental Figure S6. Finally, we have added an analysis of the impact of different sampling frequencies on observed variability at SPOT (*Section 3.5*).

*Definition of “end members”. The separation of the variability into main modes is a good idea, but I have some criticisms on the way it is conducted and presented. The modes are identified a priori in a somewhat arbitrary way, which is not very well described. I would think an objective (i.e. replicable) approach could have been running a PCA of the entire dataset, then extracting the main axes of variation and use extreme values to define “end-members”. Here it seems the Authors qualitatively selected 54 profiles, then identified PCA for them, and projected the entire dataset on the resulting PCA. (In fact, I think the entire methods are not clear, and deserve a dedicated, more detailed section, which could go in the Supplementary Information.) Now, I think expert judgment is often a reasonable approach, but more discussion of the rational between end-members and their translation to the whole dataset should be presented.*

We have edited the text to clarify how the main modes of variability (end-members) were identified and how the PCA analysis was conducted (*see sections 2.4 and 3.2 of the revised manuscript*). In fact, our method is almost exactly what the Reviewer suggests and we hope with the clarified text and expanded methods this is clearer. Briefly, a PCA was conducted without any a priori information and was used to identify the main modes of variability (*revised Figure 3*). We then re-ran the PCA using the end-member profiles, defined using a combination of a priori information about the system and the patterns from the original PCA. This allowed us to generate a framework which facilitated meaningful oceanographic interpretation of variability within the glider dataset.

To further clarify the analysis, we have also changed how we refer to the end-member profiles to better clarify what they represent:

- (1) warm, subsurface high chlorophyll (WSHC)
- (2) warm, low chlorophyll (WLC)
- (3) cool, low chlorophyll (CLC)
- (4) cool, high chlorophyll (CHC)

WSHC represents oligotrophic conditions with an enhanced subsurface chlorophyll maximum, WLC represents oligotrophic conditions with very low biomass throughout the water column, CLC

represents early upwelling with cold waters and low chlorophyll, and CHC represents a surface bloom with cool surface temperatures (nominally a coastal bloom).

*Also, by looking at Fig. a, the “offshore influence” mode could be considered, rather than an end-member, somewhat a mixture of “early upwelling” and “deep chl max” based on PCA values. Is it really an end-member?*

We hope that our revised methods and results sections, including the justification of our choice in end-members, helps address the Reviewer’s concern. The ‘offshore influence’ (now called warm, low chlorophyll) in a purely statistical sense is a mixing between ‘early upwelling’ (now called cold, low chlorophyll) and ‘deep chl max’ (now called warm, subsurface high chlorophyll). This also shows up in the original PCA analysis (*revised Figure 3*). However, based on our understanding of the oceanography of the region, we believe that this profile type is not a mixing of these water masses but is indeed a unique end-member. Specifically, there are two primary physical dynamics that impact water column signatures in the SPC: 1) coastal upwelling and 2) the Southern California Eddy. Coastal upwelling brings cold high nutrient waters to the surface and triggers large surface blooms that extend from the coast into the channel. The cool, low chlorophyll (CLC) and cool, high chlorophyll (CHC) end-members represent the beginning and end of this process. The Southern California Eddy brings in warm low nutrient waters from offshore. These waters have a distinct signature which we identify here as warm, low chlorophyll (WLC) waters. In fact, of the four end-members, warm, subsurface high chlorophyll (WSHC) is the end-member with the least oceanographic support for being a true, unique end-member. The mechanism that creates periodic elevated subsurface chlorophyll concentrations in this region is still unclear, however there are two leading hypotheses: 1) these are coastal surface blooms that have been advected along isopycnal surfaces out into the channel (e.g., Mitarai et al., 2009; Bialonski et al., 2016; Stukel et al., 2018) or 2) that internal waves result in isopycnal heave of nutrients into the euphotic zone creating enhanced chlorophyll concentrations (e.g., Noble et al., 2009a; Noble et al., 2009b; Lucas et al., 2011). We have added this discussion to the text.

*I also have a quibble about the names of the end members: I kept confusing “offshore influence” and “deep chlorophyll maximum”. The two names make me both think of offshore oligotrophic subtropical conditions, and it took me a while to realize that “off-shore influence” is in fact in between offshore oligotrophic and coastal influences. The “deep chlorophyll maximum” end-member is in fact more representative of the offshore regions than the “offshore influence”. Maybe a better naming strategy can be found.*

We have altered the names of the end-members to be more descriptive and avoid confusion (*described above*).

*Comparison between glider and satellite-based estimates of surface chlorophyll-a. This is extremely interesting, and may contain some of the most relevant implications of the study for a broader community. The mismatch between surface glider data and satellite retrieval is glaring*

(supplementary Fig. S4), and suggest that satellite data should be taken very cautiously in the nearshore SCB, or even completely discarded as a reliable source of information on phytoplankton distribution. The Authors even state in line 278 and in the caption of Fig. S4 that “no correlation was observed between glider and satellite derived integrated chlorophyll”: this result seems important enough to require a dedicated figure, at least in the Supplement. At the same time I am not completely convinced of the strength of the Authors’ comparison. The Authors do not really get to the bottom of the mismatch, and some of the hypothesis that they put forward don’t seem to be able to explain it, especially in light of the systematic variation shown in Fig. S4.

A large body of literature has commented on the relationship between satellite observable chlorophyll (within the first optical depth) and total integrated water column chlorophyll, as well as the need for increased *in situ* sampling to improve satellite chlorophyll and primary production algorithms due to mismatches and inconsistencies in modeling of the *in situ* chlorophyll profiles (e.g., Morel and Berthon, 1989; Stramska and Stramski, 2005; Sathyendranath et al., 1989; Montes-Hugo et al., 2009; Jacox et al., 2015; Seegers et al., 2015). Locally, while satellite surface chlorophyll estimates have been shown to aligned closely with *in situ* glider observations of nearshore surface blooms in the San Pedro Channel, subsurface chlorophyll layers farther offshore were undetected by satellite retrievals (Seegers et al., 2015). Here, we used our framework to identify which oceanographic states at the SPOT site may be most susceptible to satellite misinterpretation. We specifically avoided interpretation of the mismatch between the glider and satellite chlorophyll estimates for a number of reasons. Primarily, we do not find this mismatch surprising given the differences in temporal and spatial scales of these two measurements. Specifically, the glider data were collected at ~0.5km resolution continuously over 24 hours throughout the deployment while the satellite measurements represent a single pass every 1 to 2 days in the afternoon and averaged over 1 km (Esaias et al., 1998). Furthermore, inaccuracies in the CDOM corrections and atmospheric corrections could also contribute to the observed mismatch (Esaias et al., 1998;Hoge et al., 1999;Wang et al., 2009). We do not feel that our dataset or analysis is the correct one to evaluate the robustness of the MODIS product for the San Pedro Channel and certainly do not feel that we can conclude that satellite data should be disregarded as a reliable source of information for phytoplankton distributions.

We believe the important take-away from this part of our analysis is that the inherent bias in satellite data of only quantifying chlorophyll over the first optical depth is not a significant issue for samples with high PC2 values and low overall biomass. However, it becomes an increasingly important issue for samples with high biomass and low PC2 values. Specifically, the relationship between integrated primary productivity over OD1 and over the euphotic zone varies significantly based on water column profile type. The structured PCA framework provides a metric for assessing the water mass types that may be most problematic for the satellite algorithms. Specifically, our analysis suggests that the satellite vs integrated chlorophyll mismatch may be particularly problematic for some cool, high chlorophyll water mass types (nominally coastal blooms). This suggests that increased *in situ* sampling may be needed when these water mass types are present in order to accurately constrain estimates of biomass distributions and primary production. We

have edited the text (Section 3.4) and Figure 7 to clarify our incorporation of satellite data into our analyses.

*I suspect some systematic mismatch in the optical depth over which the glider data should be integrated to provide comparison with the satellite data may be behind the discrepancies.*

We calculated the first optical depth for each glider profile using matched PAR measurement and glider chlorophyll profiles. Specifically, we estimated the light attenuation with depth for each glider profile as a function of chlorophyll concentration after Jacox et al. (2015). We then calculated the first optical depth as the depth in meters where available PAR is equivalent to  $1/e$  of surface PAR after Gordon (1975) and Kirk (1994). The calculations for light attenuation with depth have been validated within the Southern California Bight using *in situ* chlorophyll profiles (Jacox et al., 2015). Using these same light attenuation calculations, glider chlorophyll profiles were used to calculate profile euphotic depths, which were in good correspondence with ship-based euphotic depth measurements from the UpRISEE cruises (Haskell et al., 2016). If anything, our estimate is a conservative one (too deep) because we do not account for additional absorption by any CDOM or for particle backscatter. Therefore, while there are several possible explanations for the satellite-glider mismatched as listed above, we do not believe that there is an issue with our definition of the first optical depth from the glider measurements.

*Also, are satellite algorithms really only representative of the first optical depth? Given the exponential nature of light-attenuation in water, perhaps satellite retrievals of ocean color may be representative of a somewhat deeper water column. I think the Authors identify an important issue, but I am not sold it is time to start ignoring satellite retrievals of chlorophyll-a in the region.*

Based on the literature for remote sensing algorithms, satellite retrievals are an integration over the first optical depth: “The penetration depth of light in the sea is defined for remote sensing purposes as the depth above which 90% of the diffusely reflected irradiance (excluding specular reflectance) originates. It is demonstrated that for a homogeneous ocean, this is the depth at which the downwelling in-water irradiance falls to  $1/e$  of its value at the surface.” Gordon, (1975). “Satellite-derived retrievals of apparent (AOPs) and inherent (IOPs) optical properties in marine surface waters correspond to a vertically integrated picture of the first optical depth.” Montes-Hugo et al., (2009).

*The use of the concept of “connectivity” for both horizontal and vertical similarities is somewhat misleading. The fact that inshore and offshore profiles may be similar doesn’t necessary imply a direct, material bath connecting the two, as the word connectivity implies, but they may be just responding to remote, synchronous variations that occurs at scales large than few tens of km sampled by the glider. I suggest using a term different than connectivity throughout the text, especially section 3.2 and 3.3. Perhaps “coherence” or “similarity” would be more accurate.*

We have edited the text to clarify this point. Specifically, we now use the terms ‘coherence’ and ‘covariation’ instead of connectivity. We have also added text to discussing the impact of southward advection into the region.

*Some of the results could be less vague and speculative, and more quantitative. For example, Line 150 “given sufficient sampling, SPOT data could be representative of the average state of the SPC”: can “sufficient sampling” be actually quantified? Similarly, line 355 in the conclusions, “higher frequency sampling”: can this be quantified based on the new data? Would weekly sampling be needed? or daily?*

We have edited the text to be more quantitative where possible. We have also added an analysis of sample frequency using the glider dataset (*Section 3.5 and Figure 8*).

*Specific comments:*

We have made the requested text edits listed below. Comments are added to answer questions.

*Line 70, “recurring membership”: please clarify or rephrase the term.*

*Line 92, “that was perpendicular to the mean flow”: add “approximately”*

*Line 105, calculation of BVF. This requires a vertical derivative, which dramatically increase the noise in the resulting variable. Was any smoothing applied to the data to reduce the noise?*

While we believe that the BVF calculation was robust, as we do not use BVF in any of our analyses, we have removed it from the manuscript.

*Line 112, conflation of depth of 12.5C isotherm and nutricline. I wonder if this relationship could be tested with SPOT data for the region. Are nutrients measured at SPOT? How well does the relationship hold there?*

We have confirmed the temperature nutrient relationship at SPOT and confirmed that the 12.5°C isotherm is a good proxy for higher nutrient waters that are within the nitricline (*Figure R1 below*). This relationship also holds within the CalCOFI data over longer time-series as shown by Lucas et al. (2011).

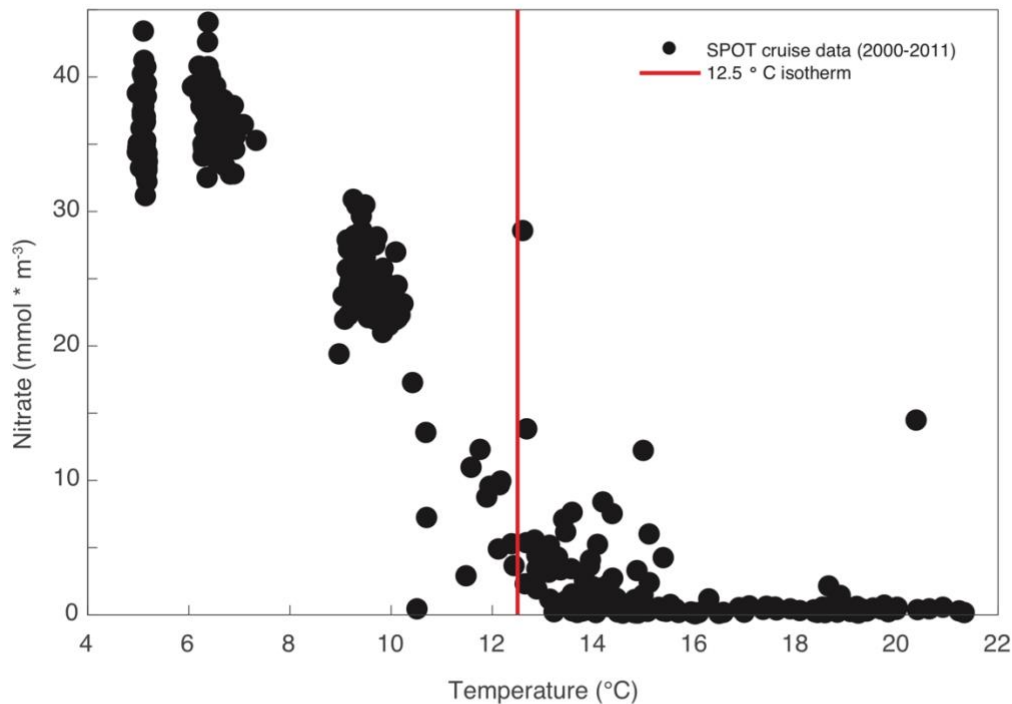


Figure R1: Nitrate versus temperature at SPOT (2000 to 2011). A linear relationship between nitrate and temperature is observed for temperatures cooler than 12.5°C. Between 12.5°C and 14°C nitrate goes to zero and remains very low. Based on this relationship, we use the 12.5°C isotherm as a proxy for higher nutrient waters that are within the nitricline.

*Line 126: the “and” after “data” seems out of place.*

*Line 141-142, “This tilt is consistent with equatorward flow through the channel”. This statement is at odds with a generally poleward flow in the very nearshore band and in the SPC, which tends to bring waters from the southern bight, and is embedded in the Southern California Eddy. The predominantly equatorward California Current is much more offshore.*

This is seasonally and event dependent. The mean circulation is poleward as the Reviewer indicates. Todd et al. (2009) showed this during the HB06 (fall 2006) experiment, and Hickey et al. (2003) supports this. However, examining the spring data from Hickey's T1 mooring shows frequent reversals (toward downcoast), and Noble et al. (2002) show frequent reversals at mooring B 30m depth.

*Line 170, “seasonal traits” clarify o rephrase.*

*Line 208-209, “we cannot distinguish between local and remote sources”: this is at odds with the previous sentence, and with the general notion that the glider data allows a characterization of the spatial domain of the time series data. Please clarify.*

The glider captures the variability along the transect, but doesn't fully inform us about along coast transport and continuity of features along the coast. Two to three parallel glider lines perpendicular



to the coast would provide a better sense of along coast transport but this unfortunately was beyond the scope of this project. We have added text to clarify this.

*Line 214, “maintained an onshore-offshore gradient on average”: please clarify the sentence.*

*Line 244, “highly offshore characteristics (Figure 6a)”: this seems to refer to the wrong panel, please double check.*

*Line 249-250: this sentence seems to undermine the idea of connectivity as a material path connecting inshore and offshore.*

*Line 288, “bloom thickness”: defined how?*

*Line 321, “decreased sedimentation”: please clarify.*

*Line 331, “events”: the term doesn’t seem appropriate for the modes considered, especially deep chlorophyll maxima which seem the common “background” state for the SPC. Please clarify.*

*Figure 1. Some bin numbers could be useful, e.g. 10,20,58, since they are used later.*

We have added these.

*Figure 2. The mean mixed layer could be shown on this figure too for the 4 end- members.*

We have indicated MLD on the Temperature plot.

*Figure 3. It would be useful to have a measure of the distance from the Palos Verdes Peninsula together with the bin numbers in the x-axis. Also, it would be useful to add the location of SPOT in the panels. The caption should also specify the months of the observations, besides the years.*

We have indicated the location of the SPOT site and included the months of the observations in the caption. We provide the distances between key bins, Palos Verdes, and Catalina Island in the revised caption of Figure 1.

*Figure 4. Are two panels really necessary? It seems that all information of panel b could be contained in panel a. Also, how were the ellipses defined?*

We have revised Figure 4, now Figure 3, to include both the glider profiles and the ship-based profiles (*see above*). Ellipse definition is now described in the revised methods.

*Figure 5 is a bit messy, and could go into the Supplement. It is not very successful in showing a clear seasonal progression or cycle, like the similar figures in Jacox, 2016 that presumably inspired it. To me the message is that the potential seasonal progression of upwelling is swamped by high frequency variability. (Or that perhaps the 2 PCA axes are not well positioned to highlight this progression.)*

We have edited Figure 5, now Figure 6, to highlight the seasonal progression in PCA space and have moved the original figure in the Supplement. The new figure uses PCA space to track the seasonal progression of water mass profile types in the San Pedro Channel.

*Figure 7: I wonder if the ratio between surface and total integrated cha may be a better variable to show here.*

We have edited this figure to show the relationship between the second principal coordinate axis, total integrated primary production over the euphotic zone, and integrated primary production within the first optical depth.

*Supplementary Table S1: many of the thresholds and combinations behind the end-member definition seem somewhat arbitrary, and could be better justified, e.g. with a dedicated Supplement section.*

We have revised the text to clarify the choice of end-members.

*Supplementary Figure S2: what are the vectors on the plot? Please explain in the caption.*

This has been added.

*Supplementary Figure S3: please correct the units in the caption of panel a, from ug to mg/m3.*

This has been fixed.

*Supplementary Figure S4: the legend of the figure states “Satellite:Glider” mach-ups, but the labels and caption state “Glider-Satellite”, please clarify.*

This has been fixed.



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## **Anonymous Referee #2**

*This paper uses high-frequency spatial and temporal glider data to quantify variability at the coastal San Pedro Ocean Time-series (SPOT) site in the San Pedro Channel (SPC) and provide insight into the underlying oceanographic dynamics for the site.*

*The glider data (a total of 1606 profiles) collected from March through July of 2013 and 2014 are used. This is a very rich data set and a detailed analysis is well justified for a publication. However, the manuscript in its current form is very difficult to read and follow. PCA is used to differentiate different profile types. It is confusing how the 54 end-member profiles are selected to define each of four dominant profile types, and then the remaining 1552 profiles are then projected onto the PC1 and PC2 coordinates. Maybe a more detailed description of the methodology is needed in the supplemental information.*

To address the overall concerns raised by the Reviewer, we have edited the text to clarify the methods, added additional analyses, and included a comparison between the glider data and ship-based SPOT measurements. To address the specific concern regarding the selection of the end-member profiles, we have added in an expanded methodology to clarify the way in which the main modes of variability (end-members) were identified and how the PCA analysis was conducted (*Sections 2.4 and 3.2 in the revised manuscript*).

*Time series are mentioned as the motivation of this paper, although the SPOT data are not used in the analysis. Both weekly and monthly time scales are mentioned in the text, what is the time interval for the SPOT measurements? It is not true "most time-series are sampled ... approximately once per month. Many time series use mooring platforms collecting data every few minutes.*

We have clarified the text to highlight our goal of using high-resolution data-sets to provide context for time-series with low sampling frequency. We have also added a comparison between the glider profiles and both ship-based SPOT data from 2000-2011 and data from a set of cruises (UpRISEE) which occurred during the time of the glider deployments (2013-2014) (*Section 3.5 in the revised manuscript*).

*p2, end of the 1st paragraph, "...at an individual site relative to a larger region may provide a path for leveraging numerous local time series sites in order to gain an understanding of larger scale oceanographic dynamics." What is the spatial scale for this "larger" region/scale? Maybe the SPOT time series can be used to quantify this spatial scale.*

We see this analysis as a proof of concept study of using high resolution glider data to determine whether coarse-resolution (monthly) sampling at a single point location is sufficient for capturing the variability within a larger (very dynamic) region. Here we use the SPOT time-series site as the point location and the San Pedro Channel as the larger region. However, based on previous work, we believe that the San Pedro Channel is in general representative of the larger Southern California Bight (e.g., Cullen and Eppley, 1981; Collins et al., 2011; Chow et al., 2013). The spatial scale for the 'larger' region will, however, be entirely site dependent and so we do not

feel that our study is able to make a generalization on the larger spatial scale which can be represented by time-series sites. However, we do feel that our framework could be applied to other time-series sites in order to provide insight into the representativeness of the site.

*p2, 2nd paragraph, "cloud contamination" is not mentioned as the primary reason to have limited coverage.*

We have added cloud contamination as a primary limitation of satellite measurements.

*"coastal and offshore processes", define "coastal" and "offshore"*

*It seems arbitrary to have the four dominant water column profile types: early upwelling, surface phytoplankton bloom, subsurface chlorophyll maximum, and offshore influence. Again define "offshore" here. Should the wind forcing be used?*

We have edited the text to clarify our terminology and choice of end-member water column profile types and provide additional details on our methodology (*Sections 2.4 and 3.2*).

*p5, satellite data are mentioned, but should be used more to study the surface and subsurface linkage*

A large body of literature has commented on the relationship between satellite observable chlorophyll (within the first optical depth) and total integrated water column chlorophyll, as well as the need for increased *in situ* sampling to improve satellite chlorophyll and primary production algorithms due to mismatches and inconsistencies in modeling of the *in situ* chlorophyll profiles (e.g., Morel and Berthon, 1989; Stramska and Stramski, 2005; Sathyendranath et al., 1989; Montes-Hugo et al., 2009; Jacox et al., 2015; Seegers et al., 2015). Locally, while satellite surface chlorophyll estimates have been shown to aligned closely with *in situ* glider observations of nearshore surface blooms in the San Pedro Channel, subsurface chlorophyll layers farther offshore were undetected by satellite retrievals (Seegers et al., 2015). Here, we used our framework to identify which oceanographic states at the SPOT site may be most susceptible to satellite misinterpretation. We specifically avoided interpretation of the mismatch between the glider and satellite chlorophyll estimates for a number of reasons. Primarily, we do not find this mismatch surprising given the differences in temporal and spatial scales of these two measurements. Specifically, the glider data were collected at ~0.5km resolution continuously over 24 hours throughout the deployment while the satellite measurements represent a single pass every 1 to 2 days in the afternoon and averaged over 1 km (Esaias et al., 1998). Furthermore, inaccuracies in the CDOM corrections and atmospheric corrections could also contribute to the observed mismatch (Esaias et al., 1998;Hoge et al., 1999;Wang et al., 2009). We do not feel that our dataset or analysis is the correct one to evaluate the robustness of the MODIS product for the San Pedro Channel and certainly do not feel that we can conclude that satellite data should be disregarded as a reliable source of information for phytoplankton distributions.

We believe the important take-away from this part of our analysis is that the inherent bias in satellite data of only quantifying chlorophyll over the first optical depth is not a significant issue



for samples with high PC2 values and low overall biomass. However, it becomes an increasingly important issue for samples with high biomass and low PC2 values. Specifically, the relationship between integrated primary productivity over OD1 and over the euphotic zone varies significantly based on water column profile type. The structured PCA framework provides a metric for assessing the water mass types that may be most problematic for the satellite algorithms. Specifically, our analysis suggests that the satellite vs integrated chlorophyll mismatch may be particularly problematic for some cool, high chlorophyll water mass types (nominally coastal blooms). This suggests that increased *in situ* sampling may be needed when these water mass types are present in order to accurately constrain estimates of biomass distributions and primary production. We have edited the text (*Section 3.4*) and Figure 7 to clarify our incorporation of satellite data into our analyses.

*p12, 5. Conclusion, end of the 1st paragraph, "...insensitive to coastal anthropogenic change...well positioned to identify a regional response to climate change." how do you derive such a conclusion?*

In the big picture, the SPOT time-series site is a coastal site. However, our analysis indicates that SPOT is more reflective of the offshore stratified environment rather than the near-coastal upwelling environment where coastal discharge (outfalls and storm water) are a more significant factor. As such, we conclude that SPOT is more likely to be influenced by regional responses to climatic shifts than to local events (e.g. increased discharge into the port of Los Angeles). We have edited the text to clarify this point.

*Table 1, define "SPOT specific profiles", "SPOT samples", what is CI? C2*

We have expanded Table 1 to include an analysis of the ship-based SPOT measurements (*see revised Table 1*) and edited the caption to clarify the contents of the table.

*Figure 1, I understand the color represents bathymetry, why don't you state this in the caption?*

We have edited the caption.

*Figure 2, what is the arrows mean below the figure, PC1, PC2? what does the "n=" mean?*

The PC1 and PC2 arrows indicate the separation of the end-member profiles on the PCA axes. For example, subsurface chl max was associated with high PC1 values while early upwelling was associated with low PC1 values. However, for clarity, we have removed the arrows from this figure. N refers to the number of glider profiles used to define these end-member profiles. We have edited the caption and text to clarify this.

*Figure 3, is "box plot" a more standard term than "whisker plot", see [https://en.wikipedia.org/wiki/Box\\_plot](https://en.wikipedia.org/wiki/Box_plot); define "bin"*

We have edited the caption.

*Supplemental Figure S2, define "ideal profiles"*

We have included additional detail describing how the end-member profiles were defined. We have replaced 'ideal profiles' with 'end-member' profiles throughout the text.



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# Contextualizing time-series data: Quantification of short-term regional variability in the San Pedro Channel using high-resolution *in situ* glider data

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## Abstract

Oceanic time-series have been instrumental in providing an understanding of biological, physical, and chemical dynamics in the oceans and how these processes change over time. However, the extrapolation of these results to larger oceanographic regions requires an understanding and characterization of local versus regional drivers of variability. Here we use high-  
20 frequency spatial and temporal glider data to quantify variability at the coastal San Pedro Ocean Time-series (SPOT) site in the San Pedro Channel (SPC) and provide insight into the underlying oceanographic dynamics for the site. The dataset was dominated by four water column profile types that typified ~~active upwelling, a surface bloom, warm-stratified-low-nutrient conditions, and offshore influence,~~ a subsurface chlorophyll maximum, and surface bloom. ~~On average, waters across the SPC were most similar to offshore profiles.~~ On weekly timescales, the SPOT station was on average representative of 64% of  
25 profiles taken within the SPC. In general, shifts in water column profile characteristics at SPOT were also observed across the entire channel, and SPOT was least similar to SPC locations that were closest to the Palos Verdes Peninsula. Subsurface chlorophyll maxima with co-located chlorophyll and particle maxima were common in 2013 and 2014 suggesting that these subsurface chlorophyll maxima might contribute significantly to the local primary production. On average, waters across the SPC were most similar to offshore profiles suggesting that SPOT time-series data would be more impacted by regional changes

30 ~~in circulation than local, coastal events. On average, waters across the SPC were most similar to offshore profiles.~~ These results indicate that high-resolution *in situ* glider deployments can be used to ~~determine~~ quantify major modes of variability and provide context for interpreting the spatial domain of time-series data, allowing for broader application of these datasets and greater integration into modeling efforts.

## 35 1. Introduction

Time-series sites have been invaluable for providing new insights into the biological, chemical, physical, and ecological processes that occur in the world's oceans. These sites provide *in situ* measurements that are critical for model development, validation, and ongoing improvement (Fasham et al., 1990; Doney et al., 1996; Spitz et al., 2001; Boyd and Doney, 2002; Moore et al., 2002; Dugdale et al., 2002; Doney et al., 2009). To date, a small number of open ocean time-series sites (e.g. 40 Hawaii Ocean Time-series and Bermuda Atlantic Time-series Study) have been heavily utilized by the oceanographic community while coastal time-series (e.g. San Pedro Ocean Time-series), which are more cost effective to run and so more numerous, have typically been under-utilized. One primary reason for this discrepancy is that the representativeness of these coastal sites to larger regions has been unclear. ~~Here we demonstrate that e~~Characterizing fine-scale temporal and spatial variability at an individual site relative to a larger region ~~may is the first step in being able to provide a path for leveraging~~ 45 data from numerous local time-series sites ~~in order~~ to gain an understanding of larger scale oceanographic dynamics.

Since most ship-based time-series are sampled at a single fixed location approximately once per month, the overall dataset is assumed to represent the mean state of a given geographical region as it varies with seasonal and annual cycles. To determine the accuracy of this assumption and to allow for the extrapolation of coastal time-series data to a larger region, high-resolution spatial and temporal monitoring of the physical and biological variability around these time-series sites is required. 50 Because of the limitations with traditional *in situ* approaches, satellite imagery is frequently used to characterize spatial and temporal variability, assuming a tight coupling between surface and sub-surface variability (e.g., DiGiacomo and Holt, 2001; Kahru et al., 2009; Nezlin et al., 2012). However, for many coastal regions satellite observations may be insufficient for assessing the biological and environmental variability due to decoupling between surface and sub-surface dynamics, the importance of fine spatial scale (<1 km) variability, ~~and~~ the presence of terrestrially derived chromophoric dissolved organic matter (CDOM), and cloud contamination. 55

High-frequency *in situ* sampling with gliders can provide uninterrupted monitoring of the surface 100 to 1000 meters vertically over tens of kilometers horizontally. These datasets provide both an understanding of kilometer-scale spatial and sub-monthly temporal dynamics as well as insight into the connectivity covariance between surface and subsurface dynamics, thereby aiding in the interpretation of satellite data. Here, we use an eight month Slocum electric glider dataset from the San 60 Pedro Channel (SPC) to investigate the representativeness of the coastal San Pedro Ocean Time-series (SPOT) site for the region. We demonstrate that high frequency sampling can be used to generate a framework for understanding and quantifying

spatial and temporal variability in a region and to gain a better understanding of the representative nature of a given time-series location

The SPOT station, which is located at 33° 33' 00" N and 118° 24' 00" W, sits in the SPC between Catalina Island and the Palos Verdes Peninsula where the water depth is approximately 900 meters (Figure 1). The SPC lies within the larger Southern California Bight (SCB), which extends from Point Conception to Mexico (Noble et al., 2009b). The Channel Islands and submarine canyons oceanographically define the SCB. Within the SCB, the Southern California Eddy is a dominant, persistent feature that generates poleward-flowing surface currents that break off from the California Current (Oey, 1999; Noble et al., 2009b; Dong et al., 2009). The SCB is characterized by strong seasonal variation, including a spring upwelling season and subsequent phytoplankton blooms. Within the SPC, however, local upwelling and post-upwelling bloom formation are less persistent or predictable than observed farther north. Post-upwelling blooms occur on the timescales of days to a couple of ~~weeks, and~~ weeks and can be quickly followed by periods of very low surface chlorophyll (Supplemental Figure S1). The SPOT station has been sampled monthly for environmental and biological parameters since 1998. Microbial communities at SPOT have been found to ~~have-be~~ annually and seasonally ~~recurring-predictable with reoccurring phylogenetic membership~~ assemblages (Fuhrman et al., 2006; Steele et al., 2011; Chow et al., 2013; Chow et al., 2014). Daily sampling at this site has shown that dominant microbial taxa vary ~~at-on~~ much shorter time-scales, indicating that monthly sampling may only represent a persistent background community (Needham et al., 2013; Needham and Fuhrman, 2016). Previous work has postulated that SPOT and the San Pedro Channel is in general representative of the larger Southern California Bight based on local circulation patterns (e.g., Cullen and Eppley, 1981; Collins et al., 2011; Chow et al., 2013). However, the ability of monthly sampling at the SPOT site to capture variability within the SPC has not been quantified. Here we present a framework for using high resolution glider data to quantify the main modes of variability in the channel and determine whether coarse-resolution (e.g. monthly) sampling at a single point location is sufficient for understanding oceanographic dynamics within a larger region. We use the SPOT time-series site as the point location and the San Pedro Channel as the larger region. We highlight how this approach can be applied to other datasets to generate new insight into the primary modes of variability.

## 2. Methods

### 2.1 Glider Deployments

The ~~vertical~~ physical and biological characteristics of the SPC were characterized using a Teledyne-Webb G1 Slocum electric glider that was deployed from March through July of 2013 and 2014. The deployment period was selected in order to maximize the likelihood that both coastal and offshore processes would be captured in the dataset (Hayward and Venrick, 1998; Di Lorenzo, 2003; Mantyla et al., 2008; Schnetzer et al., 2013). The glider was deployed on a 28 km cross-channel path between Catalina Island and the Palos Verdes Peninsula (Figure 1) and completed a single cross-channel pass every 1.5-2 days (average speed 1 km hr<sup>-1</sup>). Data were collected between ~3 and 90 meters, with the exception of when the glider crossed the



major shipping lanes where the glider was constrained to depths below 20 meters to avoid damage or loss from ship traffic. Chlorophyll-a fluorescence was measured by a WetLabs EcoPuck FL3 fluorometer, backscatter at wavelengths of 532, 660, and 880 nanometers was measured by a WetLabs EcoPuck BB3 sensor, and temperature, salinity, and pressure were measured with a SeaBird flow-through CTD. Vertical resolutions for the WetLabs pucks were approximately 0.3 m, while the vertical resolution for the SeaBird CTD was approximately 0.6 m. The glider was recovered every 3-4 weeks for cleaning, battery replacement, and recalibration using standard methods published in Cetinić et al (2009).

## 2.2 Ancillary Satellite Data

Level 3 mapped MODIS Aqua daily 9km photosynthetically active radiation (PAR) measurements were acquired from the NASA Ocean Biology (<https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/Mapped/Daily/9km/par/>). MODIS Aqua daily 1 km chlorophyll (ChlSat) data were acquired from NOAA CoastWatch West Coast Regional Node (<http://coastwatch.pfeg.noaa.gov/coastwatch/CWBrowser.jsp>). These data were then matched geographically and temporally with the *in situ* glider data.

### 2.3.2 Data Analyses Glider Data

Glider data were processed, calibrated, and quality controlled following Cetinić et al. (2009) and Seegers et al (2015). To correct for current induced drift, the glider data from each 2-day transect were then gridded onto an idealized glider transect with 500 m horizontal resolution and 1m vertical resolution that was approximately perpendicular to the mean flow and the coastline (Figure 1). Only glider data within 5 km of the idealized transect were used in this analysis (Figure 1). Each 500 m bin (N=62) corresponded approximated with a single downcast and upcast. Only profiles with data for >85% of the vertical bins were used for further analyses, thereby excluding partial profiles from under the shipping lanes. The remaining missing data (< 15% of each profile) were filled using 2D interpolation from all neighboring bins. A total of 557 profiles from 2013 and 1049 profiles from 2014 were accepted for further analyses. Of the 1606 final glider profiles, 1151 matching PAR measurements and 571 matching ChlSat measurements were available.

For each profile, the mixed layer depth (MLD) was calculated as the depth where density change exceeded the equivalent of a 0.4°C temperature drop relative to the density at 5 m (modified from Sprintall and Tomczak, (1992)). The mixed layer temperature (MLTemp) was calculated as the mean temperature within the mixed layer. The light field between 1 and 80 m was calculated for each glider profile following the regionally validated method described in Jacox et al. (2015). This method uses surface PAR measurements and *in situ* chlorophyll a profiles to calculate the diffuse attenuation coefficient at each depth. The euphotic depth, defined as the 1% light level, was then calculated for each glider profile from these light profiles (Kirk, 1994). The glider based euphotic depths were in good agreement with those collected from *in situ* PAR

25 measurements during the concurrent Upwelling Regime In-Situ Ecosystem Efficiency study (UpRISEE) cruises at the SPOT site (Haskell et al., 2016). We also calculated the first optical depth (OD1) for each glider profile as the depth in meters where available PAR was equal to 1/e of surface PAR after Gordon (1975) and Kirk (1994).

30 The temperature, salinity, and chlorophyll a data from each of the 1606 glider profiles were used to calculate secondary metrics that were used for statistical analyses. Specifically, maximum chlorophyll fluorescence (MaxCHL), depth of maximum chlorophyll fluorescence (zMaxChl), 70 meter integrated chlorophyll (ChlInt70), depth of maximum backscatter (zMaxBB), maximum backscatter (MaxBB), and ratio of integrated chlorophyll in the top 70 meters relative to the integrated chlorophyll in the top 20 meters (ChlInt70Per20) were calculated. Twenty meters was used to approximate the average mixed layer depth. Seventy meters was chosen as the maximum depth of chlorophyll integration as it included the full euphotic depth for 99% of the glider profiles from 2013 and 2014. In addition, the maximum stratification index (MaxBVF) and depth of maximum stratification (zMaxBVF) were estimated using the Brunt Vaisala Frequency (BVF):

35 \_\_\_\_\_. In addition, we estimated from the ship-based SPOT time-series data (2003 - 2011) that on average PAR at 70m was 2.6% of the surface value, with a maximum of 4.5%. 
$$BVF = \frac{g * \partial \rho}{\sqrt{\rho * \partial z}}$$

\_\_\_\_\_ (eq. 1)

40 where  $g$  is Earth's gravitational acceleration in meters per squared second,  $\rho$  is the ambient density in kilograms per cubic meter,  $\partial z$  is depth interval in meters, and  $\partial \rho$  is the change in density over that interval (Mann and Lazier, 2013). The mixed layer depth (MLD) was defined as the depth where density change exceeded the equivalent of a 0.4°C temperature drop relative to the density at 5 m (modified from Sprintall and Tomezak, (1992)). The mixed layer temperature (MLTemp) was calculated as the mean temperature within the mixed layer. Finally, the depth of the 12.5°C isotherm (z12p5) was used as a proxy for the top of the nutricline, which indicated nutrient-rich sub-thermocline waters in the SPC (Hayward and Venrick, 1998; Lucas et al., 2011). Finally, the depth of the 12.5°C isotherm (z12p5) was used as a proxy for the top of the nutricline, which indicated nutrient-rich sub-thermocline waters in the SPC and within the CalCOFI region (Hayward and Venrick, 45 1998; Lucas et al., 2011). This relationship was confirmed for the SPOT site using ship-based nitrate and temperature data.

Depth profiles of primary production (PP(z)) were estimated after Jacox et al. (2015) as:

$$PP(z) = pB(z) * chl(z) * dirr$$

50 where chl(z) is the chlorophyll concentration (mg chl m<sup>-3</sup>) from the glider profiles, and dirr is day length (hrs day<sup>-1</sup>). pB(z) is a regionally-tuned and light-dependent carbon fixation rate in mg C mg chl<sup>-1</sup> hr<sup>-1</sup> that was calculated from PAR profiles as per Jacox et al. (2015). Integrated primary production over the euphotic depth and the first optical depth (OD1) were calculated for each glider profile. Integrated primary production estimates for SPOT were within the bounds of regional estimates (Jacox et al., 2015).

## 2.4 Principal Component Analysis (PCA) (Lucas et al., 2011)

Principal component analysis (PCA) was used to differentiate between the major water column profile types observed within the glider dataset. Specifically, 54 end-member profiles were selected to define each of four dominant water column profile types observed in the SPC: early upwelling, surface phytoplankton bloom, subsurface chlorophyll maximum, and offshore influence (Table 1, Figure 2). These profile types had been observed qualitatively in glider curtain plots, and were selected from the dataset using MLTemp, ChlInt70Per20, ChlInt70, z12p5, maxCHL, zMaxChl, and MLD criteria (Supplemental Table S1). A step-wise PCA was conducted to determine the relative influence of each of the secondary characteristics on total observed variance within the end-member profile dataset. Based on this analysis, four characteristics (zMaxBB, MaxBB, zMaxBVF, and MaxBVF) were omitted from further PCA analyses as they did not strongly affect overall dataset variance or the resulting PCA distribution. The remaining 1552 glider profiles were then projected onto the PC1 and PC2 coordinates based on their secondary characteristics (Figure 4). All glider profiles from 2013 and 2014 were combined into a single PCA after normalization and standardization of the profile characteristics described above. A step-wise PCA was conducted to determine the relative influence of each of the secondary characteristics on total observed variance within the end-member profile dataset. Based on this analysis, two characteristics (zMaxBB and MaxBB) were omitted from further PCA analyses as they did not strongly affect overall dataset variance or the resulting PCA distribution. A second PCA was conducted using a subset of glider profiles (N=54) and the same set of secondary characteristics (referred to as a structured PCA). The selection of this subset of profiles is described below (section 3.2). For the structured PCA, the remaining glider profiles (N=1552) were projected onto the structured PCA axes using the function proj within R software. Confidence intervals of 95% were calculated for each clustering in PCA space using the iso-contour of the Gaussian distribution after [www.visiondummy.com/2014/04/draw-error-ellipse-representing-covariance-matrix/](http://www.visiondummy.com/2014/04/draw-error-ellipse-representing-covariance-matrix/) and the function ggbiplot within R software. In brief, the magnitude of ellipse axes were determined by the variance within each cluster, defined as the eigenvalues from the covariance matrix. The direction of the major axis was calculated from the eigenvector of the covariance matrix that corresponded to the largest eigenvalue. The loadings of the secondary characteristics onto the PCA axes were also calculated and plotted.

## 2.5 Comparison with time-series measurements

To interpret the San Pedro Ocean Time-series data (monthly sampling) within the context of the variability identified in the high resolution glider dataset, we incorporated 12 years of ~~these~~ available ship-based measurements at the site into our analysis. Specifically, profile characteristics (described above) were calculated for 64 ship-based SPOT profiles from 2000-2011. 30 of these profiles fell between March and July, the months during which the gliders were in the water. An additional 21 profiles were calculated from the UpRISEE ship-based cruises that occurred every two weeks during 2013

and 2014 (Haskell et al., 2016), with 14 profiles occurring between March and July. Though there was good coherence between temperature measurements across all three datasets, the chlorophyll fluorescence measurements from the 2000-2011 SPOT site cruises were considerably lower than the fluorescence measurements from both the in situ gliders and the ship-based UprISEE cruises from 2013 to 2014. We assumed this to be inter-instrument variation in fluorescence to chlorophyll ratio, rather than changes in in situ chlorophyll concentration itself. To allow for projection onto the glider-derived structured PCA axes, the chlorophyll fluorescence data from 2000-2011 SPOT cruises were scaled so that the March through July mean chlorophyll fluorescence value was equal to the March through July mean chlorophyll fluorescence value from the 2013 to 2014 UprISEE cruises. As all SPOT chlorophyll a data was scaled together, this correction will not impact the relative distances between samples in PCA space but was necessary to allow for comparison to the glider data. The profile characteristics (MLD, MLTemp, z12p5, zMaxChl, maxCHL, chlInt70, and chlInt70Per20) for the 85 ship-based profiles were used to project these samples onto the structured PCA axes. Corresponding PC1 and PC2 values for all ship-based SPOT site profiles were then compared with glider profiles to assess interannual profile variability at the SPOT site. 2-3

### Ancillary Satellite Data

Level 3 mapped MODIS Aqua daily 9km photosynthetically active radiation (PAR) measurements were acquired from the NASA Ocean Biology (<https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/Mapped/Daily/9km/par/>). MODIS Aqua daily 1 km chlorophyll (ChlSat) data were acquired from NOAA CoastWatch West Coast Regional Node (<http://coastwatch.pfeg.noaa.gov/coastwatch/CWBrowser.jsp>). These data were then matched geographically and temporally with the in situ glider data. Of the 1606 final glider profiles from 2013 and 2014, 1170 matching PAR measurements and 571 matching ChlSat measurements were available. PAR measurements were then used in combination with the glider chlorophyll profiles to estimate the light field at depths between 1 and 80 m for each glider profile (Jacox et al., 2015). The diffuse attenuation coefficient was calculated as a function of chlorophyll a concentration at each depth (Jacox et al., 2015). The 1% light level, hereafter referred to as the euphotic depth, and the first optical depth were then calculated for each glider profile from these light profiles (Kirk, 1994).

## 3 Results

### 3.1 Cross-Channel Oceanographic Trends

— Cross-channel comparisons of mixed layer temperature (MLTemp), mixed layer depth (MLD), depth of the 12.5°C isotherm (z12p5), and integrated chlorophyll over the upper 70 m (ChlInt70), and integrated primary production within the euphotic zone were used to identify persistent oceanographic gradients across the transect (Figure 3Figure 2). Observed physical properties in both spring 2013 and spring 2014 displayed an onshore-offshore gradient, where onshore direction was defined as towards the Palos Verdes Peninsula (PV) and offshore was defined as towards Catalina Island. This gradient could be seen most clearly in the z12p5 data, where there was a strong offshore tilt in the mean depth of this isotherm (Figure 3Figure

15 2c). This tilt is consistent with equatorward flow through the channel, which frequently occurs during the spring (Hickey et  
al., 2003; Noble et al., 2002), but could also have been amplified closest to shore with periods of active upwelling. Without  
sampling the surface data within the shipping lanes, it was not possible to determine the full profile behaviour of locations  
between the coastal and SPOT mid-channel bins. However, subsurface glider temperature data showed that patterns of  
weakened stratification during early upwelling events often extended across the entire SPC (Supplemental Figure S4  
20 XXXXX). These observations suggest that there is coherence across the shipping lanes during upwelling events.

Though the average depth of the cold, high-nutrient waters was shallowest close to shore, the cross-channel data for  
ChlInt70 displayed only a weak cross-channel gradient (Figure 3Figure 2d). Rather, ChlInt70 had fairly constant cross-channel  
values of about 100  $\text{mg chl m}^{-2}\text{mg/m}^2$ . It is important to note that integrated chlorophyll alone cannot be used to assess the  
25 productivity of a location, because it does not account for the vertical chlorophyll distribution and its overlap with the vertical  
light field. ~~These cross-channel analyses also highlight high intra-bin temporal variability over the course of the deployments,~~  
~~especially for ChlInt70 and MLD (Figure 2). As expected, estimated~~ In fact, depth integrated primary production displayed  
a much stronger an onshore-offshore gradient in both mean and variance than was observed for ChlInt70. As expected, the  
highest primary productivity was observed, highest ~~closest to the mainland and~~ with decreasing values observed across the  
30 channel lowest extending towards Catalina Island, away from coastal upwelling sites (Figure 2e).

~~These cross-channel analyses also highlight high intra-bin temporal variability over the course of the deployments,~~  
~~especially for ChlInt70 and MLD (Figure 3Figure 2).~~

To compare cross-channel differences in water column profile characteristics, three bins were selected: bin 10 (near Catalina,  
 $n = 41$  profiles), 28 (SPOT,  $n = 54$  profiles), and 58 (near the mainland,  $n = 34$  profiles). When the variance at each location  
35 was taken into account, the mixed layer depth (MLD) and integrated primary production (PP) for bins 10 and 28 were not  
significantly different from one another (two-sample  $t$ -test,  $p$ -value  $< 0.01$ ) while bins 10 and 28 were both significantly  
different from bin 58 (two-sample  $t$ -test,  $p \ll 0.01$ ). Mixed layer temperature and integrated chlorophyll (ChlInt70) were not  
significantly different across all three bins. The mean depth of the  $12.5^\circ$  isotherm ( $z_{12p5}$ ) was significantly different for all  
three bins (two-sample  $t$ -test,  $p \ll 0.01$ ). These cross-channel analyses also highlight high intra-bin temporal variability over  
40 the course of the deployments, especially for ChlInt70 and MLD (Figure 2). The importance of this temporal and spatial  
pattern of variability for ~~SPOT~~ the SPC is twofold: 1) a monthly time-series sampling scheme at SPOT may under-  
sample both biological and physical variability- in the channel at SPOT, but 2) the similarity in variance across the SPC suggests  
that, given sufficient sampling, SPOT data could be representative of the average state of the SPC.

45 **3.21 ~~Cross-Channel Oceanographic Trends~~ Dominant water column profile types**

The glider profiles were analyzed within PCA space to identify dominant water column profile types within the SPC. The PCA showed that most profiles were clustered together, with a small subset of cold, high chlorophyll (nominally surface bloom) profiles driving much of the separation on both the first principal component (PC1) and second principal component (PC2) (Figure 3a). Analysis of the PCA suggested that there were meaningful distinctions within the large cluster of profiles. Specifically, two end-members within this cluster were apparent: a cool, deep MLD, low chlorophyll water column profile type and a warm, shallow MLD, low surface chlorophyll water column profile type. Based on the PCA, we defined three 'end-member' water column profile types: (1) cool, high chlorophyll (CHC); (2) cool, low chlorophyll (CLC); (3) warm, subsurface high chlorophyll (WSHC). In addition, we identified a fourth, unique, end-member water profile type based on our examination of the glider dataset and our understanding of the oceanography of the San Pedro Channel. This fourth type represented an oligotrophic end-member with a warm, shallow MLD, and low chlorophyll throughout the water column and was termed: (4) warm, low chlorophyll (WLC).

50 These four water column profile types are consistent with our understanding of oceanographic states of the region. Specifically, there are two primary physical dynamics that impact water column signatures in the SPC (Hickey, 1979; Kim et al., 2014; Noble et al., 2009b; Dong et al., 2009): 1) coastal upwelling and 2) the Southern California Eddy. Periodic coastal upwelling in the spring brings cool, high nutrient waters to the surface and triggers large surface blooms that extend from the coast into the channel. The cool, low chlorophyll (CLC) and cool, high chlorophyll (CHC) end-members represent the beginning and end of this process. In the late spring and early summer, seasonal heating and the spin-up of the Southern California Eddy bring warm low nutrient waters into the SPC. These waters have a distinct signature that we identify here as warm, low chlorophyll (WLC) waters. In fact, of the four end-members, warm, subsurface high chlorophyll (WSHC) is the end-member with the least oceanographic support for being a true, unique end-member. The mechanism that creates periodic elevated subsurface chlorophyll concentrations in this region is still unclear, however there are two leading hypotheses: 1) these are coastal surface blooms that have been advected along isopycnal surfaces out into the channel (e.g., Mitarai et al., 2009; Bialonski et al., 2016; Stukel et al., 2018) or 2) that internal waves result in isopycnal heave of nutrients into the euphotic zone creating enhanced chlorophyll concentrations (e.g., Noble et al., 2009a; Noble et al., 2009b; Lucas et al., 2011).

70 All instances of these four end-member profile types were identified in the full data set using MLTemp, ChlInt70Per20, ChlInt70, z12p5, maxCHL, zMaxChl, and MLD criteria (Supplemental Table S1). For end-member types 1-3, we started with the profiles identified in the original PCA and refined the criteria in order to isolate the most 'pure' examples of these water mass profile types. Using our criteria, we identified 54 'end-member profiles': 10 for type 1 (CHC), 12 for type 2 (CLC), 15 for type 3 (WSHC), and 17 for type 4 (WLC). Average temperature and chlorophyll profiles for all four end-member types are shown in Figure 4. Early upwelling CLC profiles were characterized by MLTemps that were cooler than 12.5°C, a shallow chlorophyll maxima, and integrated chlorophyll that did not exceed 85 mg chl m<sup>-2</sup>. The combination of these characteristics indicated that the deep, cold, nutrient-rich water had been recently advected into the surface mixed layer. During

30 this study, the strongest surface bloom signals occurred after upwelling had begun to relax and the 12.5 °C isotherm had returned to a depth of greater than 20 m. CHC profiles. These surface blooms were characterized by MLTemp between 13°C and 17°C, MLDs deeper than 10 m, and ChlInt70 values above 150 mg chl m<sup>-2</sup>, indicating that upwelling had begun to relax, the 12.5 °C isotherm had returned to a depth of greater than 20 m, and a strong surface bloom was present. To further clearly differentiate these surface blooms from subsurface chlorophyll maxima within the dataset, the integrated chlorophyll within the surface 20 m was directly compared to that within the top 70 m. Here we define surface blooms as those with at least 50% of the total integrated chlorophyll within the top 20 m. Both WLC and WSHC profiles were characterized by high MLTemp, shallow MLD, and deep z12p5. WLC profiles were relatively oligotrophic and had values of ChlInt70 less than 80 mg chl m<sup>-2</sup> while WSHC profiles had values of ChlInt70 up to 142 mg chl m<sup>-2</sup> and but with subsurface chlorophyll maxima as having less than 5% of integrated chlorophyll in the top 20 m of the profile. Both subsurface chlorophyll maximum profiles and offshore influence profiles shared high MLTemp, shallow MLD, and deep z12p5. The offshore influence profiles were relatively oligotrophic and had values of ChlInt70 less than 80 mg chl m<sup>-2</sup> while the subsurface chlorophyll maximum profiles had values of ChlInt70 up to 142 mg chl m<sup>-2</sup>. On average, the MLD and zMaxChl were deeper during subsurface chlorophyll maxima than during offshore influence.

35 To more efficiently differentiate profile characteristics and to better represent the observed variability within the glider profile types, we conducted a second PCA which used only the 54 'end-member' profiles to define the PCA axes (hereafter referred to as the structured PCA). The structured PCA resulted in clear separation of the 4 end-member profile types and allowed for better overall separation of the glider profiles (Figure 3b). Specifically, the percent of explained variance for PC1 increased from 40.5% to 49.8%, and the percent of explained variance for PC2 increased from 21.5% to 32.7%. More importantly, the structured PCA allowed for more meaningful separation of the glider profiles into oceanographically relevant states allowing us to better understand and quantify the overall variance within the glider profile data. Movement along PC1 primarily described changes in temperature-based characteristics while movement along PC2 primarily described changes in chlorophyll-based characteristics (Figures 3b and 4; Supplemental Figure S2). Specifically, PC1 was most positive when MLTemp was greater than 19 °C and the seasonal thermocline was strongly defined. PC2 was most negative when the chlorophyll maximum was most clearly defined and ChlInt70 was greater than 120 mg chl m<sup>-23</sup>. PCA axes based on the 54 end member glider profiles were used to investigate the representativeness of SPOT to gauge the similarity between profiles collected at different locations and times. The first principal component (PC1) and second principal component (PC2) accounted for 49.8% and 32.7% of total variance, respectively (Figure 4; Supplemental Figure S2). MLTemp and the zMaxChl projected primarily onto PC1 while ChlInt70 and maxCHL projected onto PC2, suggesting that PC1 corresponded with an increased offshore signature while PC2 was inversely correlated with profile biomass (Figures 2 and 4; Supplemental Figure S2). Specifically, PC1 was most positive when MLTemp was greater than 19 °C and the seasonal thermocline was strongly defined (Figure 2). PC2 was most negative when the chlorophyll maximum was most clearly defined and ChlInt70 was greater

than  $120 \text{ mg chl m}^{-3}$  (Figure 2). To determine the relative contribution of the 4 water column profile types to the observed glider profiles, the 1606 final glider profiles were projected onto these end-member axes (Figure 3b4a). As PC1 and PC2 explained similar amounts of variance within this dataset, smaller 'distances' between points profiles in PC coordinate space approximates dissimilarity between individual profiles. Conversely, decreasing distance between profiles in PC coordinate space can be attributed to increasing similarity in profile features. As the four 'end-member' water column profile types were selected to represent the end-member profile characteristics, one would anticipate that a monthly time-series would, for the most part, capture intermediate states rather than these end members. Identifying these end-members both helps characterize the overall biological and physical variation seen in water column profiles within the SPC and provides a means for quantifying the influence of coastal (CLC, CHC) versus offshore (WLC, WSHC) waters in the channel.

————— Cross-channel comparisons of mixed layer temperature (MLTemp), mixed layer depth (MLD), depth of the  $12.5^\circ\text{C}$  isotherm (z12p5), and integrated chlorophyll over the upper 70 m (ChlInt70) were used to identify persistent oceanographic gradients across the transect (Figure 3). Observed physical properties in both spring 2013 and spring 2014 displayed an onshore-offshore gradient, where onshore direction was defined as towards the Palos Verdes Peninsula (PV) and offshore was defined as towards Catalina Island. This gradient could be seen most clearly in the z12p5 data, where there was a strong offshore tilt in the mean depth of this isotherm (Figure 3c). This tilt is consistent with equatorward flow through the channel (Hickey et al., 2003; Noble et al., 2002), but could also have been amplified closest to shore with periods of active upwelling. Though the average depth of the cold, high nutrient waters was shallowest close to shore, the cross-channel data for ChlInt70 displayed only a weak cross-channel gradient (Figure 3d). Rather, ChlInt70 had fairly constant cross-channel values of about  $100 \text{ mg/m}^3$ . It is important to note that integrated chlorophyll alone cannot be used to assess the productivity of a location, because it does not account for the vertical chlorophyll distribution and its overlap with the vertical light field. These cross-channel analyses also highlight high intra-bin temporal variability over the course of the deployments, especially for ChlInt70 and MLD (Figure 3). The importance of this temporal and spatial pattern of variability for SPOT is two fold: 1) a monthly time series sampling scheme may under sample both biological and physical variability at SPOT, but 2) the similarity in variance across the SPC suggests that, given sufficient sampling, SPOT data could be representative of the average state of the SPC.

To look specifically at variability between glider profiles during these deployments, we first identified four common water column profiles within our dataset (Table 1, Figure 2). The identification of these 'end member' profiles was done without consideration of location within the channel. These four profile types were hallmarks of specific oceanographic events within the channel with each profile uniquely defined using physical and biological criteria (Supplemental Table S1): early upwelling prior to a significant biological response, surface phytoplankton blooms, subsurface chlorophyll maximum, and offshore influence of relatively oligotrophic water. These four profile types represented the extremes that occurred within the channel during these glider deployments.



45 Early upwelling profiles were characterized by MLTemps that were cooler than 12.5°C, a shallow chlorophyll  
maxima, and integrated chlorophyll that did not exceed 85 mg chl m<sup>-2</sup>. The combination of these characteristics indicated that  
the deep, cold, nutrient rich water had been recently advected into the surface mixed layer. During this study, the strongest  
surface bloom signals occurred after upwelling had begun to relax and the 12.5 °C isotherm had returned to a depth of greater  
50 than 20 m. These surface blooms were characterized by MLTemps between 13°C and 17°C, MLDs deeper than 10 m, and  
ChlInt70 values above 150 mg chl m<sup>-2</sup>. To further differentiate these surface blooms from subsurface chlorophyll maxima  
within the dataset, the integrated chlorophyll within the surface 20 m was directly compared to that within the top 70 m. Here  
we define surface blooms as those with at least 50% of the total integrated chlorophyll within the top 20 m and subsurface  
chlorophyll maxima as having less than 5% of integrated chlorophyll in the top 20 m of the profile. Both subsurface chlorophyll  
maximum profiles and offshore influence profiles shared high MLTemp, shallow MLD, and deep z12p5. The offshore  
55 influence profiles were relatively oligotrophic and had values of ChlInt70 less than 80 mg chl m<sup>-2</sup> while the subsurface  
chlorophyll maximum profiles had values of ChlInt70 up to 142 mg chl m<sup>-2</sup>. On average, the MLD and zMaxChl were deeper  
during subsurface chlorophyll maxima than during offshore influence.

The four water column profile types described above capture the typical progression of seasonal traits for the SPC  
(Figure 2). In this region, local upwelling in the spring is followed by the appearance of surface phytoplankton blooms, which  
50 in turn is followed by an offshore influence of relatively oligotrophic waters due to seasonal heating and the spin-up of the  
Southern California Eddy (Hickey, 1979; Kim et al., 2014; Noble et al., 2009). These four water column profile types represent  
the end members of these ‘states’ such that one would anticipate that a monthly time series would, for the most part, capture  
intermediate states rather than these end members. Identifying these end members both helps characterize the overall  
biological and physical variation seen in water column profiles within the SPC and provides a means for quantifying the  
55 influence of coastal versus offshore waters in the channel.

PCA axes based on the 54 end member glider profiles were used to investigate the representativeness of SPOT to  
60 gauge the similarity between profiles collected at different locations and times. The first principal component (PC1) and second  
principal component (PC2) accounted for 49.8% and 32.7% of total variance, respectively (Figure 4; Supplemental Figure S2).  
MLTemp and the zMaxChl projected primarily onto PC1 while ChlInt70 and maxCHL projected onto PC2, suggesting that  
PC1 corresponded with an increased offshore signature while PC2 was inversely correlated with profile biomass (Figures 2  
and 4; Supplemental Figure S2). Specifically, PC1 was most positive when MLTemp was greater than 19 °C and the seasonal  
thermocline was strongly defined (Figure 2). PC2 was most negative when the chlorophyll maximum was most clearly defined  
and ChlInt70 was greater than 120 mg chl m<sup>-2</sup> (Figure 2). To determine the relative contribution of the 4 water column profile  
75 types to the observed glider profiles, the 1606 final glider profiles were projected onto these end member axes (Figure 4a). As  
PC1 and PC2 explained similar amounts of variance within this dataset, ‘distance’ between points in PC coordinate space  
approximates dissimilarity between individual profiles. Conversely, decreasing distance between profiles in PC coordinate  
space can be attributed to increasing similarity in profile features.

### 3.32 Regional Similarity to Variability at the SPOT Station

The glider profiles were analyzed within the structured PCA space with specific focus on temporal and spatial changes, as well as how the profiles taken at the SPOT site related to and varied with profiles from the rest of the San Pedro Channel cross-section. When all glider profiles were projected onto the PCA axes, 39.6% fell within one of the end-member profile type clusters, as determined by 95% confidence intervals (Table 1). Similarly, 37% of the 54 SPOT glider profiles associated with an end-member subgroup. Of the four end-member profiles, the offshore-types (WLC, WSHC) were most prevalent with 24.8% of all glider profiles falling within the WSHC subsurface chlorophyll maximum group cluster and 12.1% aligning with offshore influence WLC profiles cluster. SPOT profiles followed a very similar trend with 25.9% of profiles falling within the WSHC cluster subsurface chlorophyll maximum group and 9.3% of profiles aligning with the WLC cluster offshore influence end-member. The two coastal end members (CLC, CHC), early upwelling and surface blooms, were rare in the overall dataset as well as in the SPOT profiles themselves with less than 4% of all profiles associated with these coastal end-members. These results indicate that, for the majority of locations and times sampled during the spring and early summer of 2013 and 2014, water column profiles within the SPC most closely resembled offshore profiles. These results most likely underrepresent the overall coastal influence within the SPC due to the exclusion of data from within the shipping lanes which that influences 30% of the transect and are located close to the coast (Figure 1). However, these findings are consistent with previous research conducted at SPOT that indicated a general prevalence of open ocean bacterial groups (Chow et al., 2013) and a notable scarcity of land-derived organic matter (Collins et al., 2011). It is important to note that since the general circulation in the SPC is parallel to shore and perpendicular to the glider transect, many signatures observed in the dataset may be upstream processes that were advected into the study domain. these glider profiles were affected by upstream processes, including potential upwelling near the Santa Barbara Channel or Point Dume. Coastal signatures from these upstream locations would appear within the glider profile data, but would be disconnected from the overall onshore-offshore gradient. While our end-member framework allows us to quantify the occurrence of upstream coastal signatures within the dataset and variability in water mass characteristics, we cannot distinguish between local and remote sources of these water masses. For example, we cannot determine if CLC waters upwelled within the SPC or whether they were upwelled near the Santa Barbara Channel or Point Dume and advected into the San Pedro Channel. To improve detection of upstream influence within the SPC in future deployments, the glider transect would need to be adapted to incorporate alongshore movement as well as cross-channel travel.

To compare cross channel differences in water column profile properties, three bins were selected: bin 10 (near Catalina, n = 41 profiles), 28 (SPOT, n = 54 profiles), and 58 (near the mainland, n= 34 profiles). Physical and biological characteristics of the profiles collected at these three locations maintained an onshore-offshore gradient on average. However, when the variance at each location was taken into account, bins 10 and 28 were not significantly different from one another (two sample t test, p value < 0.01) while bins 10 and 28 were both significantly different from bin 58 (two sample t test, p <<

10 0.01). These findings suggest that, during this study, SPOT was at least partially detached from nearshore coastal dynamics, such as early upwelling or upwelling-driven surface blooms. These results also indicate that samples taken at SPOT poorly represent nearshore variability but are a relatively good representation of the channel as a whole.

15 Due to seasonal variations in local upwelling and the spin-up of the Southern California Eddy, temporal dynamics and succession play an important role in driving regional productivity. To explore temporal connectivity between SPOT and nearshore coastal bins, the time-series of profile characteristics for individual bins were analysed in PCA space (Figure 5). Early in each deployment, there was a strong coastal-mainland influence, which coincided with early upwelling events and surface blooms. This influence was more apparent in the nearshore bins, as expected, but also clearly affected the overall characteristics of vertical glider profiles taken at SPOT as well. During late April to early May of each deployment, the nearshore and SPOT bins collectively experienced a relative 'cross-over', when the profiles shifted from coastally dominated characteristics to offshore dominated (Figure 5; Supplemental Figure S1). These results imply cross-channel connectivity and suggests that, while the profiles at SPOT did not often resemble nearshore profiles, profile variability in both mid-channel and nearshore locations was likely forced by the same coastal and offshore oceanographic events.

20 To further investigate how changes in the SPOT profile characteristics were related to co-occurring changes in profile types across the cross-channel profile types, we looked at the relationship between all non-SPOT profiles and the corresponding SPOT profile. For this analysis, the PCA coordinate plane was divided into four quadrants representing low biomass and coastal dynamics (positive PC2, negative PC1), low biomass and offshore dynamics (positive PC2, positive PC1), high biomass and offshore dynamics (negative PC2, positive PC1), and high biomass with coastal dynamics (negative PC2, negative PC1) (Figure 65). These four quadrants were then used to investigate the cross-channel distribution relative to the most recent SPOT profile. The majority of profiles (64%) fell into the same PCA quadrant as the most recent SPOT profile suggesting that the majority of the channel displayed similar profile characteristics and that the SPOT site in general captured across channel variability. Broken down by profile type, SPOT profiles were most similar to co-occurring cross-channel profiles when SPOT displayed subsurface-chlorophyll maximum WSHC profile characteristics (78% of cross-channel profiles in the same quadrant as the SPOT profile, Figure 56d). SPOT profile characteristics coincided with 55% of other profiles when exhibiting characteristics of offshore influence WLC, 48% when displaying surface bloom CHC characteristics, and 33% of the channel in the one instance when the SPOT profile displayed more coastal physical CLC properties (Figure 56). The sample distributions in each of these four cases were statistically different from one another (two-tailed *t*-test,  $p < 0.01$ ), demonstrating indicating that the profile characteristics at the SPOT station-site were indicative of the state of the SPC as a whole. For example, when SPOT profiles displayed showed the most coastal signatures highly offshore characteristics (negative PC1) (Figure 56a & 5c), no channel profiles were found to be representative of either the WLC or WSHC profile types no channel profiles displayed surface bloom profile characteristics. Conversely, during periods when SPOT profiles were most similar to offshore types surface bloom (positive PC1) (Figure 5b & 5d) profiles, no channel profiles were found to be representative of either the offshore influence or subsurface-chlorophyll maximum CHC profile types.

These results are consistent with the observed simultaneous shifts in both SPOT and nearshore bins and support cross-channel oceanographic connectivity (Figure 5).

Due to strong alongshore currents within this region, it is not surprising that the nearshore and offshore sides of the channel would differentially experience local oceanographic changes. With these analyses, however, it was possible to verify that the data collected at SPOT are generally representative of the SPC. The largest variation was found when comparing the mainland coastal bins to SPOT or other offshore bins, with increased differences observed during periods of early upwelling in the spring of 2013 and 2014. Without sampling the surface data within the shipping lanes, it was not possible to determine the full profile behaviour of locations between the coastal and SPOT bins. However, subsurface glider temperature data showed that patterns of weakened stratification during early upwelling events often extended across the entire SPC (Supplemental Figure S3). These observations suggest that there is connectivity across the shipping lanes during upwelling events. This is also consistent with the finding that changes in profiles taken at SPOT are in general representative of the entire channel (Figure 6). The glider profiles were analyzed within the structured PCA space with specific focus on temporal and spatial changes, as well as how the profiles taken at the SPOT site related to and varied with profiles from the rest of the San Pedro Channel cross section. To compare cross-channel differences in water column profile properties, three bins were selected: bin 10 (near Catalina,  $n = 41$  profiles), 28 (SPOT,  $n = 54$  profiles), and 58 (near the mainland,  $n = 34$  profiles). Physical and biological characteristics of the profiles collected at these three locations on average maintained the onshore-offshore gradient observed across the channel (Figure 3). However, when the variance at each location was taken into account, bins 10 and 28 were not significantly different from one another (two sample  $t$  test,  $p$  value  $< 0.01$ ) while bins 10 and 28 were both significantly different from bin 58 (two sample  $t$  test,  $p \ll 0.01$ ). These findings indicate that, during this study, SPOT was at least partially detached from nearshore coastal dynamics, such as upwelling and upwelling driven surface blooms. These results also suggest that samples taken at SPOT poorly represent nearshore variability but are a relatively good representation of the channel as a whole.

Due to seasonal variations in local upwelling and the spin-up of the Southern California Eddy, temporal dynamics and succession play an important role in driving regional productivity. To explore-track the seasonal progression of water mass profile types for SPOT relative to more near-shore bins temporal connectivity between SPOT and nearshore coastal bins, the time-series of profile characteristics for individual bins SPOT (bin 28) and coastal bins (55-62) were analysed in PCA space (Figure 6, Supplemental Figure S35). Early in each deployment In April, there was a strong coastal mainland influence both the nearshore and SPOT bins showed significant coastal influence with profile types, which coincided with upwelling and surface blooms and profiles with CLC and CHC signatures. This influence was more apparent in the nearshore bins, as expected, but also clearly affected the overall characteristics of vertical glider profiles taken at SPOT as well. During late April to early May of each deployment, the nearshore and SPOT bins collectively experienced a relative 'cross-over', when the profiles shifted from some coastal influence dominated characteristics to offshore dominated characteristics (Figure 5; Supplemental Figure S4). In June, both the nearshore and SPOT bins showed offshore influence with profile types with WLC and WSHC signatures. These results imply-suggest cross-channel connectivity covariance and suggests that, while the profiles at SPOT did not often

~~resemble nearshore profiles~~, profile variability in both mid-channel and nearshore locations was likely forced by the same ~~coastal and offshore~~ oceanographic ~~events~~ dynamics.

~~Without sampling the surface data within the shipping lanes, it was not possible to determine the full profile behaviour of locations between the coastal and SPOT bins. However, subsurface glider temperature data showed that patterns of weakened stratification during early upwelling events often extended across the entire SPC (Supplemental Figure S4). These observations suggest that there is coherence across the shipping lanes during upwelling events.~~

### 3.43 Surface to Subsurface ~~Connectivity~~ Coherence

Our analyses indicated that subsurface chlorophyll maximum characteristics were a dominant profile type within the SPC (occurring ~25% of the time), and that these subsurface chlorophyll maxima may appear similar to offshore water intrusion from surface characteristics alone. In this study, the subsurface chlorophyll maximum was on average only 5 m deeper than the particle maximum, determined using the back-scatter maximum. The subsurface particle maxima observed within this study ~~are~~ were consistent with previous regional findings (Cullen and Eppley, 1981). The close proximity between the particle and chlorophyll maxima suggests that these subsurface phytoplankton communities may contribute significantly to local primary production (Cullen and Eppley, 1981). ~~While satellite surface chlorophyll estimates have been previously shown to aligned closely with *in situ* glider observations of nearshore surface blooms in the San Pedro Channel, subsurface chlorophyll layers farther offshore were undetected by satellite retrievals (Seegers et al., 2015). Since satellites will theoretically not detect integrated chlorophyll below the first optical depth (OD1), *in situ* integrated glider chlorophyll was analysed above and below OD1 to assess how subsurface chlorophyll maxima might impact satellite estimates of chlorophyll and primary productivity.~~ Here, we used our framework to identify which oceanographic states for the SPOT site may be most susceptible to satellite misinterpretation.

The first optical depth (OD1) was calculated from satellite PAR and glider chlorophyll-based diffuse attenuation coefficients for PAR (Kirk, 1994; Jacox et al., 2015). This method provides a conservative estimate of OD1 by ignoring light attenuation caused by dissolved organic matter. Average OD1 for these deployments was 12.3 m while the average euphotic depth, as defined by the 1% light level, was 38.3 m. This is consistent with *in situ* measurements of the euphotic depth from temporally overlapping cruises at the SPOT site that observed an average euphotic depth of 40 m (Haskell et al., 2016). Our estimates for the first optical and euphotic depths are also within the range of regional data collected during the CCE LTER process cruises from 2006-2008 (Mitchell, 2014). Here we compare glider estimates of chlorophyll and primary production integrated over the entire euphotic depth to glider estimates integrated over the first optical depth. This provides an internally consistent dataset to investigate the potential bias in quantifying chlorophyll only over OD1. MODIS Aqua *chlorophyll a* data was also acquired and compared with the *in situ* glider data. However, a low correlation between glider and satellite integrated chlorophyll over OD1 was observed which could be due to temporal and spatial mismatches between datasets, high subsurface

10 ~~biomass~~, inaccurate CDOM corrections, poor atmospheric correction, and high subsurface biomass or temporal mismatch  
between datasets (Supplemental Figure S54).

15 Overall 87% of integrated chlorophyll within the euphotic zone was located beneath the OD1 during the 2013 and 2014  
deployments. This percentage increased to 92% for samples with a significant subsurface chlorophyll maxima (i.e. WSHC)  
and ~~decreases-decreased~~ to 82% for surface blooms (i.e. CHC). For these deployments, zChlMax was generally at or below  
the 10% light level, deepening with more oligotrophic conditions. As a result of these differences in subsurface chlorophyll  
profiles, integrated primary production over OD1 varied from 1.8% to 71.3% of integrated primary production over the entire  
euphotic zone. By analyzing glider profiles based on water column characteristics, we were able to identify profile types that  
may be more susceptible to the inherent bias in satellite data of only quantifying chlorophyll over the first optical depth.  
20 Specifically, for samples with CLC signatures (high PC2 values and low overall biomass), a significant relationship was  
observed between OD1 and total integrated chlorophyll ( $r^2=0.55$ ,  $p<0.01$ ) and between OD1 and total integrated primary  
production ( $r^2=0.77$ ,  $p<0.01$ ). This relationship weakened as surface biomass increased with no relationship observed between  
OD1 and total integrated chlorophyll for profiles falling with the CHC 95% confidence interval cluster ( $p=0.62$ ). While, OD1  
integrated primary production was still significantly correlated with total integrated primary production for CHC profiles  
( $r^2=0.36$ ,  $p<0.01$ ), the slope of this relationship changed significantly from that observed for CLC profiles from 2.5 to 0.6  
(Figure 7). Similarly, profiles with offshore characteristics (WLC, WSHC) showed a correlation between OD1 and total  
25 integrated primary production ( $r^2=0.34$  and  $r^2=0.31$  respectively,  $p<0.01$ ) but with slopes of 1.6 and 1.3.

30 These results quantitatively illustrate differences in the relationship between surface properties (remote-sensing  
observable) and water column integrated properties. Moreover, we demonstrate that the relationship between OD1 integrated  
and euphotic zone integrated primary production varies significantly by water column profile type and that the relationship  
between surface and water column integrated values is more predictable for certain profile types than others. Our analysis  
suggests that the satellite observable vs integrated euphotic zone chlorophyll mismatch may be particularly problematic for  
some cool, high chlorophyll water mass types (nominally coastal blooms). This suggests that increased *in situ* sampling may  
be needed when these water mass types are present in order to accurately constrain estimates of biomass distributions and  
primary production. Oligotrophic profiles (WLC, WSHC) also present a challenge with OD1 integrated primary production  
only explaining approximately a third of the variability in total integrated primary production. However, the presence of a  
35 pronounced subsurface chlorophyll maximum did not substantially change the relationship between OD1 integrated and  
euphotic zone integrated PP as compared to oligotrophic samples with similar OD1 integrated chlorophyll but without the  
subsurface maximum. This analysis suggests that remote-sensing based estimates of PP for WSHC profiles would not be more  
biased than WLC profiles.

### 3.5 Context for time-series measurements

40 The PCA framework for quantifying variability within the San Pedro Channel described above can be leveraged to  
provide context for the SPOT time-series site measurements, which are made at a single location with monthly resolution.  
45 Figure 3b shows the projection of ship-based SPOT data from 2000-2011 and data from a set of Upwelling Regime In-Situ  
Ecosystem Efficiency study (UpRISEE) cruises that occurred during the time of the glider deployments (2013-2014) onto the  
structured PCA axes. Ship-based measurements from March-July show a similar distribution of profile types as seen in the  
glider profiles with most profiles showing an offshore signature (WLC, WSHC) (Table 1, Supplemental Figure S6). There  
was not a substantial difference between the distribution of ship-based profiles in March-July and the distribution for the full  
ship-based datasets. This suggests that there is not a significant seasonal shift in variability at the SPOT site and that the  
variability observed in the glider dataset may be relevant for the entire time-series dataset.

50 The impact of sampling frequency on the observed profile characteristics at SPOT was tested by subsampling the glider  
dataset to evaluate the difference in ~4-day (full glider dataset), 8-day, 12-day, 16-day, 20-day and 24-day sampling schemes.  
As expected, less frequent sampling resulted in more variability in the average water column profile characteristics with 8-day  
sampling showing the most similarity to the full dataset (4-day sampling) (Figure 8). There was not a noticeable difference  
between 12-day, 16-day, 20-day and 24-day sampling (Figure 8a). Overall, the differences between the 6 different sub-month  
55 sampling schemes were small compared to the observed spread in the full glider dataset (Figure 8b). This analysis indicates  
that monthly sampling at the SPOT site may be sufficient to capture the majority of the observed variability in the SPC due to  
the strong offshore influence at the site, even during the upwelling season. However, as highlighted above (*section 3.3*),  
monthly sampling will most likely underestimate the impact of infrequent events at the site such as strong surface blooms and  
upwelled waters. Similarly, a chance sampling of a rare event (e.g. upwelling or coastal bloom) might skew the estimated  
monthly state for SPOT given that these events appear to be short-lived at the SPOT site.

60 The structured PCA framework also allowed us to analyse interannual variability in water column characteristics at the  
SPOT site. While substantial interannual variability in profile characteristics was observed, as represented by changes in PC1  
and PC2, the variability in water column profiles captured by the high-resolution gliders during the upwelling period (March-  
July) of 2013-2014 was comparable to the interannual and seasonal variability observed in monthly sampling at SPOT over  
12 years (Figure 9). Significant deviations from the mean state (e.g. 2000) could indicate anomalous oceanographic conditions  
55 or chance sampling of stochastic rare events (e.g. capturing a spring bloom event). Further analysis of the SPOT data within  
this context could potentially tease apart these two signals. To determine the local oceanographic scenarios that were least  
likely to be accurately observed by satellites, total integrated chlorophyll below OD1 for the 2013 and 2014 deployments was  
compared with the profile characteristics using the end member principal component axes in order (Figure 7). By mass, the  
majority of the integrated chlorophyll that fell below OD1 was associated with surface blooms (up to  $130 \text{ mg m}^{-2}$ ), rather than  
70 subsurface chlorophyll maxima. In these cases, the first optical depth was shallower than the bloom thickness, causing  
underestimation of the surface chlorophyll layer. During subsurface chlorophyll maxima, fewer PAR match ups were

available, hindering the comparison of above and below ODI integrated chlorophyll. However, within the observed profiles, integrated chlorophyll a values of up to 63 mg/m<sup>2</sup> existed between the first optical depth and the euphotic depth (Figure 7).

75 With the observed frequency of subsurface chlorophyll maxima within the SPC during this study and their collocation with backscattering maxima, it is probable that the primary production associated with chlorophyll beneath the ODI during subsurface chlorophyll maxima is a non-negligible portion of the regional carbon budget. Furthermore, an underestimation of integrated chlorophyll during surface blooms will also likely significantly impact estimates of regional carbon export

## 4. Discussion

### 4.1 Regional Application of SPOT Data

30 This study identified four major profile types within the SPC during March through July of 2013 and 2014, cool low chlorophyll, cool high chlorophyll, warm low chlorophyll, and warm subsurface high chlorophyll~~early upwelling, surface bloom, subsurface chlorophyll maximum, and offshore influence~~. These four types represented ~~the~~ end-member oceanographic states that occurred s of vertical profiles observed within the SPC during consecutive glider deployments as a result of two primary physical drivers: coastal upwelling and the Southern California Eddy. The statistical analysis of these  
35 profile types allowed for the identification of temporal and spatial trends in local variability within the SPC and the contextualization of the SPOT station within the SPC. Our results highlight both the similarity between the SPOT station and offshore profiles (WLC, WSHC) and the similarity in water mass characteristics across the channel. This suggests that data collected at SPOT during monthly time-series sampling should be representative of the SPC. As such, long-term ecological or physical trends identified within that are found to be consistent for the entirety of the SPOT time-series data may be assumed  
90 to be applicable for the SPC and could give relevant insight into offshore regions within the Southern California Eddy as well. While infrequent events such as coastal upwelling and surface blooms do occasionally extend across the channel, our findings suggest that monthly sampling at SPOT will under-sample these biogeochemical fluctuations even during the coastally-dominated early Spring which experiences the most coastal influence.

95 During this study, glider deployments were timed to sample only during the most dynamic months for the SPOT station. This sampling scheme may have missed some seasonal variability caused by non-upwelling driven events, such as submesoscale eddies. However, our results suggest that a year-long sampling scheme would likely find similar relationships, given that the sampling occurred during the season when coastal processes (local upwelling) were most likely to occur but still concluded that SPOT was most representative of offshore water types. This is also supported by the similarity between variability with the glider dataset and the 12 year SPOT time-series dataset, which consists of monthly measurements taken throughout the year. Building on these findings, and understanding the rarity of coastal events extending across in the SPC, higher-frequency time-series sampling at SPOT during the spring season could be used to better monitor the effects of nearshore processes on the physical and biological oceanography of the SPC. However, even sub-monthly sampling at SPOT



may underestimate productivity and export within the SCB, as most of the observed upwelling signature occurred inshore of SPOT.

05 The offshore state of SPOT during this study also suggests that time-series data collected at SPOT would be sensitive to climate-derived changes to major current patterns and wind patterns, but may be relatively insensitive to local terrestrial changes such as decreased freshwater discharge or increased sedimentation. Within the SPC, the spin-up of the Southern California Eddy is a major driver of oceanographic change. We hypothesize that the eddy is the primary driver of the profile shift during late April and early May of 2013 and 2014 observed at both SPOT and nearshore locations. Utilizing our  
10 framework to identify transitions from coastally-dominated to offshore-dominated profile types, the timing of the spin-up could be monitored historically or prospectively within previous ship-based sampling at the SPOT site.

#### 4.2 Determining Regional Domains for Time-Series Sites

15 The framework developed to study the applicable domain for SPOT samples and the sensitivity of SPOT samples to regional oceanographic dynamics could easily be applied to other time-series sites. The glider deployments in this study were designed to sample a dynamic period within the SPC with high-spatial and high-temporal frequency. These high frequency samples enabled identification and statistical analysis of regional cross-channel connectivity covariance and response to local oceanographic events. In the case of the SPC, these events were upwelling and the subsequent, surface blooms, and the spin-up of the Southern California Eddy subsurface chlorophyll maxima, and offshore influence. We expectWhile these dominant water column profile types will vary with oceanographic region, the same methodology could be applied to any region to  
20 provide context for a time-series site. For example, at an open ocean site such as the Bermuda Atlantic Time-Series site these features could include winter mixing, and cyclonic or anti-cyclonic eddies. We have shown that high-frequency data can be used to identify the major regional modes and water column profile types, which could-can then be used to determine long-term trends within the time-series site itself. These profile signatures therefore allow for a more quantitative description of time-series observations and therefore a more accurate method for detecting deviations and long-term trends within the time-  
25 series. In the example of the SPOT station, increased nearshore upwelling or delayed spin-up of the Southern California Eddy would each increase the overall coastal signature of vertical profiles collected at SPOT. Historical ship-based vertical profiles as well as future profiles could be analyzed with reference to coastal and offshore signals in order to determine changes in the relative influences dominant oceanographic drivers over time.

30 Spatial contextualization of time-series sites using *in situ* glider deployments, such as those used during this study, can help to identify potentially uncharacterized sources of biological complexity within the time-series location. In the case of the SPOT station, the temporal switch from coastally influenced profiles to offshore influenced profiles implies that samples collected during late April may vary significantly from samples collected in early May simply due to changes in local currents. In addition, the glider profiles were able to identify subsurface dynamics that were not detectable in remote sensing products. Our findings suggest that these subsurface signatures could contribute significantly to regional carbon cycling.

## 35 5. Conclusions

*In situ* high-frequency regional data collection can contextualize time-series sites and identify the major modes of regional variation. This not only allows for the data to be more accurately extrapolated to provide larger scale estimates of critical dynamics such as primary production or carbon export, but also identifies the most crucial regional signals that would need to be correctly simulated to produce accurate regional modeling. In the case of the San Pedro Ocean Time-series (SPOT) station, this study identified four major regional water column profile types and suggests that time-series samples collected monthly would in general be most representative of offshore profiles. ~~However, due to cross-channel connectivity within the San Pedro Channel (SPC), higher frequency sampling at SPOT may also capture coastal signals from nearshore events such as upwelling and surface blooms.~~ Glider profile data from the SPC also indicate that ~~the~~ integrated ~~biomass~~ primary productivity of surface bloom ~~and subsurface chlorophyll maxima~~ profiles ~~would~~ may be underestimated by satellite chlorophyll measurements, suggesting that accurate observation of regional dynamics within the SPC may requires *in situ* sampling with increased resolution when these profile types are present. Finally, ~~this study suggests that time-series data collected at SPOT would be relatively insensitive to coastal anthropogenic change but that the site should be well positioned to identify a regional response to climate change. our analysis indicates that SPOT is primarily reflective of the offshore stratified environment and only rarely influenced by near-coastal processes such as upwelling. This suggests that long-term changes in the SPOT time-series dataset is more likely to reflect larger-scale regional responses (e.g. climatic shifts) than local events (e.g. increased discharge into the port of Los Angeles).~~

Without context for time-series data, physical or temporal under-sampling at time-series stations may mask local drivers of variability making it difficult to accurately scale-up local results to inform larger-scale analyses and modeling efforts. ~~In addition, monthly sampling is likely to miss infrequent events that could be important for local processes making single (monthly sampled) time-series fairly ineffective for understanding dynamic regions such as coastal systems.~~ The methods described in this study can be applied to other coastal and oceanic time-series sites in order to identify the major modes of local variability, the region represented by the time-series data, and the sensitivity of the site to anthropogenic change. Better understanding of the spatial domain represented by global marine time-series sites will aid in the extrapolation of local findings, in the improvement of regional modeling, and in the coupling of regional and global modeling efforts.

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Project, the crew of the Yellowfin, and many others at USC who helped with SPOT data collection and with glider deployment, recovery, and maintenance.

## Figure Captions:

70 **Figure 1:** Glider deployment map and idealized glider transect. Slocum electric gliders were deployed in 2013 and 2014  
between the Palos Verdes Peninsula and Catalina Island in the San Pedro Channel. The San Pedro Ocean Time-series (SPOT)  
station, located at 33° 33' 00" N and 118° 24' 00" W, is indicated by the red dot. Glider surfacings are indicated with grey  
75 dots. An idealized transect was defined running perpendicular to the mean flow (thick black line). Glider profiles collected  
within 5 kilometers of the idealized transect line (dashed black lines) were used to assess cross-channel variability of  
oceanographic properties during these glider deployments. The location of bin 10, 28 (closest to SPOT), and 58 are shown in  
red. The distance from bin 10 to Catalina Island is 5.3 km, from bin 10 to bin 28 is 9 km, from bin 28 to 58 is 15 km, and from  
bin 58 to the closest point on the mainland is 4.8 km. The bathymetry of the study area is designated by the color contours and  
ranged from ~ 20 - 900 m. The maximum glider dive depth was 90 m.

30 **Figure 2:** Temperature and chlorophyll profiles for end-member profiles. Average temperature and chlorophyll a profiles for  
the four end-member profile types in the San Pedro Channel during spring and early summer in 2013 and 2014: early  
upwelling (n=12), surface phytoplankton bloom (n=10), subsurface chlorophyll maximum (n=15), and offshore influence  
(n=17). Secondary characteristics from these four water column profile types were used to create principal component axes  
for downstream analyses.

35 **Figure 32:** Cross-channel variation of profile characteristics. Cross-channel variation in mixed layer temperature (a), mixed  
layer depth (b), the depth of the 12.5°C isotherm (c), ~~and~~ vertically integrated chlorophyll (surface to 70 meters, d), ~~and~~  
vertically integrated primary production (surface to euphotic depth, e) for gridded glider profiles from March through July of  
2013 and 2014 are shown. Cross-channel whisker box plots show the median value for each bin (white dot), data between  
90 the 25th and 75th percentiles (black box), data between the 9th and 91st percentiles (black lines), and outliers (black circles).  
Low numbered bins correspond with the western side of the San Pedro Channel (SPC), near Catalina. High numbered bins  
correspond with the eastern side of the SPC, near the Palos Verdes Peninsula (PV). Bins 35-55 correspond with the shipping  
lanes for the Port of Los Angeles and so have been removed due to incomplete profiles (<85%). Isopycnal depth and mixed  
layer depth shoaled from west to east, and mixed layer temperatures decreased west to east across the channel. Integrated  
chlorophyll observations did not display a significant cross-channel pattern.

95 **Figure 43:** Principal Component Analysis of glider profiles. The original PCA (a) and structured PCA (b) are shown. The four  
end-member water column profile types (Supplemental Figure S2) were used to create the structured principal component  
axes are indicated on both plots. All glider profiles collected in 2013 and 2014 were are then also projected onto these  
axes shown (grey dots). Physical variability was associated with PC1 (49.8% of total variance) and biological variability was  
10 associated with PC2 (32.7% of total variance). Glider profiles from the SPOT location are shown in black diamonds and  
compared against ship-based profiles (grey and black squares) in 4a, and the mean and standard deviation of those profiles are  
shown in 4b along with the mean and standard deviation for profiles collected at bin 10 near Catalina Island and bin 58 near  
the Palos Verdes Peninsula.

05 **Figure 4:** Temperature and chlorophyll profiles for end-member profiles. Average temperature and chlorophyll a profiles for  
the four end-member profile types in the San Pedro Channel during spring and early summer in 2013 and 2014: cool, low  
chlorophyll (n=12), cool, high chlorophyll (n=10), warm, subsurface high chlorophyll (n=15), and warm, low chlorophyll  
(n=17). Average mixed layer depth for each end-member profile is denoted with a circle. Secondary characteristics from these  
10 four water column profile types were used to create principal component axes for downstream analyses.

15 **Figure 5:** Temporal variation at SPOT and coastal locations. Time series of individual locations along the transect are  
projected onto the PC axes. Panels (a) and (b) show nearshore bins (55-62) and panels (c) and (d) show the SPOT bin (28).  
Though SPOT and the nearshore bins displayed a different temporal evolution during the course of each deployment, there  
appeared to be a crossover point for both groups in mid-April in both 2013 and 2014. This cross-over point can be visualized  
as a movement from more coastal profile characteristics (negative PC1) to more offshore characteristics (positive PC1).

**Figure 56:** Cross-channel connectivity coherence. SPOT profiles are grouped based on which PCA quadrant they fall into. Panel (a) displays SPOT profiles (diamonds) and the corresponding non-SPOT profiles (grey dots) that were collected during the same glider transect when SPOT was most similar to the CLC 'early upwelling' end-member. Similarly, panels (b), (c), and (d) display the profiles for which SPOT was most similar to the WLC, CHC, and WSHC end-members, 'offshore influence', 'surface bloom', and 'subsurface chlorophyll maximum' respectively.

**Figure 56:** Seasonal progression of bins along the transect. Two examples are shown: SPOT (bin 28) and nearshore bins (average for bins 55-62). The average and standard deviation for April (blues) and June (greens) are shown. Both sites show a transition from low PC1 values to elevated PC1 values indicating increased offshore influence. Temporal variation at SPOT and coastal locations. Time-series of individual locations along the transect are projected onto the PC axes. Panels (a) and (b) show nearshore bins (55-62) and panels (c) and (d) show the SPOT bin (28). Though SPOT and the nearshore bins displayed a different temporal evolution during the course of each deployment, there appeared to be a crossover point for both groups in mid-April in both 2013 and 2014. This cross over point can be visualized as a movement from more coastal profile characteristics (negative PC1) to more offshore characteristics (positive PC1).

**Figure 7:** Integrated primary production (PP) within the first optical depth (OD1) versus integrated primary production over the euphotic zone. Each profile is colored by its PC2 value. The trendlines for all profiles falling within the four end-member profile clusters are shown.

**Figure 8:** Impact of sampling frequency. Panel a shows the impact of different sampling frequencies on the estimated SPOT water column profile characteristics. The mean and standard deviation of full glider dataset for SPOT (~4 day sampling) from March-July 2013 and 2014 are shown in black. The mean and standard deviation of the subsampled glider dataset for the SPOT site (8-day, 12-day, 16-day, 20-day, 24-day) are shown as colored circles. For reference, the mean and standard deviation of the ship-based SPOT time-series samples from March -July (Ship, 30), and the ship-based UpRISEE cruise samples from March-July (Ship, 14) are shown. The 95% confidence intervals for the four end-member profiles are also shown. Panel b displays the differences in estimated characteristics for the subsampled datasets relative to the full glider dataset (4-day sampling).

**Figure 9:** Interannual variability in SPOT cruise profiles versus high-resolution glider profiles. The mean and standard deviation of the PC1 and PC2 values for the SPOT cruise profiles from 2000 to 2011 are shown. The mean (dashed line) and standard deviation (grey shading) of the 2013 and 2014 glider profiles are also indicated. Integrated chlorophyll below the first optical depth. All glider data from 2012 and 2013 were projected onto the end-member PCA axes and colored according to the integrated chlorophyll between the first optical depth and the base of the euphotic zone. Open circles show profiles for which the first optical depth was not known due to the absence of a matching satellite PAR measurement. Surface bloom profiles had the highest levels of integrated chlorophyll that would have been missed by satellites. These instances were rare, but are likely to be associated with underestimation of regional productivity and export. Subsurface chlorophyll maximum profiles were associated with up to 200 mg m<sup>-2</sup> of missing integrated chlorophyll.

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