CCE Moorings

(Moored Climate, Carbon, Biogeochemical, and Ecosystem Observations in the Southern California Current System)

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1. Project Summary

The California Current is a region of large ecological significance and known sensitivity to climate forcing. Climate processes, complex physical systems, carbon and nutrient chemistry, and ecosystem dynamics all interact to create a rich, societally important, and scientifically fascinating ocean environment off the west coast of the US. The CCE mooring project has established a unique highly multidisciplinary timeseries presence in the southern California Current, to complement ship-board observations from LTER and CalCOFI, glider and remote sensing observations, and the flow and transport monitoring system that has been initiated under CORC, and to start building a comprehensive continuous real-time monitoring system for this region.

The two moorings now operating, called CCE (California Current Ecosystem)-1 and CCE-2, are located in the offshore core and the coastal upwelling regime of the California Current along CalCOFI (*California Cooperative Oceanic Fisheries Investigations*) line 80, respectively and measure

- **atmospheric conditions** (x(CO_2), wind, temperature, humidity, precipitation, irradiance),
- **upper ocean conditions** (temperature, salinity, p(CO_2), O_2, pH, currents, point and integrated measures of phytoplankton chlorophyll content over the euphotic zone, and nitrate supply),
- **multi-frequency active-acoustic observations** of zooplankton and fish biomass.

Most of the data are telemetered in real-time and publicized via websites to other researchers, agencies, and the public.

The CCE moorings are intended to serve as an example and nucleus for enhanced autonomous observations of the California Current climate system, carbon cycle, ocean acidification (OA) processes, and ecosystem changes. They also represent a real step toward a recognized need in the sustained ocean climate observing system – techniques and implementations of observing infrastructure that jointly address the societal challenges driving the climate, ocean biogeochemistry, and living marine resources research agendas. This capability was clearly identified as a major need at the OceanObs09 conference in Venice. The merging of many new technologies, the highly collaborative nature of the mooring work, and the merging of several funding sources, is a promising example of how to enable such observations in the future.

The supported activities include operation of the two highly instrumented real-time moorings along CalCOFI line 80 and preliminary processing of the data. The activities include construction of moorings, execution of cruises, servicing and calibration of sensors, upgrading of technology, QA/QC of data streams, and participation in west coast wide ocean acidification research.

The anticipated products and outcomes include:

- long records and improved understanding of the processes and variability in the physical, biogeochemical, and ecosystem conditions in the southern California Current System
- improved understanding and assessment of fish stocks and migration in relation to habitat conditions
- data sets to develop and validate biogeochemical models
- integration of the data with other OA and ecosystem programs along the US west coast.

The users/applications include the carbon, OA, ecosystem, and fisheries research communities and agencies, modeling centers, fisheries management programs, as well as commercial fishermen. The data complement and add value to the regular ecosystem and stock assessment ship surveys along the west coast.

2. Scientific and Observing System Accomplishments

a) Field Work and Data Holdings

As already described in the last progress report, the CCE1 mooring was struck by a ship in April 2013 and it took until September 2013 to build a new mooring and re-deploy it, using the RV *R.G. Sproul*. The lesson from that accident was that it would be highly desirable to have an AIS (automatic vessel collision warning system) on the mooring, and for the subsequent CCE2 deployment we found a way to get the required licenses and hardware to work on our moorings.

Thus the CCE2 mooring deployed in April 2014 carried an AIS. The CCE2 mooring now has surface sensors for pCO_2, a SAMI-pH, and a Seacat (T/S) with a chlorophyll sensor and oxygen optode (all from PMEL) and a SeapHox pH/O_2 sensor (SIO), in addition to the usual meteorological and irradiance sensors and the 75 kHz long-ranger ADCP. At 15m there still are sensors for nutrients, pH, oxygen, chlorophyll, and T/S. At 40m we continue to have the 7-wavelength irradiance sensor, and at 75m an oxygen optode. The up/downward-looking acoustic backscatter sensor (AOS) from SWFSC is again located at 150m. The T/S measurements are collected at 1m, 7m, 15m, 27m, 45m, and 75m.

In October 2014 the CCE1 mooring was recovered and redeployed from the RV *New Horizon*. Project funds were used to replace some of the sensors lost during the previous breakage of the mooring, and the current configuration now includes surface sensors for pCO_2, a SeapHet-pH, and a Seacat (T/S) with a chlorophyll sensor and oxygen optode (all from PMEL), in addition to the usual meteorological and irradiance sensors and the long-ranger ADCP. At 30m we have a chlorophyll sensor, and at 40m the suite of nutrients, pH, oxygen, chlorophyll. At 80m there is the lower 7-wavelength irradiance sensor, at 150m the up/downward looking AOS, and T/S sensors are at 1m, 10m, 20m, 30m, 40m, 60m, 75, 150m 300m, 500m, 750, and 1000m (all for calculating dynamic height), one at 2250m, and a deep OceanSITES microcat at 3950m.

Most sensors are delivering data in real-time, with the exception of one SeapHox on CCE2 and the AOS on CCE1 at present. The data are displayed on the CCE website (http://mooring.ucsd.edu/CCE) and the realtime data are now available for download there. Further, both surface buoys carry acoustic modems for telemetering data from bottom-mounted PIES (bottom pressure plus inverted echosounder) at the same locations.The current total data holdings are shown in figures A1 and A2 in appendix A, including the current data being telemetered.

b) Data Processing and Scientific Analyses

It is important to recognize that the CCE1 and CCE2 moorings also leverage other, complementary types of programs and measurements in the southern California Current Ecosystem. These include the shipboard CalCOFI measurements; NSF-supported California Current Ecosystem Long-Term Ecological Research site; the NOAA CORC program; *Spray* ocean glider lines; satellite remote sensing; nearshore measurements made by SCCOOS, the Scripps pier, and the nonprofit Ocean Institute; the Del Mar mooring; a deep-sea benthic time series run by Ken Smith at MBARI; and different coupled modeling programs (see **Fig. 1**). This ensemble of measurements has created a unique, critical mass of integrated physical, biogeochemical, ecosystem, and fisheries measurements that are vital to understanding processes acting on different time and space scales.

Our results are relevant to several NOAA interests, including climate effects on a major Eastern Boundary Current Ecosystem, ocean acidification, deoxygenation (hypoxia), changing nutrient supplies, plankton feedbacks to ocean biogeochemistry, and assessment of fish stocks in the California Current Ecosystem (CCE). In particular, using the multi-disciplinary mooring data, we can study the physical/climate forcing of events and perform budget estimates relevant for the above topics.

The prior and ongoing analyses and results illustrate that the continuous CCE (and the Del Mar) time series observations now enable us to resolve multiple time scales of forcing and processes in the southern California region, including diurnal and internal tides (ca. 1 day), upwelling and mixing events (ca. 1 week), changes in source water masses (ca. months to a year), and ENSO (ca. 2-7 years). We wish to stress that a key characteristic of changing climate characteristics in the ocean are the **altered statistical distributions**of high-frequency perturbations, or 'event-scale' phenomena. For example, with our new ability to recognize individual upwelling 'events' from the CCE2 mooring, it has become clear that the **magnitude, frequency, and duration** of upwelling events are much more important to marine organisms than the seasonal mean

upwelling conditions. Changes in the statistical distributions of these events that accompanying climate alterations will markedly affect marine organisms and populations.

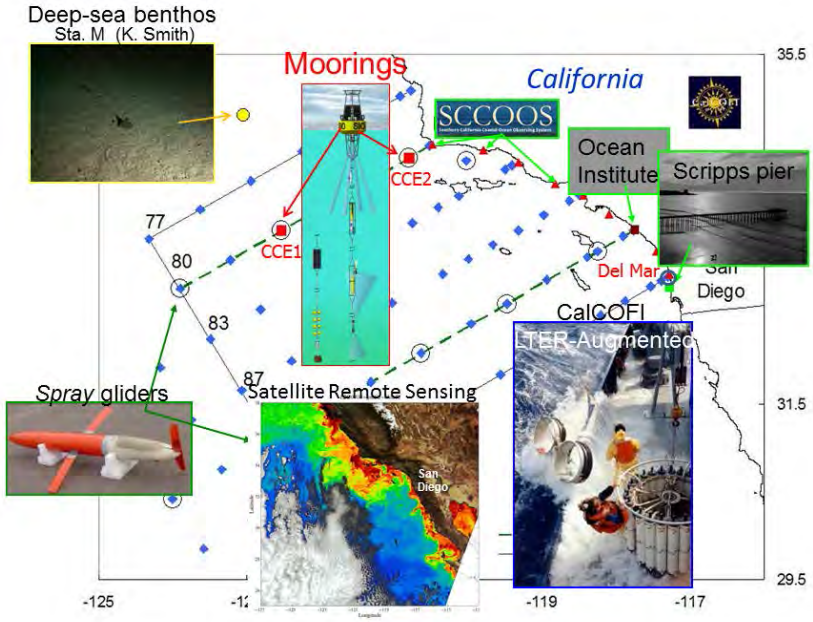

Fig.1. *CCE1 and CCE2 moorings, together with other, complementary measurement programs in the southern California Current Ecosystem.*

In previous reports we had already presented results about high-frequency physical forcing, including internal tides, about upwelling events (including demonstration of the importance of non-local winds for upwelling indices), and the construction of nutrient/chlorophyll budgets. A *new* result which also may have relevance for the unusual warm and unproductive conditions, concerns the variability in water masses. **Figure 2** shows an index of north/south water mass properties at the CCE2 and Del Mar mooring, red indicating water of southern origin. In the last two years there seems to be more southern water than usual. This is consistent with the reduction

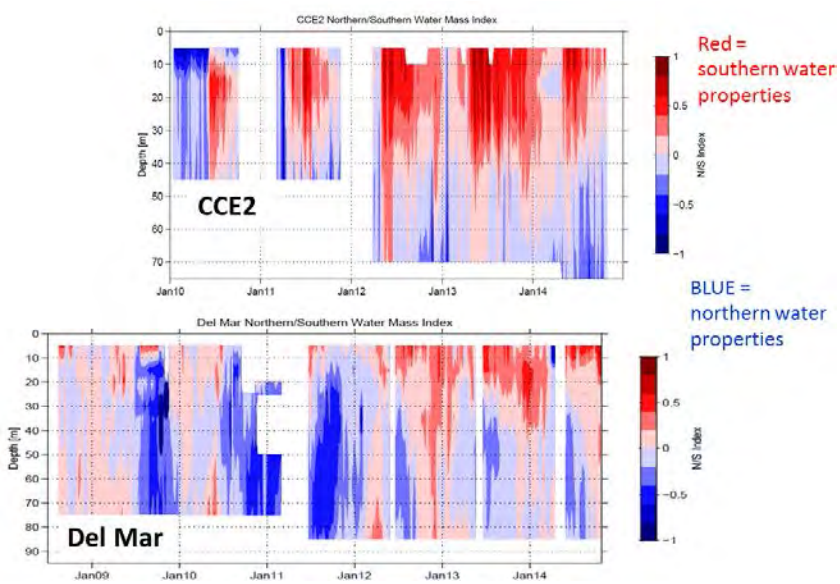

Fig. 2*. Index (based on temperature and salinity at constant density) for the likely origin of water properties. Red means water of southern origin (saltier) while blue shows water of more northern origin. There is more southern water found at CCE2 and Del Mar in the past two years.*

in northern Sardine stock habitat and in acoustic detections of near-surface fish (where sardines are found) in the last 2-3 years (**Fig. 3**). The currents observed at CCE2, integrated into the form of 'progressive vector

diagrams', show the advection of water from the south which is most likely the cause of this (**Fig. 4**): in the latter half of 2012 and 2013 there was more northward advection than in previous years, and in 2014 this flow from the south was even present from the beginning of the year. For 2014, this could have created unusual warm, stratified conditions in the region prior to the onset of the upwelling season, leading to upwelling of warm, nutrient-poor, and relatively low CO_2 water in 2014.

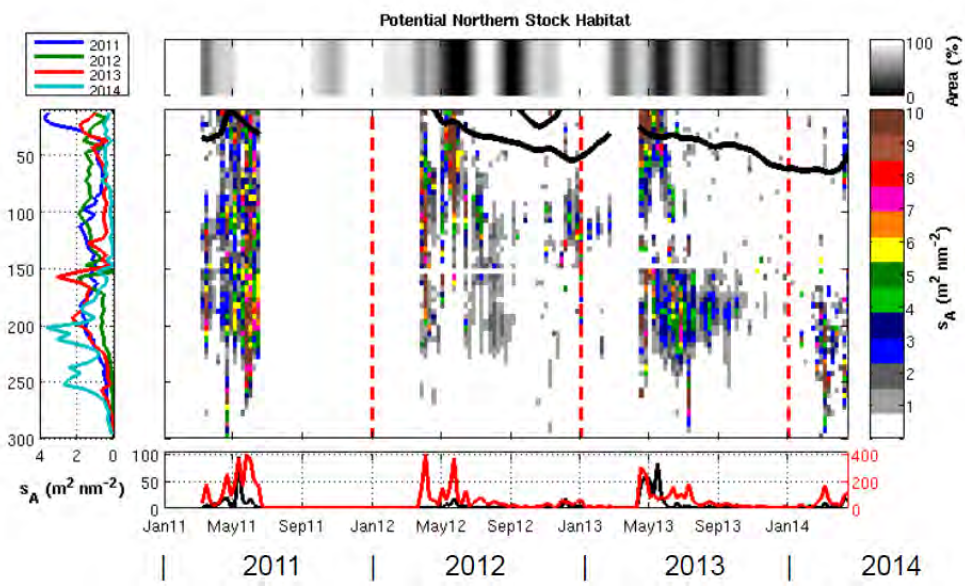

***Fig. 3**. Acoustic detections of pelagic fish on CCE2 over the upper 300m and last 3 years (main panel). Dark color in the upper panel indicate reduced northern sardine habitat. In the last 2 years, most detections were below the depth of sardines.*

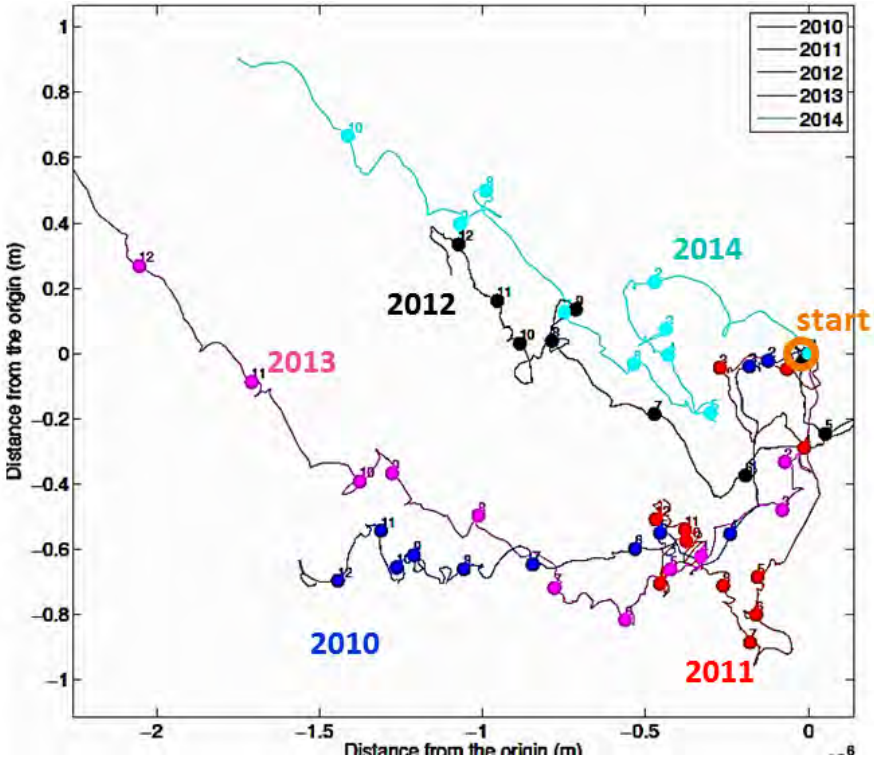

***Fig. 4**. Progressive vector diagram (time integral) of upper-layer currents measured at the CCE2 mooring. Each such artificial trajectory starts in January of each year at the orange circle. The months are marked with circles and numbers of the month. Usually there is offshore motion in the first half of a year, but in 2014 it goes north from the beginning. Also, overall more northward flow since mid-2012.*

As mentioned, the CCE1 and CCE2 moorings have revealed the biological importance of 'event-scale' phenomena in the coastal ocean, as illustrated in **Fig. 5**. Note that the NO_3 increases and corresponding O_2 and pH decreases associated with upwelling events are large in magnitude and of short duration (i.e., a few days). In contrast to the CalCOFI cruise measurements (red lines, Fig. 2), which are conducted only four times per year and suggest broad seasonal patterns of change, the high frequency mooring measurements show pronounced short-term excursions that markedly alter the conditions for phytoplankton growth, the carbonate environment for shell-bearing organisms, and the dissolved oxygen concentrations for all organisms. At the same time, the CalCOFI measurements are vitally important because they provide the 'gold standard' for calibration of the mooring measurements. CalCOFI measurements make it possible to correct for baseline drift and other sensor issues, and to develop confidence in data quality.

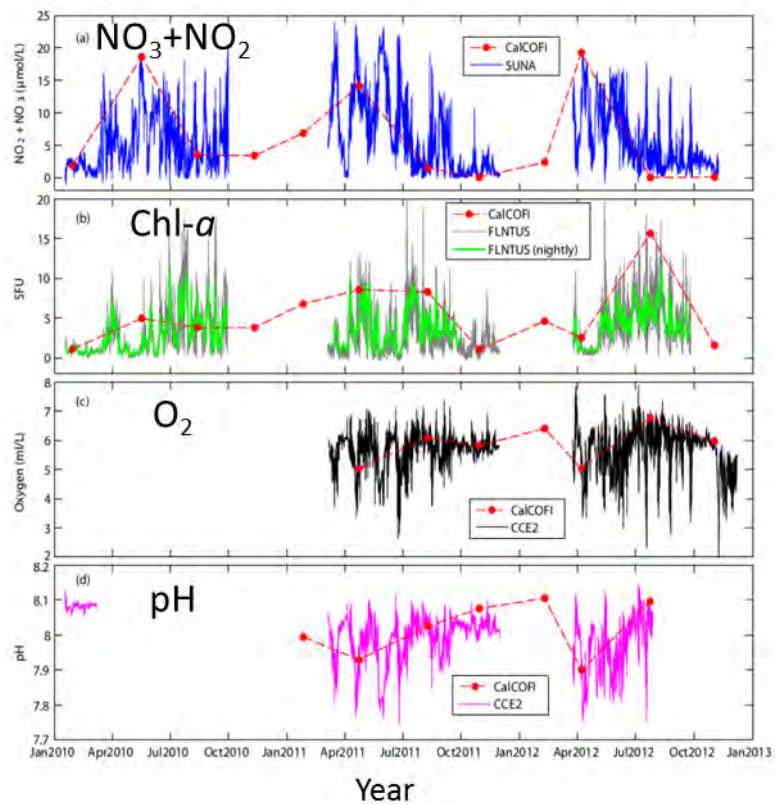

***Fig. 5**. (Solid colored lines): Autonomous mooring time series of properties at 16 m depth at the CCE2 mooring. (Dashed red lines and dots): Measurements made by the quarterly CalCOFI cruises at station 80.55, corresponding to the mooring location.*

A closeup of one upwelling event reveals the detailed time course of pulsed NO_3 supply and associated efflux in pCO_2 that we can now resolve (event on 15 March, **Fig. 6**). There is a several day time lag before phytoplankton Chl-*a* increases in response to the elevated NO_3 availability. Then, accompanying the phytoplankton biomass increase, there is a corresponding drawdown in pCO_2 and NO_3 (**Fig. 3**, dotted lines). The high temporal resolution of measurements makes it possible to resolve these cause and effect relationships and the quantitative relationship between biological and geochemical changes in the ocean.

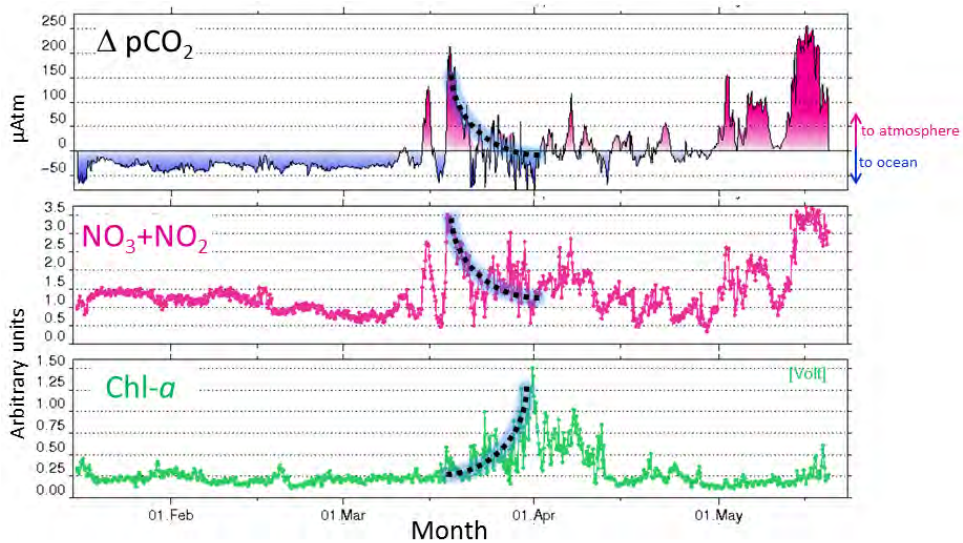

Fig. 6. *Time series measurements at the CCE2 mooring through an upwelling event. ΔpCO_2 is the difference between pCO_2 measured in the surface ocean and in the atmosphere just above the mooring buoy. Dashed lines indicate time-lagged growth of phytoplankton Chl-a and corresponding drawn down of pCO_2 and NO_3.*

An example of the benefits of colocating mooring measurements with CalCOFI measurements is Shown in **Fig. 7**, where direct measurements of pH made by Todd Martz with his SeapHOx system are compared with reconstructed pH from the proxy relationship in Alin et al. (2012) that estimates pH as a function of temperature and dissolved O_2. Many of the calibration measurements used in Alin et al. (2012) were from CalCOFI cruises and thus the relationship is directly applicable to the CCE mooring region. The degree of agreement between direct measurements and proxy estimates at one depth can be used to interpret the degree of confidence in proxy-based estimates at other depths where a pH sensor is not located.

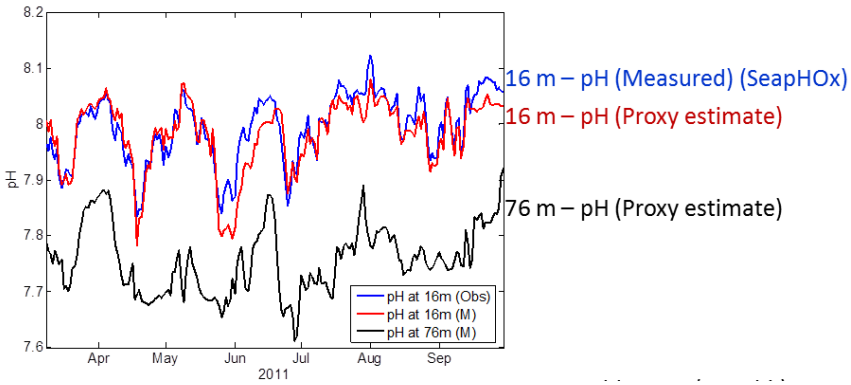

Fig. 7. *Time series of pH measured with a SeapHOx at 16 m depth (blue), and of pH at 16 m (red) and 76 m (black) as reconstructed with the proxy relationship of Alin et al. (2012). Unpublished data from Todd Martz, SIO.*

The quality of our calibrated, QC'd mooring-based measurements is reflected in the excellent agreement of mean property-property relationships with those expected from Redfield ratios (**Fig. 8**, from Martz et al. 2014). The agreement of these mean values permits us to analyze the time-dependent departures from the mean, as shown in **Fig. 9**. **Fig. 9** illustrates the f-ratio, (i.e., (New Production /New+Regenerated Production)), where the f-ratio is an indication of the proportion of primary production that can be exported from the system or used to sustain fisheries harvest. The results show that the f-ratio is relatively close to 1.0 much of the time, as would be expected in a coastal upwelling environment, but there are important intervals when

the f-ratio is at or close to 0. These results imply that there are time periods when most primary production is being fueled by recycled sources of nitrogen (e.g., NH_4, urea), hence unable to sustain carbon export or sustained harvesting.

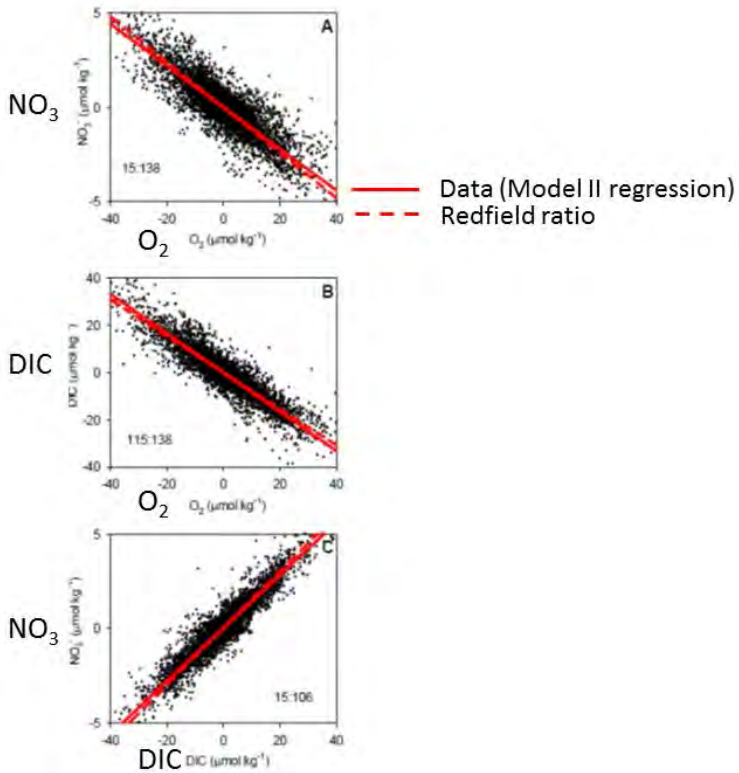

Fig. 8. *The relationship between measured (NO_3, O_2) and proxy-estimated (DIC) properties at the CCE2 mooring. Solid red line indicates a Model II regression fit and dashed red line indicates the Redfield ratio (Martz et al. 2014).*

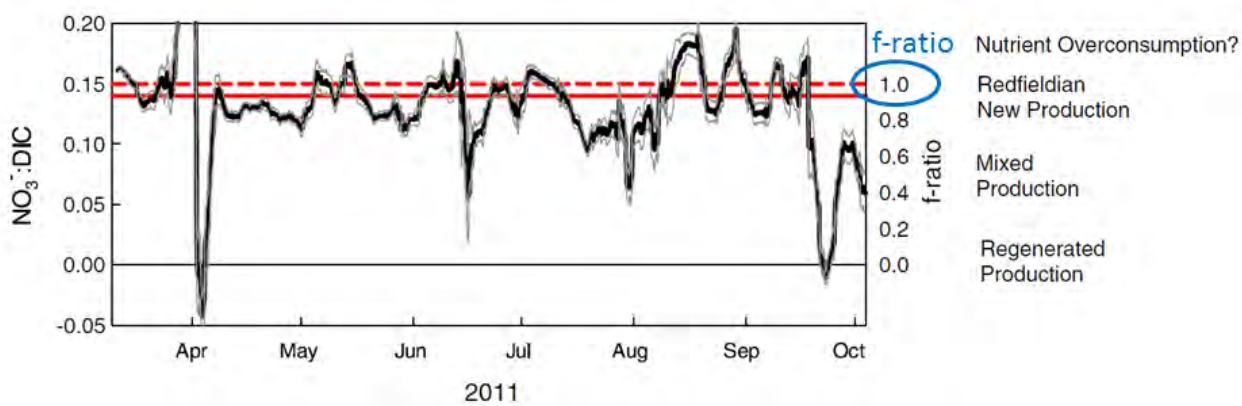

Fig. 9. *Time-dependence of the f-ratio at the CCE2 mooring through most of 2011 (Martz et al. 2014).*

The aragonite saturation state (Ω_{arag}) is an important variable that expresses the tendency of waters to favor aragonite (calcium carbonate) precipitation or dissolution. Our mooring records are now starting to become sufficiently long to be able to record interannual variations in Ω_{arag} and other geochemical properties. **Fig. 10** illustrates that the present year, 2014, was markedly different from the two preceding years with respect to aragonite saturation state. In the second quarter of 2012 and 2013, a series of upwelling events repeatedly caused Ω_{arag} to decline to <1.0 (green line), as we would expect from results presented in **Figs. 5-7** above. However, in 2014,

waters at this depth (76 m) never reached undersaturation conditions, implying that the euphotic zone was favorable for aragonite shell precipitation throughout the year. We are currently analyzing the changes in ocean and atmosphere circulation in 2014 that caused these anomalous conditions, but the result illustrates the importance of understanding interannual variability in the ecosystem. Such unusual years may be important determinants of survival and recruitment of marine populations in the California Current Ecosystem.

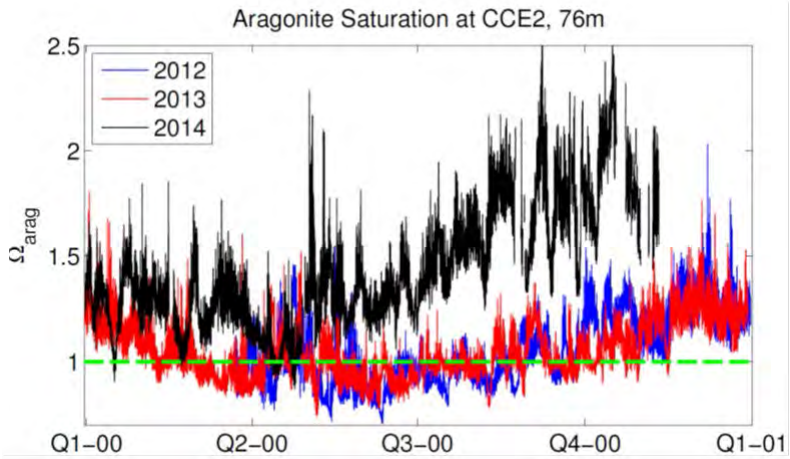

Fig. 10. *Time series of aragonite saturation state (Ω_{arag}) at a depth of 76 m at CCE2, across 3 years. Note the more typical series of undersaturation events (Ω_{arag} < 1.0) in 2012 and 2013, but the marked change in 2014.*

c) Specific questions

- How did your project deliverables address the program's priorities to provide information about the state of the world's ocean and its regional variations to address important societal needs related to the Earth's climate, including delivering continuous instrumental records for global analyses of:
  - sea surface temperature and surface currents,
  - ocean heat content and transport,
  - air-sea exchanges of heat, momentum, and freshwater,
  - sea level, and
  - ocean carbon uptake and content?

  The CCE moorings provide high-temporal resolution surface currents, heat content and transport, which represent the basic forcing of the carbon and ecosystem. The integrated carbon sensors allow analysis of the processes controlling ocean acidification and carbon uptake/release. The ecosystem and fish instrumentation gives crucial information on the impact of physical/chemical/OA changes on the ecosystem and fish habitat. The moorings thus are ideally positioned to contribute also to the societal challenge/cross-cutting theme of marine ecosystems in a changing climate.
- What were your primary achievements during FY 2014?

  - Two successful mooring turnarounds; data telemetry; and sustained sensor operations.
  - Implementation of standardized protocols for data QC.
  - Development of rigorously calibrated/validated time series of important physical, biological, and biogeochemical variables.
  - Inference of the f-ratio (New Production/New+Regenerated Production) from high frequency mooring data

- Linkage of moored acoustic fish detection (sardine) with water mass and flow regime changes

- What scientific advances were made and/or facilitated through your activities? (For multi-institution proposals, provide your top 2 or 3 advances.)
  - Recognition of unanticipated interannual variability, specifically the anomalous warm water, low chlorophyll waters of 2014, an event that does not appear to be El Nino-related. This event was accompanied by waters supersaturated with respect to aragonite at depths that are more typically undersaturated during the upwelling season. These supersaturated waters provided substantially more vertical habitat for aragonite-secreting organisms than expected. In addition, the warm-water anomaly of 2014 appeared to affect the migration of small pelagic fishes through the southern California region.
  - Recognition that the most commonly used index of coastal upwelling in the California Current System and elsewhere is often a poor predictor of the actual upwelling measured in situ by our mooring.
  - The f-ratio, a biogeochemical index that measures the proportion of primary production that is supported by sources of N from outside the euphotic zone, is highly dynamic and varies from very high values to surprisingly low values.
- What is the significance of these advances?
  - The causal mechanisms underlying the warm water anomaly of 2014 are still being evaluated, but this event implies that there can be pronounced interannual perturbations to the California Current ecosystem that do not appear to be related to the ENSO cycle. These perturbations affect the geochemical environment for shell secretion of some marine organisms and influence the migration pathways of some epipelagic fishes.
  - We expect to develop a much more useful index of upwelling that should markedly improve the ability to quantify this important process.
  - Sustained low values of the biogeochemical f-ratio imply that primary production is not always fully available to support coastal fisheries, even in a coastal upwelling environment.
- What, if any, impediments were encountered and what information was jeopardized due to a lack of funding, lack of instrumentation, or inability to carry out the work?
  - Weather conditions were quite marginal in late October 2014, resulting in a difficult mooring turnaround that could not be done from a smaller or less capable vessel. It would be far preferable to service the moorings in late summer when wind conditions are more acceptable.
  - We are still attempting to build our equipment pool to the point where we have spares on hand in case of instrument failure at sea. Building the instrument pool plus another surface buoy would also make it possible to service both the CCE1 and CCE2 moorings on the same cruise, which would result in a large savings in ship costs.
  - Funding limitations (translating to lack of manpower) mean that we are behind in quality control and disseminating the data
- What is the website for your program?
  http://mooring.ucsd.edu/cce
- Are your data distributed in real time on the Global Telecommunications System?
  no
- Where do your real time data reside? Are the data available online?

The real time data reside on our server and can be downloaded (in unverified form) from the CCE-1 and CCE-2 portion of the above website. We are working on automating delivery also to OceanSITES.

- Where do your delayed mode data reside? Are the data available online?
  We are in the process of making the delayed-mode and quality-controlled data also available at the above website. Once that is done, they will also go to OceanSITES.
- When did you make your most recent data publicly available?
  Last week
- Where are your data archived and with what frequency?
  OceanSITES is presently developing an archival system for their data holdings, which will include the CCE mooring data uploaded there. The data are also archived at an institutional server within Scripps Institution of Oceanography.
- What is the website where the data for your program can be accessed? If you haven't updated your website recently, please do so now.
  http://mooring.ucsd.edu/index.html?/projects/cce/cce1_08_tele_data.html
  http://mooring.ucsd.edu/index.html?/projects/cce/cce2_05_tele_data.html
- Have you successfully retrieved your program's data from the website or Data Assembly Center where your data reside to ensure the accessibility of the data? If not, please do this now and address any problems with data access.
  Yes.
- Do you have a publications supported through COD funding? We encourage your bibliographies to be posted online.
  Yes, we are implementing a bibliography on the above website.
- How are you tracking uptake and use of the data and products produced by your project? Some have found it helpful to establish a standard and recognizable name (e.g.. Argo, OceanSITES)? We encourage this approach to improve the recognition, discoverability, and visibility of your project.
  Colleagues we know usually inform us about publications and data requests in person. OceanSITES is developing tools to track download of the data from the ftp servers.
- How do you direct users of your data to acknowledge its use?
  The OceanSITES data files contain a request to this effect in the metadata.
- Do web pages that provide data and products from COD support acknowledge CPO/COD support?
  The CCE mooring website does so

3. Outreach and Education

We wrote an article for the general readership magazine "Oceanography" (Ohman et al. 2013) that illustrates for the general public the value and importance of autonomous mooring (and other autonomous) measurements in the California Current Ecosystem region. Our website posts real-time data to all who may be interested. The value to the public is illustrated by a concerned email we received from a sea urchin fisherman when our transmission of pCO2 data was temporarily interrupted. Unbeknownst to us, he relies on these data in his business.

In addition, the present project supports two Ph.D. students at Scripps (Catherine Nickels, Sam Wilson), who are benefitting from this interdisciplinary training. Several other graduate students have participated in mooring servicing cruises.

4. Publications and Reports

4.1. Publications by Principal Investigators

- Published

Ohman, M. D., Rudnick, D.L., Chekalyuk, A., Davis,R.E., Feely, R. A., Kahru, M., Kim, H. J., Landry, M. R., Martz, T. R.,S abine, C., Send, U. 2013: Autonomous ocean measurements in the California Current Ecosystem. *Oceanography*, **26,** 18-25. doi http://dx.doi.org/10.5670/oceanog.2013.41.

Martz, T., Send, U., Ohman, M.D., Takeshita,Y., Bresnahan, P., Kim, H.-J., and Nam, S. 2014: Dynamic variability of biogeochemical ratios in the Southern California Current System. *Geophys. Res. Lett.*, **41,** 2496-2501. doi 10.1002/2014GL059332

Bresnahan, P.J. Jr., Martz, T.R., Takeshita, Y., Johnson, K.S., LaShomb, M. 2014: Best practices for autonomous measurement of seawater pH with the Honeywell Durafet, *Meth. Oceanogr.*, **9**, 44-60, ISSN 2211-1220, http://dx.doi.org/10.1016/j.mio.2014.08.003

4.2. Other Relevant Publications which cite this work

Malone, T. C., P. M. DiGiacomo, E. Goncalves, A. H. Knap, L. Talaue-McManus, S. de Mora, and J. Muelbert, 2014: Enhancing the Global Ocean Observing System to meet evidence based needs for the ecosystem-based management of coastal ecosystem services. *Natural Resources Forum*, **38,** 168-181.

Appendix A:

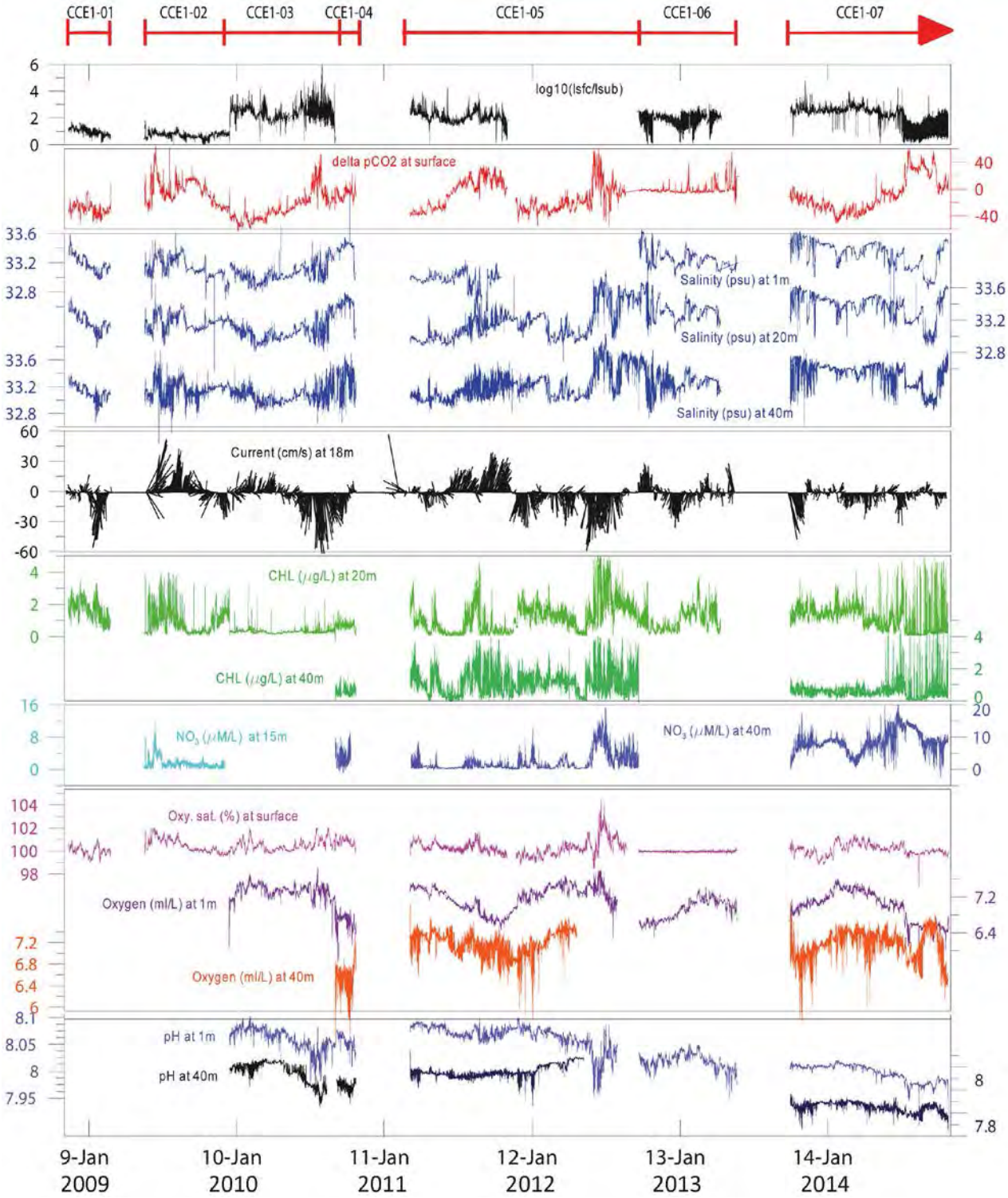

Figure A1*: Available data from all CCE1 mooring deployments for: surface-subsurface radiometers (showing a logarithmic ratio), water-air pCO2 difference (PMEL sensors), some of the T/S sensors (showing salinity), currents at 20m (mostly from an ADCP covering the upper 500m), chlorophyll estimates, nitrate concentration, dissolved oxygen data from several depths, and pH readings from two depths. All data are raw with factory calibration.*

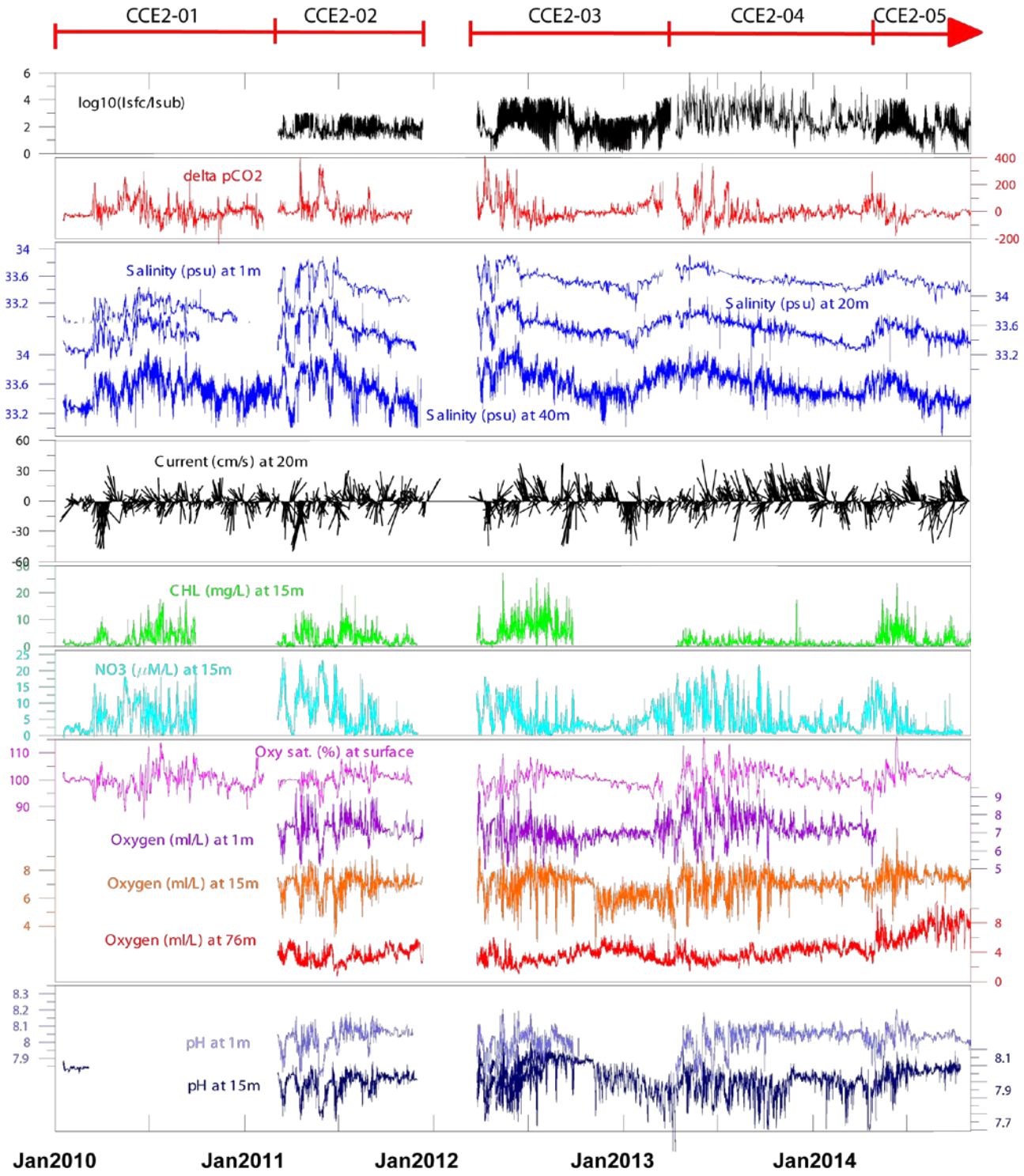

Figure A2*: As for figure A1, but for the CCE2 mooring.*