CCE Moorings

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

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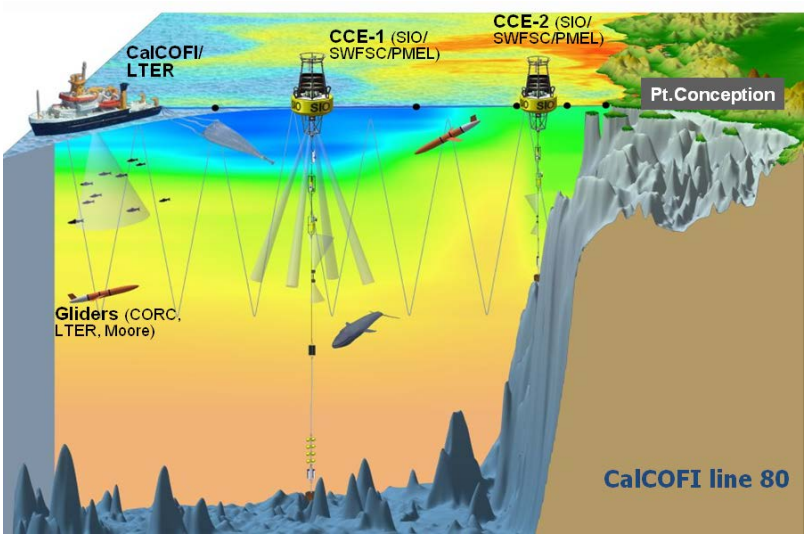

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1. Project Summary

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, complementing ship-board observations from LTER and CalCOFI, glider observations, satellite remote sensing, and the flow and transport monitoring system that has been initiated under CORC, and has initiated 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 California Current and the coastal upwelling regime, respectively, alongCalCOFI line 80, 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 concentration),
- **two-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 and agencies.

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 processes, and ecosystem changes. They also represent a real step towards a recognized need in the sustained ocean climate observing system – techniques and implementation of observing infrastructure that addresse the societal challenges motivating the climate, biogeochemistry, and ecosystem community. This type of integration was clearly identified as a major need at the OceanObs09 conference in Venice. The merging of many new technologies, the highly collaborative nature, and merging of different funding sources, is a promising example of how to enable such observations in the future. CCE1 and 2 are possibly the first sustained US sites which are aimed at filling this gap in the global ocean observing system.

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

The developing products and outcomes include:

- long records of the processes and variability in the physical, biogeochemical, and ecosystem conditions in the southern California Current
- 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 community and agencies, modeling centers, and fisheries management programs. The data complement and add value to the existing ecosystem and stock assessment ship surveys along the west coast.

2. Scientific and Observing System Accomplishments

a) Field Work and Data Holdings

The FY2011 funding was used for the first installation of two nearly identical moorings, CCE1 and CCE2 along CalCOFI line 80 in March 2011. See figure 1 for the locations in the offshore and the upwelling regimes off Pt.Conception, respectively. Figure 2 shows the CCE2 sensors in the upper 150m as an example. Prior to these deployments, CCE1 had been deployed and operated from December 2009 until October 2010 with NOAA funding (OCO and NMFS), while CCE2 was in the water as an unfunded scaled-down demonstration mooring. In October 2010 an old, borrowed titanium load cage in CCE1 broke and lead to mooring failure. The drifting buoy plus upper instrumentation were all successfully captured and retrieved. Subsequently, he bottom half of the mooring was retrieved during the redeployment cruise in March 2011, but some instruments that fell to the seafloor were crushed and flooded.
Due to the prolonged uncertainty in FY2011 funding, the re-deployment of CCE1 had to be delayed until spring 2011 (without funding it would not have been possible to continue the effort). Therefore the CCE1 timeseries shows a 6-month gap from Oct 2010 until Mar 2011. We have some demonstration deployments and data from the phases prior to NOAA funding, including CCE1 from two periods during November 2008-December 2009 and CCE2 during January 2010-March 2011. The resulting data streams from all those deployments together, for the main water column instruments (excluding the acoustic backscatter Echotag/AOS sensors and the radiometers) are shown in figures 3 and 4. It should be noted that this figure does not do justice to the richness of information due to the compressed scale. For demonstration, a zoomed view of just the first 3 months from Nov 2008-Feb 2009 is shown as an inset in figure 3 (taken from the original proposal for CCE1).

As shown in the data figures and the mooring diagrams, we have upgraded the moorings in a number ways with the new funding. At CCE1 there are now additional oxygen and pH and chlorophyll fluorescence sensors (all at 40m). At CCE2 we have added several oxygen sensors in response to research and suggestions by S.Alin and R.Feely (PMEL) and added a second pH sensor.

In addition, both moorings always carry a 7-wavelength irradiance sensor at the surface (on the buoy) and at varying depths (now 80m and CCE1 and 40m at CCE2). From the wavelength-specific overall light attenuation we are analyzing the vertically integrated total chlorophyll content in the upper water column, including the deep chlorophyll maximum – this is work in progress, see below. This integrated measure is complementary to the point source measurements made by fluorometers at fixed depths.

Further, we have deployed acoustic zooplankton/fish backscatter systems by D.Demer from SWFSC on the moorings. These instruments are still under development, but have already given useful datasets covering the upper 150-300m of the water column (depending on deployment). The summary of deployments from these instruments is given in Table 1.

During a recent mooring servicing cruise (without mooring recovery/deployment) in November 2011 we measured and analyzed the spatial gradients in the vicinity of CCE1 and CCE2. The purpose was to assess the variability in near-surface properties from the ship's seawater intake system, as well as sub-surface variability from a free-fall Moving Vessel Profiler (in the upper 200 m). Knowledge of these horizontal gradients ($\frac{\partial C}{\partial x}, \frac{\partial C}{\partial y}$) is important for estimating sea-air fluxes as well as interpreting the time series measurements from moored instruments. The results, summarized in table 2 and figure 5, indicate that on a scale of 15-20 km there is a stronger horizontal variability in the NW to SE direction in the offshore CCE1 mooring, but more pronounced variability in the NE to SW direction at the nearshore CCE2 mooring. We also periodically direct our line 80 *Spray* glider to complete a pattern of repeated dives around these moorings, to further evaluate sensor stability and drift.

New deployments of the moorings are currently planned for March 2012 (CCE2) and early summer 2012 (CCE1).

b) Data Processing and Scientific Analyses

We are allocating considerable effort to calibration and quality control of the data. As the raw plots in figures 3 and 4 show, some instruments have large offsets and/or drifts, others need work to convert the raw data (such as chlorophyll fluorescence) to the quantities that are sought. We are pursuing multiple methods for such calibration efforts, including lab calibrations, in situ comparisons of mooring sensors with independent bottle samples taken with a CTD rosette (for comparing the sensors readings with analyzed values from water samples at the site), the Moving Vessel Profile spatial survey described above, mooring-glider comparisons, and mooring-shipboard comparisons with the high quality CalCOFI analyses done four times per year very close to the locations of CCE1 and CCE2. Lab-based comparisons are done before and after the cruise, in order to verify the linearity of instrument response, record instrument drift, and assess the effects of biofouling. Together with factory calibrations this gives a complicated set of information that needs to be used in the most objective way and also requires careful management.

In order to share these calibration data and metadata, a Wiki site has been created by the Ohman lab that is the repository of a tabular chronology of instrument calibrations by serial number (figure 6 left, in blue), together with a hypertext link to the actual calibration measurements (figure 6 right), permitting users to examine details of the laboratory calibration measurements if desired. In some cases, a photograph illustrating the status of the sensing surface of the instrument is also accessible (figure 6 bottom left).

In processing the data, we are trying to use results from ship surveys from CalCOFI and CCE LTER as ground truthing/validation. The goal is to create a data set that consistent with the ship surveys, but interpolates in time to highlight the changes, processes, and events that ships (or gliders) cannot capture. One effort towards this is the analysis of the irradiance data from the surface and 80m/40m depth. We had shown in previous reports and the proposal that the logarithm of the light decay is well correlated with the chlorophyll estimates from the fluorometer, but that was relative and had arbitrary offsets/scalings. Our goal at present is to determine the absolute chlorophyll content of the water column, and initial analyses look promising: figures 7 and 8 show that using least squares fits to the measured optical attenuation at five wavelengths, determining the absolute amount of chlorophyll and yellow matter, seem to give column average chlorophyll concentrations in very good agreement with the CalCOFI

profiles available. We plan to refine this method to yield accurate estimates of total chlorophyll in the upper water column at CCE1 and CCE2 over long times.

Also acoustic backscatter data are being carefully analyzed. Figures 9 and 10 show the raw backscatter data from the AOS system deployed on CCE2. Backscatter information from the ADCP instruments in the surface buoys is shown later in figure 12.

Carbon budgets

Figure 11 shows our first attempts at building carbon budgets from the CCE moorings. The top panel contains an estimate of dissolved inorganic carbon (nDIC, black line) which was calculated from the pCO2 data and total alkalinity (the latter derived from salinity according to the method by Simone Alin). It is compared with mixed-layer density (at 8m depth), and those timeseries show a somewhat unexpected high degree of correlation.

Ship surveys were used to establish the large-scale DIC gradients alongshore and cross-shore. Then the ADCP currents from the CCE2 were used to estimate the nDIC variability resulting purely from alongshore and cross-shore advection of these gradients. This is shown in orange in the bottom panel of figure 11, and there is quantitative agreement for the overall seasonal evolution and some shorter-term variability. Since the CCE moorings also allow estimation of mixed-layer depth, this will form the basis of carbon (DIC) budget calculations (advection was the largest uncertainty in our thinking until now).

Acoustic backscatter analyses

We are also using use the acoustic backscatter data from the Longranger ADCP also as a proxy for fish concentration. In figure 12 (top panel) the backscatter intensity at 18m (red) is plotted together with the DIC and its advective estimate from figure 11. There is a surprising overall agreement in the variability thatrequires further study. The bottom panel of figure 12 shows a comparison of the backscatter with the chlorophyll estimates from the mooring. There appear to be extended phases of anticorrelation between these quantities, which is a curious result and will require further investigation.

Climate effects

Even though our timeseries at CCE are still short, we have covered part of the recent El Nino/La Nina events and we can start to analyze impacts of these climate processes on the biogeochemical system and ecosystem conditions at the moorings. This analysis is still in the early stages, but some first steps can be shown.

We have calibrated the dissolved oxygen data from our optode sensor, and they compares well with coincident CalCOFI observations. This allows us to use the long CalCOFI data set from 1950 to 2010 to construct a mean seasonal cycle (or a climatology). We can then compare the oxygen data from the El Nino and La Nina years 2009/2010 and 2010/2011 with the typical climatological conditions. At the surface no obvious signals are visible (not shown), and this is not surprising since the oxygen there is mostly in equilibrium with the atmosphere. However at 40m depth (at CCE1) and at 76m depth (at CCE2) there is a clear decrease in oxygen during the La Nina phase, which is also corroborated by the CalCOFI sampling in that period, see figure 13.

We have also started to look for climate signals in the carbon (pCO2) data. There exists no climatology in the region for pCO2, so we need to build it from our mooring data. We have only 3 and 2 years of those measurements so far at CCE1 and CCE2, respectively, but the approach is demonstrated in figure 14. The mean seasonal cycle (red line) is constructed by averaging all the

years together, for which we have mooring data. Then we can compare individual years (blue line) relative to the mean behavior, in order to detect climate-related departures from the mean. So far, the record is too short for finding anomalies, but in a few years this will become an important tool for studying how the climate processes impact the carbon cycle in the California Current.

c) Data Management

All raw data (except for the acoustic backscatter data from SWFSC) are archived and made available to all collaborators on the server of the Send group. The calibration information for all sensors is collected and shared via the Ohman group Wiki site. Realtime data are displayed on the website http://mooring.ucsd.edu/CCE. Within the available resources we make our best effort at quality controlling the CCE mooring data set and providing them to OceanSITES. Much of the temperature/salinity data are mostly processed, and are now available in OceanSITES format via OceanSITES through 2009 (more will follow on a best-effort basis). As explained above, the quality control and calibration for so many multi-disciplinary and novel sensors are challenging and a part of ongoing research efforts. The lack of resources/funding is a definite constraint here. Submission of data to OceanSITES is planned, also for the real-time data streams, but again is limited by manpower.

Summary Information:

a. Project deliverables serving the observing system's program deliverables

- Long timeseries with high temporal resolution of the physical conditions, processes and forcing, representing controls of the carbon and ecosystem in the California Current
- Long timeseries with high temporal resolution of components of the carbon system and ocean acidification processes in the California Current, enabling climate impact research
- Long timeseries with high temporal resolution of ecosystem variability and processes, yielding the response to changes in the physical and biogeochemical conditions

b. Achievements during FY2011

- First deployment of two equivalent highly instrumented realtime moorings across the California Current ecosystem with physical, chemical, carbon, and ecosystem sensors
- Improvements in sensor calibration and data quality control techniques, allowing intercomparisons with other data sets (e.g. CalCOFI)
- Improved inductive communications with real-time telemetry.
- Analyses of carbon (DIC) budgets
- analyses of climate anomalies in subsurface oxygen
- quantification of total chlorophyll using light absorption

c. Scientific advances made and/or facilitated through the project activities

- Understanding of time variability and events in the processes governing the biogeochemical and ecosystem
- Impact of climate variability on the carbon and ecosystem in the California Current
- Analyses of the offshore boundary conditions affecting the shelf regime through upwelling transport of low oxygen/pH water into near-shore regimes

d. Significance of these advances

- The results allow evaluations of the carbon cycle role and impact in the California Current
- The observations allow assessments of the ocean acidification processes and impacts in the region

- Understanding of ecosystem controls and improvement of forecasts, including fisheries management
- Improvement of biogeochemical and ecosystem models, and model validation

e. Information jeopardized due to a lack of funding, lack of instrumentation, or inability to carry out the work
- Due to the IDC rate change at SIO and due to reduced funding for this project in FY2011, the CCE mooring program currently operates at a loss and needs voluntary free contributions from several collaborators and borrowed equipment. This is not sustainable.
- Lack of a duplicate set of hardware for two moorings (buoys, sensors) means we cannot service both moorings on a single cruise. This means increased need of shiptime (which we do not have) and/or gaps in the mooring timeseries (when we bring hardware to shore for servicing)
- Data management and calibration efforts are behind and lacking funding, especially the QC and dissemination of biogeochemical and ecosystem sensors.

f. Web sites for the program
- http://mooring.ucsd.edu/CCE

g. Data Management
- Data not distributed on GTS
- Realtime data are shown in graphical form on the website. They are backed up on institutional computers. Data are not publicly available in realtime at present, primarily because careful application of calibrations needs to carried out before propagating numerical values.
- Delayed-mode data are on institutional computer with backup system, plots are provided on the website. Processed data are made available through OceanSITES ftp servers and this is implemented for microcat (T/S).
- Archival on institutional backup system happens daily; transfer of newly processed data to OceanSITES repository approx yearly. Data can be retrieved from the OceanSITES ftp server ftp://data.ndbc.noaa.gov/data/oceansites/DATA/CCE* and we have successfully retrieved our own data from there.
- Data plots are shown on http://mooring.ucsd.edu/CCE

2.1 Outreach and Education

The CCE mooring effort was presented to young researchers via a plenary talk at the CalCOFI conference in December 2011. The program is communicated to the public via various websites and also contributes to the CCE LTER program.One postdoc and several graduate students are being trained via work on the CCE program and data. Wherever possible, we invite students to participate in CCE cruises. In our teaching, and during visits of prospective students, CCE is used as a demonstration of exciting and relevant research. Many students contact us as a result of their interest in the CCE mooring program as explained on our websites.

3. Publications

Hofmann, G.E. , J.E. Smith, K.S. Johnson, U. Send, et al (2011): High-Frequency Dynamics of Ocean pH: A Multi-Ecosystem Comparison. PLoS ONE 6(12): e28983.

Nam, S., H.-J. Kim, and U. Send (2011): Amplification of hypoxic and acidic events by La Nina conditions on the continental shelf off California. Geophysical Research Letters. VOL. 38, L22602.

We, together with graduate students and colleagues, are actively working with the CCE data and anticipate many publications and PhD theses will come from this work. At present we feel it is important to fully understand issues of calibration and uncertainty, and to reproduce observations of patterns such as annual cycles, prior to publication.

4. Figures and Tables

Figure 1 *(below): Locations of the CCE1 and CCE2 moorings off Pt.Conception. Color shows chlorophyll-a concentration.*

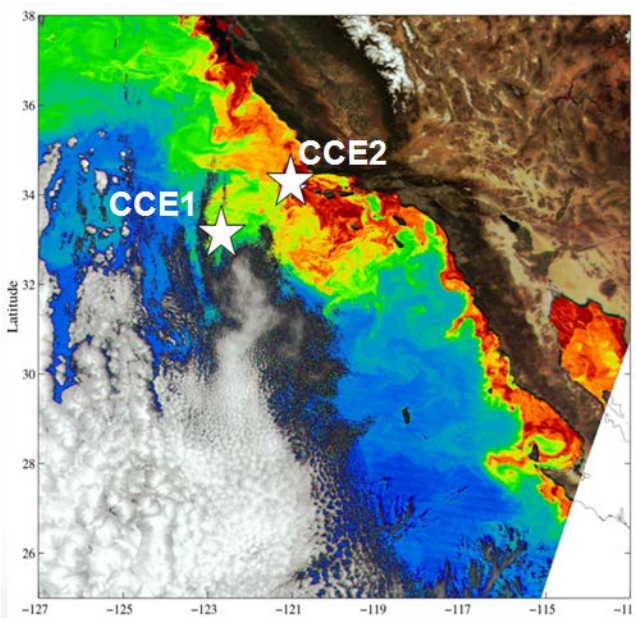
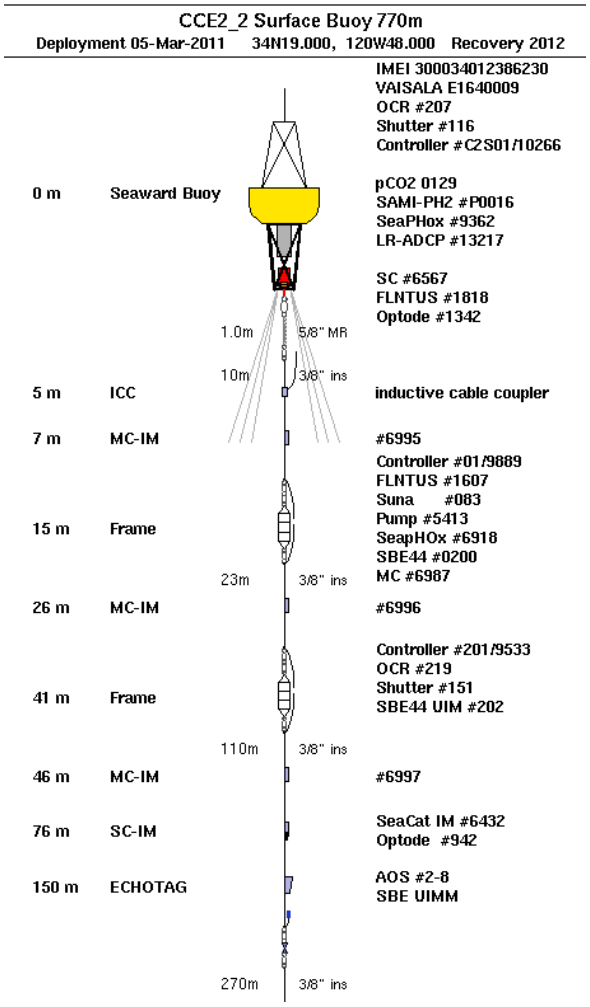


Figure 2 *(right): Design of the upper 150m of the new CCE2 mooring with a wide suite of sensors and T/S sampling (for mixed-layer depth estimates) to 76m.*



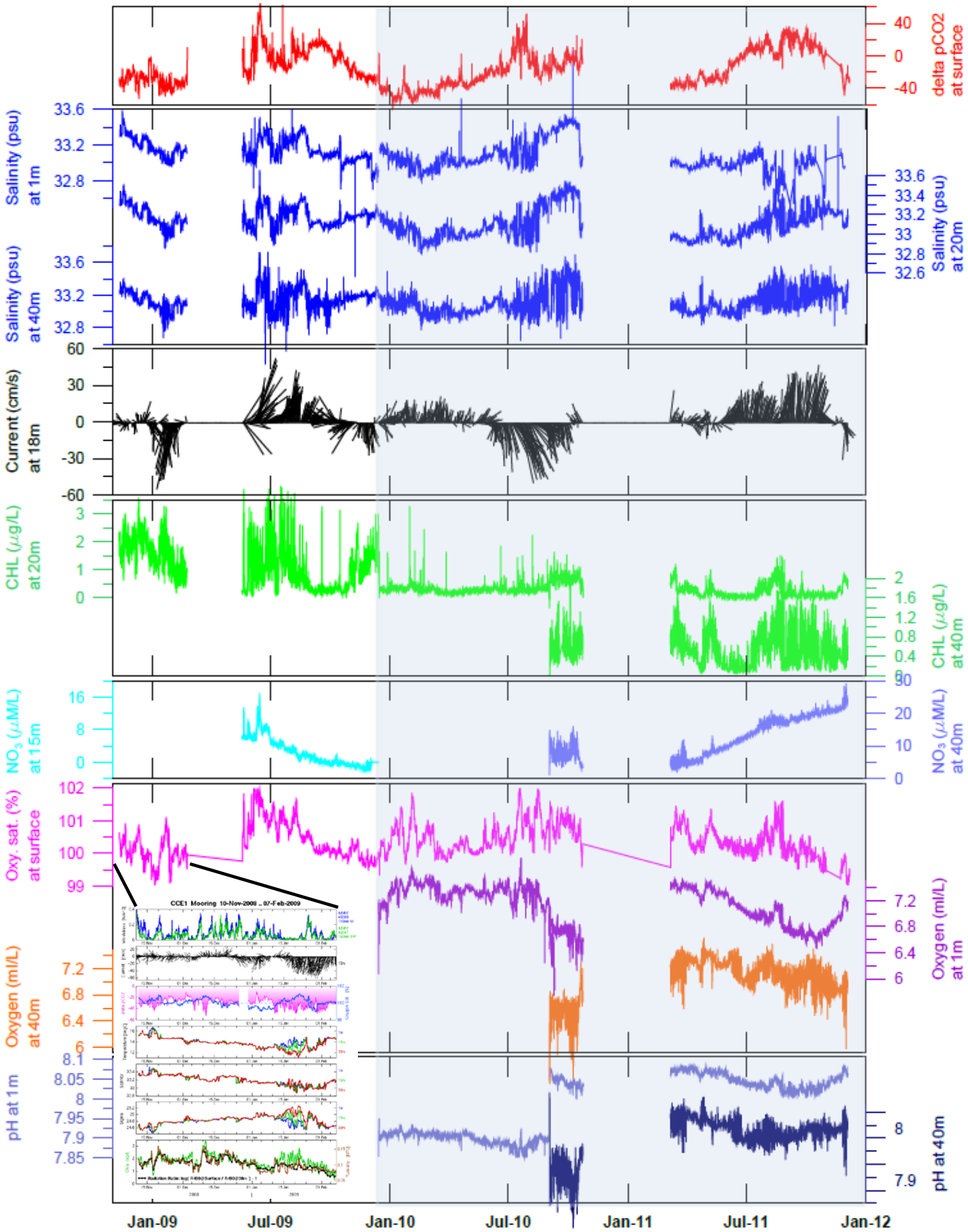

delta pCO2 at surface
Salinity (psu) at 1m
Salinity (psu) at 40m
Salinity (psu) at 20m
Current (cm/s) at 18m
CHL (μg/L) at 20m
CHL (μg/L) at 40m
NO3 (μM/L) at 15m
NO3 (μM/L) at 40m
Oxy. sat. (%) at surface
Oxygen (ml/L) at 40m
Oxygen (ml/L) at 1m
pH at 1m
pH at 40m
CCE1 Mooring 10-Nov-2008 .. 07-Feb-2009
Jan-09
Jul-09
Jan-10
Jul-10
Jan-11
Jul-11
Jan-12

Figure 3 *(previous page): Available data from all CCE1 mooring deployments from the surface pCO2 sensor (PMEL), some of the T/S sensors, currents at 20m (the shaded period has an ADCP covering the upper 500m),chlorophyll-a estimates, nitrate concentration, dissolved oxygen data, and pH readings. All data are raw with factory calibration. The shaded period shows the NOAA funded deployments.*

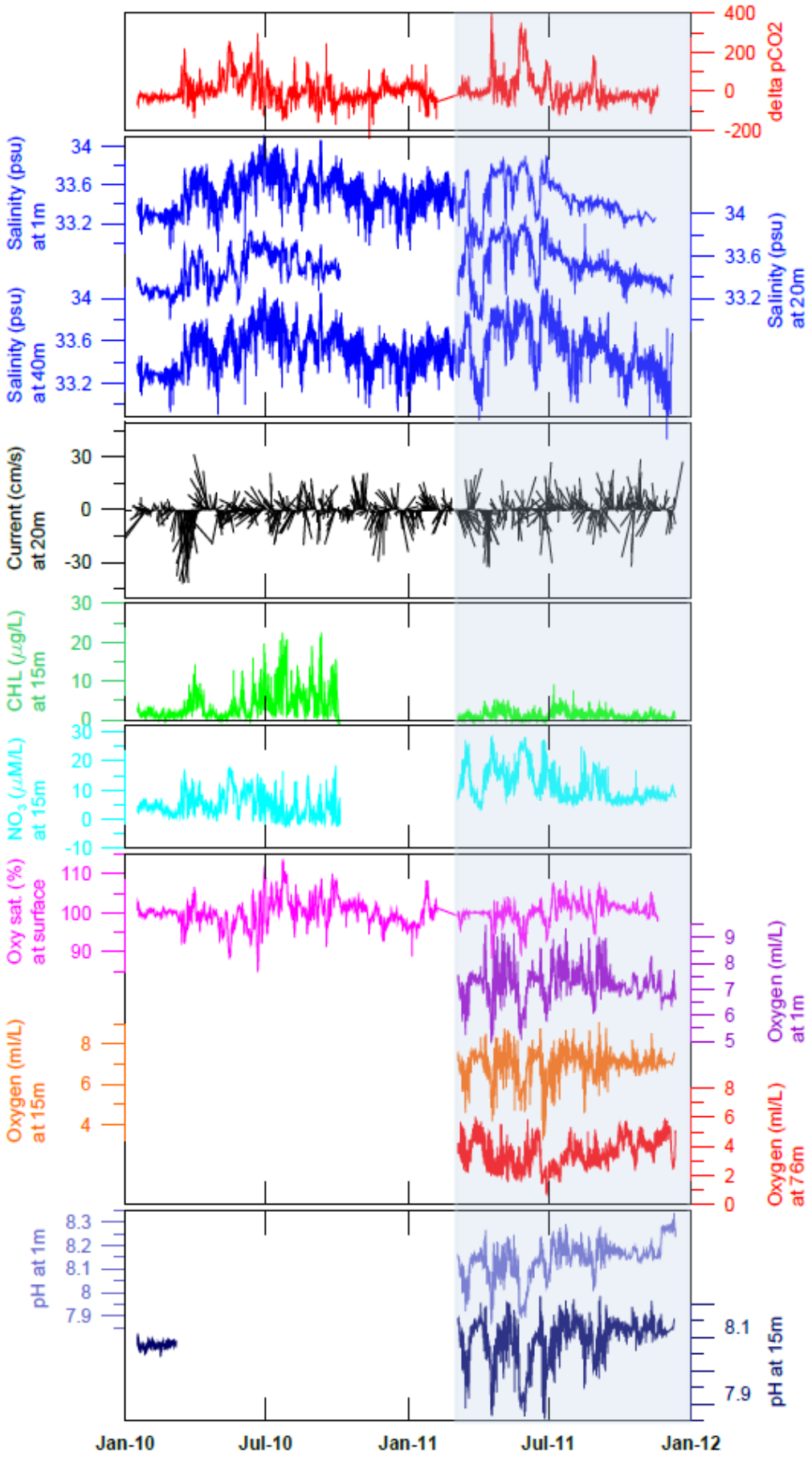


Figure 4 *(right): Same as figure 3 but for the CCE2 mooring.The x-axis is the same as figure 3, so the two can be directly compared/overlain.*

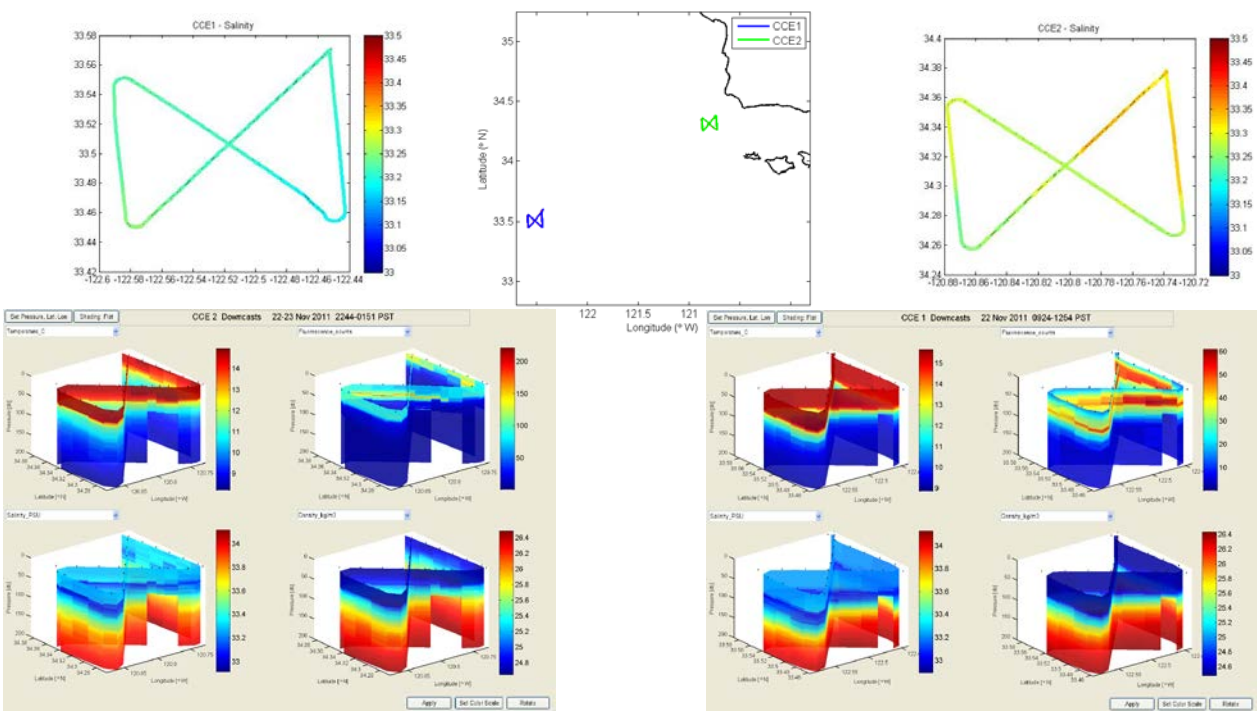
Table 1: *Overview of acoustic backscatter system deployments*

Unit	Location	Deployed	Recovered	Data Status
EchoTag 1	CCE1-01	11/10/08	02/23/09	\\pacifica\Static_2\CCE1\01\EchoTag 1
EchoTag 1	CCE1-02	5/18/09	12/14/09	\\pacifica\Static_2\CCE1\02\EchoTag 1
EchoTag 2	CCE1-03	12/14/09	09/01/10	\\pacifica\Static_2\CCE1\03\EchoTag 2
EchoTag 3	CCE1-03	12/14/09	09/01/10	\\pacifica\Static_2\CCE1\03\EchoTag 3
EchoTag 1	CCE2-01	01/16/10	03/05/11	No data (SD failure)
EchoTag 2	CCE1-04	09/02/10	10/23/10	No data (unit flooded)
AOSI	CCE1-04	09/02/10	10/23/10	No data (unit flooded)
AOSII-8	CCE2-02	03/05/11	12/20/11	\\pacifica\Static_2\CCE2\02\AOSII-8
AOSII-1	CCE1-05	03/06/11	deployed	

Table 2: *Coefficient of variation along a NE to SW section and a NW to SE section of the "bow tie" sampling patterns shown below, at moorings CCE1 and CCE2, cruise NH1111, Nov. 2011.*

	Temp	Salinity	Dissolved O_2
CCE1	c.v.	c.v.	c.v.
NE to SW leg	35.7%	3.6%	12.1%
NW to SE leg	67.6%	4.9%	22.4%
	Temp	**Salinity**	**Dissolved O_2**
CCE2	c.v.	c.v.	c.v.
NE to SW leg	76.3%	11.1%	22.2%
NW to SE leg	19.9%	1.8%	6.5%

Figure 5*: Property distributions near-surface salinity in upper left and upper right; 0-200 m temperature, salinity, Chl-a fluorescence, densityMoving Vessel Profiler sections) from ship surveys around CCE1 and CCE2:*



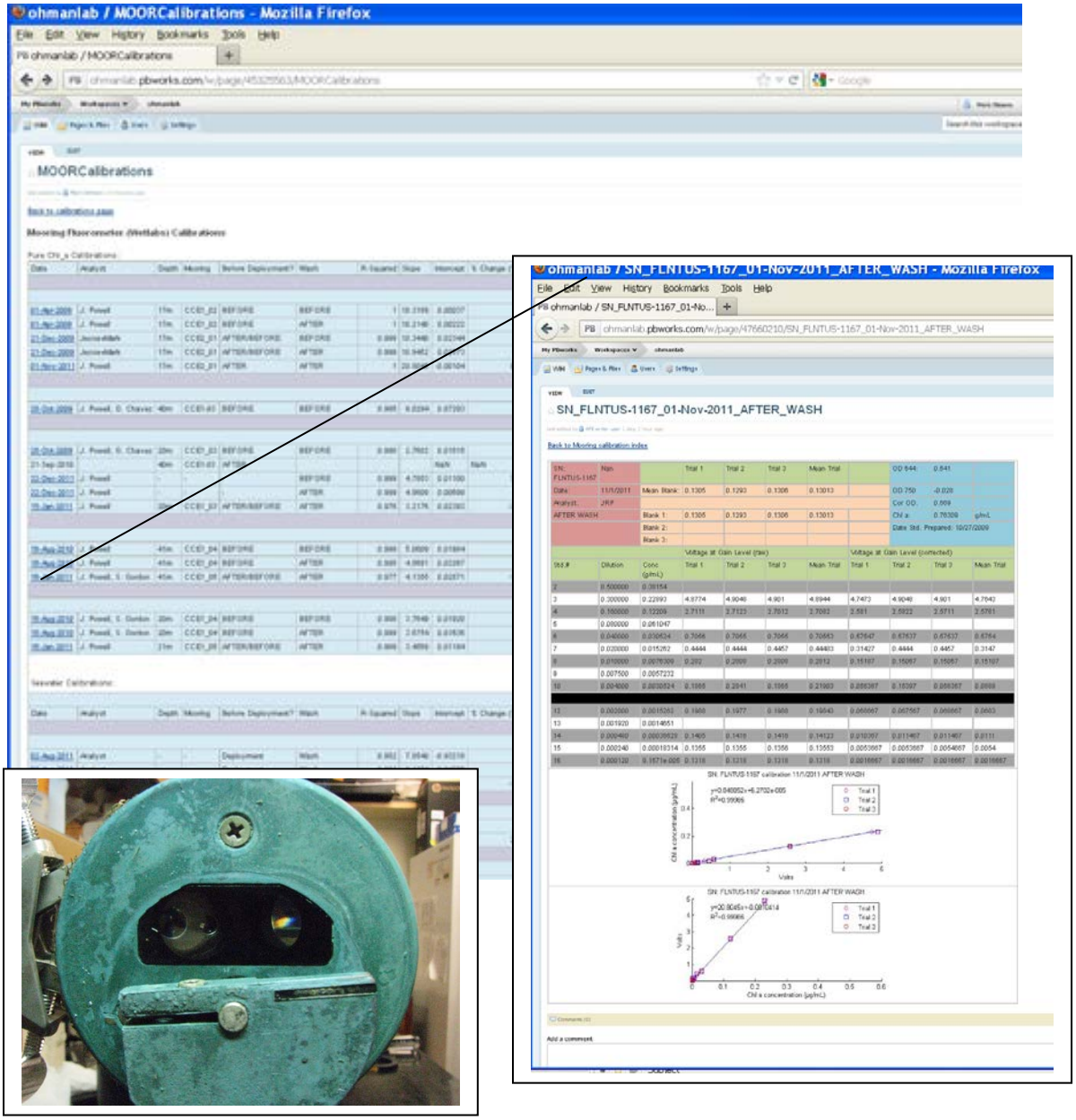
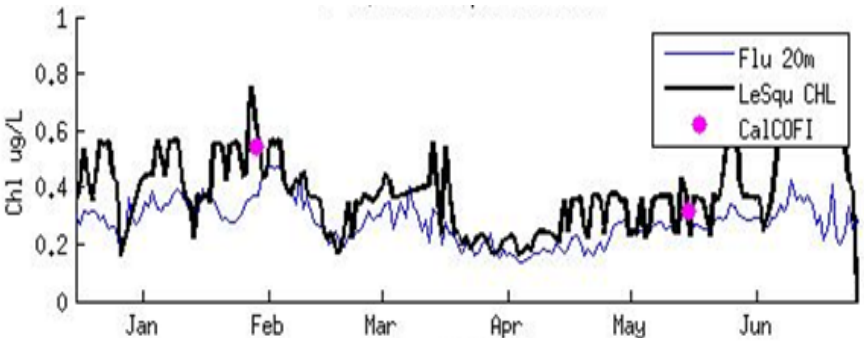


Figure 6: *Sample view of the Wiki site for instrument calibration information, including links to calibration relationships and photographs of optical surfaces of sensors..*



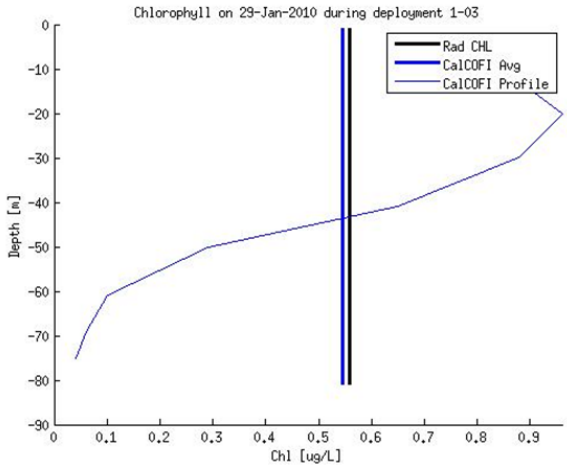
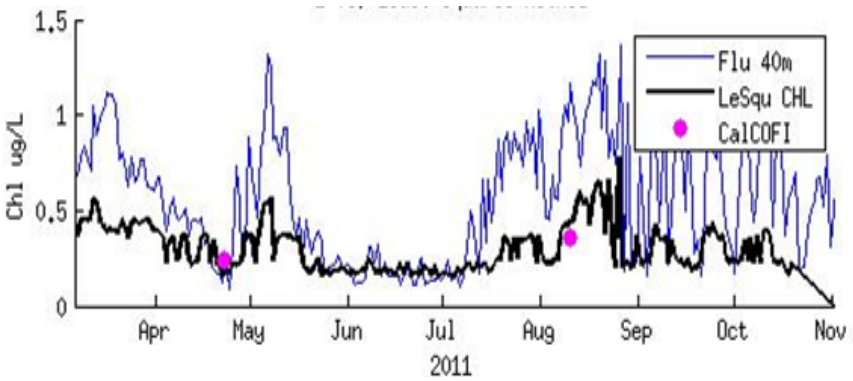


Figure 7a: *Least-squares fits of measured attenuation between surface and 80m at five wavelengths on CCE1 during 2010, to determine* *<u>absolute</u>* *0-80m mean concentrations of chlorophyll and cDOM (chromophoric dissolved organic matter) from their known empirical optical attenuation characteristics as a function of concentration and wavelength (Morel, 1988). Top panel shows timeseries of the least-squares solution for Chl-a concentration (black), compared to estimates from our fluorometer at 20m (with factory calibration, thus absolute levels are uncertain), and compared with 0-80m means from two CalCOFI cruises (magenta dots). The l panel at left shows the CalCOFI Chl-a profile for 29Jan and its 0-80m mean (blue) together with the mean from the optical attenuation solution.*



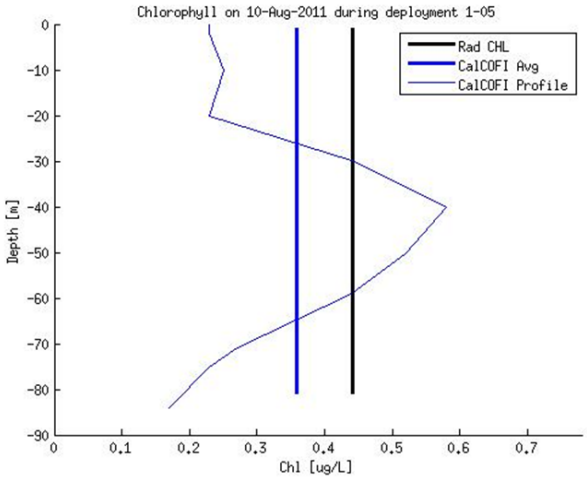


Figure 7b: *Same as fig.7a but for 2011, and comparison fluorometer data now from 40m. CalCOFI vertical profile shown in panel at left is from 10Aug.*

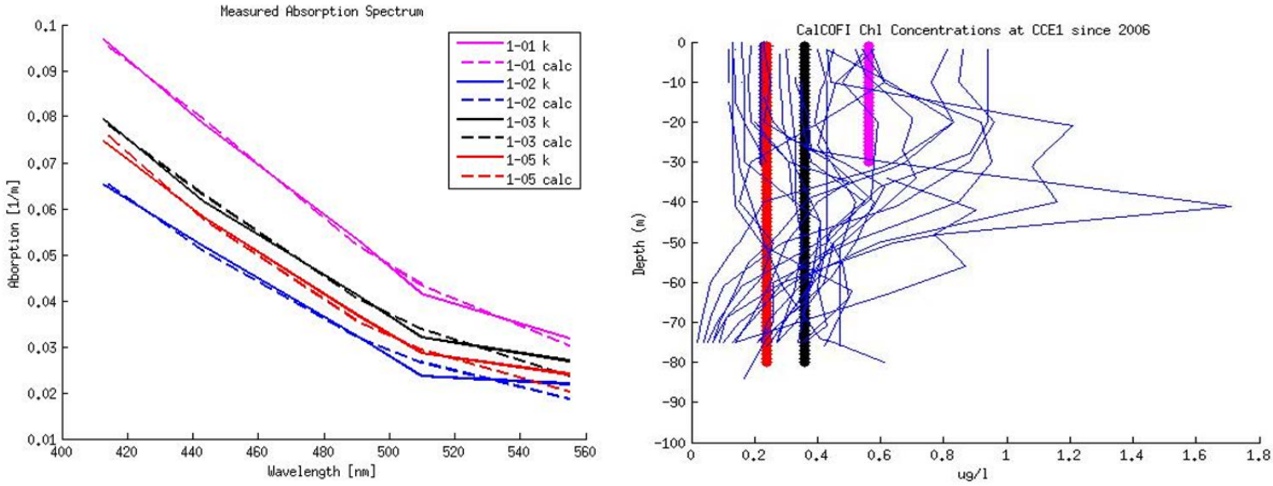


Figure 8a: *Average attenuation spectra for four deployments of CCE1 (left). Solid lines are the observed attenuations, dashed are the least-squares solutions using absolute concentrations of chlorophyll and CDOM. The deployments 1-01 and 1-02 were in 2009 and covered 0-33m depth, the deployments 1-03 and 1-05 were in 2010 and 2011, respectively, and covered 0-80m depth. The right panel shows all CalCOFI Chl-a profiles at CCE1 since 2006, together with the means from the mooring radiometers for 2009 (magenta), 2010 (black), and 2011 (red).*
The vertical profiles can explain the qualitative observation from figure 7a that the 0-80m average (black) typically is larger than values at 20m (blue) since the chlorophyll maximum usually is below 20m. The opposite is the case for figure 7b, where the blue line is at 40m and thus usually in the chlorophyll maximum while the black line as a vertical average is lower most of the time.

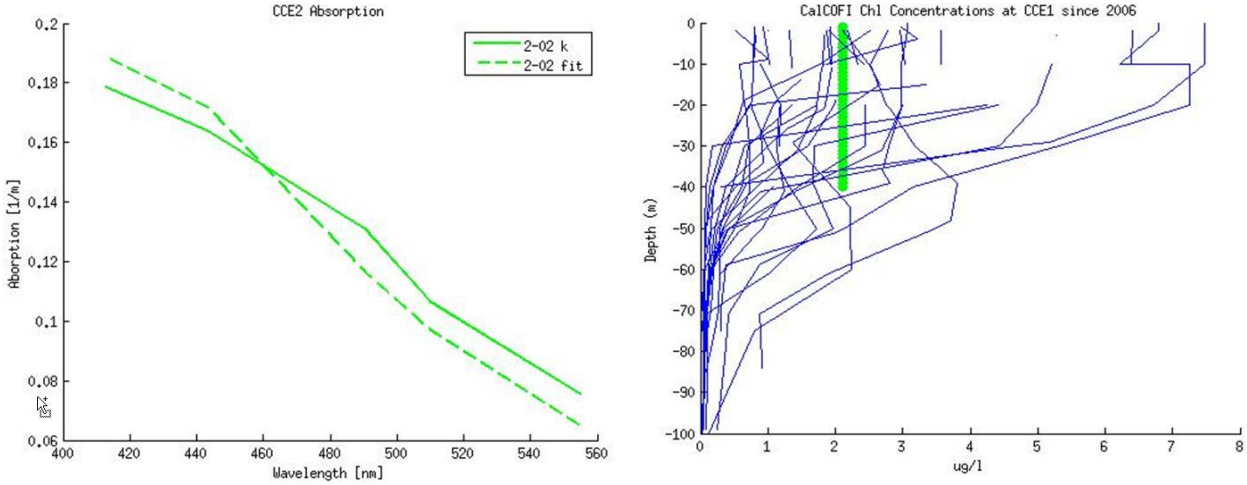


Figure 8b: *Same as fig.8a but at CCE2 for year 2011. The overall Chl-a concentrations are much larger but the least-squares fit seems to work approximately also in this more productive environment.*

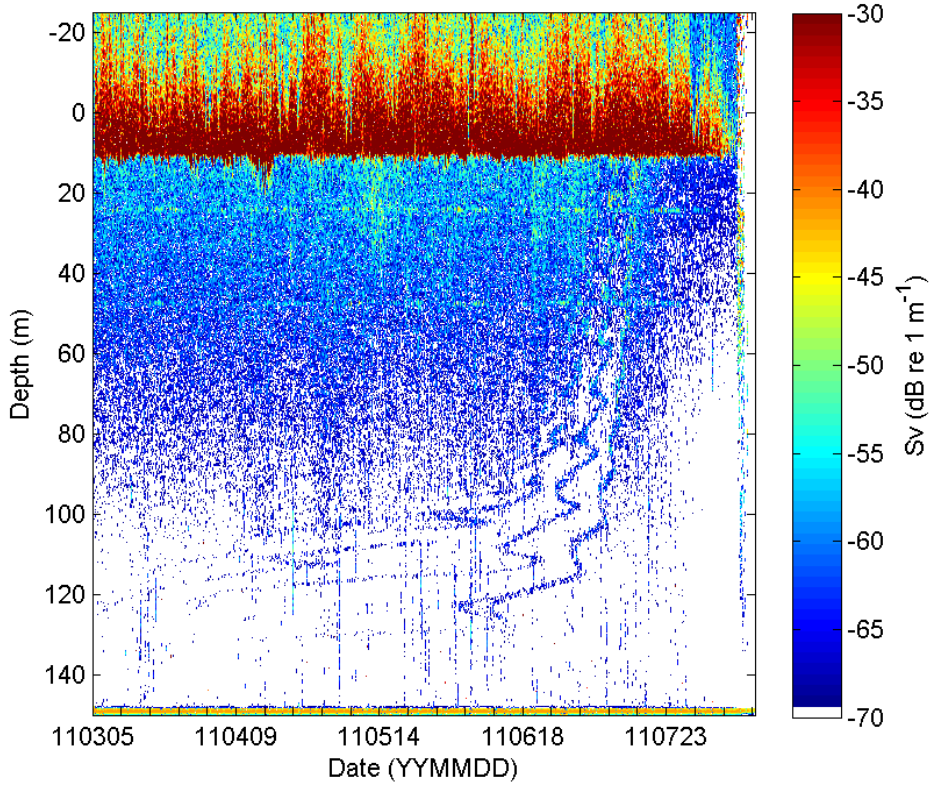


Figure 9: *CCE2-02: Acoustic backscatter data from AOSII-8 projecting upwards, 20° from vertical. The measured ranges were converted to depth, accounting for the transducer orientation. Due to the 30° beamwidth, the surface reflection received 20°off the beam axis precedes the on-axis slant range to the sea surface. The upward moving "wiggly" traces lack any explanation so far.*

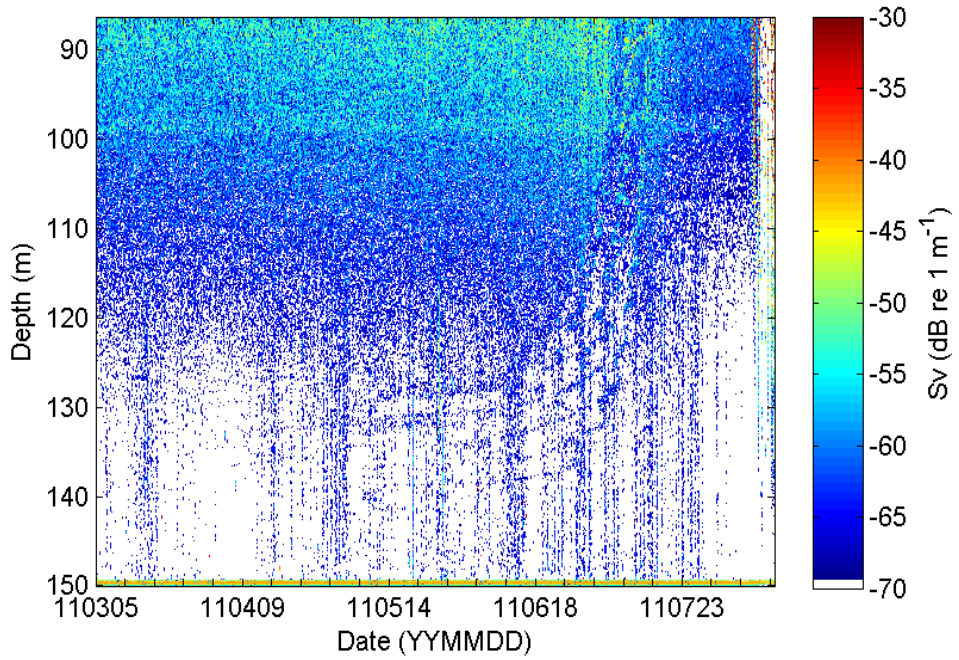


Figure 10: *CCE2-02: AOSII-8 projecting upwards, 70° from vertical.*

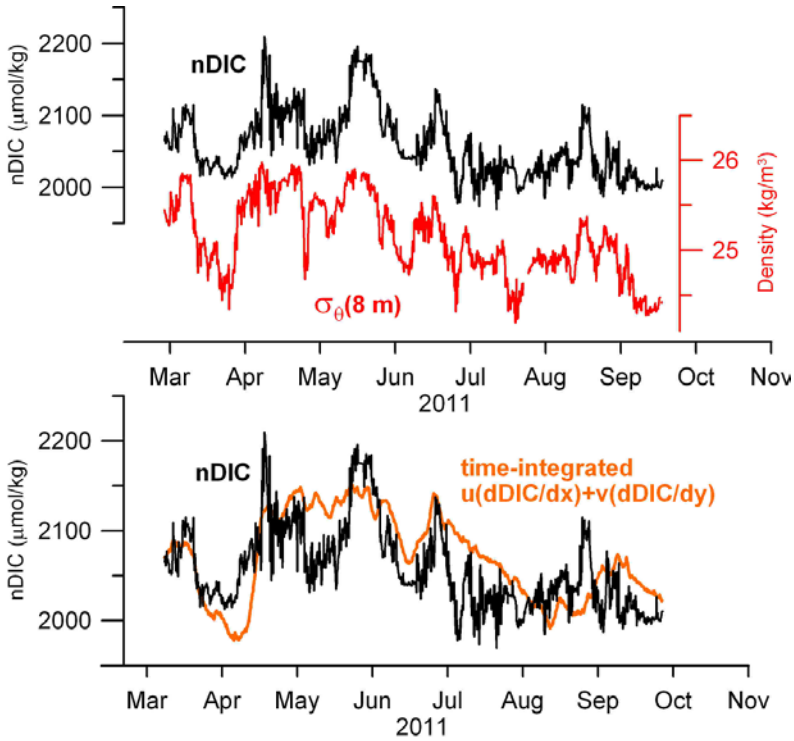


Figure 11: *Top - Dissolved inorganic carbon (black) from the CCE2 pCO2 and total alkalinity (derived from salinity) and upper-layer density (red). Bottom - nDIC as in upper panel (black) and advective change in nDIC calculated from ship-based spatial gradients and currents measured at the mooring.*

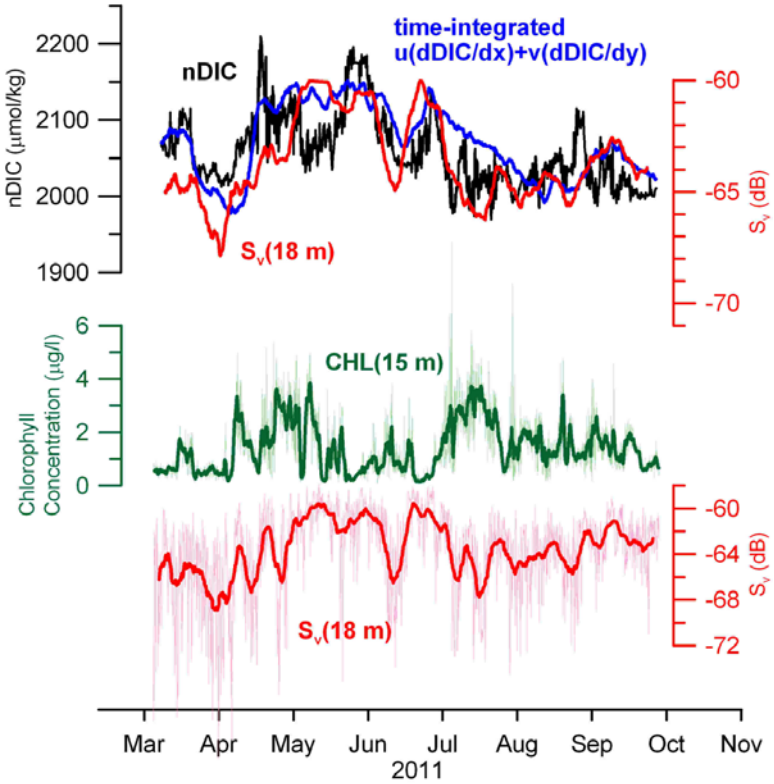


Figure 12: *Top – DIC and advection of DIC as in figure 11 bottom, together with relative acoustic backscatter cross-section from ADCP at 18m depth.*
Bottom: Comparison of acoustic backscatter cross-section (red) with chlorophyll-a concentration estimated from fluorometer (green).

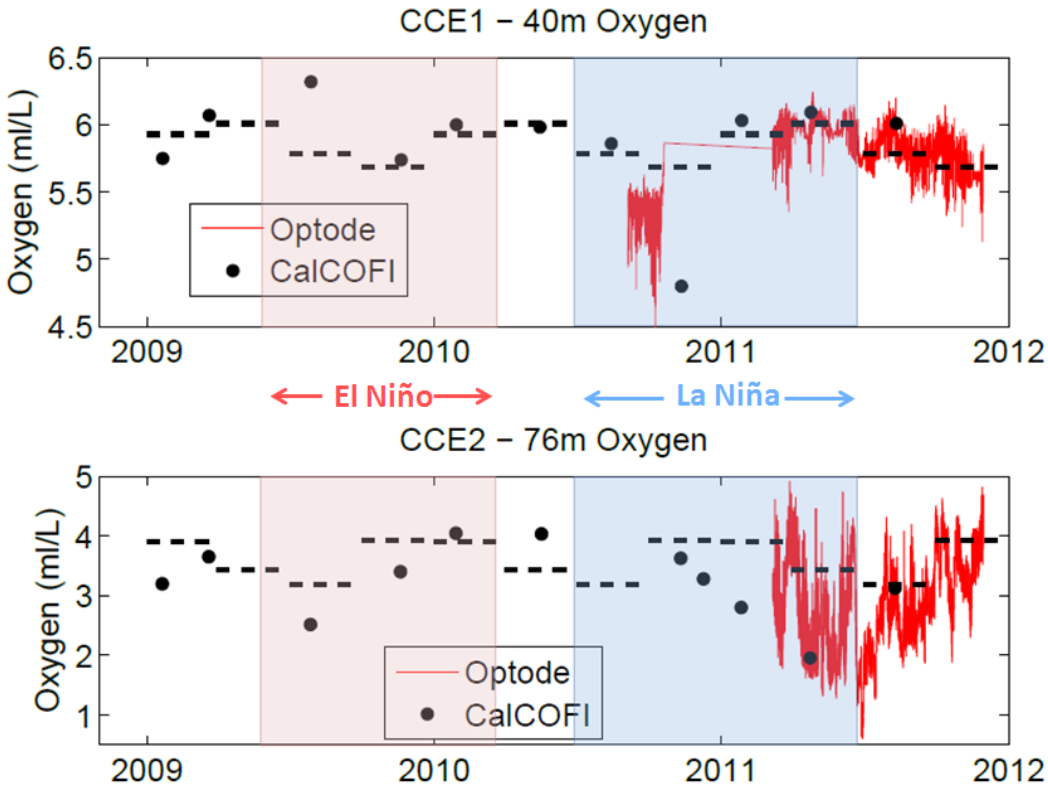


Figure 13: *Dissolved oxygen timeseries from the moorings (red) for CCE1 at 40m (top)and for CCE1 at 76m (bottom), compared to the average from 60 years of CalCOFI data at those locations/depths (dashed lines) and the actual CalCOFI values during years 2009-2012 (black dots). Large negative oxygen anomalies can be seen in the La Nina phase. The top panel also shows one large positive anomaly during El Nino, but that single point can be aliased. The continuous mooring data during La Nina show that the CalCOFI points in this case represent a real negative anomaly and are not a result of insufficient temporal resolution in a highly variable environment.*

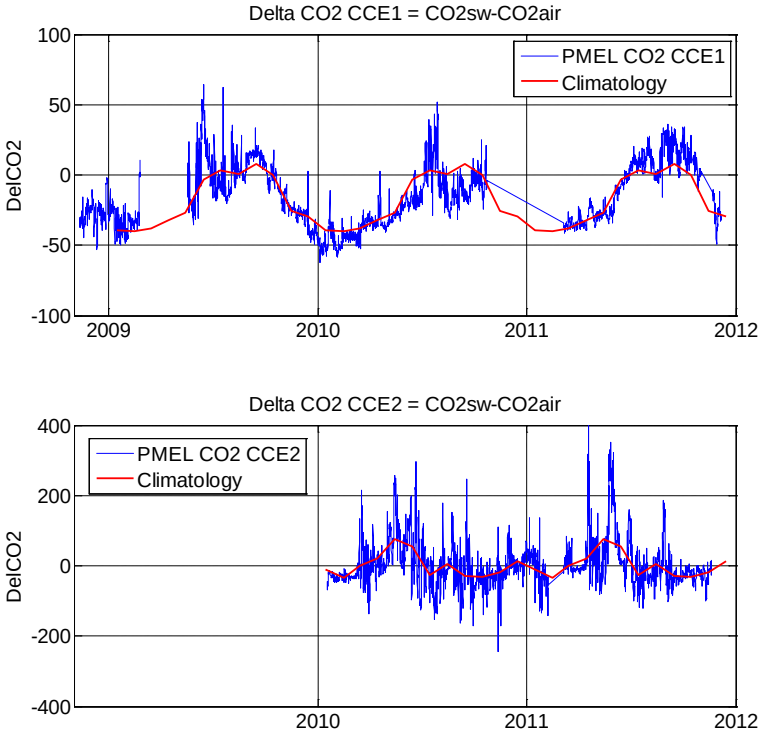


Figure 14: *First steps toward building a delta pCO2 climatology from the moored timeseries at CCE1 (top) and CCE2 (bottom), using data from the PMEL system. The red line in each case shows the mean annual cycle computed from all available years (3 years for CCE1, 2 years for CCE2), and the blue line shows the actual year-to-year measurements. It is too early to interpret anomalies with any faith, but the significance of these will increase in the subsequent years.*