The Lucinda Jetty Coastal Observatory's role in satellite ocean colour calibration and validation for Great Barrier Reef coastal waters

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***Abstract-* The Lucinda Jetty Coastal Observatory (LJCO) was established as part of Australia's Integrated Marine Observing System, to provide reliable data streams in coastal waters to unravel the inaccuracies in remotely-sensed satellite ocean colour products, LJCO is located at the end of a 5.76 km long Lucinda Jetty (18.52S, 146.39E) in the coastal waters of the Great Barrier Reef World Heritage Area close to the Herbert River Estuary and the Hinchinbrook Channel. The Lucinda Jetty Coastal Observatory generates two complementary data streams: above water radiometry and in water measurement of the optical properties. An autonomous above-water radiometer performs radiometric measurements for determining water-leaving radiance and atmospheric measurements for retrieving aerosol optical properties. An *in situ* underwater instrument package is deployed to characterize the inherent optical properties of these complex coastal waters. The instruments were commissioned in October 2009. Details on the instrument setup, data acquisition and some preliminary data acquired for LJCO are presented.**

I. INTRODUCTION

In coastal waters the performance of ocean colour algorithms is hampered by the optical complexity caused by the variability in concentrations of the dissolved and particulate matter [1-3]. As stated in NASA's plan for the long term calibration and validation of oceanic biogeochemical data, "A significant challenge for future ocean colour research will be to maintain the level of success achieved in deep-ocean waters in the coastal and marginal seas, which means the influence of dissolved and particulate constituents will be increasingly important [4]."

The establishment of the Lucinda Jetty Coastal Observatory (LJCO, Figure 1) in the tropical coastal waters of the Great Barrier Reef (GBR) lagoon close to the Herbert River Estuary and the Hinchinbrook Channel addresses this challenge. As part of Australia's Integrated Marine Observing System (IMOS), LJCO was established to provide a continuous time series of above water radiometry and below water optical measurements in these complex coastal waters for improving and validating coastal and continental shelf remotely-sensed satellite ocean colour products.

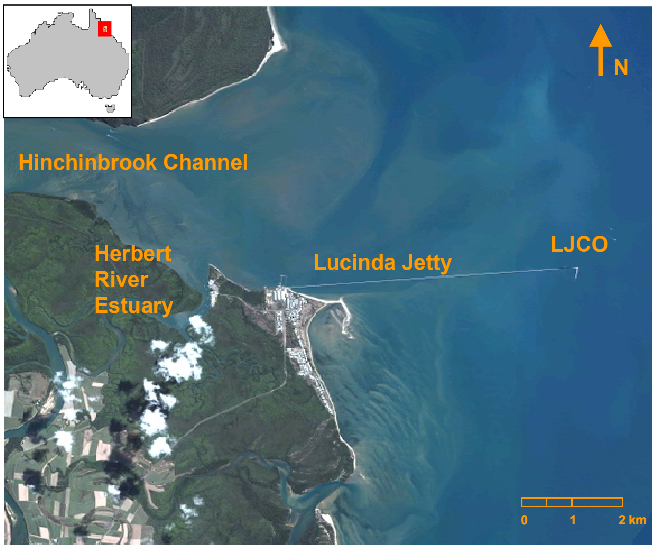

Figure 1. Location of the Lucinda Jetty Coastal Observatory (18.52 S, 146.39 E).

II. STUDY SITE

At 5.76km long the Lucinda Jetty provides an ideal platform for the long term deployment of instrumentation. Access to the end of the jetty is possible by vehicle enabling the retrieval and servicing of instruments. As an operating bulk sugar loading facility, mains power, water and other services are all available at the end of the jetty.

Due to the high frequency of visits required for the servicing of underwater optical instruments, access by vessel to mooring based instruments for maintenance and calibration is costly. Also, the opportunity for collection of above water radiometric data is limited by the need for a stable above water surface for the mooring [5]. At LJCO, access by vehicle, the power supply and platform stability overcome most of the limitations which make collecting continuous high quality optical data difficult with traditional moorings or ship-based methods.

The Jetty is close to the estuary of the Herbert River and the Hinchinbrook Channel in the wet tropics of the central Great Barrier Reef with pronounced monsoonal dry and wet

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seasons. With mean sea surface temperatures ranging from 21 to 30˚C and a maximum tidal range of 3.5 m, the coastal ocean in the vicinity of LJCO encompasses a range of habitats including fringing and mid-shelf coral reefs, sand and mud bottoms, sand and rubble intertidal flats, mangrove forests, as well as sandy, cobble and boulder beaches [6].

The Herbert River is the largest of the river systems (mean annual flow 5 x 10^6ML) in the wet tropics region of northeast Australia and the fourth largest fluvial system draining into the GBR [7]. With a catchment area of 10130km^2 and a mean annual rainfall exceeding 2000mm/yr flooding and runoff events are seasonal occurrences in the Herbert catchment, delivering particulate and dissolved matter to the coastal waters of the GBR lagoon. Due to simultaneous entry of the flood tide at the northern and southern entrances to the Hinchinbrook Channel, large amounts of sediment from the Herbert River are trapped and reworked in the mangrove flats which line the channel [8].

The location of the LJCO is ideal to monitor and characterize the optical properties in a coastal system where the sources of particulate and dissolved matter substantially vary during the tidal and seasonal cycles.

III. Infrastructure Design and Installation

A. *The terminal complex at the Lucinda Jetty*

The terminal complex at the Lucinda Jetty consists of a single berth designed to accommodate ships up 320m long or the "Panamax" Class of bulk carriers. Located to the north and south of the sugar loading berth are two mooring dolphins used as mooring points for ships at berth.

The instrument housing infrastructure of LJCO is installed over the exposed beams on the northern mooring dolphin giving access to the water below the enclosure. The northern dolphin provides an uninterrupted sky/sun view for the radiometric instrumentation and an unobstructed line of sight view for the 3G telemetry equipment (Figure 1).

B. *Design constraints*

The site posed a number of challenges for designing the instrument housing. Located 5.76km offshore, the mooring dolphin experiences strong winds during storm and cyclone events. High seas can cover the dolphin in salt spray resulting in a highly corrosive environment for the deployment of infrastructure and instrumentation.

A number of requirements were placed on the installation by the Jetty operator (Queensland Sugar Ltd, QSL). The instrument housing could not be directly bolted to the jetty as QSL regulations prevented any modifications to the existing jetty structure. Metal components needed to be electrically isolated from the jetty to prevent electrolysis caused by dissimilar metals. The enclosure needed to be removable for periodic re-application of anti fouling coatings and enable the future removal at the cessation of deployment. Access from the jetty to the northern mooring dolphin is confined to a narrow 30m gantry, limiting both the weight and size of items that can be transported to the dolphin.

A structural engineering firm was contracted to provide a design to meet the environmental conditions and stringent operational requirements.

The instrument enclosure was designed as a fully prefabricated structure which could be lifted into place on the jetty by barge. The resulting design was cyclone rated, fully insulated, constructed entirely from aluminium and met or exceeded all of the required building codes and OHS standards for structure of its type and location.

C. *Instrument housing structure features*

The structure of the instrument housing consists of an internal frame supporting two, 300kg rated winch rails and a rooftop instrument platform. Aluminium-faced cold-room paneling with high thermal insulation properties is used in the construction of the walls, the built-in cabinet and the covered access walkway. The instrument housing sits on a ladder frame base of 250mm aluminium structural beams with trapdoors for instrument deployment integrated into the aluminium chequer plate floor. Attachment points are provided on the four corners of the enclosure with removable access panels for fitting and and inspecting the tie down bolts.

Supports are integrated into the structural frame of the enclosure; these transfer the load of the upper deck directly to the base of the enclosure and provide a solid base for mounting of instruments. Reinforced 12mm aluminium plates provide a rigid base for the instrument attachment points on the two northern corners of the upper deck. The deck is accessed using a fixed ladder and is fitted with safety rails and attachment points for fall protection equipment.

Computers, communications and power supply are housed in a built-in cabinet maintained at a constant temperature of 25ºC by a marine-grade air-conditioning unit. A removable door allows access for maintenance of all the devices. Waterproof cable entry plates allow the instrument cabling to enter the cabinet whilst minimizing air exchange and moisture ingress

The instrument housing is hard-wired with both lighting and power circuits; an electrical distribution board inside the enclosure is supplied via a waterproof service cable. Separate circuits are provided for lighting and ventilation, UPS back-up and winches and other ancillary equipment. All circuits are RCD protected including the main feed from the terminal complex. The instrument housing is also equipped with a hard wired local Ethernet network consisting of Cat5e cabling terminated at wall plates with RJ45 sockets in both the air-conditioned cabinet and the instrument deployment area.

D. *Installation of the instrument housing*

The instrument housing was fully prefabricated in Townsville and transported to Lucinda for installation. The housing was installed onto the mooring dolphin using a 30T landing barge chartered out of Lucinda on the 3rd of October

2009. Installation was carried out at the peak high tide under calm conditions; the barge maneuvered into place against the mooring dolphin with the loading door held against the dolphin structure using the barge engines. A mobile crane was then used to lift the observatory into position on the mooring dolphin (Figure 2). The enclosure was attached to the jetty structure using marine-grade stainless-steel bolts and aluminium plates.

Figure 2. Installation of the instrument housing of observatory by crane on the 3rd October 2009.

IV. Instrumentation

At LJCO three main data streams are acquired: apparent optical properties of the water column measured using above water radiometry, inherent optical properties of the water column measured with an *in situ* water optical package, and ancillary information on weather and sky and sea conditions (Figure 3). The instruments were commissioned on 26 October 2009.

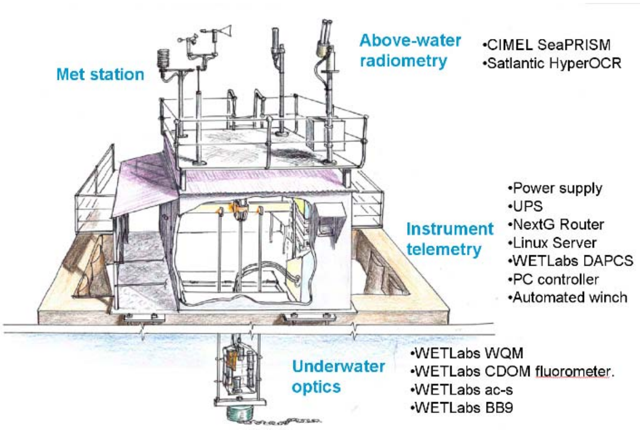

Figure 3. Schematics of the setup and instrumentation installed at the Lucinda Jetty Coastal Observatory

A. Above-water Radiometry

The SeaPRISM (SeaWiFS Photometer Revision for Incident Surface Measurements) above-water radiometer was installed on the upper deck of observatory's instrument housing (Figure 3, Figure 4). The SeaPRISM autonomously performs multiple sky- and sea-radiance observations at programmable viewing and azimuth angles at nine center wavelengths in the 412–1020 nanometer spectral range [5, 9]. The SeaPRISM is a CIMEL CE-318 automated sun-photometer modified to perform above-water radiometric measurements in addition to the regular atmospheric measurements defined for NASA's Aerosol Robotic Network (AERONET).

Figure 4. The CIMEL SeaPRISM (left) and the Satlantic HyperOCR (right) are mounted on the rooftop platform.

The AERONET standard measurements include direct sun irradiance and sky radiance to estimate atmospheric optical thickness and atmospheric scattering phase function respectively. The SeaPRISM performs a series of sea-viewing measurements following the AERONET – Ocean Color (AERONET-OC) protocols [9], including measurements of direct sun irradiance, water radiance and sky radiances, which are performed with a nadir viewing angle θ=40º and a relative azimuth with respect to the sun φ=90º [5]. If the sun is cloud covered, which is detectable through direct sun irradiance measurements, the measurement sequence is cancelled.

A Satlantic HyperOCR was installed on the upper deck to provide hyperspectral measurements of total downwelling irradiances (Figure 3, Figure 4). By combining the SeaPRISM and HyperOCR measurements it is possible to estimate the water remote sensing reflectance.

B. Underwater optics

The *in situ* water optical package deployed at the LJCO consist of a comprehensive array of instruments (Figure 3). Conductivity, temperature, pressure, dissolved oxygen, chlorophyll fluorescence and turbidity are measured using a WETlabs Water Quality Meter (WQM); coloured dissolved organic matter (CDOM) fluorescence is measured using a WETStar fluorometer; particulate and dissolved absorption and attenuation spectral coefficients are measured with a WETLabs ac-s, and total backscattering coefficients are measured with WETLabs BB9.

The *in situ* water optical package is deployed on a cage assembly which is lowered on a set of guide cables. The guide cables are kept taut by a spreader bar and 250kg of steel weights suspended above the seabed, any movement is damped by a 16mm x 5m drag chain which extends to the sea bed (Figure 3, Figure 5). At the start of each deployment the optical package is lowered to 12 m depth for a few minutes to ensure that the ac-s tubing is purged of all air-bubbles. The cage is then winched to 2 m below the lowest astronomical low tide to ensure that the instruments are never exposed to the air, as this may otherwise cause air-bubbles to be trapped in the ac-s tubing.

C. Ancillary instruments

Weather conditions at the site are measured using a Vaisala WXT520 multi parameter instrument which measures barometric pressure, humidity, precipitation, air temperature, wind speed and direction.

V. Data Acquisition and Processing

A. Controllers and telemetry

Data from all the instruments is acquired in real time or in delayed mode using a mix of instrument controllers, loggers, a rack mounted Dell PowerEdge 2950 Linux Server and an Advantech ARK PC installed in the air-conditioned cabinet (Figure 6).

Computers and communication devices are powered via an uninterruptible power supply. Remote control over circuit switching is obtained through the use of a power distribution unit allowing devices to be remotely powered on and off via an Ethernet interface.

Network connectivity is provided thorough a broadband connection on Telstra's NextG Mobile Network. Static IP addresses are provided to all the devices installed on site by a CISCO VPN gateway allowing direct connection to the CSIRO network for data transfer and acquisition.

Connectivity of all the devices at LJCO to the network is monitored by Big Brother ® network monitoring software. In the event of failure e-mail and SMS alert messages are automatically generated.

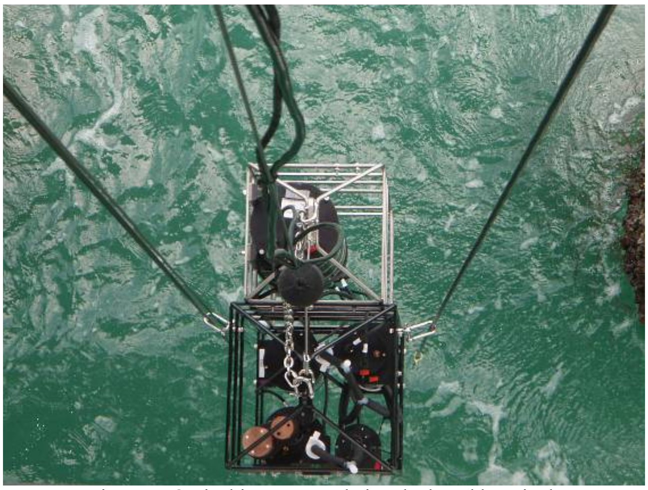

Figure 5. Optical instruments being deployed by winch

Figure 6. Image of the computers, communications and power supply devices installed in the 19" rack in the air-conditioned cabinet.

B. SeaPRISM

SeaPRISM sea-viewing measurements are performed every 15 minutes with the objective of collecting data between 8 AM and 4 PM local time. Data is acquired and stored on a custom data logger, from where it is retrieved remotely via the Advantech ARK PC by an operator on a weekly basis and uploaded to NASA Goddard Space Flight Center (Greenbelt, Md.) where it is processed using the AERONET-OC common protocols and then archived [9].

C. Data Acquisition and Power Conditioning System

The data acquisition of the *in situ* water optical package is managed with a Data Acquisition and Power Conditioning System (DAPCS) developed by WETLabs. The DAPCS is specifically designed to enable high speed/bandwidth communications and power control to support data collection from a broad suite of environmental sampling instruments.

This controller manages a scheduled operation of the system including powering up sensors, acquiring data, and operating the active anti-biofouling systems. The base system hardware consists of a dedicated host computer (the Dell PowerEdge 2950 Linux Server), a deck unit, a sub-unit, and an NTP server. The entire system is based around a self-contained Ethernet network connecting the host computer and time server to each of the individual instrument nodes. The sub-unit is connected to the deck-unit via two separate cables: one to support Ethernet communications (8 conductor twisted pair) and one to support power delivery (375 VDC, 2 conductors). Maximum length of these sea cables is 25 m, which is the maximum length to support 1 Gbps Ethernet communications. Data from the *in situ* water optical package is acquired and saved continuously on the Dell PowerEdge 2950 Linux Server.

D. Satlantic HyperOCR

Data from the Satlantic HyperOCR is acquired every minute using the Satlantic SatView scheduling and acquisition software on the Advantech ARK PC on site.

E. Weather station

Data from the Vaisala WXT520 multi parameter instrument is acquired using a Campbell Scientific CR200 data logger through a SDI-12 data interface. Readings are taken at 10 minute intervals with the data collected using scheduling software on the Advantech ARK PC onsite.

F. Data processing and access

The SeaPRISM derived data products are accessible through the AERONET-OC web page at NASA Goddard Space Flight Center [http://aeronet.gsfc.nasa.gov/][5, 9].

The raw data-streams for the *in situ* water optical package, the Satlantic HyperOCR and the weather data are uploaded via NextG broadband to CSIRO's data storage in Canberra.

Details on the pre –processing and QA/QC protocols for the data analysis of inherent optical properties of the water column can be found in [10]. After pre-processing and QA/QC protocols are applied to each data stream, the near real time data will be packaged into IMOS compatible netCDF files and uploaded to eMII (the IMOS data and information facility) for archiving and distribution.

When the provisioning phase of the data streams is completed all the data streams generated at LJCO will be made freely available according to the IMOS data policy. As all IMOS data, LJCO data will be accessible through the IMOS Ocean Portal [http://imos.aodn.org.au/webportal/].

This data stream will enable researchers and policy makers to reduce the uncertainties in remotely-sensed satellite ocean colour products due to the optical complexity in coastal waters and the overlying atmosphere.

VI. Instrument Servicing and Calibration

A. Instrument on-site servicing

LJCO instrumentation is serviced on a fortnightly basis and includes cleaning of the optics of the SeaPRISM and the Satlantic HyperOCR, and change-over of the *in situ* water optical package.

On site maintenance of the SeaPRISM includes removal of the collimators, inspection of the aperture, cleaning of the optical windows and the quad sensor. The robot and sensor cable are also checked to ensure that are not tangled.

Bio-fouling is a major challenge in acquiring consistent and high quality optical measurements in the near shore environment. To minimize fouling a number of strategies have been adopted. Sensor systems deployed at LJCO are completely surrounded by copper either by copper shielding or adhesive backed copper tape. Instruments with active bio fouling protection were selected: the WETLabs WQM utilizes the bio-wiper^{TM} active cleaning and protection system which cleans the optical faces of the instrument prior to taking a reading and closes when not in use. Regular servicing has also allowed instruments to be retrieved and cleaned before severe fouling occurs.

B. Instrument calibration

The SeaPRISM is calibrated by NASA following the AERONET-OC protocols prior and following each 6-12 months deployment. Only after the post deployment calibration the data will be processed to L2 and released after QA/QC [9].

Following instrument changeover the *in situ* optical instruments are returned to the laboratory for cleaning, calibration and re-application of anti fouling copper coatings. All instruments are tested and calibrated with MilliQ water prior to each deployment. The fortnightly timing of servicing has proven to be an acceptable balance between data quality, instrument fouling and servicing time.

VII. Tropical Cyclone Risk Management

There are risks of instrument loss, failure or breakage at LJCO due to tropical cyclones. A response plan for tropical cyclones has been developed and is enacted when the LJCO is within the areas identified to be at risk by the strong gale force winds generated by tropical cyclone within 48 to 72 hours. Bureau of Meteorology alerts and warnings are closely monitored during cyclone season.

In this event, instruments installed on the upper deck (i.e. SeaPRISM and HyperOCR) are dismounted and the underwater instruments are retrieved and secured within the instrument housing. Normal operations are restored as soon as practical. Although it will inevitably create a gap in the data streams up to a week long, this conservative approach is deemed acceptable as it offsets the risk of a partial or total loss of instrumentation that would cause a longer gap in the data stream.

A recent implementation of this plan was carried out on 19 March 2010 in response to tropical cyclone Ului (Figure 7).

VIII. Applications of LJCO Data

A. Validation of coastal-ocean colour products

LJCO will deliver continuous *in situ* measurements for the validation of coastal-ocean colour products in the GBR. The match up analysis of satellite retrievals vs. *in situ* measurements will enable the assessment of accuracy for aerosol optical properties, normalized water-leaving radiances, water inherent optical properties and biogeochemical concentrations [as in 1, 3, 9].

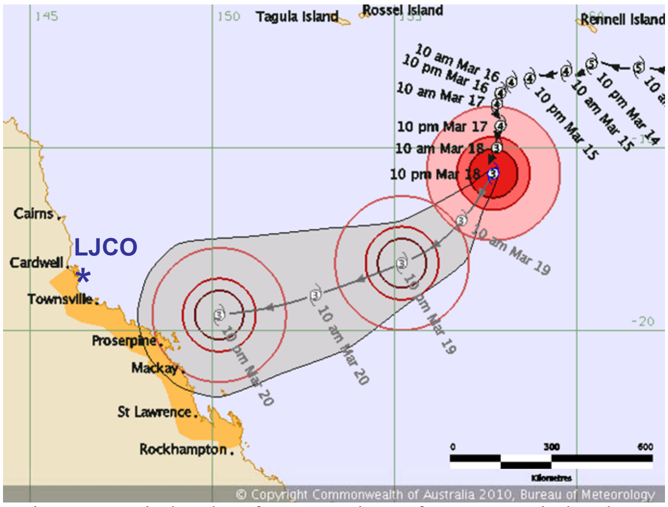

Figure 7. Tropical cyclone forecast track map for severe tropical cyclone Ului issued at 10:54 pm EST Thursday 18 March 2010 by the Bureau of Meteorology. The location of LJCO is marked with *.

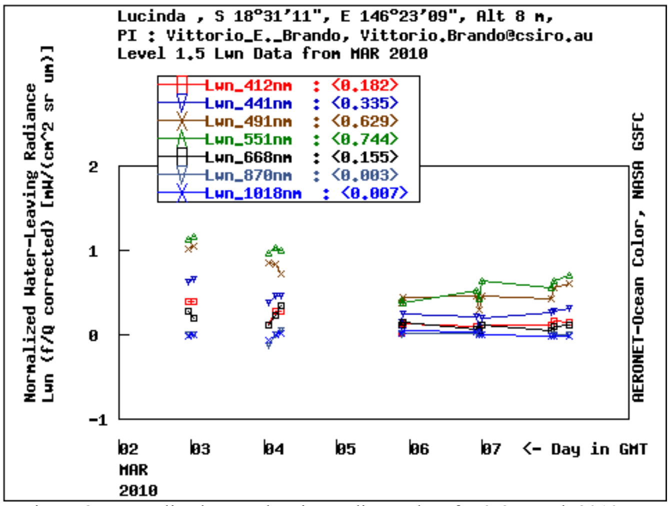

Figure 8. Normalized water-leaving radiance data for 2-8 March 2010 at LJCO. AERONET-OC Level 1.5. Real Time Cloud Screened downloaded from the AERONET-OC web interface.

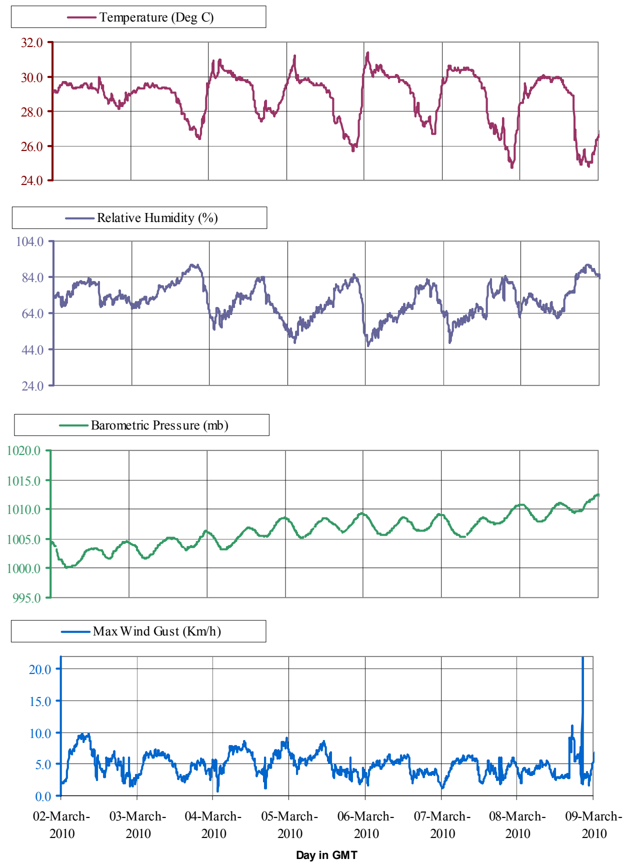

Figure 9. Weather observations for 2-8 March 2010

The accuracy of atmospheric correction algorithms will be evaluated using the SeaPRISM data stream i.e. water leaving radiance (or remote sensing reflectance) and atmospheric optical thickness, as well as ancillary weather and sky information. The accuracy of the algorithms for the retrieval of optical properties from ocean colour data (i.e. absorption and scattering, apportioned to phytoplankton, dissolved and non-algal particulate matter) will be quantified using the inherent optical properties estimated from the instruments data collected with ac-s and BB9. The accuracy of ocean colour algorithms for the retrieval of biogeochemical quantities will be assessed using the laboratory-based measurements of concentrations of chlorophyll, coloured dissolved organic matter and particulate matter from direct sampling of the water column.

An example of the AERONET-OC data products derived from the SeaPRISM measurements, the normalized water-leaving radiances for 2-8 March 2010 are presented in Figure 8, with the corresponding weather observations presented in Figure 9. The weather observations show smaller diurnal changes in temperature and relative humidity, higher wind speed and lower barometric pressure for March 2-4 that for March 5-8 (Figure 9). For the corresponding period the real-time cloud-screened normalized water-leaving radiances were higher on March 3-4 than on March 6-8 (Figure 8). The Real Time Cloud Screened data were automatically cloud cleared but do not have final calibration applied and are not Quality Assured. This process will happen only at the end of each deployment and calibration cycle, every 12 months.

The weather conditions for March 3-5 are likely to have produced higher seas possibly with white caps or foam which could explain the observed higher normalized water-leaving radiances. Availability of images of sky and sea conditions would have strengthened this preliminary analysis.

B. Process studies

In addition to the validation activities the combined bio-optical observations will be useful for a variety of process studies such as particle and phytoplankton temporal dynamics (e.g. assessing diurnal to seasonal variability), modeling of the underwater light climate for primary production, identifying optical proxies linking optical observations to biogeochemical properties and radiative transfer modeling studies to derive optical closure between inherent and apparent optical properties.

These studies will benefit from the broad range of conditions occurring at this site where the sources of particulate and dissolved matter substantially vary during the tidal and seasonal cycles due to the interaction of the Herbert River, the Hinchinbrook Channel and the costal waters of the GBR lagoon.

An example of data measured with *in situ* water optical package during a 24 hours-cycle is presented in Figure 10. The 2.5m depth variability reflects the tidal range at the site, as the in situ water optical package is deployed at a fixed distance from the seabed, at 2m below the lowest astronomical low tide. The salinity and temperature show a distinct increase towards the end of the tidal cycle that is reflected in the chlorophyll and turbidity record and is probably due to a different water mass moving past the site.

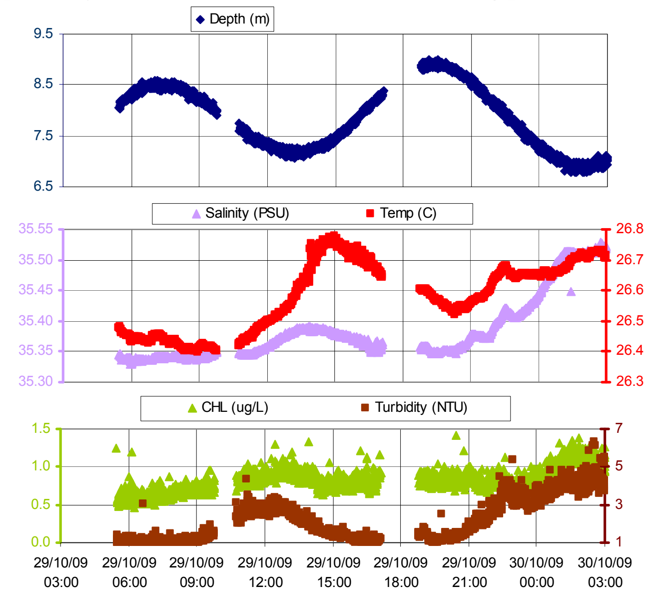

Figure 10. Daily cycle for 29 October 2009 of pressure, salinity, temperature, chlorophyll fluorescence and turbidity measured using a WETLabs Water Quality Meter (WQM)

IX. Future Work

A. *Enhancement to the instrument setup*

Automation of the winch control via the DACPS will enable the water optical cage to be maintained at a nominal depth of 1.5m below the water surface by using a feedback system between the depth measured by WQM and the electric winches. Automatic winch control will also enable unattended profiling of the water column.

In addition to the measurement of the total absorption (by particulate and dissolved matter) with the ac-s, the implementation of a switchable filtering and pump system will enable the apportioning of the absorption to dissolved and particulate components.

B. *Hemispherical cameras*

From April 2010, the radiometric data collected at the LJCO will complemented by three webcams; two hemispherical cameras mounted on the upper deck to capture a full sky view for use in post processing and interpretation of radiometric data. One camera is dedicated to the sky observation while the second hemispherical camera will be installed in a northern orientation to monitor simultaneously both sky and sea states. The IPIX CommandView^{TM} cameras were selected for the LJCO; the 2.0 megapixel network camera provides a hemispherical field of view. The hemispherical cameras will interface directly with the router onsite and will be assigned static IP addresses. Image collection and handling will be managed offsite with image collection software polling the cameras at pre determined intervals to collect both still images and video clips.

C. *Biogeochemical sampling*

The fortnightly maintenance visits offer an opportunity for collection of surface water samples for the characterization of the bio-optical and biogeochemical properties of the water column. Water samples for the determination of phytoplankton pigments will be filtered through Whatman 47 mm diameter GF/F glass-fiber filters and stored in liquid nitrogen until analysis by high-performance liquid chromatography (HPLC) will be performed at CMAR laboratories in Hobart. For the total particulate material, water samples will be filtered through Whatman 25 mm GF/F glass-fiber filters and stored flat in liquid nitrogen until analysis. Water samples for CDOM measurements will be filtered through 0.22 µm polycarbonate filters and stored in glass bottles, kept in cool and dark conditions until laboratory analysis. Further details on all the methods for sampling, laboratory determination and data analysis can be found in [10].

D. *Spatial and temporal variability of the site at the match-up scale*

In coastal waters, match up analysis of satellite retrievals vs. *in situ* measurements is challenged by the high spatial/temporal variability of seawater optical properties; effects of bottom visibility in shallow waters; and also adjacency effects in satellite data products due to the higher albedo of the mainland with respect to that of the sea [3].

A rigorous error analysis of the *in situ* data will be conducted to quantify measurement and sampling errors. The in-sample and between sample variability for bio-optical and biogeochemical properties will be investigated, and protocols for the measurement of apparent optical properties will be compared using a range of spectroradiometers.

In order to understand how the spatial and temporal variability at the site could influence what is captured in the satellite imagery, the scales of temporal and spatial variability of the optical properties surrounding LJCO will be assessed during the tidal and seasonal cycles. A series of dedicated measurement campaigns will be carried out to characterize the sources and variability of the inherent optical properties of particulate and dissolved matter and their effect on the apparent optical properties such the water leaving radiance and remote sensing reflectance measured on site.

X. Conclusion

The establishment of the LJCO has enabled real time simultaneous measurement of the downwelling light field, aerosol optical properties, water leaving radiance and the optical properties of the water column. These measurements are complemented by an array of ancillary equipment including a weather station and hemispherical cameras to record both sky and sea state.

In the coming months, all the data streams generated at LJCO will be made freely available according to the IMOS data policy. The data will be accessible in a near real-time through the IMOS Ocean Portal http://imos.aodn.org.au/webportal/]..

The data generated at LJCO will be exploited by researchers and policy makers for the validation and improvement of satellite ocean colour products in coastal waters and also for carrying out process studies on the interactions of the various sources of particulate and dissolved matter experienced at the site during the tidal and seasonal cycles.

Acknowledgment

This work was funded by IMOS, CSIRO Land & Water and CSIRO Wealth from Oceans. IMOS is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and the Super Science Initiative. Queensland Sugar Ltd. is acknowledged for the access to the site and support with infrastructure. The authors also wish to thank the whole AERONET team for the continuous effort in supporting AERONET-OC.

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