

Including high frequency variability in coastal ocean acidification projections

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This discussion paper is/has been under review for the journal Biogeosciences (BG).
Please refer to the corresponding final paper in BG if available.

Including high frequency variability in coastal ocean acidification projections

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Received: 15 April 2015 – Accepted: 24 April 2015 – Published: 13 May 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Assessing the impacts of anthropogenic ocean acidification requires knowledge of present-day and future environmental conditions. Here, we present a simple model for upwelling margins that projects anthropogenic acidification trajectories by combining high-temporal resolution sensor data, hydrographic surveys for source water characterization, empirical relationships of the CO₂ system, and the atmospheric CO₂ record. This model characterizes CO₂ variability on timescales ranging from hours (e.g. tidal) to months (e.g. seasonal), bridging a critical knowledge gap in ocean acidification research. The amount of anthropogenic carbon in a given water mass is dependent on the age, therefore a density–age relationship was derived for the study region, and was combined with the 2013 Intergovernmental Panel on Climate Change CO₂ emission scenarios to add density-dependent anthropogenic carbon to the sensor time series. The model was applied to time series from four autonomous pH sensors, each deployed in the surf zone, kelp forest, submarine canyon edge, and shelf break in the upper 100 m of the Southern California Bight. All habitats were within 5 km of one another, and exhibited unique, habitat-specific CO₂ variability signatures and acidification trajectories, *demonstrating the importance of making projections in the context of habitat-specific CO₂ signatures*. In general, both the mean and range of pCO₂ increase in the future, with the greatest increases in both magnitude and range occurring in the deeper habitats due to reduced buffering capacity. On the other hand, the saturation state of aragonite (Ω_{Ar}) decreased in both magnitude and range. This approach can be applied to the entire California Current System, and upwelling margins in general, where sensor and complementary hydrographic data are available.

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1 Introduction

It has become increasingly apparent that upwelling systems, including the California Current System (CCS), are particularly vulnerable to anthropogenic ocean acidification due to their unique physical and chemical traits (Feely et al., 2008, 2010; Gruber et al., 2012; Hauri et al., 2013a, b). Upwelled waters have been isolated from the atmosphere and are naturally elevated in CO_2 from remineralization of organic matter; depending on the age of the upwelled water mass it may also contain anthropogenic carbon (Harris et al., 2013; Sabine et al., 2002). Recent observations estimate the saturation horizon with respect to aragonite (depth at which $\Omega_{\text{Ar}} = 1$) along the CCS has shoaled by approximately 50 m since preindustrial times, and undersaturated waters ($\Omega_{\text{Ar}} < 1$) have been observed at the surface near the California–Oregon border during a strong upwelling event (Alin et al., 2012; Feely et al., 2008; Harris et al., 2013). Furthermore, the rate of acidification (i.e. $\Delta \text{pH yr}^{-1}$) is expected to be significantly higher along upwelling margins than observed in the surface open ocean (Bates et al., 2014; Gruber et al., 2012; Hauri et al., 2013b; Leinweber and Gruber, 2013; Rykaczewski and Dunne, 2010) due to the reduced buffering capacity of seawater at higher levels of CO_2 (Frankignoulle, 1994). This effect has caused parts of the CCS to venture beyond the envelope (defined as: mean $\pm 1\text{SD}$) from modeled preindustrial Ω_{Ar} conditions (Hauri et al., 2013b). This is a concern because organisms may need to survive outside of the environmental conditions to which they are acclimatized, and the evolutionary potential for key ecological species to adapt to such rapid and unprecedented changes is poorly understood. For example, a significant decrease in calcareous benthic organisms was observed along a natural pH gradient near a cold volcanic CO_2 vent (Hall-Spencer et al., 2008; Kroeker et al., 2011). However, some calcareous organisms such as limpets seemed to have adapted to higher CO_2 levels compared to corals and mussels in the same system (Rodolfo-Metalpa et al., 2011). Furthermore for upwelling margins, CO_2 co-varies with other environmental stressors such as temperature and

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O₂ (Reum et al., 2015), making predictions more difficult due to potential non-linear synergistic effects (Frieder et al., 2014).

A critical component in making accurate impact assessments of ocean acidification is the development of robust, ecosystem-specific projections of future CO₂ conditions (Andersson et al., 2013; Cai et al., 2011; Feely et al., 2009, 2010; McNeil and Matear, 2008; Sunda and Cai, 2012). Development of surface, open-ocean acidification projections has been relatively straightforward, as they rely on well-defined chemical principles of CO₂ equilibrium at the air–sea interface (Byrne et al., 2010; Lauvset and Gruber, 2014). Models become more complicated when attempting to resolve biological and physical processes that contribute significantly to the natural variability of the system. For example, biologically mediated “enhanced acidification” was identified in the northern Gulf of Mexico, causing significantly faster rates of acidification than the open ocean (Cai et al., 2011). On many tropical coral reefs, seasonal patterns in CO₂ are minimal, whereas the dominant frequency of variability occurs on diel and tidal frequencies (Hofmann et al., 2011). On upwelling margins, both biological and physical processes contribute to the observed natural variability of carbonate conditions (Fassbender et al., 2011).

One approach to develop region-specific ocean acidification projections is to apply an eddy-resolving regional ocean model system (ROMS) coupled with a biogeochemical component, as has been developed for the CCS (Gruber et al., 2011, 2012; Hauri et al., 2013b). Such models have highlighted the importance of capturing physical and biological processes in highly dynamic upwelling systems. The model simulations show complex spatiotemporal variability (Hauri et al., 2013b), and predict that the frequency of “corrosive” upwelling events will intensify in both magnitude and duration by the year 2050 (Hauri et al., 2013a). However, the eddy-resolving ROMS project *p*CO₂ and saturation state conditions on a 5 km grid, whereas many marine animals experience the environment on the scale of centimeters to meters. In addition, regional models can largely resolve event-scale (weeks) and seasonal features, but cannot capture fluctuations on diel to tidal time scales, which can be the dominant frequency of variability

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in many near-shore environments (Duarte et al., 2013; Frieder et al., 2012; Hofmann et al., 2011). Due to this discrepancy in both space and time, numerical models tend to underestimate or entirely miss the high-frequency variability that exists for the microclimate of organisms.

To transition from region-specific to habitat-specific ocean acidification projections, high temporal resolution data from autonomous chemical sensors deployed across many habitat types can be used to directly quantify the full range of present-day carbonate conditions (Harris et al., 2013; Hofmann et al., 2011, 2014; Martz et al., 2014; Sutton et al., 2014). The CCS supports many ecosystems that are of great ecological and economic value. In particular, there is great habitat and species diversity near-shore on the shelf, which includes a large number of commercially important invertebrates and fishes. Habitats in the region include bays and estuaries, rocky and sandy intertidal, eelgrass beds and kelp forests, sub-tidal reefs, canyons and extensive sandy sea floor. There are many endangered and harvested benthic organisms that inhabit only one or a subset of these habitats.

Sensor data provide key observations for the mechanistic understanding of the controls on environmental conditions, and are particularly needed for coastal marine environments where complex physical and biological processes influence the observed variability. For example, sensor data from a near-shore kelp forest in the southern CCS revealed that local biological feedbacks and episodic upwelling events were the dominant drivers of CO₂ variability, with *p*CO₂ fluctuating by 600 μatm at 17 m water depth (Frieder et al., 2012). This scale of variability associated with near-shore environments is not captured by regional model simulations, but is most relevant for organisms living inside the kelp forest.

Here, we present an anthropogenic ocean acidification model to project CO₂ chemistry into the future by combining autonomous chemical sensor data, regional empirical relationships for the CO₂ system (Alin et al., 2012), hydrographic data, and the atmospheric CO₂ record (Keeling et al., 2005). This model was applied to four habitats ranging from the surface to 100 m water depth and all within 5 km of each other in the

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Southern California Bight (SCB). Each site showed distinct CO₂ variability signatures and acidification trajectories, highlighting the importance of interpreting ocean acidification projections in the context of present and future habitat-specific CO₂ signatures. Implications for future ocean acidification research are discussed.

2 Methods

2.1 Study sites

Moored autonomous sensor packages SeapHOx or SeaFET (Bresnahan et al., 2014) were deployed at four depths (4, 17, 30, and 88 m) within several distinct habitats on the San Diego continental shelf for 1 year starting June 2012 (Fig. 1). All sensors were deployed near the seafloor; the three shallowest sensors were deployed within 3 m of the bottom, and the deepest sensor was moored 12 m above the seafloor (Table 1).

A SeaFET was deployed at the Ellen Browning Scripps Pier 2 m above the benthos as a part of the Scripps Ocean Acidification Real-time Monitoring Program. The sensor was located approximately 400 m from the shore in the surf zone. Weekly discrete samples for total alkalinity (TA) and dissolved inorganic carbon (DIC) were taken alongside the sensors for calibration and quality control following standard protocols (Dickson et al., 2007). The sensor was serviced every 1–2 months to remove biofouling organisms.

The La Jolla kelp forest is part of the South La Jolla State Marine Reserve and is characterized by a dense population of *Macrocystis pyrifera*. The chemical variability in this ecosystem is strongly influenced by regional physical processes (e.g., upwelling and stratification) and local biological feedbacks (e.g., production and respiration). A SeapHOx was deployed at 17 m in the southern portion of the kelp forest, 3 m above the bottom. The reader is referred to Frieder et al. (2012) for further details on site and deployment description.

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The La Jolla canyon is a submarine canyon plunging from approximately 20 m to a depth of 1000 m within several km from shore. A SeapHOx was deployed over a sandy bottom at the southern canyon edge at 30 m depth within the Matlahuayl state marine reserve; the O₂ sensor malfunctioned and thus is not included. The water in the La Jolla canyon is characterized by higher salinity, and lower temperature, O₂, and pH (data not shown). Tidal energy in submarine canyons is significantly amplified (Swart et al., 2011), bringing deep water from the canyon to the canyon edge. Therefore, physical forcings are the dominant drivers for chemical variability at this site (Navarro et al., 2013).

The Del Mar Buoy was first deployed in 2006 at 100 m off of Del Mar in northern San Diego at the shelf break, and has provided continuous time series data (e.g. temperature, salinity, oxygen, and current) at discrete depths (Frieder et al., 2012; Send and Nam, 2012). A SeaFET sensor was deployed on the mooring at 88 m in 2011, and has provided a near-continuous time series of pH since. Co-located sensors include temperature, salinity (SBE 37), and dissolved oxygen (O₂; Aanderaa Optode). Water at this depth is isolated from the atmosphere and below the euphotic zone, and thus influenced primarily by upwelling and tidal dynamics.

2.2 Cruise data

Hydrographic data were collected aboard R/V *Melville* during the student-led San Diego Coastal Expedition cruises in June/July and December of 2012 (Fig. 1). The SCB is characterized by relatively weak (compared to the northern CCS), but nearly year-round upwelling. However, there is a clear seasonal cycle based on climatological data, where upwelling intensifies generally between April and August, with the maximum occurring in May (Bograd et al., 2009). The cruises therefore corresponded with upwelling (June/July) and non-upwelling (December) seasons. Water samples were collected at stations ranging from > 100 km from shore at 1200 m water depth, to within 5 km from shore at 30 m depth. Discrete samples were analyzed for O₂, pH, and DIC; duplicate samples were collected during every cast.

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Discrete samples for O_2 were collected and analyzed by titration using a custom-built system (Martz et al., 2012). The titrant was standardized prior to and after each cruise using KIO_3 standard solutions prepared in house (Fisher, lot 105595); no detectable drift was observed for either cruise. Precision was $\pm 0.6 \mu\text{mol kg}^{-1}$ (duplicate $n = 62$, 1 SD), and the accuracy was estimated to be $\pm 0.5\%$ because KIO_3 standards were not recrystallized (Emerson, 1999).

Samples for DIC and pH were collected in 150 or 250 mL Pyrex serum bottles (13 mm neck) following standard procedures (Dickson et al., 2007). However, rather than leaving headspace, the bottle was filled completely, and a gray butyl stopper was inserted to prevent gas exchange and samples were analyzed within 4 h of collection.

DIC samples were analyzed using custom-built system based on an infrared analyzer (LI-COR 7000) similar to systems built by others (Friederich et al., 2002; O'Sullivan and Millero, 1998). The DIC measurements were calibrated using Certified Reference Materials provided by the Dickson Lab at SIO, by applying a gain correction (slope) and assuming an offset of zero (intercept). The reference materials were stored in CO_2 impermeable bags (3 L Scholle DuraShield[®]), and were measured frequently throughout the cruise. The stability of the reference material in the bag was verified by daily measurements of a new bottle; no drift was observed. Precision and accuracy of the DIC measurements were $\pm 2.5 \mu\text{mol kg}^{-1}$ (duplicate $n = 67$, 1 SD).

Samples for pH were analyzed spectrophotometrically at 20°C (Clayton and Byrne, 1993) using an automated system (Carter et al., 2013). The pH is reported on the total hydrogen ion concentration scale. The indicator dye (m-cresol purple, ACROS Lot A0264321) was used as received from the manufacturer without further purification. An offset was applied based on measurements in certified Tris buffer provided by the Dickson Lab. The precision and accuracy of the measurements were estimated to be ± 0.0015 (duplicate $n = 86$, 1 SD) and ± 0.02 (Liu et al., 2011), respectively. TA and pCO_2 were calculated using CO2SYS (van Heuven et al., 2011) using pH and DIC as inputs, and carbonic acid dissociation constants from Mehrbach et al. (1973) refit by Lueker et al. (2000).

2.3 Sensor data

The SeapHOx and SeaFET sensor packages utilize a modified Honeywell Durafet III pH combination electrode for high-frequency pH measurements (Martz et al., 2010). These sensor packages have been successfully deployed in ecosystems worldwide (Frieder et al., 2012; Hofmann et al., 2011; Kroeker et al., 2011; Martz et al., 2014; Price et al., 2012), and have been shown to have excellent stability in seawater for months to years (Bresnahan et al., 2014). The SeapHOx is an integrated sensor package that also consists of an Aanderaa 3835 oxygen optode, and a Seabird SBE 37 Conductivity–Temperature sensor all plumbed into a pumped flow stream; the SeaFET measures pH using a passively flushed cell. Sampling frequencies were 1 h^{-1} or greater at all depths.

All pH measurements were calibrated based on discrete TA and DIC samples taken alongside the sensor ($n > 4$ for every site) (Bresnahan et al., 2014). The resolution of the pH measurements is better than 0.0005 pH , stability is estimated to be better than 0.005 , and accuracy is estimated to be ± 0.15 . Sensors were removed periodically for maintenance, but all were deployed for > 50 days during both the upwelling and relaxation season.

At the surf zone (surface waters), a constant TA value of $2240 \mu\text{mol kg}^{-1}$ was assumed, since discrete TA samples showed low variability (2240 ± 7 (1 SD) $\mu\text{mol kg}^{-1}$, $n = 57$). For the three subsurface sensors, TA was estimated (TA^{est}) using a regional empirical relationship (Alin et al., 2012). An offset of $+8 \mu\text{mol kg}^{-1}$ was applied to TA^{est} based on discrete samples to account for a regional surface TA influence that is not incorporated in the empirical relationship developed for the whole CCS (RMSE = $6 \mu\text{mol kg}^{-1}$, $n = 25$). DIC, $p\text{CO}_2$, and Ω_{Ar} were calculated using CO2SYS (van Heuven et al., 2011) using pH sensor data and TA^{est} as inputs. Uncertainty for the calculated DIC, $p\text{CO}_2$, and Ω_{Ar} is pH-dependent, but on average is estimated to be $\pm 13 \mu\text{mol kg}^{-1}$, $\pm 25 \mu\text{atm}$, and ± 0.04 , respectively. Daily range of sensor data was calculated by first high-pass filtering the data with a 36 h window, and then taking the

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difference between the daily maximum and minimum. The mean daily range was then calculated by averaging the resultant time series.

2.4 Modelling future carbonate chemistry

2.4.1 Approach

5 The carbonate conditions were modeled by decreasing or increasing DIC while using TA conditions from 2012. Modeled projections were made for preindustrial times and for year t , where t ranges between 2012 and 2100. The model presented here is based on the ΔC_t^* approach (Gruber et al., 1996), but instead of using tracers to estimate the age of the water mass (e.g. CFC's), we used the atmospheric CO₂ record as
10 a quasi-age tracer. The age of the water mass ranged between 0 and 50 years in this study region. Although this approach must be used with caution, we demonstrate that our estimates are in good agreement with previously published anthropogenic carbon inventory estimates using age tracer measurements in this region (Feely et al., 2008; Sabine et al., 2002). In this model, it was assumed that ocean acidification is due to
15 anthropogenic CO₂ invasion through the air–sea interface alone. We also assumed that both the path of a particular water mass between the subduction and upwelling site and the rate of remineralization processes remain unchanged. Sensitivity to these assumptions is explored in the Discussion.

The DIC of the modeled year t (DIC _{t}) is calculated by

$$20 \text{ DIC}_t = \text{DIC}_{2012} + \Delta \text{DIC}_{\text{anth}} \quad (1)$$

where DIC₂₀₁₂ is the DIC observed in 2012, and $\Delta \text{DIC}_{\text{anth}}$ is the additional anthropogenic CO₂ that the water mass would have absorbed since 2012. Different formulations for $\Delta \text{DIC}_{\text{anth}}$ were used for surface waters (i.e., above the seasonal mixed layer depth, defined here as $\sigma_\theta \leq 25.2 \text{ kg m}^{-3}$) and subsurface waters ($\sigma_\theta > 25.2 \text{ kg m}^{-3}$),
25 and are outlined below.

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For surface waters, $\Delta\text{DIC}_{\text{anth}}$ was calculated as the difference in surface DIC between year t and 2012. Surface DIC was calculated by assuming atmospheric equilibrium with $\text{TA} = 2240 \mu\text{mol kg}^{-1}$ (based on water samples from the Scripps pier) and using $p\text{CO}_{2,\text{atm}}$ projection under the 2013 IPCC RCP6. scenario (Hijioka et al., 2008).

Although large deviations from equilibrium conditions are often observed in the coastal ocean due to upwelling and biological production (Hales et al., 2005), the mean $p\text{CO}_2$ calculated from sensor data at the surf zone was $394 \mu\text{atm}$, suggesting that the surface water at the study site was near atmospheric equilibrium.

For subsurface waters, $\Delta\text{DIC}_{\text{anth}}$ was quantified as the increase in DIC due to anthropogenic CO_2 when the water parcel was last in contact with the atmosphere. The mass balance of DIC for subsurface waters is:

$$\text{DIC} = \text{DIC}^o + \Delta\text{DIC}_{\text{bio}} \quad (2)$$

where DIC^o is the preformed DIC, and $\Delta\text{DIC}_{\text{bio}}$ is the DIC added by remineralization processes in the ocean interior. DIC^o can be expressed as the sum of DIC if it were in equilibrium with the atmosphere (DIC_{eq}) and the degree of air–sea disequilibrium due to slow gas exchange kinetics and biological processes ($\Delta\text{DIC}_{\text{diseq}}$):

$$\text{DIC}^o = \text{DIC}_{\text{eq}} + \Delta\text{DIC}_{\text{diseq}} \quad (3)$$

Since anthropogenic CO_2 only enters the ocean at the surface, the increase in DIC_{eq} represents the anthropogenic ocean acidification signal, $\Delta\text{DIC}_{\text{anth}}$, assuming $\Delta\text{DIC}_{\text{diseq}}$ is invariant with time. However, in order to use this approach, the age of the water parcel must first be quantified, as this determines the $p\text{CO}_{2,\text{atm}}$ with which it was last in contact.

The age of the water parcel was established by combining Eqs. (2) and (3):

$$\text{DIC}_{\text{eq}}^{2012-\text{age}} = \text{DIC} - \Delta\text{DIC}_{\text{bio}} - \Delta\text{DIC}_{\text{diseq}} \quad (4)$$

where the superscript denotes the year at which the water parcel was last at the surface (i.e. equal to $2012 - \text{age}$ of the water mass). The age of the water mass was

calculated by comparing the atmospheric CO₂ record to the $p\text{CO}_{2,\text{atm}}$ that is necessary to generate $\text{DIC}_{\text{eq}}^{2012-\text{age}}$. $\Delta\text{DIC}_{\text{diseq}}$ was estimated from published values in the region (Sect. 2.4.3). Using this information, we calculated $\Delta\text{DIC}_{\text{anth}}$ by:

$$\Delta\text{DIC}_{\text{anth}} = \text{DIC}_{\text{eq}}^{t-\text{age}} - \text{DIC}_{\text{eq}}^{2012-\text{age}} \quad (5)$$

where the superscripts denote the year at which the water parcel was last at the surface, and age is the age of the water parcel. For example, if age = 30 yr and $t = 2050$, then CO₂ projections for the year 2020, would be used to calculate $\text{DIC}_{\text{eq}}^{t-\text{age}}$; $\text{DIC}_{\text{eq}}^{2012-\text{age}}$ was calculated from Eq. (4). The $\Delta\text{DIC}_{\text{anth}}$ for subsurface waters was modeled for each projection year as a linear function of σ_θ , and the surface and subsurface $\Delta\text{DIC}_{\text{anth}}$ were connected assuming a two end member linear mixing between σ_θ 25.2 and 25.5 kg m⁻³ to prevent step changes (Fig. 2).

2.4.2 Calculation of $\Delta\text{DIC}_{\text{bio}}$

$\Delta\text{DIC}_{\text{bio}}$ was quantified following formulations in Sabine et al. (2002):

$$\Delta\text{DIC}_{\text{bio}} = r_{\text{C:O}}(\text{AOU}) - 0.5 (\text{TA}_{\text{obs}} - \text{TA}^0 + r_{\text{N:O}}(\text{AOU})) \quad (6)$$

where AOU = Apparent Oxygen Utilization = ($\text{O}_{2,\text{sat}} - \text{O}_{2,\text{obs}}$), TA^0 is the preformed alkalinity, and the r 's are the elemental remineralization ratios (Anderson and Sarmiento, 1994). The oxygen saturation concentration ($\text{O}_{2,\text{sat}}$) was calculated using the equations in Garcia and Gordon (1992), and TA^0 was estimated based on historical near-surface TA data in the Pacific (Eq. 3 in Sabine et al., 2002). Phosphate concentrations necessary to estimate TA^0 were not directly measured, but were estimated from a regional empirical relationship using historical data (Supplement); the uncertainty in estimating phosphate using this approach propagates to an error in TA^0 of 4 $\mu\text{mol kg}^{-1}$.

2.4.3 Estimation of $\Delta\text{DIC}_{\text{diseq}}$

Making accurate estimates of $\Delta\text{DIC}_{\text{diseq}}$ is important because it is a source of large uncertainty for anthropogenic carbon inventory calculations (Matsumoto and Gruber, 2005). Traditionally, age of the water mass is quantified using tracers such as CFCs and then the $\Delta\text{DIC}_{\text{diseq}}$ is subsequently calculated (Gruber et al., 1996; Sabine and Tanhua, 2010). However, such tracer measurements were not made for this study. Alternatively, we estimated $\Delta\text{DIC}_{\text{diseq}}$ based on θ and S data to overcome this limitation (Sabine et al., 2002). The mean θ and S between σ_θ of 25.5 and 26.5 kg m^{-3} were 10.0 °C and 33.9, respectively, resembling water type 1e in Sabine et al. (2010) with a corresponding $\Delta\text{DIC}_{\text{diseq}} = -6.24 \mu\text{mol kg}^{-1}$, the value used in this study.

2.4.4 Calculation of the age of water parcel

In order to estimate the age of the water mass, we use Eq. (4) to calculate $\text{DIC}_{\text{eq}}^{2012-\text{age}}$, the DIC of the water parcel was in equilibrium with the atmosphere when it was last at the surface (i.e. equal to 2012 – age of the water mass). Therefore the age of the water mass can be calculated by comparing the atmospheric CO_2 record to the $p\text{CO}_{2,\text{atm}}$ that is necessary to generate $\text{DIC}_{\text{eq}}^{2012-\text{age}}$. The latter was calculated from the fugacity of CO_2 of the water mass when it was last in contact with the atmosphere at the time of subduction ($f\text{CO}_{2,\text{eq}}^{2012-\text{age}}$), assuming 100% relative humidity, and barometric pressure of 1 atm (Dickson, 2007). The year that the water parcel subducted was determined by matching the calculated $\text{CO}_{2,\text{atm}}$ to the mean annual $\text{CO}_{2,\text{atm}}$ record (Keeling et al., 2005); the age is the difference between 2012 and the calculated year (Fig. 3). A relationship between σ_θ and the age was established by fitting a second order polynomial to the subsurface data ($n = 186$, $R^2 = 0.92$), and assuming the age of the surface water ($\sigma_\theta < 25.2$) is 0 (Fig. 3). The non-zero age of the water that appears around $\sigma_\theta = 24.4 \text{ kg m}^{-3}$ corresponds to the shallow oxygen maximum layer that formed during the summer. However, since this density range is still shallower than the seasonal

mixed layer, its age was considered to be 0. The age of the water ranged between 0 and 50 years between σ_θ of 25.2 and 26.5 kg m⁻³.

2.4.5 Estimation of preindustrial DIC

In order to calculate the preindustrial DIC, Eq. (3) is written as:

$$5 \quad \text{DIC}^o = \text{DIC}_{\text{eq}}^{\text{prein}} + \text{DIC}_{\text{anth}} + \Delta\text{DIC}_{\text{diseq}} \quad (7)$$

where DIC_{anth} represents the anthropogenic carbon present in the water parcel in 2012, and $\text{DIC}_{\text{eq}}^{\text{prein}}$ is the DIC of the water parcel if it were in equilibrium with $p\text{CO}_{2,\text{atm}} = 280 \mu\text{atm}$. Combining Eqs. (2) and (7) and rearranging gives

$$\text{DIC}_{\text{anth}} = \text{DIC} - \Delta\text{DIC}_{\text{bio}} - \text{DIC}_{\text{eq}}^{\text{prein}} + \Delta\text{DIC}_{\text{diseq}} \quad (8)$$

10 Calculated DIC_{anth} as a function of σ_θ is shown in Fig. 4. Note that the values calculated here are in good agreement with published values using age tracers (Feely et al., 2008; Sabine et al., 2002) for higher σ_θ , but are significantly higher at lower densities. This is because the literature values were quantified using offshore subsurface waters, whereas our study region is near the coast along an upwelling margin, where subsurface waters are brought near the surface and are thus affected by surface processes. The agreement at higher density where surface influence is minimal demonstrates that the model presented here is capable of making accurate estimates of anthropogenic CO_2 . Furthermore, the comparison illustrates the importance of incorporating surface influence when making acidification projections in shallow, coastal ecosystems. Preindustrial DIC ($\text{DIC}_{\text{prein}}$) was calculated by subtracting DIC_{anth} from DIC observed in 2012. Preindustrial $p\text{CO}_2$, Ω_{Ar} , and pH were calculated using $\text{DIC}_{\text{prein}}$ and TA conditions from 2012.

3 Results

3.1 Carbonate chemistry variability observed in 2012

The results are presented using pH, $p\text{CO}_2$, or Ω_{Ar} , since pH was directly measured, and $p\text{CO}_2$ and Ω_{Ar} are commonly used as stress indicators for respiration (Brewer and Peltzer, 2009) and calcification (Langdon et al., 2010), respectively. Across all four sites in 2012, $p\text{CO}_2$ increased with depth. In 2012, the mean $p\text{CO}_2$ in the surf zone was near atmospheric equilibrium ($394 \mu\text{atm}$), while the mean $p\text{CO}_2$ at 88 m was $878 \mu\text{atm}$ (Table 2), and reached a maximum of $1270 \mu\text{atm}$. The variability of $p\text{CO}_2$ also increased with depth (indicated by the SD of the time series), which was only $43 \mu\text{atm}$ in the surf zone, but was $149 \mu\text{atm}$ at 88 m depth. The mean (± 1 SD) Ω_{Ar} decreased with depth; the mean Ω_{Ar} in the surf zone was 2.4 ± 0.25 , where it was 1.5 ± 0.18 at 88 m. Undersaturated conditions ($\Omega_{\text{Ar}} < 1$) were observed 48% of the time at 88 m in 2012, but were not observed at other sites. However, unlike $p\text{CO}_2$, the variability of Ω_{Ar} , indicated by the SD, decreased with depth (Table 2; see Discussion). The mean pH decreased with depth; the mean pH in the surfzone was 8.05, where it was 7.73 at 88 m. The variability in pH increased with depth until 30 m, but decreased at 88 m (Table 2).

Distinct, habitat-specific signatures were observed at the four deployment sites (Figs. 5–7). In the surf zone, the conditions were near atmospheric equilibrium, with intrusions of higher $p\text{CO}_2$ waters through internal tidal bores, a common feature observed in shallow, upwelling environments (Booth et al., 2012; Pineda, 1991). This leads to a high, mean daily range of CO_2 conditions (Table 3). However, the signature from the internal bores usually only lasted several hours, and remained at near atmospheric equilibrium for the large majority of the time. Higher occurrence of tidal bores were observed during the spring and summer months relative to winter (Fig. 5), consistent with previous observations (Pineda, 1991).

The mean (\pm SD) CO_2 conditions in the kelp forest and the canyon edge were similar, and the SD for Ω_{Ar} and pH were the highest among the sites (Table 2). However, the

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timescales of the variability were different, indicating that distinct processes control the CO_2 conditions in these two habitats. For example, the mean daily range for all the variables was significantly higher at the canyon edge compared to the kelp forest (Table 3). Submarine canyons are known to amplify tidal energy (Navarro et al., 2013; Swart et al., 2011), and in fact, periodic variability at the canyon edge occurred on semi-diurnal and diurnal cycles, indicative of tidal forcing. On the other hand, while tidal forcings and daily biological production are drivers for carbonate chemistry in the La Jolla kelp forest, the largest variability occurred on event time scales (Frieder et al., 2012); event time scales are defined as longer than a day, but shorter than several weeks. For example, pH, $p\text{CO}_2$, and Ω_{Ar} regularly changed by up to 0.3, 250 μatm , and 1.3 on event time scales, more than three times the mean daily range. Variability on event time scales is due to a combination of changing water mass, stratification, and biological respiration (Frieder et al., 2012). In addition, a clear seasonal pattern was observed at the canyon edge, where higher $p\text{CO}_2$ and lower pH and Ω_{Ar} were observed during the spring and summer months (upwelling season) and lower $p\text{CO}_2$ and higher pH and Ω_{Ar} were observed during the fall and winter (relaxation season). Due to incomplete data coverage, a seasonal trend at the kelp forest and pier sites could not be discerned. The largest seasonal change among the four sites for Ω_{Ar} (~ 1) was observed at the canyon edge; $p\text{CO}_2$ differed by roughly 200–300 μatm between the two seasons.

The shelf break experienced the highest mean CO_2 conditions, and the highest and lowest SD for $p\text{CO}_2$ and Ω_{Ar} , respectively (Table 2); the SD of pH was lower than the kelp forest or the canyon edge. Variability on tidal, event, and seasonal time scales were observed at this site (Figs. 5–7), as has been previously reported for oxygen (Send and Nam, 2012). In general, upwelling on event time scales led to greater changes in $p\text{CO}_2$ and pH than on tidal frequencies (Figs. 5 and 6). The largest variability for all parameters occurred between the seasons, where a change in $p\text{CO}_2$, pH, and Ω_{Ar} were approximately 350 μatm , 0.2, and 0.5, respectively. The close proximity of these

four sites demonstrates the wide variety of habitat-specific CO₂ signatures that exist over a small spatial scale, especially in near shore environments.

3.2 Modeled carbonate chemistry

Each habitat showed distinct trends in both modeled mean and variability of $p\text{CO}_2$, pH, and Ω_{Ar} owing to increased levels of anthropogenic DIC ($\Delta\text{DIC}_{\text{anth}}$) (Table 2). For example, the mean $p\text{CO}_2$ at the surf zone (4 m), canyon edge (30 m), and shelf break (88 m) increased by 225, 435, and 738 μatm , respectively, from 2012 to 2100; this drastic difference in increased mean $p\text{CO}_2$ is driven by different buffer factors between the sites. The increase in variability (i.e. SD) was also larger at 88 m compared to the surf zone, although the largest increase occurred at the canyon edge at 30 m (Table 2). Similar trends were observed for mean pH, where the largest mean decrease in pH occurred at 88 m water depth (0.26). However, the SD increased into the future for the three shallowest sites, whereas the SD decreased at the shelf break (88 m). In contrast, the largest decrease in the mean Ω_{Ar} occurred at the surface relative to the deeper sites, whereas the decrease in range was equivalent across all depths.

The measured and modeled time series for $p\text{CO}_2$ and Ω_{Ar} at the shelf break for the year 2012 and 2100 are shown in Figs. 8 and 9. The variability of $p\text{CO}_2$ increases on both seasonal and tidal time scales; the seasonal amplitude increases from approximately 350 to 650 μatm and the mean daily range increases from 110 to 325 μatm by 2100. This greater variability is in addition to an increase in mean $p\text{CO}_2$ of > 700 μatm . On the other hand, the variability of Ω_{Ar} on both seasonal and shorter time scales decreases. Furthermore, the shelf break is projected to experience undersaturated waters over 90 % of the time by 2060, compared to 48 % in 2012.

Preindustrial $p\text{CO}_2$ and Ω_{Ar} were compared to conditions observed in 2012 (Table 2). At most sites, the observed $p\text{CO}_2$, pH, and Ω_{Ar} in 2012 were already outside of their preindustrial variability envelopes (defined as mean ± 1 SD), which is consistent with results from a previous ROMS simulation in the CCS (Hauri et al., 2013b). These results suggest that all habitats studied here have left, or are about to leave, the $p\text{CO}_2$,

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pH, and Ω_{Ar} conditions that were experienced during preindustrial times. This is significant as organisms at these sites are now surviving in conditions that are significantly different than the conditions under which their ancestors evolved.

The modeled habitat-specific pCO_2 and Ω_{Ar} conditions for preindustrial, 2012, 2060, and 2100 are shown in Fig. 10. The histograms represent the full range of carbonate conditions at each habitat that was captured by the sensors, which includes both the seasonal and high-frequency variability. The shape of each distribution skews towards more “corrosive” conditions at all sites as the model steps forward into the future. This translates to not only increases in mean pCO_2 , but also greater extremes and amount of time spent in extremes.

The projected pCO_2 and Ω_{Ar} envelopes (mean \pm SD) at each habitat throughout the modeled period are shown in Fig. 11. An increasing rate of change in pCO_2 ($\Delta pCO_2 yr^{-1}$) is observed, whereas Ω_{Ar} tends to decrease at a relatively constant rate. The rate of increase of pCO_2 is higher than the projected atmospheric CO_2 increase at all subsurface sites. This indicates that as ocean acidification progresses, the effects due to elevated pCO_2 are more likely to become exacerbated with increasing depth. Mean Ω_{Ar} is projected to be < 1 at the shelf break by 2020, and leave the 2012 variability envelope around 2070.

4 Discussion

4.1 Changes in the buffer factors

The general patterns of the acidification trajectories presented here can be explained by changing buffer factors of seawater, as deeper sites are more strongly influenced by CO_2 rich upwelled waters. The buffer factors Π_{pCO_2} , Π_{pH} , and Π_{CO_3} , are defined as

$$\Pi_{pCO_2} = \frac{\partial pCO_2}{\partial DIC}, \quad \Pi_{pH} = \frac{\partial pH}{\partial DIC}, \quad \Pi_{CO_3} = \frac{\partial CO_3^{2-}}{\partial DIC} \quad (9)$$

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representing the change in each carbonate parameter with respect to a change in DIC (Frankignoulle, 1994). The effect of temperature on Π is small ($< 10\%$) between $0\text{--}15^\circ\text{C}$ for the DIC and TA values observed here, thus subsequent values were calculated assuming a temperature of 10°C , $\text{TA} = 2240\ \mu\text{mol kg}^{-1}$, and salinity = 33.5 (Fig. 12). The ability for seawater to buffer changes in $p\text{CO}_2$ diminishes under higher concentrations of DIC. For example, $\Pi_{p\text{CO}_2}$ increases from 1.6 to 3.3 at the surface between 2012 and 2100 under the RCP6.0 scenario. However, since deeper waters are naturally elevated in DIC, this effect is more pronounced at the shelf break: $\Pi_{p\text{CO}_2}$ increases from 6.2 to 12.3 during the same time interval. This explains why the surf zone had the lowest mean increase in $p\text{CO}_2$ ($225\ \mu\text{atm}$) despite having the highest increase in DIC ($82\ \mu\text{mol kg}^{-1}$) out of all of the sites. The shelf break on the other hand had the highest increase in $p\text{CO}_2$ ($737\ \mu\text{atm}$) while having the smallest increase in mean DIC ($77\ \mu\text{mol kg}^{-1}$) during the same time period. Furthermore, the increase in variability with depth can be explained as well, as the same biological and physical forcings on tidal to seasonal cycles cause a larger change in $p\text{CO}_2$.

Changes in Π_{CO_3} can explain the patterns for Ω_{Ar} , since $[\text{Ca}^{2+}]$ and K_{SP} remain unchanged. Unlike $\Pi_{p\text{CO}_2}$, $|\Pi_{\text{CO}_3}|$ decreases at higher concentrations of DIC (Fig. 12b); $|\Pi_{\text{CO}_3}|$ decreases from 0.62 to 0.57 at the surface, and 0.49 to 0.3 at 88 m between 2012 and 2100. This change in Π_{CO_3} explains both the decrease in rate and range of Ω_{Ar} as anthropogenic CO_2 continues to infiltrate the ocean.

The Π_{pH} follows a parabolic shape, where there is a maximum decrease in pH per DIC added (Fig. 12c). In a pure carbonate solution, this maximum occurs when $\text{DIC} = \text{TA}$, but in seawater it occurs at slightly lower DIC (Frankignoulle, 1994); this maxima occurs at $\text{DIC} = 2225\ \mu\text{mol kg}^{-1}$ using the parameters listed above. Therefore we would expect to see a similar trend for pH as $p\text{CO}_2$, where greatest changes occur at depth relative to the surface as long as the mean DIC is lower than this threshold. This condition is only met at the shelf break (88 m) near the end of the century, thus as expected greater decrease in mean pH, and increase in variability (i.e. SD) was observed with depth (Table 2). One exception was observed where the SD decreased

as ocean acidification progressed at the shelf break. This is because an increased proportion of time is spent at greater DIC where Π_{pH} is past its maxima, leading to a smaller variability in pH under the same changes in DIC. It is important to note that the buffer factor of H^+ (Π_{H^+}) follows a similar pattern as $p\text{CO}_2$, where it continues to increase as DIC increases (Fig. 12d). Therefore the rate of increase of $[\text{H}^+]$ will continue to increase as ocean acidification progresses, thus biological responses to $[\text{H}^+]$ may become exacerbated in the future.

4.2 Observed and modeled carbonate chemistry variability

The carbonate conditions presented here are consistent with previous studies. For example at the shelf break, Ω_{Ar} had a strong seasonal cycle, where undersaturated waters were observed almost continuously throughout the upwelling season, and remained supersaturated for the rest of the year. This is in good agreement with previous hydrographic surveys in this region, where aragonite-undersaturated waters have been observed as shallow as 60 m during the beginning of the upwelling season (Feely et al., 2008), but were not observed in the upper 100 m at the end of the upwelling season in this region (Bednaršek et al., 2014). Furthermore, estimates based on empirical equations showed a similar seasonal pattern in Ω_{Ar} at 88 m, where undersaturated waters were observed every upwelling season (Alin et al., 2012). However, undersaturated waters were not observed in the upper 30 m, unlike northern parts of the CCS where undersaturated conditions are repeatedly observed at the surface during the upwelling season (Bednaršek et al., 2014; Feely et al., 2008; Harris et al., 2013). Due to these traits, the southern portion of the CCS is commonly considered less vulnerable to ocean acidification compared to its northern counterpart. However, our results demonstrate that Ω_{Ar} as low as 1.3 is routinely observed in the kelp forest (17 m), demonstrating the imminent threat of anthropogenic ocean acidification to the southern CCS.

The subsurface habitats characterized in this study routinely experience Ω_{Ar} conditions that have been shown to have non-lethal chronic effects on various bivalve larvae

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between Ω_{Ar} of 1.2 to 2.0 (Barton et al., 2012; Gaylord et al., 2011; Gazeau et al., 2011; Hettinger et al., 2012; Waldbusser et al., 2015). However, the length of exposure to these unfavorable conditions varies between habitats. For example, the organisms in the kelp forest would be exposed to low Ω_{Ar} conditions for days to weeks, whereas large tidal variability at the canyon edge could result in periodic exposure to low Ω_{Ar} conditions on the order of hours. Therefore the effects of low Ω_{Ar} will largely depend on the reproductive timing and environmental variability that occurs on event to seasonal time scales; the effects of exposure on various timescales are poorly understood. Such events are expected to become more severe in the future (Hauri et al., 2013a), and thus could lead to an increased rate of failed recruitment of bivalves and other keystone organisms (Byrne et al., 2013).

The trajectories are sensitive to the choice of the emission scenario (Fig. 13). Trends are similar at all depths, thus only the mean $p\text{CO}_2$ and Ω_{Ar} projections at the shelf break are shown in Fig. 13. The highest emission scenario (RCP8.5) diverges from the two intermediate scenarios around 2030, while the lowest emission scenario (RCP2.6) diverges around 2050. The two intermediate scenarios (RCP4.5 and RCP6.0) do not diverge significantly until 2070. The delayed response to different atmospheric CO_2 trajectories occurs because upwelled waters have spent several decades since they were last in contact with the atmosphere (Feely et al., 2008). Therefore the anthropogenic ocean acidification trajectory for the Southern California Bight is already determined for the next several decades, and any mitigation due to changing CO_2 emissions will be delayed.

The results presented here are site specific, and do not necessarily reflect conditions at all kelp forests, canyon edges, and shelf breaks. However, if sensor pH data and corresponding regional hydrographic surveys are available, then a $\Delta\text{DIC}_{\text{anth}}-\sigma_\theta$ relationship can be established for that region and applied to the sensor data. For example, this approach can potentially expanded to many regions for the CCS, using the North American Carbon Program West Coast Cruise (Feely et al., 2008) and the

$\Delta\text{DIC}_{\text{diseq}}$ for the Pacific Ocean (Sabine et al., 2002). If similar data exist, then this approach can be expanded to other upwelling margins as well.

The Southern California Bight experiences a steady but weaker degree of upwelling compared to the northern regions of the CCS, where upwelling events are more pronounced (Bograd et al., 2009). These regions could experience more extreme conditions regularly, as well as significantly higher variability of carbonate conditions (Harris et al., 2013). However, such dynamics are poorly understood, and more high-frequency observations of carbonate parameters along this system are needed. Source water properties must be characterized through hydrographic surveys. Alternatively, for regions where such data for source waters are not available, sensor data can be combined with either Global Circulation Model or ROMS outputs. This approach will alleviate the cost associated with characterizing source waters, and to a large degree will incorporate processes such as interannual variability, decadal changes in source water properties, and reduced ventilation. It is critical that inorganic carbon sensors (e.g. pH or $p\text{CO}_2$) are co-located with basic physical oceanographic measurements (e.g. T and S) to determine source water properties especially for subsurface deployments.

4.3 Model assessment

The sensitivity of the projected carbonate conditions to the assumptions made in the model is explored here. For example, temperatures observed in 2012 were used to parameterize the model. Sea surface temperature has increased over the past century due to climate change (Smith et al., 2008), and is expected to continue. This will affect the CO_2 equilibrium concentration (DIC_{eq}), but the effects are small and will reduce DIC_{eq} by only several $\mu\text{mol kg}^{-1}$. Both $p\text{CO}_2$ and Ω_{Ar} are dependent on in situ temperature; the effects on Ω_{Ar} are negligible ($\Delta\Omega/\Delta T < 0.01\text{ }^\circ\text{C}^{-1}$), whereas $\Delta p\text{CO}_2/\Delta T$ increases at higher $p\text{CO}_2$ levels, and can be as large as $60\text{ }\mu\text{atm }^\circ\text{C}^{-1}$ at the end of the century, compared to $30\text{ }\mu\text{atm }^\circ\text{C}^{-1}$ at present day at the shelf break. These tempera-

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ture dependencies will affect the mean conditions, but the magnitude of the variability will be relatively unaffected.

TA conditions from 2012 were used to calculate $p\text{CO}_2$ and Ω_{Ar} for all years. Changes in TA affect the buffer factors of seawater, thus, alterations in TA distribution will either speed up or slow down the progression of ocean acidification. However, trends in TA along the CCS on decadal time scales are unknown due to insufficient data. Reduced ventilation in high latitude seas, altered precipitation patterns, and changes in surface calcification and water-column dissolution rates would all lead to changes in upwelled TA conditions (Fassbender et al., 2011; Lee et al., 2006). Quantifying these processes is difficult and out of the scope of this study. Nevertheless, to demonstrate the magnitude of the uncertainty due to TA, $p\text{CO}_2$ was projected for the year 2100 with a $+20 \mu\text{mol kg}^{-1}$ bias to TA. The effects were strongly dependent on depth: mean $p\text{CO}_2$ was reduced by approximately 240, 130, and 70 μatm at 88, 30 m, and the surface, respectively.

Finally, the model presented here projects future carbonate conditions by assuming the dynamics that control the variability at each habitat (e.g. seasonal and episodic upwelling events, internal waves and tides, and biological production and respiration) remain the same as 2012 conditions, and does not account for any variability that occurs on inter-annual to decadal timescales. For example, changes in O_2 and pH on the continental shelf associated with interannual climate events, such as El Niño, have been observed (Nam et al., 2011). However, since 2012 did not correspond with a strong El Niño or La Niña phase, we believe that it was not strongly biased by such events. Furthermore, recent evidence suggests that the proportion of Pacific Equatorial Waters in the California Undercurrent has been increasing over the past several decades, thus modifying the source water properties for upwelled waters onto the continental shelf (Bograd et al., 2015). Since waters of equatorial origin observed between 100–500 m are elevated in DIC and lower in O_2 (Bograd et al., 2015), it is expected that the Southern California Bight will experience higher levels of acidification than predicted from this study if this redistribution of water masses of equatorial origin continues. However, at

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this time, we lack observations with sufficient longevity to predict how climate variability on interannual to decadal time scales might modify the acidification trajectory over the course of the next century. Sustained, high-frequency time series of inorganic carbon parameters are required to elucidate such effects.

5 4.4 Implications for ocean acidification research

In order to properly assess the impacts of anthropogenic ocean acidification through laboratory manipulation experiments, the control and experimental conditions should accurately reflect the study organism's present-day and future habitat conditions (McElhany and Busch, 2013; Reum et al., 2015). The most common control treatment used in ocean acidification experiments for organisms found in the CCS was a $p\text{CO}_2$ value of $\sim 400 \mu\text{atm}$, reflecting atmospheric conditions (compiled by Reum et al., 2015). However, our sensor data showed that all subsurface habitats had significantly greater $p\text{CO}_2$ relative to the atmosphere (Table 2). For example, the mean $p\text{CO}_2$ at the kelp forest is about $100 \mu\text{atm}$ greater than the atmosphere, and routinely experiences conditions of more than $300 \mu\text{atm}$ above atmospheric. Therefore utilizing atmospheric $p\text{CO}_2$ conditions for control treatments will necessarily underestimate the baseline $p\text{CO}_2$ for organisms collected from subsurface habitats.

Recent studies that incorporate natural variability into ocean acidification experiments observed modified responses relative to constant conditions (Dufault et al., 2012; Frieder et al., 2014). However, the effect of natural variability on organismal response to ocean acidification, especially through various life stages is still poorly understood. Our model results demonstrate that variability trajectories are also habitat specific. For example, in the kelp forest, the variability, approximated by the SD, was $93 \mu\text{atm}$ in 2012, whereas this increased to $202 \mu\text{atm}$ in 2100 (Table 2). Furthermore, despite having similar mean CO_2 conditions, the largest variability was observed on event time scales in the kelp forest, whereas the dominant variability occurred on tidal and seasonal cycles at the canyon edge. Therefore future ocean acidification studies investigating the effect of natural variability should not only incorporate increasing

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magnitude into their experimental design, but also consider variability patterns on appropriate time scales.

Temperature and O_2 were tightly correlated with carbonate parameters across habitats and various time scales (daily to seasonal) in this study (Fig. 14); similar correlation has been documented across the CCS in general (Reum et al., 2014, 2015). These parameters can potentially act as additional stressors (Padilla-Gamiño et al., 2013) or stress reliefs (Gooding et al., 2009) for ocean acidification. However, laboratory experiments incorporating the effects of temperature (Gooding et al., 2009; Padilla-Gamiño et al., 2013) and O_2 (Frieder et al., 2014; Navarro et al., 2015) have just started to be explored for the CCS, and no studies have been conducted that incorporate all three variables in their experimental design. Future studies investigating the synergistic effects of O_2 , temperature, and CO_2 should establish experimental conditions based on environmental data (Fig. 14). Although development of systems that can manipulate individual parameters is challenging, important strides have been made to make such experimental set ups accessible to the community (Bockmon et al., 2013). The development of habitat-specific ocean acidification models provides a link between environment and laboratory to facilitate interpretations of physiological responses to elevated CO_2 in the context of current and future environmental conditions.

Discerning habitat-specific CO_2 signatures could lead to the discovery of local populations that are more tolerant of future CO_2 conditions. For example, large high-frequency variability of CO_2 could lead to a greater capacity for physiological and phenotypic plasticity, as organisms are routinely exposed to a wide range of CO_2 . The embryos of *Doryteuthis opalescens*, an important fishery species in California, can tolerate low pH and O_2 , perhaps due to the fact that they routinely experience a wide range of pH and O_2 (Navarro, 2014). Furthermore, such environmental conditions may be conducive for the existence of high CO_2 tolerant subpopulations, allowing for adaptation to buffer some of the negative effects of ocean acidification (Hofmann and Todgham, 2010). Alternatively, these populations could be living near critical biological thresholds, as has been suggested for the thermal stress of some organisms

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living in the intertidal (Somero, 2002). A massive failure in an oyster hatchery in Oregon was linked to upwelling of high CO₂ waters during a critical life-stage of oyster larvae (Barton et al., 2012), indicating the existence of CO₂ thresholds for some marine organisms (Bednaršek et al., 2014). However, such thresholds may be dependent on species, life-stage, and/or environmental history. As we begin to realize which populations of species and life stages are living near acidification thresholds vs. those that exhibit acidification tolerance, implementation of habitat-specific acidification models can be used as a tool to aid protection, management and remediation efforts of critical marine habitats now and in the future.

5 Conclusions

Here we have presented habitat-specific carbonate chemistry projections for four coastal habitats along an upwelling margin. The projections were generated by combining high-frequency sensor measurements, a regional empirical relationship for TA, hydrographic survey data to quantify source-water properties of upwelled waters, and the atmospheric CO₂ record. Even though the four habitats were within 5 km of one another, distinct habitat-specific variability signatures and acidification trajectories were observed. These results reveal the existence of highly variable CO₂ signatures within a small geographic area, and the potential for discoveries of habitats that could act as refugia from ocean acidification. Changes in the buffer factors largely explained the observed patterns; however, local biological feedbacks could also produce a large acidification signal. In all habitats studied, carbonate conditions have left, or are leaving preindustrial variability envelopes. Model projections suggest that anthropogenic ocean acidification will continue to progress in the CCS and other upwelling margins over the next several decades regardless of any changes in CO₂ emissions; any impacts from reduced emissions will only be observed mid-century and beyond. This demonstrates the urgency of the situation, and this delayed response must be taken into account

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when assessing the impacts of ocean acidification and developing mitigation and monitoring strategies.

**The Supplement related to this article is available online at
doi:10.5194/bgd-12-7125-2015-supplement.**

5 *Acknowledgements.* Hydrographic data and kelp forest time series data are available at BCO-
DMO project SeapHOx (<http://www.bco-dmo.org/project/2122>). Sensor time series data are
available for the Del Mar buoy at <http://mooring.ucsd.edu>, and upon request for the Scripps
Pier (smithj@ucsd.edu).

10 We would like to thank the University of California Ship Funds for providing ship time for
maintenance of the Del Mar Buoy and the San Diego Coastal Expedition cruises. We thank
Emily Kelly for DIC analysis at sea, and all of the ship crew and volunteers that aided in
sample collection. We would like to thank Emily Donham for providing discrete TA data from
the kelp forest. The Del Mar Buoy platform has been maintained by the Ocean Time-series
15 Group (<http://mooring.ucsd.edu>); we acknowledge their efforts to continuously collect and main-
tain the time-series data. The canyon edge deployment was supported by the NOAA Grant
#NA10OAR4170060 and the California Sea Grant College Program Project #R/CC-04. The
kelp forest deployment was supported by NSF-OCE Award No. 0927445. We would also like
to thank the Ellen Browning Scripps Foundation, the Scripps Family Foundation, the Bohn
and Grand families, and the California State Water Board for financial support for the Scripps
20 Ocean Acidification Real-time Monitoring Program. S. Nam was partly supported by the Re-
search Resettlement Fund for the new faculty of Seoul National University. Financial support
for Richard A. Feely was provided by the National Oceanic and Atmospheric Administration
under the NOAA Ocean Acidification Program and the Climate Observations Division of the
NOAA Climate Program, Contribution Number 4313 from the NOAA Pacific Marine Environ-
25 mental Laboratory. The statements, findings, conclusions and recommendations are those of
the authors and do not necessarily reflect the views of California Sea Grant, state agencies,
NOAA, NSF or the U.S. Department of Commerce.

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- Alin, S. R., Feely, R. A., Dickson, A. G., Hernández-Ayón, J. M., Juranek, L. W., Ohman, M. D., and Goericke, R.: Robust empirical relationships for estimating the carbonate system in the southern California Current System and application to CalCOFI hydrographic cruise data (2005–2011), *J. Geophys. Res.*, 117, C05033, doi:10.1029/2011JC007511, 2012.
- Anderson, L. A. and Sarmiento, J. L.: Redfield ratios of remineralization determined by nutrient data analysis, *Global Biogeochem. Cy.*, 8, 65–80, 1994.
- Andersson, A. J., Yeakel, K. L., Bates, N. R., and de Putron, S. J.: Partial offsets in ocean acidification from changing coral reef biogeochemistry, *Nat. Clim. Chang.*, 3, 1–6, doi:10.1038/nclimate2050, 2013.
- Barton, A., Hales, B., Waldbusser, G. G., Langdon, C., and Feely, R. A.: The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects, *Limnol. Oceanogr.*, 57, 698–710, doi:10.4319/lo.2012.57.3.0698, 2012.
- Bates, N. R., Astor, Y. M., Church, M. J., Currie, K., Dore, J. E., Gonzalez-Davila, M., Lorenzoni, L., Muller-Karger, F., Olafsson, J., and Santana-Casiano, J. M.: A time-series view of changing surface ocean chemistry due to ocean uptake of anthropogenic CO₂ and ocean acidification, *Oceanography*, 27, 126–141, 2014.
- Bednaršek, N., Feely, R. A., Reum, J. C. P., Peterson, B., Menkel, J., Alin, S. R., and Hales, B.: *Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem., *P. Roy. Soc. B-Biol. Sci.*, 281, 20140123, doi:10.1098/rspb.2014.0123, 2014.
- Bockmon, E. E., Frieder, C. A., Navarro, M. O., White-Kershek, L. A., and Dickson, A. G.: Technical Note: Controlled experimental aquarium system for multi-stressor investigation of carbonate chemistry, oxygen saturation, and temperature, *Biogeosciences*, 10, 5967–5975, doi:10.5194/bg-10-5967-2013, 2013.
- Bograd, S. J., Schroeder, I., Sarkar, N., Qiu, X., Sydeman, W. J., and Schwing, F. B.: Phenology of coastal upwelling in the California Current, *Geophys. Res. Lett.*, 36, 1–5, doi:10.1029/2008GL035933, 2009.
- Bograd, S. J., Buil, M. P., Lorenzo, E. Di, Castro, C. G., Schroeder, I. D., Goericke, R., Anderson, C. R., Benitez-Nelson, C., and Whitney, F. A.: Changes in source waters to the Southern California Bight, *Deep-Sea Res. Pt. II*, 112, 42–52, doi:10.1016/j.dsr2.2014.04.009, 2015.

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- Booth, J. A. T., McPhee-Shaw, E. E., Chua, P., Kingsley, E., Denny, M., Phillips, R., Bograd, S. J., Zeidberg, L. D., and Gilly, W. F.: Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast, *Cont. Shelf Res.*, 45, 108–115, doi:10.1016/j.csr.2012.06.009, 2012.
- 5 Bresnahan, P. J., Martz, T. R., Takeshita, Y., Johnson, K. S., and LaShomb, M.: Best practices for autonomous measurement of seawater pH with the Honeywell Durafet, *Methods Oceanogr.*, 9, 44–60, 2014.
- Brewer, P. G. and Peltzer, E. T.: Limits to marine life, *Science*, 324, 347–348, 2009.
- Byrne, M., Lamare, M., Winter, D., Dworjany, S. A., and Uthicke, S.: The stunting effect of
10 a high CO₂ ocean on calcification and development in sea urchin larvae, a synthesis from the tropics to the poles, *Philos. T. R. Soc. B*, 368, 1–13, doi:10.1098/rstb.2012.0439, 2013.
- Byrne, R. H., Mecking, S., Feely, R. A., and Liu, X.: Direct observations of basin-wide acidification of the North Pacific Ocean, *Geophys. Res. Lett.*, 37, 1–5, doi:10.1029/2009GL040999, 2010.
- 15 Cai, W.-J., Hu, X., Huang, W.-J., Murrell, M. C., Lehrter, J. C., Lohrenz, S. E., Chou, W.-C., Zhai, W., Hollibaugh, J. T., Wang, Y., Zhao, P., Guo, X., Gundersen, K., Dai, M., and Gong, G.-C.: Acidification of subsurface coastal waters enhanced by eutrophication, *Nat. Geosci.*, 4, 766–770, doi:10.1038/ngeo1297, 2011.
- Carter, B. R., Radich, J. A., Doyle, H. L., and Dickson, A. G.: An automated system for spectrophotometric seawater pH measurements, *Limnol. Oceanogr.-Meth.*, 11, 16–27,
20 doi:10.4319/lom.2013.11.16, 2013.
- Clayton, T. D. and Byrne, R. H.: Spectrophotometric seawater pH measurements: total hydrogen ion concentration scale calibration of m-cresol purple and at-sea results, *Deep-Sea Res. Pt. I*, 40, 2115–2129, 1993.
- 25 Dickson, A. G., Sabine, C. L., and Christian, J. R. (Eds.): Guide to Best Practices for Ocean CO₂ Measurements, PICES Special Publication 3, 2007.
- Duarte, C. M., Hendriks, I. E., Moore, T. S., Olsen, Y. S., Steckbauer, A., Ramajo, L., Carstensen, J., Trotter, J. A., and McCulloch, M.: Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH, *Estuar. Coast.*, 36, 221–236, doi:10.1007/s12237-013-9594-3, 2013.
- 30 Dufault, A. M., Cumbo, V. R., Fan, T.-Y., and Edmunds, P. J.: Effects of diurnally oscillating pCO₂ on the calcification and survival of coral recruits, *P. Roy. Soc. B-Biol. Sci.*, 279, 2951–2958, doi:10.1098/rspb.2011.2545, 2012.

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- Emerson, S. R.: Accurate measurement of O₂, N₂, and Ar gases in water and the solubility of N₂, *Mar. Chem.*, 64, 337–347, doi:10.1016/S0304-4203(98)00090-5, 1999.
- Fassbender, A. J., Sabine, C. L., Feely, R. A., Langdon, C., and Mordy, C. W.: Inorganic carbon dynamics during northern California coastal upwelling, *Cont. Shelf Res.*, 31, 1180–1192, doi:10.1016/j.csr.2011.04.006, 2011.
- 5 Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D., and Hales, B.: Evidence for upwelling of corrosive “acidified” water onto the continental shelf., *Science*, 320, 1490–1492, doi:10.1126/science.1155676, 2008.
- Feely, R. A., Doney, S. C., and Cooley, S. R.: Ocean acidification: present conditions and future changes in a high-CO₂ world, *Oceanography*, 22, 36–47, 2009.
- 10 Feely, R. A., Alin, S. R., Newton, J., Sabine, C. L., Warner, M., Devol, A., Krembs, C., and Maloy, C.: The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary, *Estuar. Coast. Shelf S.*, 88, 442–449, doi:10.1016/j.ecss.2010.05.004, 2010.
- 15 Frankignoulle, M.: A complete set of buffer factors for acid/base CO₂ system in seawater, *J. Marine Syst.*, 5, 111–118, 1994.
- Frieder, C. A., Nam, S. H., Martz, T. R., and Levin, L. A.: High temporal and spatial variability of dissolved oxygen and pH in a nearshore California kelp forest, *Biogeosciences*, 9, 3917–3930, doi:10.5194/bg-9-3917-2012, 2012.
- 20 Frieder, C. A., Gonzalez, J. P., Bockmon, E. E., Navarro, M. O., and Levin, L. A.: Can variable pH and low oxygen moderate ocean acidification outcomes for mussel larvae?, *Glob. Change Biol.*, 20, 754–764, doi:10.1111/gcb.12485, 2014.
- Friederich, G. E., Walz, P. M., Burczynski, M. G., and Chavez, F. P.: Inorganic carbon in the central California upwelling system during the 1997–1999 El Niño–La Niña event, *Prog. Oceanogr.*, 54, 185–203, 2002.
- 25 Garcia, H. E. and Gordon, L. I.: Oxygen solubility in seawater: better fitting equations, *Limnol. Oceanogr.*, 37, 1307–1312, 1992.
- Gaylord, B., Hill, T. M., Sanford, E., Lenz, E. A., Jacobs, L. A., Sato, K. N., Russell, A. D., and Hettinger, A.: Functional impacts of ocean acidification in an ecologically critical foundation species, *J. Exp. Biol.*, 214, 2586–2594, 2011.
- 30 Gazeau, F., Gattuso, J.-P., Greaves, M., Elderfield, H., Peene, J., Heip, C. H. R., and Middelburg, J. J.: Effect of carbonate chemistry alteration on the early embry-

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onic development of the Pacific oyster (*Crassostrea gigas*), PLoS One, 6, e23010, doi:10.1371/journal.pone.0023010, 2011.

Gooding, R. A., Harley, C. D. G., and Tang, E.: Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm, P. Natl. Acad. Sci. USA, 106, 9316–9321, doi:10.1073/pnas.0811143106, 2009.

Gruber, N., Sarmiento, J. L., and Stocker, T. F.: An improved method for detecting anthropogenic CO₂ in the oceans, Global Biogeochem. Cy., 10, 809–837, 1996.

Gruber, N., Lachkar, Z., Frenzel, H., Marchesiello, P., Münnich, M., McWilliams, J. C., Nagai, T., and Plattner, G.-K.: Eddy-induced reduction of biological production in eastern boundary upwelling systems, Nat. Geosci., 4, 787–792, doi:10.1038/ngeo1273, 2011.

Gruber, N., Hauri, C., Lachkar, Z., Loher, D., Frölicher, T. L., and Plattner, G.-K.: Rapid progression of ocean acidification in the California Current System, Science, 337, 220–223, doi:10.1126/science.1216773, 2012.

Hales, B., Takahashi, T., and Bandstra, L.: Atmospheric CO₂ uptake by a coastal upwelling system, Global Biogeochem. Cy., 19, 1–11, doi:10.1029/2004GB002295, 2005.

Hall-Spencer, J. M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S. M., Rowley, S. J., Tedesco, D., and Buia, M.-C.: Volcanic carbon dioxide vents show ecosystem effects of ocean acidification, Nature, 454, 96–99, 2008.

Harris, K. E., DeGrandpre, M. D., and Hales, B.: Aragonite saturation state dynamics in a coastal upwelling zone, Geophys. Res. Lett., 40, 2720–2725, doi:10.1002/grl.50460, 2013.

Hauri, C., Gruber, N., McDonnell, A. M. P., and Vogt, M.: The intensity, duration, and severity of low aragonite saturation state events on the California continental shelf, Geophys. Res. Lett., 40, 3424–3428, doi:10.1002/grl.50618, 2013a.

Hauri, C., Gruber, N., Vogt, M., Doney, S. C., Feely, R. A., Lachkar, Z., Leinweber, A., McDonnell, A. M. P., Münnich, M., and Plattner, G.-K.: Spatiotemporal variability and long-term trends of ocean acidification in the California Current System, Biogeosciences, 10, 193–216, doi:10.5194/bg-10-193-2013, 2013b.

Hettinger, A., Sanford, E., Hill, T. M., Russell, A. D., Sato, K. N. S., Hoey, J., Forsch, M., Page, H. N., and Gaylord, B.: Persistent carry-over effects of planktonic exposure to ocean acidification in the Olympia oyster, Ecology, 93, 2758–2768, doi:10.1890/12-0567.1, 2012.

Hijioka, Y., Matsuoka, Y., Nishimoto, H., Masui, M., and Kainuma, M.: Global GHG emissions scenarios under GHG concentration stabilization targets, J. Glob. Environ. Eng., 13, 97–108, 2008.

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Hofmann, G. E. and Todgham, A. E.: Living in the now: physiological mechanisms to tolerate a rapidly changing environment, *Annu. Rev. Physiol.*, 72, 127–45, doi:10.1146/annurev-physiol-021909-135900, 2010.

Hofmann, G. E., Smith, J. E., Johnson, K. S., Send, U., Levin, L. A., Micheli, F., Paytan, A., Price, N. N., Peterson, B., Takeshita, Y., Matson, P. G., Crook, E. D., Kroeker, K. J., Gambi, M. C., Rivest, E. B., Frieder, C. A., Yu, P. C., and Martz, T. R.: High-frequency dynamics of ocean pH: a multi-ecosystem comparison, *PLoS One*, 6, e28983, doi:10.1371/journal.pone.0028983, 2011.

Hofmann, G. E., Evans, T. G., Kelly, M. W., Padilla-Gamiño, J. L., Blanchette, C. A., Washburn, L., Chan, F., McManus, M. A., Menge, B. A., Gaylord, B., Hill, T. M., Sanford, E., Lavigne, M., Rose, J. M., Kapsenberg, L., and Dutton, J. M.: Exploring local adaptation and the ocean acidification seascape – studies in the California Current Large Marine Ecosystem, *Biogeosciences*, 11, 1053–1064, doi:10.5194/bg-11-1053-2014, 2014.

Keeling, C. D., Piper, S. C., Bacastow, R. B., Wahlen, M., Whorf, T. P., Heimann, M., and Meijer, H. A.: Atmospheric CO₂ and 13CO₂ exchange with the terrestrial biosphere and oceans from 1978 to 2000: observations and carbon cycle implications, in: *A History of Atmospheric CO₂ and its Effects on Plants, Animals, and Ecosystems*, edited by: Ehleringer, J. R., Cerling, T. E., and Dearing, M. D., Springer Verlag, New York, 83–113, 2005.

Kroeker, K. J., Micheli, F., Gambi, M. C., and Martz, T. R.: Divergent ecosystem responses within a benthic marine community to ocean acidification, *P. Natl. Acad. Sci. USA*, 108, 14515–14520, doi:10.1073/pnas.1107789108, 2011.

Langdon, C., Gattuso, J., and Andersson, A.: Measurements of calcification and dissolution of benthic organisms and communities, in: *Guide to Best Practices for Ocean Acidification Research and Data Reporting*, Publications Office of the European Union, Luxembourg, 213–232, 2010.

Lauvset, S. K. and Gruber, N.: Long-term trends in surface ocean pH in the North Atlantic, *Mar. Chem.*, 162, 71–76, doi:10.1016/j.marchem.2014.03.009, 2014.

Lee, K., Tong, L. T., Millero, F. J., Sabine, C. L., Dickson, A. G., Goyet, C., Park, G.-H., Wanninkhof, R., Feely, R. A., and Key, R. M.: Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans, *Geophys. Res. Lett.*, 33, 1–5, doi:10.1029/2006GL027207, 2006.

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- Leinweber, A. and Gruber, N.: Variability and trends of ocean acidification in the Southern California Current System: a time series from Santa Monica Bay, *J. Geophys. Res.-Oceans*, 118, 3622–3633, doi:10.1002/jgrc.20259, 2013.
- Liu, X., Patsavas, M. C., and Byrne, R. H.: Purification and characterization of meta-cresol purple for spectrophotometric seawater pH measurements, *Environ. Sci. Technol.*, 45, 4862–4868, doi:10.1021/es200665d, 2011.
- Lueker, T. J., Dickson, A. G., and Keeling, C. D.: Ocean $p\text{CO}_2$ calculated from dissolved inorganic carbon, alkalinity, and equations for K1 and K2: validation based on laboratory measurements of CO_2 in gas and seawater at equilibrium, *Mar. Chem.*, 70, 105–119, doi:10.1016/S0304-4203(00)00022-0, 2000.
- Martz, T. R., Connery, J. G., and Johnson, K. S.: Testing the Honeywell Durafet for seawater pH applications, *Limnol. Oceanogr.-Meth.*, 8, 172–184, 2010.
- Martz, T. R., Takeshita, Y., Rolph, R., and Bresnahan, P.: Tracer monitored titrations: measurement of dissolved oxygen, *Anal. Chem.*, 84, 290–296, 2012.
- Martz, T. R., Send, U., Ohman, M. D., Takeshita, Y., Bresnahan, P., Kim, H.-J., and Nam, S.: Dynamic variability of biogeochemical ratios in the Southern California Current System, *Geophys. Res. Lett.*, 41, 2496–2501, 2014.
- Matsumoto, K. and Gruber, N.: How accurate is the estimation of anthropogenic carbon in the ocean? An evaluation of the ΔC^* method, *Global Biogeochem. Cy.*, 19, 1–17, doi:10.1029/2004GB002397, 2005.
- McElhany, P. and Busch, D. S.: Appropriate $p\text{CO}_2$ treatments in ocean acidification experiments, *Mar. Biol.*, 160, 1807–1812, doi:10.1007/s00227-012-2052-0, 2013.
- McNeil, B. I. and Matear, R. J.: Southern Ocean acidification: a tipping point at 450-ppm atmospheric CO_2 , *P. Natl. Acad. Sci. USA*, 105, 18860–18864, doi:10.1073/pnas.0806318105, 2008.
- Mehrbach, C., Culberson, C. H., Hawley, J. E., and Pytkowicz, R. M.: Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure, *Limnol. Oceanogr.*, 18, 897–907, doi:10.4319/lo.1973.18.6.0897, 1973.
- Nam, S., Kim, H.-J., and Send, U.: Amplification of hypoxic and acidic events by La Niña conditions on the continental shelf off California, *Geophys. Res. Lett.*, 38, 1–5, doi:10.1029/2011GL049549, 2011.
- Navarro, M. O.: Consequences of environmental variability for spawning and embryo development of inshore market squid *Doryteuthis opalescens*, Ph.D. thesis, ProQuest Dissertations

and Theses (Publication No. 3644287), University of California San Diego. Ann Arbor, USA, 2014.

Navarro, M. O., Parnell, P. E., and Levin, L. A.: Year-round spawning of the Market Squid, *Doryteuthis opalescens* and associated critical habitat along an upwelling margin, in: Coastal and Estuarine Research Federation National Conference, San Diego, 2013.

O'Sullivan, D. W. and Millero, F. J.: Continual measurement of the total inorganic carbon in surface seawater, *Mar. Chem.*, 60, 75–83, doi:10.1016/S0304-4203(97)00079-0, 1998.

Padilla-Gamiño, J. L., Kelly, M. W., Evans, T. G., and Hofmann, G. E.: Temperature and CO₂ additively regulate physiology, morphology and genomic responses of larval sea urchins, *Strongylocentrotus purpuratus*, *P. Roy. Soc. B-Biol. Sci.*, 280, 20130155, doi:10.1098/rspb.2013.0155, 2013.

Pineda, J.: Predictable upwelling and the shoreward transport of planktonic larvae by internal tidal bores, *Science*, 253, 548–551, 1991.

Price, N. N., Martz, T. R., Brainard, R. E., and Smith, J. E.: Diel variability in seawater pH relates to calcification and benthic community structure on coral reefs, *PLoS One*, 7, e43843, doi:10.1371/journal.pone.0043843, 2012.

Reum, J. C. P., Alin, S. R., Feely, R. A., Newton, J., Warner, M., and McElhany, P.: Seasonal carbonate chemistry covariation with temperature, oxygen, and salinity in a fjord estuary: implications for the design of ocean acidification experiments, *PLoS One*, 9, e89619, doi:10.1371/journal.pone.0089619, 2014.

Reum, J. C. P., Alin, S. R., Harvey, C. J., Bednarsek, N., Evans, W., Feely, R. A., Hales, B., Lucey, N., Mathis, J. T., McElhany, P., Newton, J., Newton, J., and Sabine, C. L.: Interpretation and design of ocean acidification experiments in upwelling systems in the context of carbonate chemistry co-variation with temperature and oxygen, *ICES J. Mar. Sci.*, 528–536, doi:10.1093/icesjms/fsu231, 2015.

Rodolfo-Metalpa, R., Houlbrèque, F., Tambutté, É., Boisson, F., Baggini, C., Patti, F. P., Jeffrey, R., Fine, M., Foggo, A., Gattuso, J.-P., and Hall-Spencer, J. M.: Coral and mollusc resistance to ocean acidification adversely affected by warming, *Nat. Clim. Chang.*, 1, 308–312, doi:10.1038/nclimate1200, 2011.

Rykaczewski, R. R. and Dunne, J. P.: Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model, *Geophys. Res. Lett.*, 37, 1–5, doi:10.1029/2010GL045019, 2010.

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12, 7125–7176, 2015

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- Sabine, C. L. and Tanhua, T.: Estimation of anthropogenic CO₂ inventories in the ocean, *Ann. Rev. Mar. Sci.*, 2, 175–198, doi:10.1146/annurev-marine-120308-080947, 2010.
- Sabine, C. L., Feely, R. A., Key, R. M., Bullister, J. L., Millero, F. J., Lee, K., Peng, T.-H., Tilbrook, B., Ono, T., and Wong, C. S.: Distribution of anthropogenic CO₂ in the Pacific Ocean, *Global Biogeochem. Cy.*, 16, 1–17, doi:10.1029/2001GB001639, 2002.
- Send, U. and Nam, S.: Relaxation from upwelling: the effect on dissolved oxygen on the continental shelf, *J. Geophys. Res.*, 117, 1–9, doi:10.1029/2011JC007517, 2012.
- Smith, T. M., Reynolds, R. W., Peterson, T. C., and Lawrimore, J.: Improvements to NOAA's historical merged land–ocean surface temperature analysis (1880–2006), *J. Climate*, 21, 2283–2296, doi:10.1175/2007JCLI2100.1, 2008.
- Somero, G. N.: Thermal physiology and vertical zonation of intertidal animals: optima, limits, and costs of living, *Integr. Comp. Biol.*, 42, 780–789, 2002.
- Sunda, W. G. and Cai, W.-J.: Eutrophication induced CO₂-acidification of subsurface coastal waters: interactive effects of temperature, salinity, and atmospheric pCO₂, *Environ. Sci. Technol.*, 46, 10651–10659, doi:10.1021/es300626f, 2012.
- Sutton, A. J., Feely, R. A., Sabine, C. L., McPhaden, M. J., Takahashi, T., Chavez, F. P., Friederich, G. E., and Mathis, J. T.: Natural variability and anthropogenic change in equatorial Pacific surface ocean pCO₂ and pH, *Global Biogeochem. Cy.*, 28, 1–15, doi:10.1002/2013GB004679, 2014.
- Swart, N. C., Allen, S. E., and Greenan, B. J. W.: Resonant amplification of subinertial tides in a submarine canyon, *J. Geophys. Res.*, 116, 1–14, doi:10.1029/2011JC006990, 2011.
- Van Heuven, S., Pierrot, D., Rae, J. W. B., Lewis, E., and Wallace, D. W.: MATLAB Program Developed for CO₂ System Calculations, ORNL/CDIAC-105b., Oak Ridge National Laboratory, Oak Ridge, Tennessee, doi:10.3334/CDIAC/otg.CO2SYS_MATLAB_v1.1, 2011.
- Waldbusser, G. G., Hales, B., Langdon, C. J., Haley, B. A., Schrader, P., Brunner, E. L., Gray, M. W., Miller, C. A., and Gimenez, I.: Saturation-state sensitivity of marine bivalve larvae to ocean acidification, *Nat. Clim. Chang.*, 5, 273–280, doi:10.1038/NCLIMATE2479, 2015.

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Table 1. Summary of sensor deployments.

| Habitat Type | Deployment Site | DD ^a | BD ^b | Latitude | Longitude | Days ^c |
|--------------------------|----------------------|-----------------|-----------------|----------|-----------|-------------------|
| Surf Zone | Scripps Pier | 4 | 6 | 32.87° N | 117.26° W | 122 |
| Kelp Forest | La Jolla Kelp Forest | 17 | 20 | 32.81° N | 117.29° W | 128 |
| Canyon Edge ^d | La Jolla Canyon | 30 | 30 | 32.86° N | 117.27° W | 302 |
| Shelf Break | Del Mar Buoy | 88 | 100 | 32.94° N | 117.32° W | 335 |

^a Sensor deployment depth in m.^b Bottom depth in m.^c Total deployment days between June 2012 and June 2013.^d A linear drift correction for salinity was applied for 2 of the 4 deployments.

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Table 2. Mean \pm SD of modeled carbonate parameters at in situ conditions for preindustrial, 2012, 2060, and 2100 using the RCP6.0 projection at each habitat.

| | Year | $p\text{CO}_2$ (μatm) | Ω_{Ar} | pH |
|-----------------------|---------|------------------------------------|----------------------|------------------|
| Surf Zone (4 m) | Preind. | 267 ± 26 | 3.09 ± 0.21 | 8.19 ± 0.034 |
| | 2012 | 394 ± 43 | 2.38 ± 0.25 | 8.05 ± 0.038 |
| | 2060 | 473 ± 56 | 2.09 ± 0.19 | 7.98 ± 0.041 |
| | 2100 | 619 ± 80 | 1.71 ± 0.18 | 7.88 ± 0.045 |
| Kelp Forest (17 m) | Preind. | 365 ± 74 | 2.28 ± 0.42 | 8.08 ± 0.078 |
| | 2012 | 516 ± 108 | 1.77 ± 0.36 | 7.95 ± 0.083 |
| | 2060 | 683 ± 156 | 1.43 ± 0.33 | 7.84 ± 0.094 |
| | 2100 | 937 ± 231 | 1.11 ± 0.29 | 7.72 ± 0.105 |
| Canyon Edge (30 m) | Preind. | 365 ± 68 | 2.29 ± 0.37 | 8.08 ± 0.068 |
| | 2012 | 529 ± 105 | 1.75 ± 0.31 | 7.94 ± 0.075 |
| | 2060 | 702 ± 155 | 1.40 ± 0.29 | 7.83 ± 0.085 |
| | 2100 | 964 ± 231 | 1.09 ± 0.25 | 7.70 ± 0.095 |
| Shelf Break (88 m) | Preind. | 637 ± 132 | 1.38 ± 0.27 | 7.86 ± 0.083 |
| | 2012 | 878 ± 149 | 1.05 ± 0.18 | 7.73 ± 0.070 |
| | 2060 | 1195 ± 200 | 0.80 ± 0.15 | 7.61 ± 0.070 |
| | 2100 | 1639 ± 246 | 0.60 ± 0.10 | 7.47 ± 0.065 |

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Table 3. Mean daily range of carbonate parameters at in situ conditions for 2012 at each habitat.

| | $p\text{CO}_2$ (μatm) | Ω_{Ar} | pH |
|-------------|------------------------------------|----------------------|-------|
| Surf Zone | 96 | 0.46 | 0.085 |
| Kelp Forest | 68 | 0.22 | 0.054 |
| Canyon Edge | 167 | 0.48 | 0.120 |
| Shelf Break | 110 | 0.14 | 0.053 |

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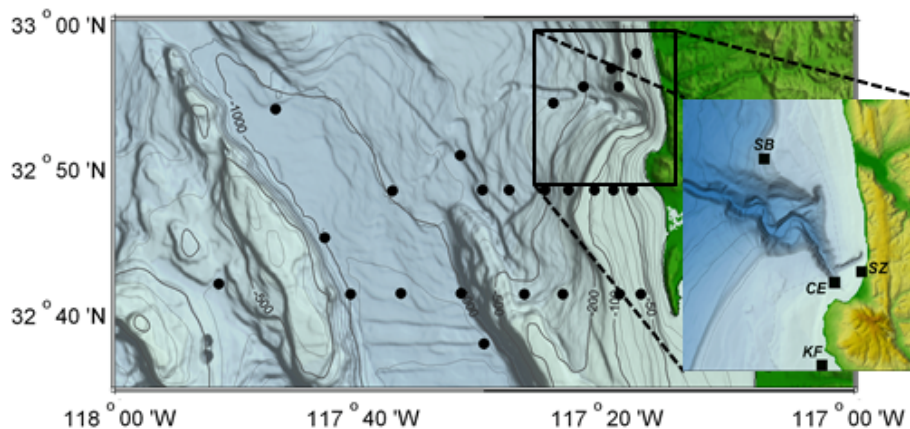


Figure 1. Map of study region. Hydrographic stations (black dots) and sensor deployment sites (black squares) are shown. Initials are: CE = canyon edge, SB = shelf break, SZ = surf zone, and KF = kelp forest.

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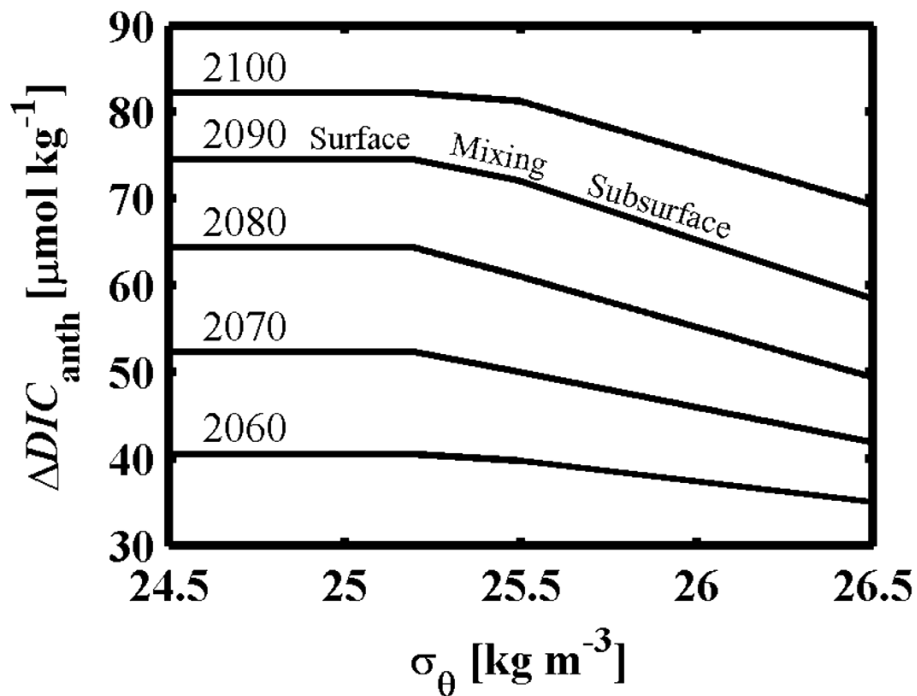


Figure 2. ΔDIC_{anth} as a function of σ_{θ} for certain modeled years (indicated above line) using the ICPP RCP6.0 projection. The three regimes used in this model, surface, mixing, and subsurface, are labeled.

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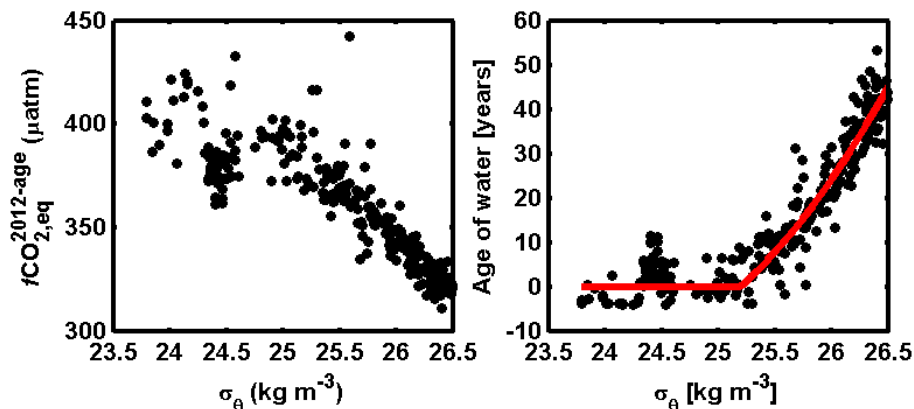


Figure 3. $f\text{CO}_{2,\text{eq}}^{2012-\text{age}}$ calculated from hydrographic data (left) and the calculated age– σ_θ relationship (right) is shown. Good agreement ($R^2 = 0.87$) between the data (black circles) and the fit (age = $8.852(\sigma_\theta - 25.2)^2 + 23.132(\sigma_\theta - 25.2)$; red line) is observed (right). Age of surface waters ($\sigma_\theta < 25.2 \text{ kg m}^{-3}$) was assumed to be 0.

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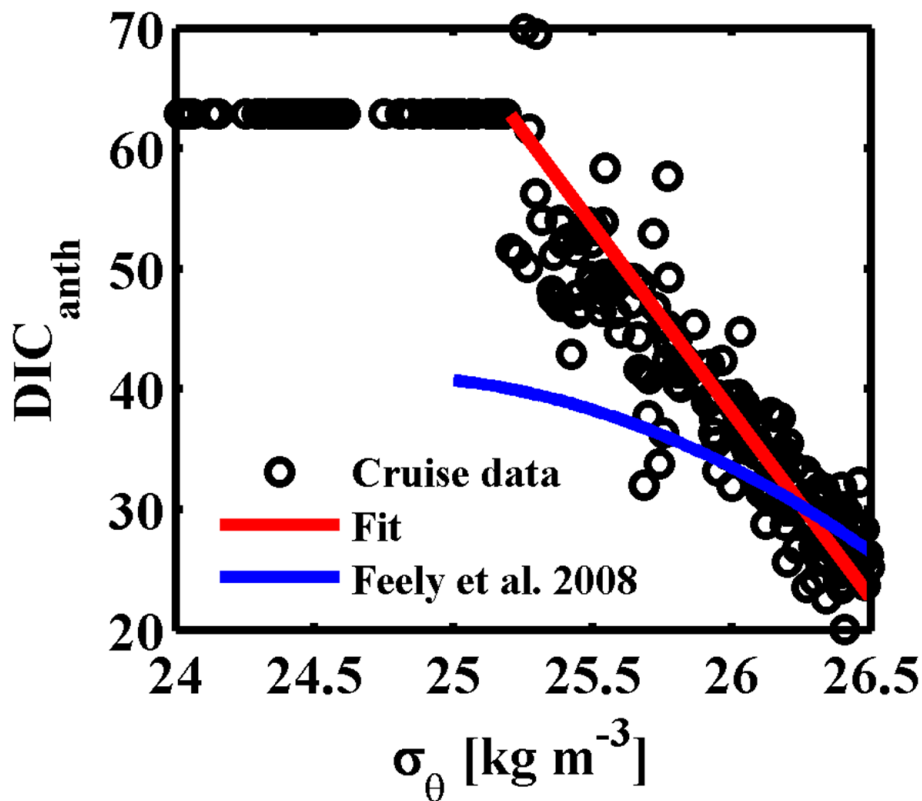


Figure 4. DIC_{anth} as a function of σ_θ. The calculated values and the fit are represented by black circles and a red line, respectively. The blue line shows DIC_{anth} using the formulations from Feely et al. (2008).

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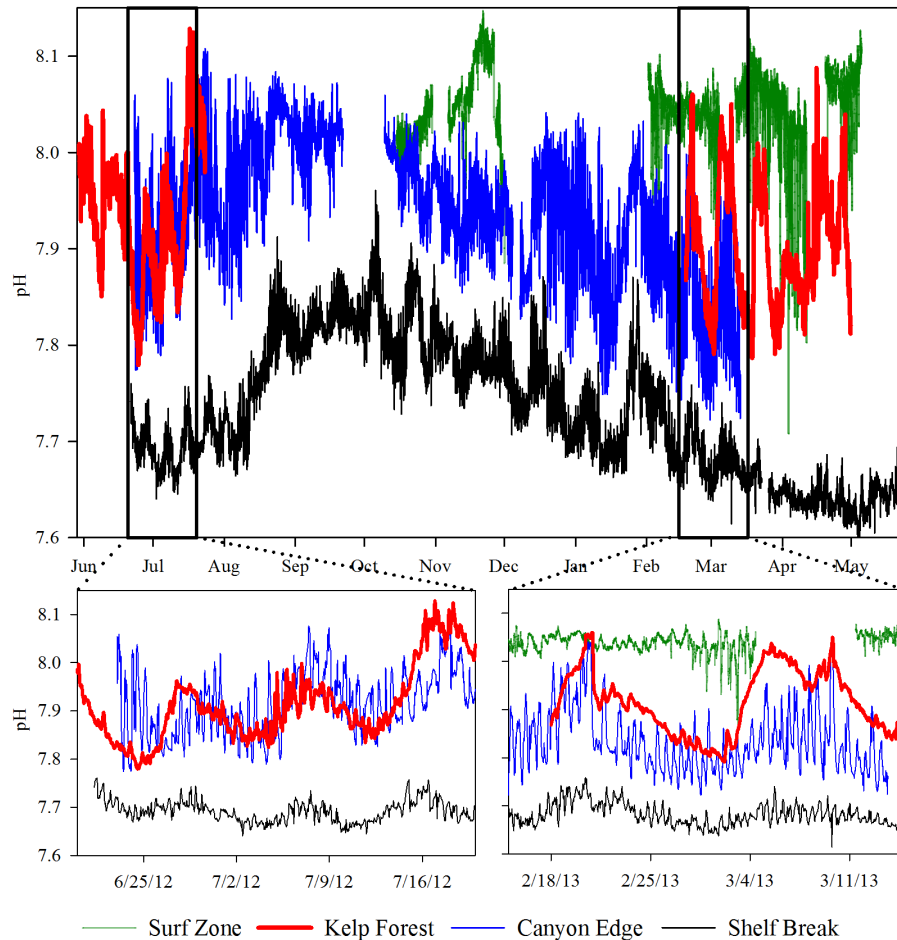


Figure 5. Time series of sensor pH between June 2012 to June. Two lower panels are month-long snapshots. pH is reported at in situ conditions.

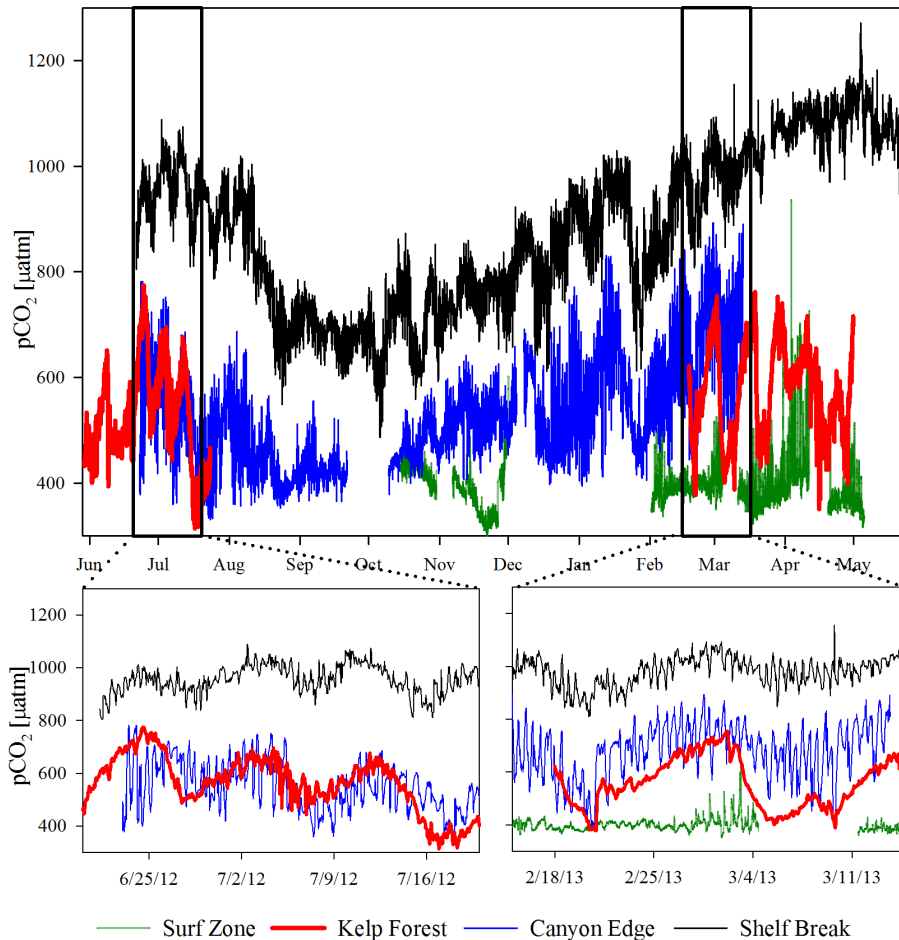


Figure 6. Time series of $p\text{CO}_2$ calculated from sensor pH and TAest between June 2012 to June 2013. Two lower panels are month-long snapshots. $p\text{CO}_2$ is reported at in situ conditions.

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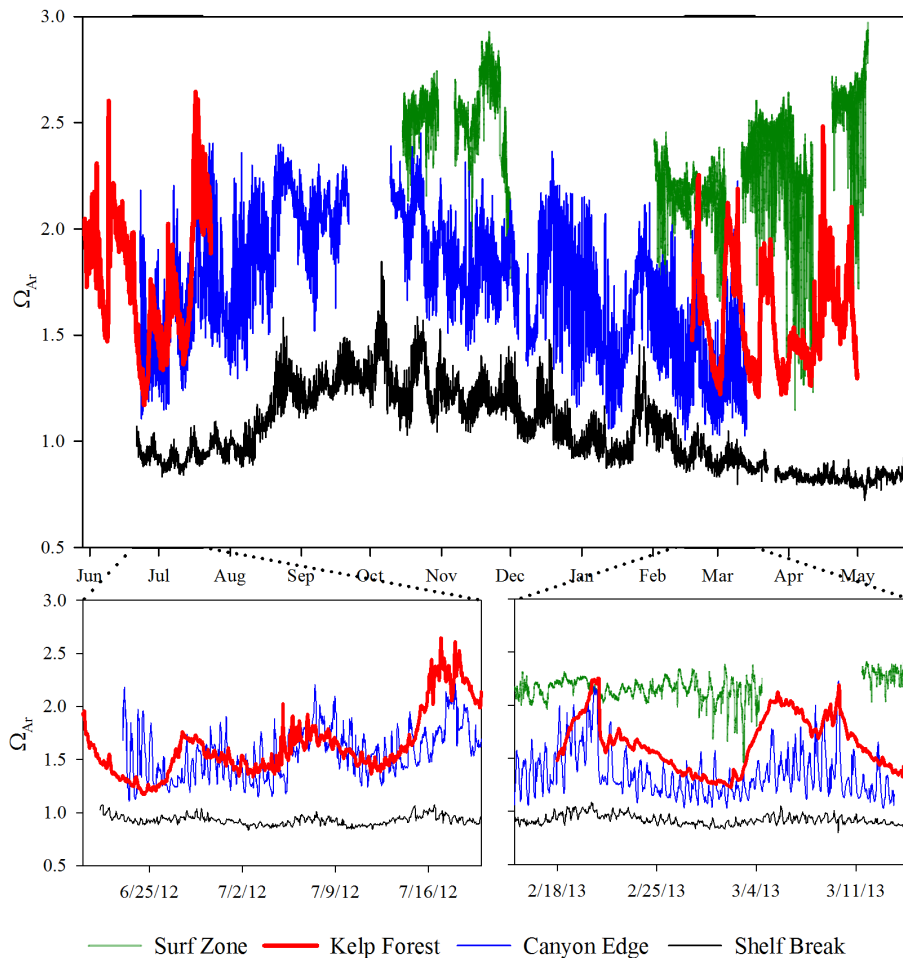


Figure 7. Time series of Ω_{Ar} calculated from sensor pH and TA_{est} between June 2012 to June 2013. Two lower panels are month-long snapshots. Ω_{Ar} is reported at in situ conditions.

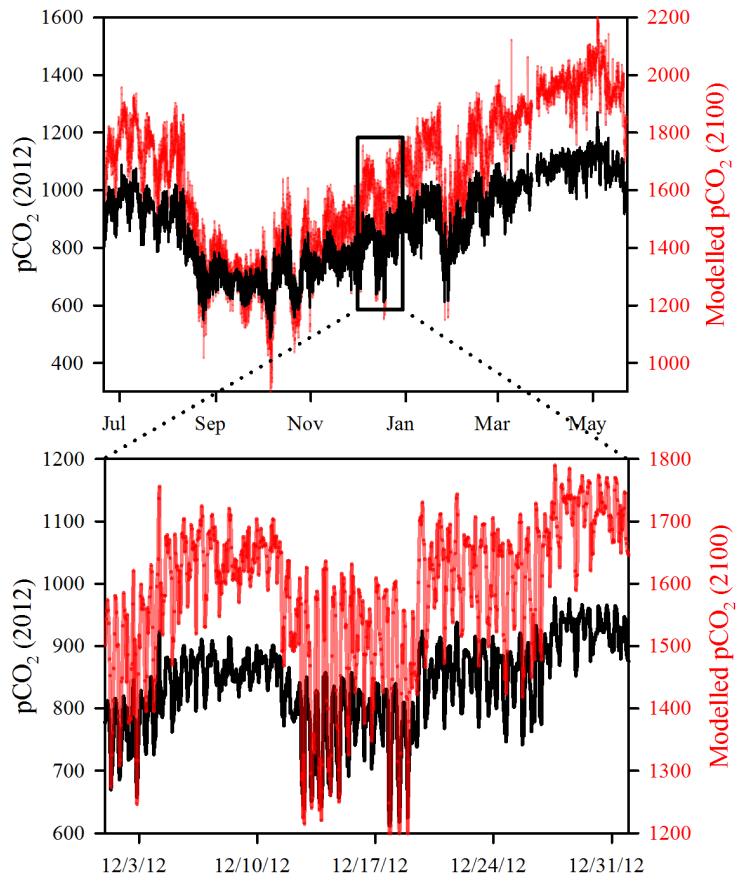


Figure 8. Observed $p\text{CO}_2$ in 2012 (black) and modeled $p\text{CO}_2$ using the IPCC RCP 6.0 scenario for the year 2100 (red) at the Del Mar Buoy (88 m) over an annual cycle (top). A close up for the month of December is shown on the bottom. Note that the range, but not the absolute values, of the vertical axes for each figure is the same.

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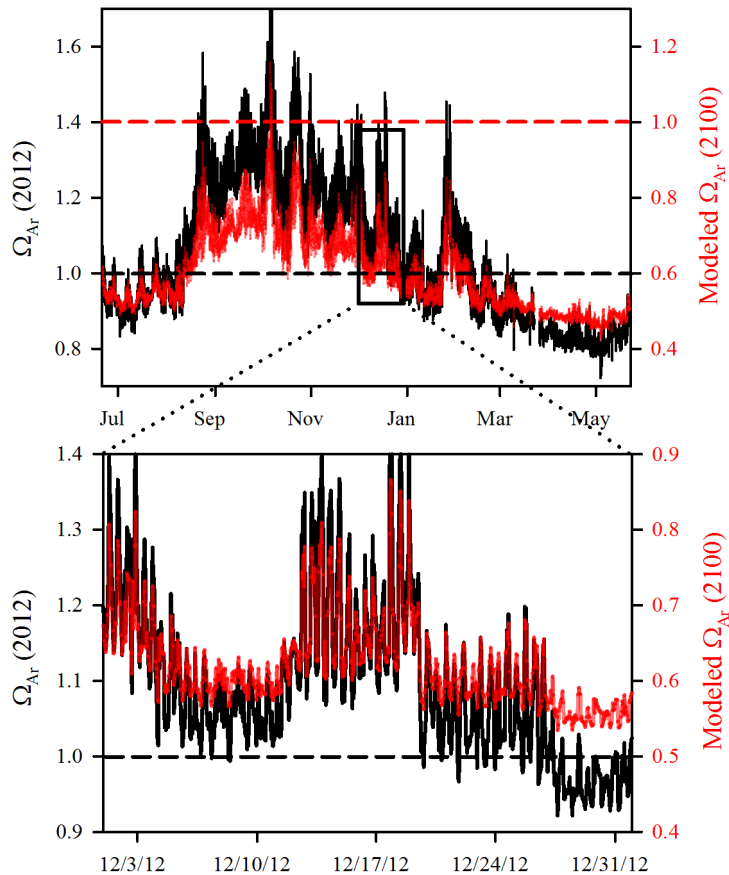


Figure 9. Observed Ω_{Ar} in 2012 (black) and modeled Ω_{Ar} using the IPCC RCP6.0 scenario for the year 2100 (red) at the shelf break (88 m) over an annual cycle (top). A close up for the month of December is shown on the bottom. Dashed lines represent $\Omega_{Ar} = 1$. Note that the range, but not the absolute values, of the vertical axes for each figure is the same.

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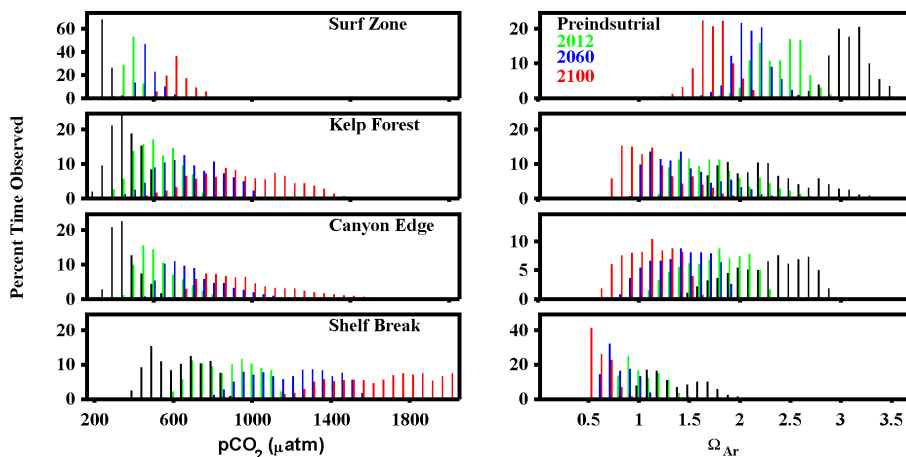


Figure 10. Histogram of modeled $p\text{CO}_2$ (left) and Ω_{Ar} (right) distribution at the four depths for preindustrial (black), 2012 (green), 2060 (blue), and 2100 (red). Atmospheric $p\text{CO}_2$ for the years 2060 and 2100 roughly correspond to 510 and 670 μatm based on the IPCC RCP6.0 scenario.

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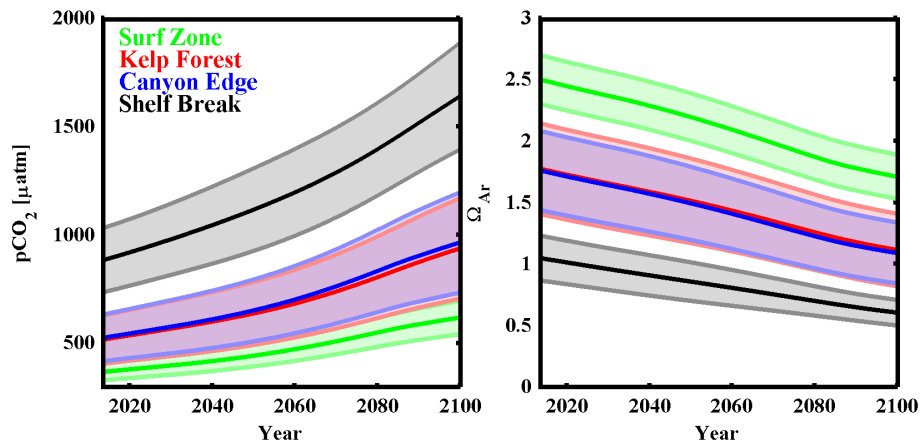


Figure 11. Projected $p\text{CO}_2$ (left) and Ω_{Ar} (right) between 2013 and 2100 under the IPCC RCP6.0 scenario. The solid line and the shaded region represent the mean and ± 1 SD, respectively.

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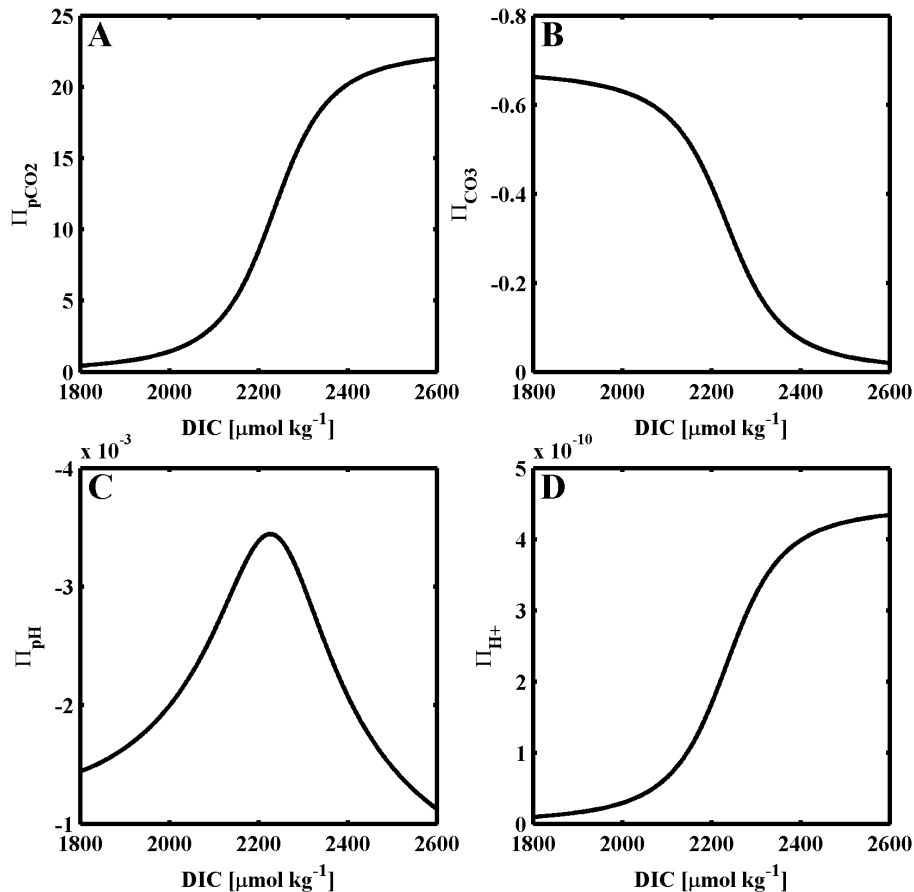


Figure 12. Buffer factor Π for $p\text{CO}_2$ (a), CO_3^{2-} (b), pH (c), and $[\text{H}^+]$ (d) as a function of DIC. Note the inverted y axis in (b) and (c). Model parameters to calculate the Π values were: TA = $2240 \mu\text{mol kg}^{-1}$, temperature = 10°C , salinity = 33.5, pressure = 1.013 bar.

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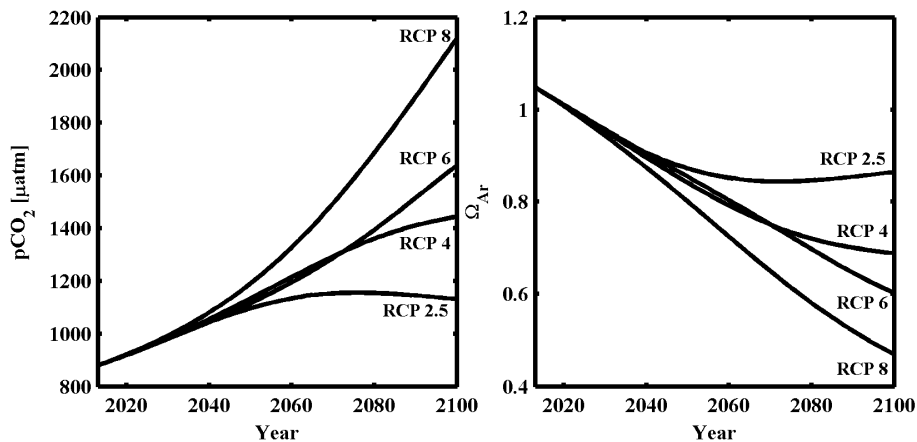


Figure 13. Projections of mean $p\text{CO}_2$ (left) and Ω_{Ar} (right) at the shelf break (88 m) based on four projections from the Fifth Assessment of the IPCC.

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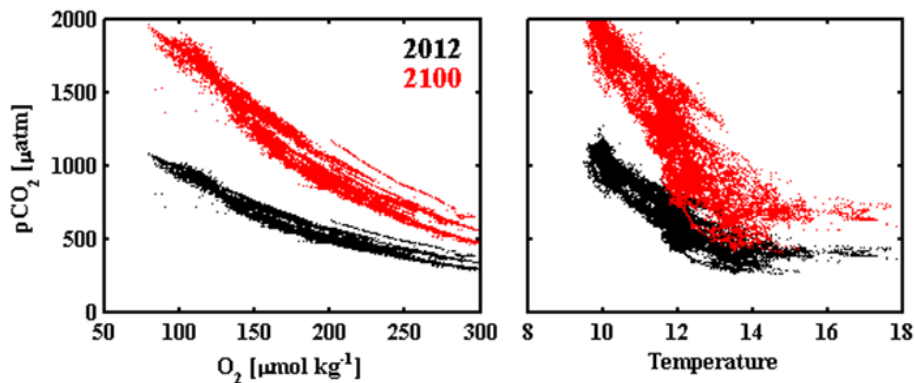


Figure 14. $p\text{CO}_2$ as a function of O_2 (left) and temperature (right) from the kelp forest and shelf break. Data observed in 2012 and projected for 2100 are plotted.

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