**Lagrangian studies of net community production: The effect of diel and multi-day non-steady state factors and vertical fluxes on O2/Ar in a dynamic upwelling region**

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**Key points:**

**\*** We employ Lagrangian observations of O2/Ar in the California Current to test assumptions inherent to the O2/Ar-based NCP method.

**\*** We demonstrate the significance of vertical fluxes and diel patterns in O2/Ar that can bias NCP measurements.

**\*** Non-steady-state conditions and vertical fluxes strongly complicate efforts to evaluate O2/Ar-based NCP on short timescales.

**Abstract**The ratio of dissolved oxygen to argon in seawater is frequently employed to estimate rates of net community production (NCP) in the oceanic mixed layer. The *in situ* O2/Ar-based method accounts for many physical factors that influence oxygen concentrations, permitting isolation of the biological oxygen signal produced by the balance of photosynthesis and respiration. However, this technique traditionally relies upon several assumptions when calculating the mixed layer O2/Ar budget, most notably the absence of vertical fluxes of O2/Ar and the principle that the air-sea gas exchange of biological oxygen closely approximates net productivity rates. Employing a Lagrangian study design and leveraging data outputs from a regional physical oceanographic model, we conducted *in situ* measurements of O2/Ar in the California Current Ecosystem in spring 2016 and summer 2017 to evaluate these assumptions within a ‘worst-case’ field environment. Quantifying vertical fluxes, incorporating non-steady-state changes in O2/Ar, and comparing NCP estimates evaluated over several-day versus longer timescales, we find differences in NCP metrics calculated over different time intervals to be considerable, also observing significant potential effects from vertical fluxes, particularly advection. Additionally, we observe strong diel variability in O2/Ar and NCP rates at multiple stations. Our results reemphasize the importance of accounting for vertical fluxes when interpreting O2/Ar-derived NCP data and the potentially large effect of non-steady-state conditions on NCP evaluated over shorter timescales. In addition, diel cycles in surface O2/Ar can also bias interpretation of NCP data based on local productivity and the time of day when measurements were made.

**Plain language summary:**

Marine microbes produce and consume oxygen as a product of a balance between photosynthesis and respiration, thereby causing changes in the concentration of oxygen in the surface ocean. Taking advantage of known relationships between the gas properties of oxygen and argon, researchers can isolate changes in biologically-produced oxygen from changes that result from physical processes. This calculation relies on several simplifying assumptions. In this study, we test the importance of these assumptions by tracking changes in biological oxygen while following several water parcels over the course of 2-4 days. We find that accounting for vertical mixing processes and the rate of change in biological oxygen is important when estimating biological oxygen production rates. We also find that daily shifts in oxygen as photosynthesis rises through the day and falls to zero at night can influence measurements based on time of collection.

**Index terms and keywords:**

**4227 Diel, seasonal, and annual cycles, 0460 Marine systems, 0414 Biogeochemical cycles, processes, and modeling, 4806 Carbon cycling, 4820 Gases**

**1. Introduction**

Basic measurements of oceanic primary production are essential to studying marine carbon fluxes, ecosystem dynamics, and carbon biogeochemistry. Marine net primary production, which accounts for half of total global primary production (Field, Behrenfeld, Randerson, & Falkowski, 1998), plays a correspondingly important role in regulating carbon fluxes between the atmosphere and the biosphere. Furthermore, marine biological uptake of inorganic carbon represents a key global climate feedback, with sequestration of sinking organic biomass into the deep ocean acting as a sink for atmospheric carbon. Improving the accuracy of marine primary production measurements can enhance our ability to both constrain the potential strength of this carbon pump to the ocean interior as well as to study marine ecosystems.

Numerous approaches for measuring marine primary production exist, spanning multiple incubation-based and *in situ* methods (Chavez, Messié, & Pennington, 2010; Ducklow & Doney, 2013); Within the last decade, an increasing number of studies e.g. (N. Cassar et al., 2011; Eveleth et al., 2017; H. R. Stanley, Kirkpatrick, Cassar, Barnett, & L Bender, 2010; Ulfsbo et al., 2014; Wang, Lin, Gifford, Eveleth, & Cassar, 2018) are utilizing underway techniques to continuously measure tracers of productivity in the surface ocean at fine resolution. Currently, an underway method in prevalent use employs measurements of the dissolved O2/Ar ratio in seawater using either Equilibrator Inlet Mass Spectrometry (EIMS) (N Cassar et al., 2009) or Membrane Inlet Mass Spectrometry (MIMS) (Kaiser, Reuer, Barnett, & Bender, 2005; Philippe D. Tortell, 2005).  
 The O2/Ar method is based upon isolation of the biologically-driven signal in dissolved oxygen saturation within the surface ocean mixed layer and is widely used to generate estimates of surface net community production (NCP), defined as the difference between gross primary production (GPP) and community respiration (CR). NCP represents the net production of biomass remaining after accounting for consumption of organic carbon via respiration, and thus reflects the total biological production available for export to depth (Berger & Wefer, 1990; Ducklow & Doney, 2013; Dugdale & Goering, 1967; Li & Cassar, 2017; Williams et al, 1989). While dissolved oxygen concentrations alone are subject to physical influences (temperature, atmospheric pressure, bubble-injection) in addition to biological drivers (photosynthesis, respiration), dissolved argon is not utilized in biological processes and possesses similar physical and temperature-based solubility characteristics compared to oxygen (Craig & Hayward, 1987). Consequently, changes in the ratio of dissolved O2/Ar reflect biological production/respiration over the residence time of oxygen within the surface mixed layer. By measuring the O2/Ar ratio in surface seawater continuously, the EIMS and MIMS techniques enable the collection of large NCP datasets with unprecedented spatiotemporal resolution. These methods represent important recent methodological advances in marine biogeochemistry.  
 While powerful, the O2/Ar method is subject to some limitations. The O2/Ar tracer can be influenced by advection and mixing of neighboring or subsurface waters with contrasting O2/Ar signatures into the volume being sampled. In addition, assumptions involved in the parameterization of the air-sea gas exchange term represent a significant source of uncertainty (Bender, Kinter, Cassar, & Wanninkhof, 2011). Diel variations in the magnitude of the O2­/Ar-derived biological oxygen saturation anomaly have also been commonly observed across a range of ocean settings (Ferron, Wilson, Martinez-Garcia, Quay, & Karl, 2015; R. C. Hamme et al., 2012; P. D. Tortell et al., 2014). The signal from diel cycling in the biological oxygen saturation anomaly is superimposed over underway measurements of O2/Ar, thereby influencing spatial surveys based on the time of day at which observations are recorded. Such diel oscillations in the biological oxygen saturation anomaly vary in amplitude, ranging from ~0.2% in the oligotrophic North Pacific Subtropical Gyre (Ferron et al., 2015) to up to ~2% or more during highly-productive blooms off the Antarctic coast (P. D. Tortell et al., 2014).

The *in situ* O2/Ar method was traditionally a steady-state approach, in which mixed-layer biological oxygen production is balanced by efflux to the atmosphere over the residence time of oxygen in the surface mixed layer (Reuer, Barnett, Bender, Falkowski, & Hendricks, 2007). Both field (R. C. Hamme et al., 2012; P. D. Tortell et al., 2014) and model-based (Jonsson, Doney, Dunne, & Bender, 2013; P. D. Tortell et al., 2014) studies have indicated that steady-state conditions can be violated in practice over both diel and multi-day timescales, particularly during periods of intense or rapidly-changing biological production and/or when measurements capture physical effects such as entrainment due to changes in mixed layer depth (MLD). However, a recent analysis (Teeter, Hamme, Ianson, & Bianucci, 2018), concludes that the steady state assumption is not strictly required to estimate NCP on timescales several times longer than the surface residence time of biological oxygen, as the gas flux rate closely matches an exponentially-weighted time-average of past NCP rates even if non-steady-state conditions are present. Over shorter timescales however, ocean-atmosphere biological oxygen flux can significantly diverge from NCP rates under non-steady-state conditions, causing issues when attempting to interpret O2/Ar-based NCP on shorter time scales, such as when making inter-method comparisons with in-situ productivity rates.

In recent years, investigators have made efforts to better address and to correct for the abovementioned sources of error. The contribution of vertical fluxes of O2/Ar to the mixed-layer biological oxygen balance has now been estimated in field studies using a variety of approaches ranging from oxygen profile-based calculations of entrainment and vertical eddy diffusive fluxes (Castro-Morales, Cassar, Shoosmith, & Kaiser, 2013; Haskell Ii, Prokopenko, Stanley, & Knapp, 2016) to quantification of the total vertical mixing flux using an N2O-based approach (Cassar, Nevison, & Manizza, 2014; Izett, Manning, Hamme, & Tortell, 2018). Furthermore, continued efforts have been made to examine the influence of non-steady-state factors and to further improve the accuracy of the gas exchange parameterization term (Teeter et al., 2018). While non-Lagrangian study designs necessarily increase the difficulty of estimating the impact of diel and multi-day non-steady-state changes in the biological oxygen saturation anomaly, efforts have also been made to quantify these factors in Lagrangian (R. C. Hamme et al., 2012) and stationary (P. D. Tortell et al., 2014) field settings.

The California Current upwelling zone is a highly-dynamic coastal ecosystem characterized by steep cross-shore gradients in physical and biochemical conditions (Lynn & Simpson, 1987). Strong coastal upwelling in this region is driven by wind circulation, which generates sustained upwelling and Ekman transport along much of the California coastline (Chelton, 1982; Ohman et al., 2013; Rykaczewski & Checkley, 2008). Rising waters from depth carry high nutrient concentrations, fueling dramatic ecosystem production rates throughout much of the growing season (Munro, Quay, Juranek, & Goericke, 2013; Ohman et al., 2013). With nitrogen and phosphorus in ample supply, portions of this region have been demonstrated to exhibit iron limitation (Hutchins, DiTullio, Zhang, & Bruland, 1998; King & Barbeau, 2007). Productivity in the California Current Ecosystem (CCE) often follows a seasonal cycle, with the peak of the spring bloom typically occurring in April-May, followed by continued high production into the summer prior to subsiding over the course of the fall to low winter productivity rates (Munro et al., 2013). Offshore and alongshore currents, influenced by both Ekman transport and meso- and submesoscale fronts and eddies also lead to substantial mesoscale spatial variability and large advective fluxes (Landry et al., 2012; Strub & James, 2000)

Given its strong vertical and lateral fluxes, considerable spatial variability, and high rates of productivity, the California Current region arguably represents a “worst-case” field environment for the assumptions made when measuring NCP using traditional underway measurements of O2/Ar. Errors associated with such conditions are often considerable, leading investigators to discard data collected within regions influenced by strong upwelling or to avoid field deployments in such regions altogether (Cassar et al., 2014; Reuer et al., 2007). Because of this practice, however, only relatively few attempts (Haskell & Fleming, 2018) have been made to quantify the sources of error within such a challenging setting to date. Such efforts have the potential to help us more critically evaluate the strengths and weaknesses of the assumptions involved in calculating community production rates from dissolved O2/Ar.

In this paper, we present Lagrangian *in-situ* measurements of O2/Ar saturation anomalies and NCP from seven multi-day deployments over two field expeditions in the California Current Ecosystem in spring 2016 and 2017. Thisdynamic region represents a unique study environment for assessing the respective impact of diel and multi-day non-steady-state conditions and vertical fluxes upon O2/Ar-derived estimates of NCP on short-term (multi-day) and longer-term (30-day exponentially-weighted) timescales. By estimating the contribution over time of vertical O2/Ar fluxes as well as diel and longer-term non-steady-state conditions to the overall biological oxygen signal in various water masses within this region, we demonstrate the critical importance of accounting for such potential sources of measurement error, underlining the need for quantification of these factors via concurrent N2O sampling and/or other means when measuring NCP in similarly dynamic ocean regions around the world.

**2. Methods  
2.1 Cruise background:**

Underway measurements and CTD-Niskin rosette casts were conducted during an expedition aboard the *R/V Sikuliaq* from 19 April to 12 May 2016 during the RAPID CCE-LTER process cruise (P1604), as well as from 1 June to 2 July 2017 aboard the *R/V Roger Revelle* during the subsequent year’s CCE-LTER process cruise (P1706) (Figure 1). 3-4 quasi-Lagrangian experiments (hereafter ‘cycles’) were conducted in each year while following selected water masses over ~3 day periods at various locations in the CCE. Following the completion of a towed Moving Vessel Profiler (MVP) survey of the local area to ensure that the deployment site represented a cohesive water mass free of strong frontal gradients (Landry et al., 2012; Ohman, Powell, Picheral, & Jensen, 2012; Stukel, Ohman, Benitez-Nelson, & Landry, 2013), each cycle began when a drogued sediment trap array and a drogued experimental array were deployed (Landry, Ohman, Goericke, Stukel, & Tsyrklevich, 2009; Stukel et al., 2013). Each array included a 3×1-m holey sock drogue centered at 15-m depth to track the mixed layer (10-81 m) (Landry et al., 2009; Niiler, Sybrandy, Bi, Poulain, & Bitterman, 1995).  
 In 2016, the first Lagrangian cycle (P1604-1) was aborted due to an on-ship emergency and we do not evaluate data collected during this deployment. The second cycle (P1604-2) was located within the heart of the California Current, while the third and fourth cycles were both situated within the inshore zone of sustained upwelling off Point Conception (Table 1). P1604-3 was located within the wind stress curl upwelling region, while P1604-4 was conducted inside the coastal boundary upwelling zone. For additional details on plankton communities during the P1604 cruise, see (Morrow et al., 2018) and (Nickels & Ohman, 2018). During the 2017 cruise, the first cycle was conducted in the inshore upwelling region, the second cycle was initiated in aged upwelled waters and lasted four days, and the third cycle was conducted in post-bloom waters. The fourth cycle in 2017 (P1706-4) lasted two days and represented a ‘continuation’ of P1706-2 where the *Revelle* returned to a surface-tethered drifting sediment trap, which had been deployed at the end of P1706-2. All other deployments in 2016 and 2017 apart from P1706-2 and P1706-4 were conducted for a duration of three days.

**2.2 Underway O2/Ar measurements via EIMS:**  
Using the equilibrator inlet mass spectrometry (EIMS) method (N Cassar et al., 2009), we conducted high-resolution measurements of the dissolved O2/Ar ratio in surface seawater. Briefly, intake seawater collected at a depth of 5 m by the ship’s underway system was circulated continuously via a magnetic gear pump through a membrane contactor. Within the membrane contactor, dissolved gases from the seawater flow rapidly equilibrate within the headspace at pressures reflecting *in situ* concentrations. Equilibrated gas was measured using a Pfeiffer Prisma QMS 200 M1 quadrupole mass spectrometer. Every 2-4 hours, an automated program or user input was used to switch a multi-port Valco valve in order to sample ambient room air from a second capillary of equal length for 20-30 minutes. These “air calibrations”, measuring the constant ratio of atmospheric O2/Ar, are used in downstream processing to express the *in situ­* O2/Ar saturation anomaly relative to the ratio at atmospheric equilibrium and to calibrate “water” O2/Ar measurements for instrumental drift.

Apart from occasional breaks in measurements for cleaning, service, or to troubleshoot technical issues, EIMS measurements were collected continuously throughout both cruises during all Lagrangian cycles. Gaps in data due to instrument downtime never exceeded 4.5 hours during Lagrangian measurements, apart from a 9.5 hour break in data during the first cycle of P1706.

Potential respiration in the ship’s lines (Juranek, Hamme, Kaiser, Wanninkhof, & Quay, 2010) was assessed in 2016 using five paired sets of discrete Winkler dissolved oxygen samples taken from CTD casts and from the underway seawater tap over the course of the cruise. Winkler samples from CTD casts were collected from a surface depth of around five meters. Samples were immediately fixed with pickling reagents and measured via Winkler titration at Scripps Institute of Oceanography shortly after returning to port following the procedure outlined in the CalCOFI program’s Winkler sampling and analysis protocol (http://www.calcofi.org/ccpublications/calcofi-methods/13-dissolved-oxygen.html). Measured Winkler samples showed no consistent difference between underway and *in situ* oxygen concentrations (average offset of <0.43 µmol/kg, standard deviation of 1.73 µmol/kg, average percent difference of -0.1%), suggesting that the effect of microbial respiration in the *R/V* *Sikuliaq*’s underway plumbing was negligible. *In-situ* Winkler samples were not taken during the P1706 cruise.

**2.3 Calculation of biological oxygen saturation anomaly (ΔO2/Ar):**

Raw EIMS data was time-averaged at a two-minute timestep. Mass spectrometer data collected during testing, periods of technical failure, and during shutoffs of the ship’s underway seawater flow were filtered using times recorded in a cruise log sheet. EIMS data collected during periods in which mass spectrometer pressure was anomalously high or low (< 1 × 10-6 or > 9 × 10-6 mbar), as well as data recorded during the 80-minute period following any instrument restart were also filtered. At times when a valve switch between air and water capillaries occurred, the nearest 6 minutes of water measurements and the nearest 4 minutes of air measurements were also filtered from the dataset to avoid transition artifacts.

Biological O2 saturation anomaly was subsequently calculated from the measured ion current ratio according to the following formula:

(1)

where O2/Armeasuredcorresponds to the oxygen-argon ratio measured from sampled seawater and O2/Arsaturation represents the O2/Ar ratio expected at air-sea gas exchange equilibrium, which is assumed to correspond to the O2/Ar ratio found in air. A continuous vector of O2/Arequil values was generated by calculating the mean O2/Ar recorded during each air calibration, followed by linear interpolation of the O2/Arequil ratio between each set of successive air calibrations. Data collected between air calibrations at which the difference in O2/Ar exceeded .02 were filtered, as were data collected when the interpolated ion current ratio of air measurements was outside the range of 15 to 28. Following filtration of anomalous data, the ΔO2/Ar dataset was then merged with two-minute averaged ship data (time, position, temperature, salinity, PAR, and wind speed).

Mixed-layer depth calculations, subsurface oxygen concentrations, as well as oxycline gradients are necessary for parameterizing the gas exchange term for NCP calculations and to estimate vertical O2/Ar fluxes from vertical entrainment, eddy diffusion, and advective fluxes. These parameters were calculated from CTD cast measurements conducted during both the 2016 and 2017 cruises. Quality-checked, 1 m depth-averaged CTD cast data was downloaded from the CCE LTER online database (<https://oceaninformatics.ucsd.edu/datazoo/catalogs/ccelter/datasets>). Mixed-layer depths were determined using a density difference criterion of 0.03 kg/m3 from the density measurement at a reference depth of 10 m (Dong, Sprintall, Gille, & Talley, 2008). Additionally, using bisector least squares regression, oxygen measurements from the 20 m below the calculated MLD were used to determine subsurface gradients in oxygen immediately below the mixed layer. MLD values and oxygen gradients were then linearly approximated across each cycle.  
 As the residence time of ΔO2/Ar in the surface ocean is on the order of days to weeks, prior local wind speed data from the period preceding real-time measurements are required to incorporate wind speed history into parameterization of the gas transfer velocity. Daily North American Regional Reanalysis (NARR) wind speeds in the 30-day period prior to the day of measurement were downloaded from the NOAA ESRL online database (https://www.esrl.noaa.gov/psd/data/gridded/data.narr.monolevel.html), then 2-D interpolated to yield wind speed history data along our cruise coordinates. For both years of NARR data, we compared NARR and 10-m height-corrected (Thomas, Kent, & Swail, 2005) ship-measured wind speeds, then corrected the former using a linear model to more closely match field wind speed data. Ship and uncorrected NARR wind speeds tracked changes in wind speeds over time similarly, although NARR wind speed data typically exceeded ship-recorded winds. We observed a mean offset of 2.1 m s-1 (std dev: 2.2 m s-1). Gas transfer velocity was parameterized following (Wanninkhof, 2014), applying the wind speed history-based weighting scheme of (Reuer et al., 2007) with the modification advocated by (Teeter et al., 2018).

Exponentially-weighted net community production rates, reflecting raw biological oxygen fluxes uncorrected for vertical mixing, were calculated using Equation 2:

*NCPprior* (2)

where signifies the O2/Ar saturation anomaly relative to atmospheric equilibrium (see Equation 1), represents the density of seawater (kg/m3) as calculated from the UNESCO 1983 equation of state, and *k* denotes the weighted gas transfer velocity. Lastly, is the oxygen concentration at saturation, calculated from (Garcia & Gordon, 1992, 1993).

Following calculation of preliminary NCP data, a distance filter was applied to remove likely non-Lagrangian data collected at distances of more than 8 km from the sediment trap and drifter array. We further calculated uncertainty associated with NCPprior values (not including vertical fluxes), by propagating uncertainty in the following terms: *k* (20% (Wanninkhof, 2014)), ΔO2/Ar (0.3% (N Cassar et al., 2009)).

This uncorrected NCP data represents an exponentially-weighted average of NCP over the residence time of oxygen within the mixed layer, so we henceforth term this calculated rate as NCPprior as in (R. C. Hamme et al., 2012). An open source pipeline of R scripts has been developed to perform NCPprior calculations and was used to process data from both cruises (Kelly, 2019).

**2.4 Detrending and curve fitting of NCPprior data and calculation of diel cycle characteristics**

To better isolate and quantify the diel pattern of ΔO2/Ar and measured NCPprior observed at each cycle, our raw data required detrending to remove the long-term non-diel rate of change. We further matched a fitted curve to each cycle’s data to model the observed diel pattern in the data.

Linear models (using the ‘regstats’ function in MATLAB) were fit to a subset of each cycle’s data beginning and ending at the same time of day (typically around 4AM local time). Linear trends were observed for all cycles apart from P1604-2, although the observed slopes were modest for several of the cycles. For each cycle, the trendline was subtracted from the data in order to detrend the cycle NCPprior for greater ease of isolating the diel signal. All regressions were statistically significant (p<<0.01).  
 To model the observed diel cycle of NCPprior rates for each Lagrangian study, a Fourier series was fit to the corrected, detrended NCPprior data using the curve fitting toolbox in MATLAB. In most cases, we selected the most parsimonious Fourier series fit that gave the correct number of diel cycles for the observation period. This generally corresponded to a four-term Fourier series fit apart from P1706-4, where we employed a three-term fit due to the abbreviated length (two days) of this cycle. For P1604-3 and P1706-2, a fifth term was added to further improve the goodness-of-fit.

Local times for apparent sunrise and sunset were calculated using the NOAA ESRL Solar Calculator (https://www.esrl.noaa.gov/gmd/grad/solcalc/), using the cycle dates and starting coordinates of each Lagrangian cycle as inputs.

The approximate range of the diel variability in Δ(O2/Ar) and NCPprior rates was calculated from the median of the daily maxima and minima of raw Δ(O2/Ar) and NCPprior values observed over the course of a particular multi-day cycle.

**2.5 Assessment of non-steady-state impacts on calculated net community production**

Due to our Lagrangian study design, we were able to measure the change in mixed-layer ΔO2/Ar in real time over the observational period and thereby theoretically estimate NCP over a shorter timescale without having to employ an assumption of steady state (Figure 2). To do this, we utilized Equation 2 of (R. C. Hamme et al., 2012):

(3)

Note that *kinst* represents the unweighted rather than weighted gas exchange coefficient, using daily-averaged wind on the day of observations. z denotes the MLD.

Similar to when detrending uncorrected NCPprior data as described above, the long-term (over the period of observation) rate of change in Δ(O2/Ar) (i.e. in equation 3) was determined via a linear regression, yielding the slope of Δ(O2/Ar) measurements for each cycle. To minimize the influence of diel changes in Δ(O2/Ar) upon the calculated multi-day slope, each cycle’s data were trimmed to start and end at the same time of day as previously described. All relationships obtained for Δ(O2/Ar) linear regressions were statistically significant (p<<0.01).

Following the terminology of (R. C. Hamme et al., 2012), we henceforth refer to our NCP rates calculated using the above method, evaluated over a multi-day timescale without the use of a steady-state assumption, as real-time NCP (NCPRT). We further calculated uncertainty associated with NCPRT values (not including vertical fluxes), by propagating uncertainty in the following terms: *kinst* (20% (Wanninkhof, 2014)), ΔO2/Ar (0.3% (N Cassar et al., 2009)), *z* (5 m (R. C. Hamme et al., 2012)), and (using the standard error of the linear model).

**2.6 Calculation of vertical O2/Ar fluxes:**

Following (Castro-Morales et al., 2013; Emerson, Stump, & Nicholson, 2008), the vertical flux-corrected mass balance of biological oxygen in the surface ocean would be expressed as:

*NCPVflux* = NCPprior (4)

where Fv and Fe represent the impact of vertical eddy diffusive flux and entrainment flux, respectively, Fadv denotes the advective flux, and NCPprior represents the uncorrected NCP (see Eq. 2). We estimated the magnitude of vertical eddy diffusion and entrainment fluxes to mixed-layer biological oxygen fluxes following (Castro-Morales et al., 2013):

(5)

(6)

Where represents the eddy diffusivity coefficient (m2 s-1), the gradient of oxygen in the 20 m beneath the MLD, and the change in MLD over the time interval between CTD casts (). Negative values for Fv and Fe in Equations 5 and 6 represent vertical addition of biological O2 to the mixed layer resulting from increasing oxygen with depth, while decreasing oxygen with depth results in positive values for Fv and Fe.

Advective flux of biological oxygen into the mixed layer from the subsurface was calculated using the following equation:

(7)

where w denotes the vertical velocity (positive upwards) and zmix represents the mixed-layer depth. Upwards vertical velocities (positive) and increasing oxygen with depth thus result in negative Fadv, and vice versa. Note that advective fluxes are only significant in the case of upwelling—in the absence of large horizontal gradients in O2/Ar, downwelling does not alter the biological O2 concentration of the mixed layer, and so we assume that Fadv = 0 when w < 0.

Values for Kz and w were extracted from a three-dimensional physical model (9 km horizontal resolution, 42 vertical layers) developed using the Regional Ocean Modeling System (ROMS) four-dimensional variational data assimilation system (4DVAR) (Moore et al., 2011), then depth-interpolated linearly to calculate values at the MLD. Initial and boundary conditions were taken from the California Current System Reanalysis product produced by the University of California, Santa Cruz. Surface forcing was taken from the 9-km resolution Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (Doyle, Jiang, Chao, & Farrara, 2009; Hodur, 1997). We assimilated satellite remote sensing products, including sea surface height from Ssalto/Duacs (59964 observations) and sea surface temperature from AVHRR (357 063 observations), surface current data from coastal HF radar observations (39 127 observations), and in situ temperature and salinity data vertical profiles collected during CTD measurements on our cruise (30 675 observations). Assimilated data were used to update model initial conditions and surface forcing to generate a dynamically-consistent month-long model fit covering the duration of each cruise and producing 8-hr averaged outputs. Following iterative updating of the incremental model, we obtained a reduction of the cost function, a metric reflecting the change in the model from its initial conditions as well as its success in minimizing differences between the model state and the observational dataset, of 72% and 57% for the 2017 and 2016 model fits, respectively (Figure S1). Reductions in the errors between observations and modeled values for surface currents, temperature, salinity, and sea surface height ranged between 24% and 74% (Table S1). For detailed descriptions of our ROMS 4DVAR approach, see (Song et al., 2012) and (Miller, Song, & Subramanian, 2015). Kz and w were interpolated to CTD cast locations from the 9-km ROMS 4DVAR solution using bilinear 2D interpolation from the four points comprising the nearest neighbors to the cast coordinates. Median Kz values and median positive vertical velocities (w) at the MLD for each Lagrangian cycle were then calculated and employed for vertical eddy diffusion and vertical advection estimates.

Incorporating these vertical flux estimates into our calculation of NCPRT described above yields:

(8)

NCPRT\_Vflux thereby captures both the multi-day rate of change in the biological oxygen saturation anomaly over the observational period and the influence of vertical fluxes via eddy diffusion, entrainment, and advection.

Due to large uncertainties in Fadvresulting from the use of modeled vertical velocities, we did not calculate NCP*RT\_VFlux* directly, as the margin of uncertainty associated with advective fluxes dwarfed the O2/Ar signal. Potential error in the advective flux term was very large, to the point where NCP*RT\_VFlux* would no longer represent a meaningful estimate of community production. Instead, we separately calculated and report the magnitude and variability of the individual vertical flux components: Fv, Fe, and Fadv.

**3. Results**

**3.1 General patterns of net community production from Lagrangian measurements in the California Current in spring/summer 2016 and 2017**

In both 2016 and 2017, mean MLD-integrated NCPprior values observed during each cycle were largest at the cycles closest to the shore (Table 2, Figure 3). The cycles conducted closest to shore exhibited mean NCPprior rates of 47±11 and 68±16 mmol O2 m-2 d-1 for P1604-4 and P1706-1, respectively. Located just off the Point Conception upwelling center, these locations were distinguished by high Chl-*a* concentrations, peaks of O2/Ar saturation anomaly (>15%), and large diel variation in the O2/Ar signal (Figure 4). The range of NCPprior for a given cycle also broadened for cycles located closer to shore. Throughout the day, coastal NCPprior rates could exhibit a surprising degree of volatility, with rapid short-term changes in biological oxygen saturation anomaly of as much as 10% occurring at points during the observation period. Ecologically, we observed this coastal region to be a productive ecosystem rich in marine life. Algal biomass was high in the surface layer (~4 µg Chl-*a* L-1), with high abundances of krill, copepods, and even tuna crabs (*Pleuroncodes planipes*) choking the *R/V Sikuliaq*’s sea strainers during P1604-4. During the 2017 cruise the coastal region had high chlorophyll (surface Chl averaged 9 μg Chl-*a* L-1) and high nutrient concentrations (surface NO3- averaged 6 μmol L-1). Data on the heterotrophic plankton community for the 2017 cruise was not yet available but will eventually be published on the CCE-LTER datazoo database.

P1604-2, conducted in the heart of the California Current, was unique in several respects. For one, P1604-2 displayed a narrow range of low NCPprior rates (4 to 10±1 mmol O2 m-2 d-1) compared to all other cycles in both years (range for all other cycles was -66 to 127 mmol O2 m-2 d-1. This location was also characterized by deeper mixed-layer depths (65 to 76 m) than all other cycles (10-30 m).

Cycles conducted further offshore (P1604-2, P1604-3, P1706-3, P1706-4) shared similarities in terms of NCPprior rate ranges with values generally varying between -20 and 20 mmol O2 m-2 d-1.

**3.2 Exponentially-weighted versus short-term, non-steady-state-based calculation of *in situ* NCP**

Non-steady state changes in mixed-layer biological oxygen implied by the slopes of the linear fits suggest that non-steady state conditions were non-negligible when integrated over multiple days, with changes in ΔO2/Ar ranging from -3.13 to 1.95 % saturation anomaly d-1 at some stations. The observed rates of change in the NCPprior signal across the cycles corresponded to slopes varying between -13 and 13 mmol O2 m-2 d-2 (Table 2).

The secular increases and decreases in mixed-layer biological oxygen during a cycle resulted in corresponding offsets between NCPRT and NCPprior proportional to the magnitude of the slope in ΔO2/Ar. The relationship between d(ΔO2/Ar)/dt and the offset between NCPRT and NCPprior was statistically significant when tested using a linear model (p<0.001, R2=0.97, n=7). These offsets were more modest (i.e. <15 mmol O2 m-2 d-1 difference in median NCPprior versus NCPRT) for stations located further offshore (P2016-2, P2017-3, P2017-4) than for stations closer to the coast, where median real-time NCP over the measurement period differed from NCPprior by up to an order of magnitude and could even flip estimated NCP rates from positive to negative. For instance, NCPRT calculations for P1706-1 produce an overall strong negative biological oxygen flux, while NCPprior yields a strong positive flux (Table 2).

**3.3 Diel non-steady-state variation in O2/Ar-derived NCP signal** Clear diel patterns were evident in both the measured ΔO2/Ar saturation anomaly and calculated NCPprior rates across six of the seven sites occupied (Figure 5). Additionally, we observed a consistent pattern of increasing amplitude to the diel signal in O2/Ar with closer proximity to shore. Increasingly larger diel signal amplitudes also tended to correspond to stations at which more elevated Chl-*a* concentrations were also observed.

At the two stations closest to the coast, diel variations in biological oxygen saturation anomaly were dramatic, leading to approximately twofold changes in ΔO2/Ar (%) over the course of a daylong period. The range of the diel signal at these inshore stations was also large: regularly over 10% and as large as 17%. Such oscillations are similar in magnitude to diel changes in ΔO2/Ar (%) observed off the coast of Palmer Station on the West Antarctic Peninsula in summer (P. D. Tortell et al., 2014). This diel variability resulted in daily shifts of apparent measured NCPprior of up to ~100 mmol O2 m-2 d-2 (Table 3). A greater degree of day-to-day variability in the magnitude of diel variation was also shown at inshore sites, with the amplitude of the diel pattern exhibiting changes of up to twofold throughout the observational period.

In contrast, the cycles furthest offshore also exhibited clear diel behavior, but with substantially smaller amplitude (changes in ΔO2/Ar of <1 to 2 % saturation anomaly). Nevertheless, such diel patterns are significant relative to the margin of error inherent to the method (~ 0.3 %), and relative to the magnitude of the local NCP.

Two study locations, P1604-3 and P1706-3, did not demonstrate diel patterns with the same degree of clarity. This absence of a clear diurnal behavior for these cycles was related to strong multi-day trends in the ΔO2/Ar signal (Figure 3) possibly connected to an increase in wind speed during P1706-3.

**3.4 Influence of vertical fluxes of O2/Ar upon calculated *in situ* NCP**

Relative to the difference between NCPprior and NCPRT, the influence of vertical O2/Ar fluxes was comparable and often even larger (Table 2). Consequently, the surface layer O2/Ar budget at our study locations is significantly and often dominantly influenced by the vertical flux terms.

Across all cycles, the influence of vertical advection dominated both other vertical fluxes, with advective fluxes an order of magnitude larger than NCPprior or NCPRT at some stations. Calculated ranges in vertical advective fluxes were generally large as well, in excess of 400 mmol O2 m-2 d-1 at four of seven cycles with a maximum Fadv rate of 2580 mmol O2 m-2 d-1 estimated for P1706-1. These values are however highly sensitive to the vertical velocity estimates used in calculations and to the strength of and variations in the subsurface O2 gradient (i.e. -5.2 to -3.4 mmol O2 m-4 for P1706-2), which drive much of the variability in calculated advective fluxes.

Entrainment fluxes and vertical eddy diffusive fluxes were generally less influential than advective fluxes but could still represent non-negligible sources of error. As entrainment flux only comes into effect upon a deepening of the surface mixed layer, cycle entrainment flux values were absent for some cycles during which mixed layer depths predominantly shoaled or remained stable during the observed period. Both vertical eddy diffusion and entrainment fluxes appeared to generally increase in both median magnitude and range of values with closer proximity to shore (Table 2).

**4. Discussion**

**4.1 Differences in short-term non-steady-state and exponentially-weighted calculations of NCP**

The large difference in median cycle NCP when comparing NCPprior (calculated using an exponential wind speed history weighting) to real time NCPRT is primarily driven by the magnitude of the trend in ΔO2/Ar over the length of observations. While changes in measured MLD would affect the NCPRT calculation, the overall offset between NCPRT and NCPprior appears generally dominated by the slope produced by the rate of change in ΔO2/Ar over the 2-4 day period. A multi-day decrease in ΔO2/Ar over time results in a negative offset in which NCPprior rates are significantly greater than NCPRT values, and vice versa. Consequently, NCPprior agrees well with NCPRT when the rate of change in ΔO2/Ar is small, as for P1604-2 (Table 2).

Prior studies observing non-steady-state changes in ΔO2/Ar over time have attributed part of the rate-of-change term to changes in the biological community, as evidenced by patterns in Chl-*a* over the observational period (R. C. Hamme et al., 2012). Based on supporting Advanced Laser Fluorometry (ALF) measurements from our 2017 cruise (available from the CCE-LTER website), however, we do not observe any multi-day increases or decreases in Chl-*a* that might explain the observed non-steady-state trends in biological oxygen saturation anomaly. Intriguingly, we do observe a correspondence between the magnitude of the diel signal changes in ΔO2/Ar and diel behavior in Chl-*a* across our cycles (Figure S2), qualitatively supporting the relationship between diel optical POC measurements, reflecting organic biomass, and 14C primary production rates established in a study in the North Pacific Subtropical Gyre (White, Barone, Letelier, & Karl, 2017).

It is important to note that NCPprior and NCPRT are not expected to be directly comparable as the integration time for each metric is distinct as previously mentioned. While NCPprior purports to integrate over the residence time of dissolved O2 in the surface mixed layer (several days to weeks), NCPRT is intended to reflect the rate of production over the period of observed measurements only.

We acknowledge that our Lagrangian time series observations were of relatively short duration, subjecting our estimate of the slope term in surface layer O2/Ar saturation anomaly to some uncertainty. In particular, P1706-4 was occupied for a period of just two days compared to the 3-4 day study length employed at other sites. Notably, this cycle, intended as an extension of P1706-2 several days later, differs from P1706-2 considerably in terms of the implied rates of change in ΔO2/Ar observed during the two respective cycles (Figure 6). This observation indeed suggests that short deployments (2-3 days) can produce differing rates of change in mixed-layer biological oxygen saturation anomaly compared to calculations using longer-term (weeklong or greater) measurements. Such longer timescales are generally more characteristic of the residence time of biological oxygen in the surface ocean. At the same time, however, the residence time of biological oxygen in the surface layer in this region with respect to the biology is short, as evidenced by rapid changes in oxygen concentrations.

A number of experimental limitations to the Lagrangian design of this study also warrant mention. The possibility does exist that the drogued experimental array drifted relative to the water mass. First, the array is fitted with a surface float, which is subject to surface currents and winds, imparting some influence on the array’s trajectory. Second, the array was fitted with racks and bottles for other experiments at several depths, including depths deeper than 15m. The hydrodynamic drag resulting from the surface float and these bottle experiments is another source of potential divergence between the original water mass and the drogued array.

We also do reemphasize that the California Current system in many ways represents a worst-case environment for the quantification of NCP from EIMS and/or MIMS-based O2/Ar measurements. Upwelling waters from depth in this region are often highly undersaturated in O2/Ar and likely violate the assumption of negligible vertical fluxes frequently. Under certain local conditions, ongoing equilibration between the undersaturated surface mixed layer and the atmosphere may result in apparent O2/Ar undersaturation even while mixed layer production rates are high and positive. Alternatively, elevated productivity in the surface mixed layer might contribute to O2/Ar supersaturation despite the presence of a strong influence from vertical fluxes of low O2/Ar waters, leading investigators to take productivity rates at face value when they in fact represent underestimates. Multi-day trends in O2/Ar can thus be driven by a combination of biology as well as the physics of air-sea gas exchange. Finally, community metabolic rates along this highly-productive coast might be of a sufficiently dramatic magnitude to unbalance air-sea-exchange from net production/respiration even in the absence of vertical fluxes. Investigators have long cautioned against deploying the O2/Ar method in environments characterized by such factors (Castro-Morales et al., 2013; Haskell & Fleming, 2018; Reuer et al., 2007), and indeed, exponentially-weighted NCPprior appears to line up much more closely with NCPRTat greater distance offshore, an environment more typical of settings where the O2/Ar technique has been employed to date.

As a result of these factors, we overall assess NCPRT to be of limited utility in upwelling regions as a means to estimate NCP over short timescales from O2/Ar measurements. Whereas the d(ΔO2/Ar)/dt term in NCPRT purportedly corrects for lag between air-sea gas exchange of biological oxygen and real rates of biological oxygen production, it can be impacted by changes in wind speeds as well as shifts in surface ocean biology that occurred prior to the deployment period. Given the significant weight of the d(ΔO2/Ar)/dt term as previously noted, such effects introduce considerable uncertainty into NCPRT. Furthermore, accurately correcting for vertical fluxes from depth would require not only estimating or measuring such fluxes but correcting for changes in those fluxes over the measurement period. Consequently, NCPRT\_Vflux (see Methods) does not satisfactorily reflect productivity on short timescales, but at best can measure the total production or consumption of biological oxygen in the surface mixed layer as a combination of physical and biological processes.

**4.2 Influence of diel patterns in O2/Ar upon measured NCPprior**

Our observation of strong diel signals within Lagrangian observations of the O2/Ar saturation anomaly reinforce earlier findings (Ferron et al., 2015; R. C. Hamme et al., 2012; P. D. Tortell et al., 2014) that diel effects can be significant across diverse environments, a consequence of the inherently strong influence of the most recent time period upon the recorded O2/Ar signal. Consequently, the time of day can matter considerably when conducting non-Lagrangian measurements, affecting measured values by a factor of two or more. We demonstrate that the amplitude of the diel signal increases consistently along a cross-shore gradient in our study region during the growing season, with the effect exhibiting an increased magnitude for a higher productivity regime.

Using our measurements as an example, this phenomenon means that were a vessel hypothetically conducting point measurements of NCP to arrive on-station close to the coast at 3AM as opposed to 3PM local time, the difference in measured NCP calculated from the ΔO2/Ar signal might be as large as 20-50 mmol O2 m-2 d-1: an effect approaching 50% of the median NCP measured at inshore stations. Ultimately, if considering only the effect of biology under constant, non-zero wind speed, this diel factor would bias NCP measurements low if conducted close to dawn and high if taken close to dusk. However, the magnitude of the bias scales proportionally to the total metabolic rate of the surface ocean community, and thus the absolute effect of diel variations in O2/Ar is low in less-productive settings.Nevertheless, due to the lower overall NCP­prior­ rates, diel effects remain a large source of variability in terms of relative proportions.

A consistent trend between both volumetric and MLD-integrated Chl-*a* measurements and diel O2/Ar signal amplitude was observed in both years of our study (Table 3). Consequently, volumetric or depth-integrated Chl-*a* alone may potentially serve as the basis for a field indicator of potential diel variability in biological oxygen saturation anomaly. In this study, we observe that median cycle Chl-*a* concentrations above 1 µg/L correspond to diel variability in ΔO2/Ar on the order of 3% in amplitude or more, suggesting that diel effects are of potential concern for most “productive” ecosystems. However, more Lagrangian observations will likely be required to develop a robust metric that might be used to gauge the risk of significant diel behavior in O2/Ar.

Additionally, we point out that a number of other factors not captured by the surface Chl-*a* inventory may also be responsible for driving diel signals. For instance, it is possible that diel variations in respiration due to heterotrophic activity, potentially due to zooplankton vertical migration or other factors, may also explain a component of the diel O2/Ar signal, confounding efforts to assess the diel signal amplitude in relation to Chl-*a* alone. Additionally, the magnitude of diel behavior in O2/Ar is also determined by the extent of gas exchange between the atmosphere and surface ocean, where more vigorous air-sea equilibration may act to dampen the diel cycle. Finally, the influence of other factors like PAR, light attenuation, and tidal effects may also impact diel variability by influencing the biological community.

Unfortunately, it remains difficult to say how investigators can correct for this diel effect while conducting Eulerian measurements. When deploying underway O2/Ar measurements at sites of particular interest, a best practice might be to occupy the station for a period extending through a 12-hour period in order to capture the daily range and median of the O2/Ar signal. However, in practice such an approach may not be possible due to time and logistical constraints. Ultimately, our results re-emphasize that such diel effects can be considerable and ought to be factored in when interpreting non-Lagrangian measurements of NCP determined using both discrete and underway ΔO2/Ar-based approaches.

**4.3 Influence of vertical fluxes of O2/Ar upon apparent NCPprior**

Overall, we assess the impact of vertical fluxes of O2/Ar to be a dominant and large influence. The largest vertical flux term overall by a considerable margin comprised the effect of vertical advection, which we calculated to potentially produce fluxes several-fold to a full order of magnitude larger than uncorrected NCPprior rates (Table 2). This finding parallels the conclusions of (Haskell & Fleming, 2018), who calculated vertical transport fluxes of 50-124 mmol O2 m-2 d-1 off the California coast in spring 2013 and 2014 that left uncorrected NCP estimates just 15-16% of corrected NCP rates. The dominant impact of vertical fluxes is also supported by N2O-calculated mixing corrections for O2/Ar NCP measurements off British Columbia that yielded vertical flux contributions of 150-200 mmol O2 m-2 d‑1 in coastal shelf waters in spring and summer that significantly elevated corrected NCP rates by several-fold relative to uncorrected NCP estimates (Izett et al., 2018).

Our vertical flux estimates, however, are considerably larger than estimated vertical contributions from these studies. This may be primarily driven by our strong modeled vertical velocities near the base of the mixed layer in this region, with average velocities during each cycle of 3.8-9.7 m d-1. Such vertical velocities are nevertheless within expectations for this region (17-20 m d-1,and substantially larger during upwelling events) (Huyer, 1983; Münchow, 2000), and are well within the range of upwelling rates observed in dynamic ocean regions at the submesoscale (Lévy, Ferrari, Franks, Martin, & Rivière, 2012). In contrast, (Haskell & Fleming, 2018) estimated lower vertical velocities of no more than 4.2 m d-1 at the San Pedro Ocean Time-series (SPOT) using the 7Be tracer approach.

Uncertainty in these vertical advective flux estimates has the potential to produce overestimates of advective fluxes of O2/Ar between the surface layer and subsurface. Modeled vertical velocities may not be consistently reliable for estimating advection, particularly when leveraged on such short time scales. Advection thus represents a considerable factor to correct for but is itself difficult to confidently constrain without direct measurements.

Consequently, we would not consider NCPRT\_Vflux estimates (see Methods) made using Fadv calculated in this study to be reliable metrics of vertically-corrected productivity. For instance, mean Fadv is strongly positive during P1604-4, P1706-1, and P1706-2 due to strong local upwelling of undersaturated waters. Taking such fluxes at face value would produce implausibly high corrected NCP rates (>700 mmol O2 m-2 d-1). Phytoplankton biomass during those cycles was insufficiently high to produce such rates, with mean *Chl-a* of 3.1 to 9.3 mg/m3. In comparison, 14C primary production measurements during spring and summer blooms in Chesapeake Bay yielded rates of <300 mmol O2/m2/d (assuming a photosynthetic quotient of 1.4) despite Chl-a measurements as high as 25-27 mg/m3 (Adolf, Yeager, Miller, Mallonee, & Harding, 2006). Long-term primary productivity datasets from the California Current region show annual peaks in photic-zone production rates of no more than 150 mmol O2/m2/d (Mantyla, Bograd, & Venrick, 2008). Given the high sensitivity of our calculation to the strength and sign of the vertical velocities used, our method for estimating the advective flux term is thus subject to substantial error. Nevertheless, the considerable magnitude of potential vertical advective fluxes reemphasizes the importance of considering vertical advection in this region.

Contributions from non-advective vertical fluxes of O2 are also non-negligible, with entrainment fluxes and vertical eddy diffusion also producing estimated fluxes of up to 96 and 22 mmol O2 m-2 d-1 during some cycle measurements, respectively. Therefore, our assessment also reinforces the need to account for these vertical terms in both Eulerian and Lagrangian surveys employing underway ΔO2/Ar measurements, as well as discrete ΔO2/Ar sampling.

When considering the impact of vertical eddy diffusion, entrainment, and advection upon Eulerian NCPprior measurements, however, these fluxes should ideally be evaluated over the residence time of the O2/Ar signal, and we also suggest that time-weighting based on the weighted gas transfer velocity approach of (Reuer et al., 2007) might be employed to more accurately constrain these terms. Due to our lack of reliable means to estimate subsurface O2 gradients, eddy diffusivities, vertical velocities, and MLD changes prior to our arrival onsite, however, we were unable to evaluate Fv, Fe, and Fadv over a longer, more appropriate timescale. Furthermore, our Lagrangian study approach here allowed us to neglect horizontal advective fluxes and focus only on vertical terms. When using an Eulerian sampling approach, the inclusion of horizontal advection terms might lead to significant impacts. We further note that Eulerian surveys of NCPprior in fact represent point measurements of exponentially-weighted NCP over the past Lagrangian path of the water parcel, meaning that an ideal accounting of vertical fluxes would hypothetically track the influence of such terms in space and time along the same path. One potentially fruitful approach for future incorporation of vertical advection into NCP calculations would be to use mean upwelling velocities derived from simulated Lagrangian particles, rather than velocities from the Eulerian model. If such Lagrangian particles were released backwards in time from the measurement location their dispersion in space would give an estimate of the multiple historical upwelling trajectories that brought water to the sampling location. Such a Lagrangian model is, however, beyond the scope of this study.

At a minimum, vertical profiles of oxygen from frequent CTD casts can be employed as demonstrated here to assess the impact of these factors. Preferably, discrete or high-frequency vertical sampling of the O2/Ar ratio with depth can greatly improve the accuracy and confidence of such calculations. At the same time, the recently-developed N2O method (Cassar et al., 2014) also shows promise (Izett et al., 2018) as an approach for correcting the influence of vertical fluxes by simultaneously quantifying multiple sources of vertical mixing. We suggest that this method simplifies the complications detailed above regarding attempts to model vertical physical O2/Ar fluxes and the difficulty of back-calculating their magnitude along the Lagrangian path traveled by sampled water masses. However, this method is also limited by assumptions, including negligible N2O production in the mixed layer and minimal horizontal heterogeneity. Alternatively, direct measurements of vertical mixing using approaches such as the 7Be method (Kadko & Johns, 2011) could directly quantify the strength of mixing, although this technique possesses a different residence time relative to O2, and incorporating the method may present logistical challenges for cruise planners.

We do note that our calculations of vertical fluxes utilize measurements of O2 and O2 gradients rather than O2/Ar, and therefore involve the assumption that changes in O2 with depth are mirrored by the O2/Ar signal. Typically, fairly small gradients in Ar saturation are expected with depth within the first few hundred meters from the surface (Roberta C. Hamme, Nicholson, Jenkins, & Emerson, 2019; R. C. Hamme & Severinghaus, 2007), with deviations of under 2% saturation anomaly from surface values. Nevertheless, our use of O2 concentrations for vertical flux calculations represents a potential source of error if Ar saturation was in fact significantly variable over the first couple hundred meters below the surface layer. Finally, our vertical flux calculations likely represent overestimates of the overall vertical O2/Ar transport, as they do not account for horizontal divergence at the surface layer.

To summarize, vertical advection is generally the more important vertical O2/Ar flux relative to eddy diffusion and mixed layer entrainment, with advection a particularly difficult-to-constrain source of uncertainty. The contribution of vertical fluxes to the mixed layer O2/Ar budget, however, is dependent on local conditions, particularly on upwelling rates and the strength of the vertical gradient in biological oxygen. Overall, the effect of vertical fluxes of O2/Ar also appears to be of major importance to consider, capable of introducing very large uncertainties into calculations of NCPprior in this region.

**5. Conclusions**

Ultimately, our study further highlights the importance of considering the potential impact of vertical fluxes, diel variation, and the specific timescales of interest when assessing surface layer productivity using *in situ* ΔO2/Ar measurements, particularly within a highly-productive, dynamic region such as the California Current Ecosystem. Taking advantage of our Lagrangian study design as well as model output data, we are able to contrast exponentially-weighted NCPprior rates calculated using traditional assumptions with shorter-term NCP estimates calculated without reliance on a steady-state condition and also assess the potential influence of vertical fluxes.We conclude that the non-steady-state rate of change term represents a considerable influence upon attempts to estimate short-term NCP rates in this region. At the same time, we observe the calculated and potential influence of vertical fluxes of O2/Ar from entrainment, vertical eddy diffusion, and particularly vertical advection to be significant, contributing substantially to the real mixed layer O2/Ar budget.

We reiterate that our study region and results represent conditions that have long been held to be poorly-suited to deployment of the *in situ* O2/Ar method. While assumptions of negligible vertical fluxes may be valid for given regions and seasons, such factors should nevertheless be assessed in any field deployment to ensure that their potential impact is truly small. Techniques such as the N2O approach for quantifying the influence of vertical fluxes upon O2/Ar (Cassar et al., 2014) may be well-suited to help correct EIMS or MIMS measurements of NCP conducted in environments presenting similar challenges to the California Current system (Izett et al., 2018).

Similarly, when performing non-Lagrangian measurements in regions of high diel metabolic activity, we find that adequate consideration of the impact of time of day upon measured values is also important. We observed diel cycles in ΔO2/Ar of up to 17% in range at some locations, adding a considerable source of variability to the median cycle ΔO2/Ar signal on hourly time scales. Lastly, our study highlights conditions under which diel and multi-day non-steady-state factors exert relatively low influence over calculated NCP rates. Less-productive ecosystems more characteristic of the open ocean, with Chl-*a* concentrations below 1 µg/L tend to exhibit both lower diel variability as well as considerably smaller absolute offsets between NCP estimated using steady-state versus non-steady-state assumptions.

To alleviate the influence of such diel impacts on future studies, we suggest that when monitoring throughout the course of the solar day at a field location is not possible, investigators should endeavor to capture O­2/Ar measurements that cover a 12-hour period fully capturing the local daily solar maximum. Another logical next step would be the identification of a clear predictor for diel non-steady-state conditions, using metrics such as Chl-*a*, MLD, wind speed, or other parameters, to flag biased conditions while in the field.

While vertical flux effects as well as diel patterns in ΔO2/Ar can be considerable in the field, particularly within highly-productive and physically-dynamic settings, investigators possess means to evaluate the impact of such factors upon *in situ* productivity rate estimates. Our findings within a challenging study environment reemphasize the importance of critically evaluating basic assumptions inherent to the O2/Ar method and stress the utility of careful planning and study design when conducting O2/Ar measurements under non-ideal conditions.

**Acknowledgements:**

This research was made possible by a RAPID NSF OCE-1614359 and federal funding provided to the California Current Ecosystem (CCE) LTER project, NSF OCE-1637632. HS acknowledges the support by National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2019R1C1C1003663) and Yonsei University Research Fund of 2018-22-0053. We are sincerely grateful to the captain, crew, and marine technicians of the *R/V Sikuliaq* and the *R/V Roger Revelle* for their assistance prior to and during our 2016 and 2017 expeditions. We are additionally thankful for helpful suggestions and input from Susan Lozier, Laifang Li, Sijia Zou, and Kimberly Drouin, as well as Roberta Hamme and one anonymous reviewer. We also thank Susan Becker, Melissa Miller, and Megan Roadman for their assistance processing and analyzing collected Winker samples. We are additionally grateful to Ralf Goericke for his help processing vessel cruise data and to Chief Scientist Mark Ohman and the rest of the CCE LTER team. Lastly, we thank the staff of Scripps Institution of Oceanography for their cruise logistical and organizational support.

The authors declare no conflict of interest. Data reported and presented in this study can be accessed at the CCE-LTER Datazoo online database.

**References:**

Adolf, J. E., Yeager, C. L., Miller, W. D., Mallonee, M. E., & Harding, L. W. (2006). Environmental forcing of phytoplankton floral composition, biomass, and primary productivity in Chesapeake Bay, USA. *Estuarine, Coastal and Shelf Science, 67*(1), 108-122. doi:<https://doi.org/10.1016/j.ecss.2005.11.030>

Bender, M. L., Kinter, S., Cassar, N., & Wanninkhof, R. (2011). Evaluating gas transfer velocity parameterizations using upper ocean radon distributions. *Journal of Geophysical Research: Oceans, 116*(C2). doi:10.1029/2009JC005805

Berger, W. H., & Wefer, G. (1990). Export production: seasonality and intermittency, and paleoceanographic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology, 89*(3), 245-254. doi:<https://doi.org/10.1016/0031-0182(90)90065-F>

Cassar, Nevison, C., & Manizza, M. (2014). Correcting oceanic O2/Ar-net community production estimates for vertical mixing using N2O observations. *Geophysical Research Letters, 41*(24), 8961-8970. doi:10.1002/2014GL062040

Cassar, N., Barnett, B., Bender, M., Kaiser, J., Hamme, R., & Tilbrook, B. (2009). Continuous High-Frequency Dissolved O-2/Ar Measurements by Equilibrator Inlet Mass Spectrometry. *Analytical Chemistry, 81*(5), 1855-1864. doi:10.1021/ac802300u

Cassar, N., DiFiore, P. J., Barnett, B. A., Bender, M. L., Bowie, A. R., Tilbrook, B., . . . Lefevre, D. (2011). The influence of iron and light on net community production in the Subantarctic and Polar Frontal Zones. *Biogeosciences, 8*(2), 227-237. doi:10.5194/bg-8-227-2011

Castro-Morales, K., Cassar, N., Shoosmith, D. R., & Kaiser, J. (2013). Biological production in the Bellingshausen Sea from oxygen-to-argon ratios and oxygen triple isotopes. *Biogeosciences, 10*(4), 2273-2291. doi:10.5194/bg-10-2273-2013

Chavez, F. P., Messié, M., & Pennington, J. T. (2010). Marine Primary Production in Relation to Climate Variability and Change. *Annual Review of Marine Science, 3*(1), 227-260. doi:10.1146/annurev.marine.010908.163917

Chelton, D. J. C. O. F. I., Univ. of Calif., San Diego, La Jolla. (1982). Large-scale response of the California Current to forcing by wind stress curl CalCOFI Rep. 23, 130–148 Calif.

Craig, H., & Hayward, T. (1987). Oxygen Supersaturation in the Ocean: Biological Versus Physical Contributions. *Science, 235*(4785), 199. Retrieved from <http://science.sciencemag.org/content/235/4785/199.abstract>

Dong, S., Sprintall, J., Gille, S. T., & Talley, L. (2008). Southern Ocean mixed‐layer depth from Argo float profiles. *Journal of Geophysical Research: Oceans, 113*(C6). doi:doi:10.1029/2006JC004051

Doyle, J. D., Jiang, Q. F., Chao, Y., & Farrara, J. (2009). High-resolution real-time modeling of the marine atmospheric boundary layer in support of the AOSN-II field campaign. *Deep-Sea Research Part Ii-Topical Studies in Oceanography, 56*(3-5), 87-99. doi:10.1016/j.dsr2.2008.08.009

Ducklow, H. W., & Doney, S. C. (2013). What Is the Metabolic State of the Oligotrophic Ocean? A Debate. *Annual Review of Marine Science, 5*(1), 525-533. doi:10.1146/annurev-marine-121211-172331

Dugdale, R. C., & Goering, J. J. (1967). UPTAKE OF NEW AND REGENERATED FORMS OF NITROGEN IN PRIMARY PRODUCTIVITY. *Limnology and Oceanography, 12*(2), 196-&. Retrieved from <Go to ISI>://WOS:A19679423500002

Emerson, S., Stump, C., & Nicholson, D. (2008). Net biological oxygen production in the ocean: Remote in situ measurements of O-2 and N-2 in surface waters. *Global Biogeochemical Cycles, 22*(3). doi:10.1029/2007gb003095

Eveleth, R., Cassar, N., Sherrell, R. M., Ducklow, H., Meredith, M. P., Venables, H. J., . . . Li, Z. (2017). Ice melt influence on summertime net community production along the Western Antarctic Peninsula. *Deep Sea Research Part II: Topical Studies in Oceanography, 139*, 89-102. doi:<https://doi.org/10.1016/j.dsr2.2016.07.016>

Ferron, S., Wilson, S. T., Martinez-Garcia, S., Quay, P. D., & Karl, D. M. (2015). Metabolic balance in the mixed layer of the oligotrophic North Pacific Ocean from diel changes in O-2/Ar saturation ratios. *Geophysical Research Letters, 42*(9), 3421-3430. doi:10.1002/2015gl063555

Field, C. B., Behrenfeld, M. J., Randerson, J. T., & Falkowski, P. (1998). Primary production of the biosphere: Integrating terrestrial and oceanic components. *Science, 281*(5374), 237-240. doi:10.1126/science.281.5374.237

Garcia, H. E., & Gordon, L. I. (1992). Oxygen solubility in seawater: Better fitting equations. *Limnology and Oceanography, 37*(6), 1307-1312. Retrieved from <Go to ISI>://WOS:A1992KR91400015

Garcia, H. E., & Gordon, L. I. (1993). Erratum: Oxygen solubility in seawater: Better fitting equations. *Limnology and Oceanography, 38*(3), 656.

H. R. Stanley, R., Kirkpatrick, J., Cassar, N., Barnett, B., & L Bender, M. (2010). *Net community production and gross primary production rates in the western equatorial Pacific* (Vol. 24).

Hamme, R. C., Cassar, N., Lance, V. P., Vaillancourt, R. D., Bender, M. L., Strutton, P. G., . . . Hargreaves, B. R. (2012). Dissolved O-2/Ar and other methods reveal rapid changes in productivity during a Lagrangian experiment in the Southern Ocean. *Journal of Geophysical Research-Oceans, 117*. doi:10.1029/2011jc007046

Hamme, R. C., Nicholson, D. P., Jenkins, W. J., & Emerson, S. R. (2019). Using Noble Gases to Assess the Ocean's Carbon Pumps. *Annual Review of Marine Science, 11*(1), 75-103. doi:10.1146/annurev-marine-121916-063604

Hamme, R. C., & Severinghaus, J. P. (2007). Trace gas disequilibria during deep-water formation. *Deep-Sea Research Part I-Oceanographic Research Papers, 54*(6), 939-950. doi:10.1016/j.dsr.2007.03.008

Haskell Ii, W. Z., Prokopenko, M. G., Stanley, R. H. R., & Knapp, A. N. (2016). Estimates of vertical turbulent mixing used to determine a vertical gradient in net and gross oxygen production in the oligotrophic South Pacific Gyre. *Geophysical Research Letters, 43*(14), 7590-7599. doi:10.1002/2016GL069523

Haskell, W. Z., & Fleming, J. C. (2018). Concurrent estimates of carbon export reveal physical biases in ΔO2/Ar-based net community production estimates in the Southern California Bight. *Journal of Marine Systems, 183*, 23-31. doi:<https://doi.org/10.1016/j.jmarsys.2018.03.008>

Hodur, R. M. (1997). The Naval Research Laboratory's coupled ocean/atmosphere mesoscale prediction system (COAMPS). *Monthly Weather Review, 125*(7), 1414-1430. doi:10.1175/1520-0493(1997)125<1414:tnrlsc>2.0.co;2

Hutchins, D. A., DiTullio, G. R., Zhang, Y., & Bruland, K. W. (1998). An iron limitation mosaic in the California upwelling regime. *Limnology and Oceanography, 43*(6), 1037-1054. doi:10.4319/lo.1998.43.6.1037

Huyer, A. (1983). Coastal upwelling in the California current system. *Progress in Oceanography, 12*(3), 259-284. doi:<https://doi.org/10.1016/0079-6611(83)90010-1>

Izett, R. W., Manning, C. C., Hamme, R. C., & Tortell, P. D. (2018). Refined Estimates of Net Community Production in the Subarctic Northeast Pacific Derived From O-2/Ar Measurements With N2O-Based Corrections for Vertical Mixing. *Global Biogeochemical Cycles, 32*(3), 326-350. doi:10.1002/2017gb005792

Jonsson, B. F., Doney, S. C., Dunne, J., & Bender, M. (2013). Evaluation of the Southern Ocean O2/Ar-based NCP estimates in a model framework. *Journal of Geophysical Research: Biogeosciences, 118*(2), 385-399. doi:doi:10.1002/jgrg.20032

Juranek, L. W., Hamme, R. C., Kaiser, J., Wanninkhof, R., & Quay, P. D. (2010). Evidence of O-2 consumption in underway seawater lines: Implications for air-sea O-2 and CO2 fluxes. *Geophysical Research Letters, 37*. doi:10.1029/2009gl040423

Kadko, D., & Johns, W. (2011). Inferring upwelling rates in the equatorial Atlantic using 7Be measurements in the upper ocean. *Deep Sea Research Part I: Oceanographic Research Papers, 58*(6), 647-657. doi:<https://doi.org/10.1016/j.dsr.2011.03.004>

Kaiser, J., Reuer, M. K., Barnett, B., & Bender, M. L. (2005). Marine productivity estimates from continuous O2/Ar ratio measurements by membrane inlet mass spectrometry. *32*(19). doi:10.1029/2005gl023459

Kelly, T. B. (2019). An Open Source Pipeline for O2Ar Flux Analysis.

King, A. L., & Barbeau, K. (2007). Evidence for phytoplankton iron limitation in the southern California Current System. *Marine Ecology Progress Series, 342*, 91-103. doi:10.3354/meps342091

Landry, M. R., Ohman, M. D., Goericke, R., Stukel, M. R., Barbeau, K. A., Bundy, R., & Kahru, M. (2012). Pelagic community responses to a deep-water front in the California Current Ecosystem: overview of the A-Front Study. *Journal of Plankton Research, 34*(9), 739-748. doi:10.1093/plankt/fbs025

Landry, M. R., Ohman, M. D., Goericke, R., Stukel, M. R., & Tsyrklevich, K. (2009). Lagrangian studies of phytoplankton growth and grazing relationships in a coastal upwelling ecosystem off Southern California. *Progress in Oceanography, 83*(1-4), 208-216. doi:10.1016/j.pocean.2009.07.026

Lévy, M., Ferrari, R., Franks, P. J. S., Martin, A. P., & Rivière, P. (2012). Bringing physics to life at the submesoscale. *Geophysical Research Letters, 39*(14). doi:10.1029/2012GL052756

Li, Z. C., & Cassar, N. (2017). A mechanistic model of an upper bound on oceanic carbon export as a function of mixed layer depth and temperature. *Biogeosciences, 14*(22), 5015-5027. doi:10.5194/bg-14-5015-2017

Lynn, R. J., & Simpson, J. J. (1987). THE CALIFORNIA CURRENT SYSTEM - THE SEASONAL VARIABILITY OF ITS PHYSICAL CHARACTERISTICS. *Journal of Geophysical Research-Oceans, 92*(C12), 12947-&. doi:10.1029/JC092iC12p12947

Mantyla, A. W., Bograd, S. J., & Venrick, E. L. (2008). Patterns and controls of chlorophyll-a and primary productivity cycles in the Southern California Bight. *Journal of Marine Systems, 73*(1), 48-60. doi:<https://doi.org/10.1016/j.jmarsys.2007.08.001>

Miller, A. J., Song, H., & Subramanian, A. C. (2015). The physical oceanographic environment during the CCE-LTER Years: Changes in climate and concepts. *Deep-Sea Research Part Ii-Topical Studies in Oceanography, 112*, 6-17. doi:10.1016/j.dsr2.2014.01.003

Moore, A. M., Arango, H. G., Broquet, G., Powell, B. S., Weaver, A. T., & Zavala-Garay, J. (2011). The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems Part I - System overview and formulation. *Progress in Oceanography, 91*(1), 34-49. doi:10.1016/j.pocean.2011.05.004

Morrow, R. M., Ohman, M. D., Goericke, R., Kelly, T. B., Stephens, B. M., & Stukel, M. R. (2018). CCE V: Primary production, mesozooplankton grazing, and the biological pump in the California Current Ecosystem: Variability and response to El Nino. *Deep-Sea Research Part I-Oceanographic Research Papers, 140*, 52-62. doi:10.1016/j.dsr.2018.07.012

Münchow, A. (2000). Wind Stress Curl Forcing of the Coastal Ocean near Point Conception, California. *Journal of Physical Oceanography, 30*(6), 1265-1280. doi:10.1175/1520-0485(2000)030<1265:WSCFOT>2.0.CO;2

Munro, D. R., Quay, P. D., Juranek, L. W., & Goericke, R. (2013). Biological production rates off the Southern California coast estimated from triple O2 isotopes and O2 : Ar gas ratios. *Limnology and Oceanography, 58*(4), 1312-1328. doi:10.4319/lo.2013.58.4.1312

Nickels, C. F., & Ohman, M. D. (2018). CCEIII: Persistent functional relationships between copepod egg production rates and food concentration through anomalously warm conditions in the California Current Ecosystem. *Deep-Sea Research Part I-Oceanographic Research Papers, 140*, 26-35. doi:10.1016/j.dsr.2018.07.001

Niiler, P. P., Sybrandy, A. S., Bi, K. N., Poulain, P. M., & Bitterman, D. (1995). Measurements of the water-following capability of holey-sock and TRISTAR drifters. *Deep-Sea Research Part I-Oceanographic Research Papers, 42*(11-12), 1951-&. doi:10.1016/0967-0637(95)00076-3

Ohman, M. D., Barbeau, K., Franks, P. J. S., Goericke, R., Landry, M. R., & Miller, A. J. (2013). Ecological Transitions in a Coastal Upwelling Ecosystem. *Oceanography, 26*(3), 210-219. doi:10.5670/oceanog.2013.65

Ohman, M. D., Powell, J. R., Picheral, M., & Jensen, D. W. (2012). Mesozooplankton and particulate matter responses to a deep-water frontal system in the southern California Current System. *Journal of Plankton Research, 34*(9), 815-827. doi:10.1093/plankt/fbs028

Reuer, M. K., Barnett, B. A., Bender, M. L., Falkowski, P. G., & Hendricks, M. B. (2007). New estimates of Southern Ocean biological production rates from O-2/Ar ratios and the triple isotope composition of O-2. *Deep-Sea Research Part I-Oceanographic Research Papers, 54*(6), 951-974. doi:10.1016/j.dsr.2007.02.007

Rykaczewski, R. R., & Checkley, D. M. (2008). Influence of ocean winds on the pelagic ecosystem in upwelling regions. *Proceedings of the National Academy of Sciences of the United States of America, 105*(6), 1965-1970. doi:10.1073/pnas.0711777105

Song, H., Miller, A. J., McClatchie, S., Weber, E. D., Nieto, K. M., & Checkley, D. M. (2012). Application of a data-assimilation model to variability of Pacific sardine spawning and survivor habitats with ENSO in the California Current System. *Journal of Geophysical Research-Oceans, 117*. doi:10.1029/2011jc007302

Strub, P. T., & James, C. (2000). Altimeter-derived variability of surface velocities in the California Current System: 2. Seasonal circulation and eddy statistics. *Deep-Sea Research Part Ii-Topical Studies in Oceanography, 47*(5-6), 831-870. doi:10.1016/s0967-0645(99)00129-0

Stukel, M. R., Ohman, M. D., Benitez-Nelson, C. R., & Landry, M. R. (2013). Contributions of mesozooplankton to vertical carbon export in a coastal upwelling system. *Marine Ecology Progress Series, 491*, 47-+. doi:10.3354/meps10453

Teeter, L., Hamme, R. C., Ianson, D., & Bianucci, L. (2018). Accurate Estimation of Net Community Production From O2/Ar Measurements. *Global Biogeochemical Cycles, 0*(0). doi:doi:10.1029/2017GB005874

Thomas, B. R., Kent, E. C., & Swail, V. R. (2005). Methods to homogenize wind speeds from ships and buoys. *International Journal of Climatology, 25*(7), 979-995. doi:10.1002/joc.1176

Tortell, P. D. (2005). Dissolved gas measurements in oceanic waters made by membrane inlet mass spectrometry. *Limnology and Oceanography: Methods, 3*(1), 24-37. doi:10.4319/lom.2005.3.24

Tortell, P. D., Asher, E. C., Ducklow, H. W., Goldman, J. A. L., Dacey, J. W. H., Grzymski, J. J., . . . Morel, F. M. M. (2014). Metabolic balance of coastal Antarctic waters revealed by autonomous pCO(2) and Delta O-2/Ar measurements. *Geophysical Research Letters, 41*(19), 6803-6810. doi:10.1002/2014gl061266

Ulfsbo, A., Cassar, N., Korhonen, M., van Heuven, S., Hoppema, M., Kattner, G., & Anderson, L. G. (2014). Late summernet community production in the central Arctic Ocean using multiple approaches. *Global Biogeochemical Cycles, 28*(10), 1129-1148. doi:10.1002/2014gb004833

Wang, S., Lin, Y., Gifford, S., Eveleth, R., & Cassar, N. (2018). Linking patterns of net community production and marine microbial community structure in the western North Atlantic. *The ISME Journal*. doi:10.1038/s41396-018-0163-4

Wanninkhof, R. (2014). Relationship between wind speed and gas exchange over the ocean revisited. *Limnology and Oceanography: Methods, 12*(6), 351-362. doi:10.4319/lom.2014.12.351

White, A. E., Barone, B., Letelier, R. M., & Karl, D. M. (2017). Productivity diagnosed from the diel cycle of particulate carbon in the North Pacific Subtropical Gyre. *Geophysical Research Letters, 44*(8), 3752-3760. doi:10.1002/2016gl071607

Williams et al, P. J. L. (1989). Group report: Export productivity from the photic zone. In W. H. Berger, V. Smetacek, & G. Wefer (Eds.), *Productivity of the Ocean: Present and Past* (pp. 99-115). Hoboken, N.J.: John Wiley and Sons.

**Table 1: Basic metadata for Lagrangian observations conducted in 2016 and 2017.** Lat/Lon coordinates, date, and time are given as the starting values for each cycle.Parameters are listed as mean cycle values, with values in parentheses indicating standard deviations.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Cycle | Latitude (N) | Longitude (E) | Date/Time (PST) | O2 residence time (d) | Temp (°C) | MLD (m) | Chl-a (µg/L) |
| P1604-2 | 33.59 | -122.22 | 28.Apr.2016 21:07 | 16.2 (1.2) | 15.4 (0.1) | 70 (4) | 0.1 (0.0) |
| P1604-3 | 34.77 | -121.29 | 02.May.2016 23:47 | 6.8 (0.7) | 14.0 (0.3) | 17 (0) | 1.1 (0.2) |
| P1604-4 | 34.50 | -120.79 | 07.May.2016 21:23 | 9.8 (0.4) | 14.8 (0.3) | 14 (1) | 4.1 (0.8) |
| P1706-1 | 35.07 | -121.09 | 09.Jun.2017 01:29 | 9.0 (1.0) | 13.3 (0.3) | 20 (6) | 9.3 (2.7) |
| P1706-2 | 34.73 | -121.71 | 13.Jun.2017 02:55 | 4.4 (0.7) | 13.2 (0.2) | 27 (1) | 3.1 (1.0) |
| P1706-3 | 34.38 | -123.17 | 18.Jun.2017 01:46 | 2.9 (0.8) | 15.2 (0.6) | 18 (4) | 0.6 (0.5) |
| P1706-4 | 34.40 | -123.07 | 23.Jun.2017 01:50 | 4.7 (0.6) | 15.7 (0.5) | 12 (0) | 0.2 (0.1) |

**Table 2: Statistics for community production rates, vertical flux magnitudes, oxygen gradients, and regression-derived slopes in ΔO2/Ar and NCP for each cycle.** Values in parentheses indicate standard deviations. All units are in mmol O2 m-2 d-1 unless otherwise stated. Positive values for Fv, Fe, or Fadv indicate contributions of oxygen-undersaturated waters from below, while negative values denote upwards introduction of supersaturated waters.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Cycle | Mean NCPprior | Mean NCPRT | Range of NCPRT | Mean Fv | Mean Fe | Mean Fadv | Range of  Fadv | O2 gradient (mmol O2 m-4) | Slope in ΔO2/Ar  (% d-1) | Slope in NCPprior  (mmol O2 m-2 d-2) |
| P1604-2 | 7±5 (1) | -3±7 (6) | -11 to 6 | 0 (1) | -1 (1) | -32 (108) | -302 to 153 | 0.1 (0.2) | -0.06 | -1 |
| P1604-3 | -2±2 (13) | 84±29 (4) | 73 to 91 | 1 (0) | 0 (0) | 44 (20) | 2 to 76 | -0.6 (0.2) | 1.95 | 13 |
| P1604-4 | 47±11 (13) | -15±35 (11) | -36 to 6 | 7 (0) | 2 (0) | 781 (556) | 60 to 2252 | -4.9 (0.3) | -1.00 | -4 |
| P1706-1 | 68±16 (26) | -60±85 (65) | -229 to 104 | 6 (1) | 96 (7) | 1085 (567) | 205 to 2580 | -4.2 (0.1) | -3.13 | 0 |
| P1706-2 | -22±9 (24) | -72±25 (33) | -128 to 66 | 22 (4) | 2 (0) | 745 (136) | 536 to 954 | -4.2 (0.5) | -0.63 | -13 |
| P1706-3 | -11±7 (12) | -26±12 (15) | -55 to 3 | 0 (0) | -1 (0) | -14 (9) | -32 to -4 | 0.1 (0.1) | -0.32 | -5 |
| P1706-4 | -1±2 (4) | 14±9 (1) | 10 to 16 | 1 (0) | 0 (0) | 48 (23) | -65 to -12 | -0.9 (0.3) | 0.45 | 3 |

**Table 3: calculated mean diel range of diel cycles in ΔO2/Ar and NCPprior observed during each cycle alongside mean volumetric and integrated Chl-*a*.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Δ O2/Ar range (%) | NCP range (mmol O2 m-2 d-1) | Chl-a (µg/L) | MLD-integrated Chl-a (mg/m2) |
| P1604-2 | 0.3 | 3 | 0.1 (0.0) | 10 |
| P1604-3 | 3.9 | 26 | 1.1 (0.2) | 17 |
| P1604-4 | 11.4 | 40 | 4.1 (0.8) | 50 |
| P1706-1 | 15.4 | 100 | 9.3 (2.7) | 160 |
| P1706-2 | 4.3 | 67 | 3.1 (1.0) | 76 |
| P1706-3 | 1.4 | 24 | 0.6 (0.5) | 11 |
| P1706-4 | 2.1 | 13 | 0.2 (0.1) | 3 |

Figure 1: Map of cruise tracks during Lagrangian deployments in spring 2016 and summer 2017 within the California Current Ecosystem. White lines indicate observations in 2016. Red lines denote cycle locations in 2017. Colored dots mark the starting location for each cycle. Numbering indicates chronological order of cycles in 2016 and 2017. Background blue color scale indicates regional bathymetry.

Figure 2: Conceptual diagram illustrating underlying assumptions behind three models for O2/Ar-derived NCP: NCPprior, NCPRT, and NCPRT\_Vflux.

Figure 3: NCPprior measured for each Lagrangian cycle (black points). The line of best fit for each cycle’s NCP data, derived from a linear regression against a subset of the cycle data beginning and ending at the same local time of day, is shown in red. Shaded sections of background indicate nighttime periods.

Figure 4:Time series of ΔO2/Ar observations for each cycle (black). The line of best fit for each cycle’s ΔO2/Ar data, derived from a linear regression against a subset of the cycle data beginning and ending at the same local time of day, is shown in red. Shaded sections of background indicate nighttime periods.

Figure 5:NCPprior measured for each Lagrangian cycle and detrended using the linear fits previously obtained (black). The curves corresponding to the Fourier series functions chosen to fit the diel pattern in the NCP data are shown in red. Shaded sections of background indicate nighttime periods.

Figure 6: Time series of a) NCPprior and b) ΔO2/Ar saturation anomaly for Cycles 2017 #2 and #4. Red line segments illustrate best-fit linear regression lines and trends for each multi-day series of observations.