Coral reef ecosystem integrated observing system: *In-situ* oceanographic observations at the US Pacific islands and atolls

RK Hoeke, JM Gove, E Smith, P Fisher-Pool, M Lammers, D Merritt, OJ Vetter, CW Young
Joint Institute for Marine and Atmospheric Research, University of Hawaii at Manoa and Coral Reef Ecosystem Division, Pacific Islands Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA), Hawaii, USA
KB Wong, RE Brainard
Coral Reef Ecosystem Division, Pacific Islands Fisheries Science Center, National Marine Fisheries Service, NOAA

The National Oceanic and Atmospheric Administration (NOAA) established the Coral Reef Ecosystem Integrated Observing System (CREIOS) to provide integrated and interdisciplinary environmental and ecological observations. NOAA Pacific Islands Fisheries Science Center (PIFSC) Coral Reef Ecosystem Division (CRED) leads the Pacific portion of CREIOS, conducting biennial biological and hydrographic surveys of US Pacific coral reefs and maintaining a diverse network of *in situ* instrumentation providing time series of ecosystem variables. This paper focuses on the oceanographic and environmental observations and data products of CREIOS across the Pacific and provides an overview of the methods, challenges, and future directions of the observing system

LEAD AUTHORS' BIOGRAPHIES

Ron Karl Hoeke completed a master of science in coastal oceanography from the Florida Institute of Technology. He has since worked as an oceanographer for the Joint Institute of Marine and Atmospheric Research. He has participated with NOAA Pacific Islands Fisheries Science, Center Coral Reef Ecosystem Division on many multi-disciplinary research cruises throughout the Pacific, serving as Chief Scientist for the 2009 cruise to Wake Atoll and Guam. He is currently a Doctoral candidate at James Cooke University.

Jamison Gove has been engaged with the Coral Reef Ecosystem Division's extensive field research and monitoring program. He is currently pursing a PhD in the Oceanography Department, School of Ocean and Earth Science and Technology, University of Hawaii.

Dr Rusty Brainard is the Chief of the Division and overall principal investigator on most of the Division's programs. Dr Kevin Wong leads and coordinates the Division's Instrumentation and Oceanography Teams. All other authors are integrally involved with various facets of the Division's coral reef observing system activities.

INTRODUCTION

Coral reef ecosystems are among the most biologically diverse and productive ecosystems on earth. They provide economic and environmental services to hundreds of millions of people in terms of shoreline protection; areas of natural beauty and recreation; and sources of food, pharmaceuticals, chemicals, jobs, and revenue.[1] At present, coral reef ecosystems worldwide are deteriorating at alarming rates due to local anthropogenic stressors, such as overexploitation, habitat destruction, disease, invasive species, land-based runoff, pollution, and marine debris; and to stressors associated with global climate change, especially increased ocean temperatures and ocean acidification.[2,3] A thorough understanding of coral reef ecosystem dynamics is required if these valuable natural resources are to be conserved and, in some cases, restored. In addition to basic research, an increased level of assessment and monitoring is required for the sustainable management and resilience of coral reefs, echoing calls for increased coastal monitoring at all latitudes.[4,5,6]

Overview of CREIOS

In response to calls for increased assessment, monitoring, and mapping to facilitate improved management and conservation of coral reef ecosystems, the United States Coral Reef Task Force (USCRTF) was established in 1998 by Presidential Executive Order. Through the coordinated efforts of its members, composed of federal agencies as well as state, territorial, and freely associated state governments, the task force coordinates US efforts to protect, restore, and promote the sustainable use of the nation's coral reef ecosystems. As part of this national effort, and in conjunction with ongoing efforts to establish an Integrated Ocean Observing System (IOOS), the NOAA Coral Reef Conservation Program initiated the development of CREIOS to provide a diverse suite of long-term ecological and environmental observations and information products over a broad range of spatial and temporal scales. The goal of CREIOS is to better understand the condition of and processes influencing the health of the nation's coral reef ecosystems and to provide this information to resource managers and policymakers to assist them in making timely, science-based management decisions to conserve coral reefs.

Marine ecosystems are structured by physical, chemical, and geological processes that all interact synergistically through a hierarchy of physical-ecological interactions.[5] Understanding these relationships is complicated by the interplay of complex trophic interactions which naturally vary over a diverse range of space and time scales. Understanding is further confounded by the difficulties inherent in making direct concurrent observations of these physical-chemical-biological interactions.

Most existing sensors are capable of measuring physical environmental trends but currently lack the ability to observe many of the corresponding biological processes over the time scales needed for understanding long-term variability. Instruments that monitor biological parameters or surrogates typically require an optical or other interface that rapidly degrades due to marine biofouling, and are thus unsuitable for long-term measurements in remote areas. Human-mediated survey efforts, on the other hand, are effective at measuring biological conditions but are limited in the ability to monitor fine-scale temporal changes because of their inherently high logistical and staffing costs. The CREIOS-Pacific Network addresses these challenges by using a combination of oceanographic instrumentation, passive acoustic monitoring, analysis of remotely-sensed data products, and human-mediated surveys to achieve long-term monitoring of appropriate physical and ecological variables.

CREIOS Pacific Reef Assessment and Monitoring Program (RAMP)

As part of the CREIOS Pacific network, NOAA's PIFSC CRED is engaged in a long-term program to assess and monitor changes in the ecology and underlying oceanographic and meteorological conditions of coral reefs in and around the US-affiliated Pacific islands and atolls. CREIOS Pacific is an interdisciplinary observing system that combines oceanographic, atmospheric, and ecological information over diverse spatial (island, archipelago, ocean basin) and temporal (diurnal, seasonal, interannual) scales. In collaboration with local, state, and territorial partners, CRED leads the Pacific Reef Assessment and Monitoring Program (RAMP) in conducting biennial assessment and monitoring surveys of the coral reef ecosystems around 54 islands, atolls, or reefs in the State of Hawaii (the Northwestern Hawaiian Islands and the main Hawaiian Islands), the Territories of Guam and American Samoa, the Commonwealth of the Northern Mariana Islands, and the Pacific Remote Island Areas (PRIA) which include Howland, Baker, and Jarvis Islands, and Palmyra, Kingman, Wake, and Johnston Atolls (Fig 1).

These surveys include towed-diver surveys, benthic habitat mapping, rapid ecological assessments (REA) of fish, coral, algae, and other invertebrates, hydrographic surveys, and water quality sampling. During the surveys, instrumented platforms are deployed to record and, in some cases, telemeter data until the next biennial Pacific RAMP survey when they are recovered, serviced, and redeployed. Time series observations from these platforms are augmented with satellite remote-sensing observations and numerical modelling outputs. The CREIOS Pacific platforms and field observations are located across diverse gradients of human impacts, ranging from some of the most remote and pristine coral reef ecosystems on the planet to areas heavily impacted by local human activities.

The principal goals of the oceanographic and water quality monitoring component of the CREIOS-Pacific network include:

- Characterising the variability of the prevailing climate and oceanographic conditions influencing the condition of coral reefs;
- Quantifying key physical forcing mechanisms (ie, currents, temperature, waves, etc) pertinent to biological processes such as the distribution of organisms, overall biological productivity and species richness, dispersal

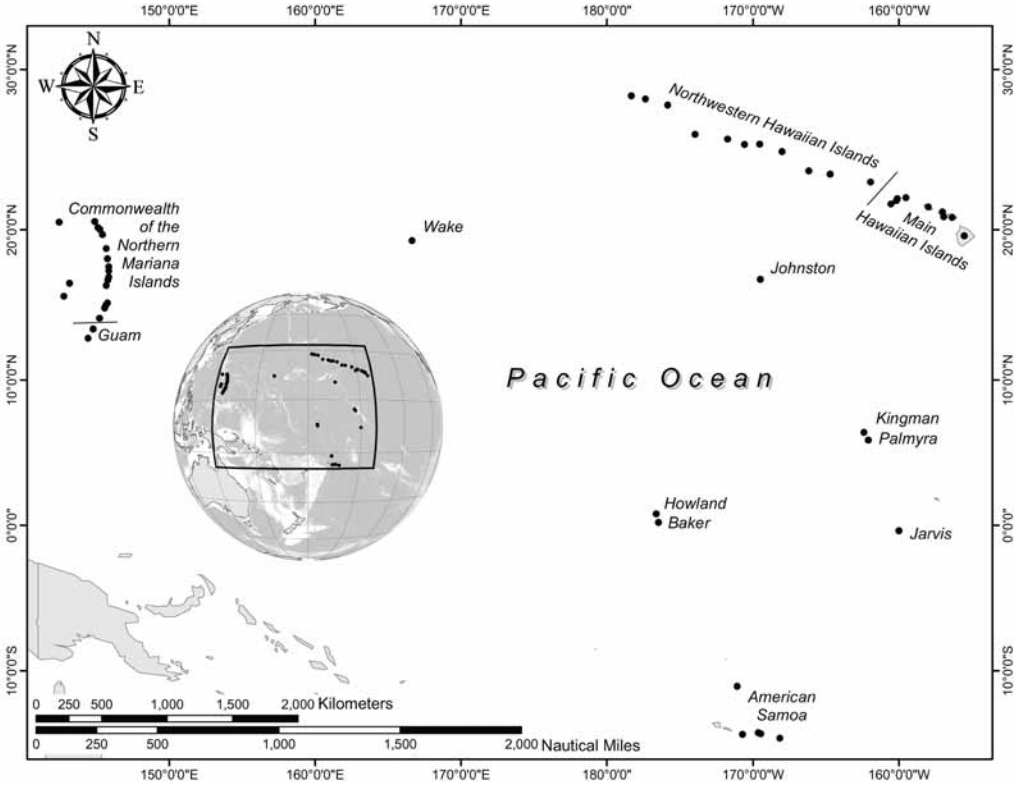

Fig 1: CREIOS-Pacific network currently includes: the Territory of Guam, the Commonwealth of the Northern Mariana Islands, the Territory of American Samoa, the Northwestern Hawaiian Islands, the main Hawaiian Islands, Howland, Baker, and Jarvis Islands, and Palmyra, Kingman, Wake, and Johnston Atolls

and recruitment of larvae, localised and large-scale patterns of coral bleaching, and degree of disturbance due to episodic storms;

- Generating climatologies from long-term time series of *in situ* observations for the purpose of detecting important environmental changes, thereby increasing the information base of environmental conditions, particularly in remote areas of the Pacific where information is sparse;
- Generating synoptic morphological and benthic habitat maps.

This paper provides a detailed overview of the *in situ* oceanographic and water quality observations of the CREIOS Pacific network. Generally, these observations include the following:

(1) Spatial hydrographic and water quality surveys performed during biennial Pacific RAMP research cruises;

(2) High-resolution time series observations of key oceanographic properties collected using an array of instrumented moorings (surface buoys and subsurface platforms).

These observations are augmented by satellite remote-sensing and numerical modelling products. Rationale, methodology, and data management are presented and some examples of applications of CREIOS data are discussed.

For a more general overview of broader integrated ecosystem observations of Pacific RAMP, including the benthic habitat mapping and ecological observations of fish, corals, other invertebrates, and algae, readers are referred to the first comprehensive *Coral Reef Ecosystem Monitoring Report for American Samoa: 2002–2006* and the following references: Preskitt *et al*, 2004 (benthic REA methods[7]); Schroeder *et al*, 2008 (fish REA methods[8]); Kenyon *et al*, 2006 (towed-diver benthic surveys[9]); for morphological and benthic habitat mapping methods, refer to Lundblad *et al*, 2006.[10]

METHODS

The CREIOS-Pacific network of *in situ* telemetering instrumentation deployed at various remote atolls and islands provides a near real-time, high-resolution time series of sea surface temperature (SST), salinity, photosynthetic active radiation (PAR; surface and subsurface), ultraviolet B radiation (UV-B; surface and subsurface), air temperature, barometric pressure, and wind velocity. The surface telemetered observations are augmented by a cost-effective network of subsurface moored instrumentation recording water temperature, conductivity, current profiles, passive acoustics, and wave and tide observations. At present, 54 sites (islands, atolls or banks) are instrumented with 24 telemetering surface buoys and 239 subsurface data recorders (Table 1).

Hydrographic field surveys are also performed during research cruises to provide a detailed assessment of the oceanographic and water quality conditions around the near-shore waters of each of the islands and atolls surveyed. Both field surveys and moored instrument platforms are essential in understanding and interpreting environmental observations. The long-term time series data sets from surface and subsurface instrument platforms provide context for the more detailed biennial spatial ‘snapshots’ that field observations afford. Data collected include shipboard acoustic Doppler current profiler (SADCP), conductivity, temperature, depth (CTD), dissolved oxygen, turbidity (beam transmittance), chlorophyll-*a*, nutrients, seawater carbonate chemistry (including dissolved inorganic carbon [DIC] and

Geographic area	Instrument type						
	CREWS – ENH*	CREWS – STD*	SST*	STR	WTR	ODP	EAR
Main Hawaiian Islands	-	-		23	1	-	4
Northwestern Hawaiian Islands	1	3	4	54	4	2	4
Guam and the Commonwealth of the Northern Mariana Islands (CNMI)	-	-	4	38	2	-	2
American Samoa	-	-	6	37	4	-	4
Pacific Remote Island Areas	1	-	5	56	5	2	5
Total	**2**	**3**	**19**	**208**	**19**	**4**	**19**

Table 1: Telemetered and non-telemetered instrumentation currently deployed in each of the CREIOS-Pacific network jurisdictions.
*Near real-time telemetered instrument

total alkalinity [TA], SST and salinity, and ocean current drifter information.

Sensor deployment locations and the location and level of detail of hydrographic surveys at each site attempt to be as synoptic as possible but are arbitrated though the input of local government and other partner agencies, the ability to augment existing observing system infrastructure, local ecological/oceanographic phenomena, and logistical/funding constraints. Most sensor deployment locations are quasi-stationary; every attempt is made to provide a continuous record with sufficient fidelity to detect trends amid short-term, seasonal, and climate shifts in the data. As with any long-term endeavour, the CREIOS-Pacific network continues to evolve with advances in technology and scientific knowledge of coral reef ecosystems.

Instrumentation

- **Coral Reef Early Warning System (CREWS) Buoy**
  Standard (STD) moored buoys provide near real-time high resolution SST and surface conductivity at a depth of 1m (Sea-Bird Electronics, SBE37; accuracy of 0.002°C, 0.0003 S m^{-1}), air temperature (Young Instruments, WS425; accuracy of 0.3°C), barometric pressure (Heise Instruments, DXD; accuracy of 0.02% FS), and wind speed and wind direction (Vaisala Instruments; accuracy of 0.135ms^{-1} in speed and 2° in direction). Enhanced (ENH) CREWS buoys also measure PAR and three bands of ultraviolet radiation (305nm, 330nm, 380nm) measured at 2m (nominal) above the surface of the water and 1m (nominal) below the surface. Internally recorded data are sampled throughout the hour at various intervals (depending on the sensor). Fig 2 illustrates an Enhanced CREWS and some associated data products. Subsets of these data are transmitted daily via satellite telemetry. See[11] for additional information on CREWS development and alerting.
- **Sea Surface Temperature (SST) Buoy**
  Moored buoy that provides high resolution SST data (nominal depth of 0.3m, Sea-Bird Electronics, SBE39; accuracy of 0.002°C). Internally recorded data are sampled at 30min intervals. Hourly data are batched and transmitted, at least once per day, via satellite telemetry.
- **Subsurface Temperature Recorder (STR)**
  STRs, deployed at depths ranging from 0.5–40m, are typically attached to the reef structure or positioned on the seafloor with added weights. They provide high resolution temperature observations (Sea-Bird Electronics, SBE39; accuracy of 0.002°C), internally recorded at 30min intervals.
- **Ocean Data Platform (ODP)**
  Deployed on the seafloor, at depths typically ranging from 15–40m, the ODP provides directional current profiles and wave spectra using a 3-beam 1000 kHz acoustic Doppler profiler (SonTek Inc; accuracy of 0.005ms^{-1} in current and 0.1% in pressure), and high resolution temperature and conductivity time series observations (Sea-Bird Electronics, SBE37; accuracy of 0.002°C, 0.0003 S m^{-1}). Sample intervals for current and wave data vary depending on duration of deployment; temperature and salinity are sampled at 30min intervals.
- **Acoustic Doppler Profiler (ADP)**
  Typically deployed on reef flats and shallow reef passes (channels), at depths typically ranging from 2–10m, the ADP provides full-depth, directional, current profiles and wave spectra using a 3-beam 2 MHz acoustic Doppler profiler (Nortek USA; accuracy is 1% of measured horizontal velocity and a pressure resolution is 0.005%).
- **Wave and Tide Recorder (WTR)**
  Deployed on the seafloor, at depths typically ranging from 10–25m, the WTR provides high-resolution wave and tide records (Sea-Bird Electronics, SBE26*plus*; accuracy of 0.01% in pressure). Data are internally recorded with variable sample intervals depending on duration of deployment.
- **Ecological Acoustic Recorder (EAR)**
  The EAR is a passive acoustic device developed specifically for monitoring marine mammals, fish, crustaceans, other sound-producing marine life, and human activity in marine habitats. The EAR is a digital, low-power system that records ambient sounds up to 30 kHz on a programmable schedule and can also respond to transient acoustic events that meet specific criteria, such as motorised vessels passing nearby or cetaceans. Deployment depths typically range from 5–25m.

Hydrographic surveys

- **Shallow Water Conductivity-Temperature-Depth (CTD) casts**
  CTD casts in the nearshore environment provide vertical profiles of water column conductivity, tem-

perature, and pressure (Sea-Bird Electronics, SBE19-plus; accuracy of 0.005 S m^{-1} in conductivity, 0.0002°C in temperature, and 0.1% in pressure). A transmissometer (Wetlabs Inc; provides profiles of beam transmittance, related to turbidity) and a dissolved oxygen sensor (Sea-Bird Electronics, SBE43; accuracy of 2% of saturation) are also attached. Data are collected by lowering the CTD in a profiling mode from a small boat at a descent rate of approximately 0.5 to 0.75m s^{-1} to a maximum depth of 30m.

- **Deepwater CTD casts**
  Shipboard CTD casts provide high resolution vertical profiles of water column conductivity, temperature, and pressure (Sea-Bird Electronics, SBE911*plus*; accuracy of 0.003 S m^{-1} in conductivity, 0.001°C in temperature, and 0.015% in pressure). Dissolved oxygen (Sea-Bird Electronics, SBE43; accuracy of 2% of saturation), fluorescence and turbidity (Wetlabs, Inc, ECO FLNTU; accuracy of 0.01 µg l^{-1} fluorescence and 0.01 NTU turbidity) measurements are performed in concert with CTD measurements. Data are collected to cast depths of 500m.
- **Shipboard Acoustic Doppler Current Profiler (SADCP)**
  This shipboard sensor provides directional ocean current data (RD Inc, 75 kHz Ocean Surveyor). The system is configured with an 8m pulse length, 16m depth bins starting at 25m and extending typically to 600m (the depth range depends on the density and abundance of acoustic scattering materials in the water column), and 5min averaged ensembles. Data are continuously collected while the vessel is underway.
- **Water Chemistry**
  Water samples are collected for analysis of chlorophyll-*a*, nutrients (phosphate (PO_4^{-3}); silicate ($Si(OH)_4$); nitrate (NO_3^-); nitrite (NO_2^-)) , salinity, dissolved inorganic carbon (DIC) and total alkalinity (TA). These samples are collected concurrently with shallow water and shipboard CTD profiles at select locales. Sample depths are typically 1, 10, 20 and 30m for shallow water operations, and 3, 80, 100, 125 and 150m for shipboard operations.
- **Thermosalinograph (TSG)**
  Shipboard instrument providing near-surface temperature and conductivity data (Sea-Bird Electronics 21; accuracy of 0.0001 S m^{-1} in conductivity and 0.001°C in temperature). Data are continuously collected while the vessel is underway.
- **Surface Velocity Program (SVP) Drifters**
  Lagrangian current devices **drogued** to a 15m depth provide mixed-layer current observations in the upper ocean. Lumpkin and Pazos[12] offer additional information about the history of drifter development and data processing.
- **Shipboard Meteorology Data**
  Shipboard measurements of air temperature, wind speed and direction, barometric pressure, and relative humidity are collected continuously while the vessel is underway.

Data

The surface buoys (CREWS, SST) provide near real-time data with hourly observations batched and transmitted via the Argos, Iridium or Inmarsat satellite services. Telemetry of SST buoy data are delayed four hours and CREWS buoy data are delayed 24 hours. Automated alerts notify CRED personnel if a buoy has strayed beyond a defined watch circle or if data transmissions cease. The PIFSC (http://www.pifsc.noaa.gov/cred) and Coral Reef Information System (CoRIS) (http://www.coris.noaa.gov) have additional information about the availability of near real-time and archived data products and provide several publicly available data discovery tools.

Higher resolution data from CREWS and SST surface buoys and all subsurface moorings are downloaded from the instruments when they are recovered every two years. Raw data streams are quality controlled to remove unreliable or erroneous measurements and are processed to a consistent format and data quality standard. Certain data types must be processed via specific software packages (eg, Seabird data processing) to transfer the data from a raw (eg, hexadecimal) format to a more user-friendly, editable format (eg, ASCII).

CRED uses NOAA Pathfinder SST,[13] Coral Reef Watch satellite SST,[14,15] Quickscat Seawinds product[16], and Wavewatch III wave model[17] products. Time series and climatologies are established from these products for all CRED sites and are compared to *in situ* data and/or serve as a proxy to fill *in situ* data gaps. An example of the combination of satellite, model, and *in situ* data sources to produce site climatologies can be found in Fig 2.

Chlorophyll analyses are conducted internally or by contract water quality laboratories using standard methods; nutrient, salinity, DIC and TA analyses are performed in partnership with NOAA Pacific Marine Environmental Laboratory (PMEL) and the University of Washington. The resulting data are managed and distributed by CRED.

Challenges

The extreme remoteness of many (often uninhabited) Pacific coral reef ecosystems and large distances between them are significant factors driving the design and implementation of an integrated observing system (IOS). Considerable resources (oceangoing vessels, technical divers, support personnel, etc) are required to deploy and recover the *in situ* instruments distributed over such a large region of ocean. Even with the use of multiple-mission cruises, shared support staff, and other cost-saving measures, visits to most of the US-affiliated Pacific islands are constrained to biennial expeditions, with time at each site (island/atoll) limited to 3-4 days. This 24-month servicing interval has significant implications in terms of instrument design and selection due to instrument memory and power limitations and biofouling.

Inherent in sustained long-term observing systems is a cycle of instrument deployment, retrieval, refurbishment, recalibration, and redeployment. Measurement uncertainty for CREIOS is generally within acceptable limits for the

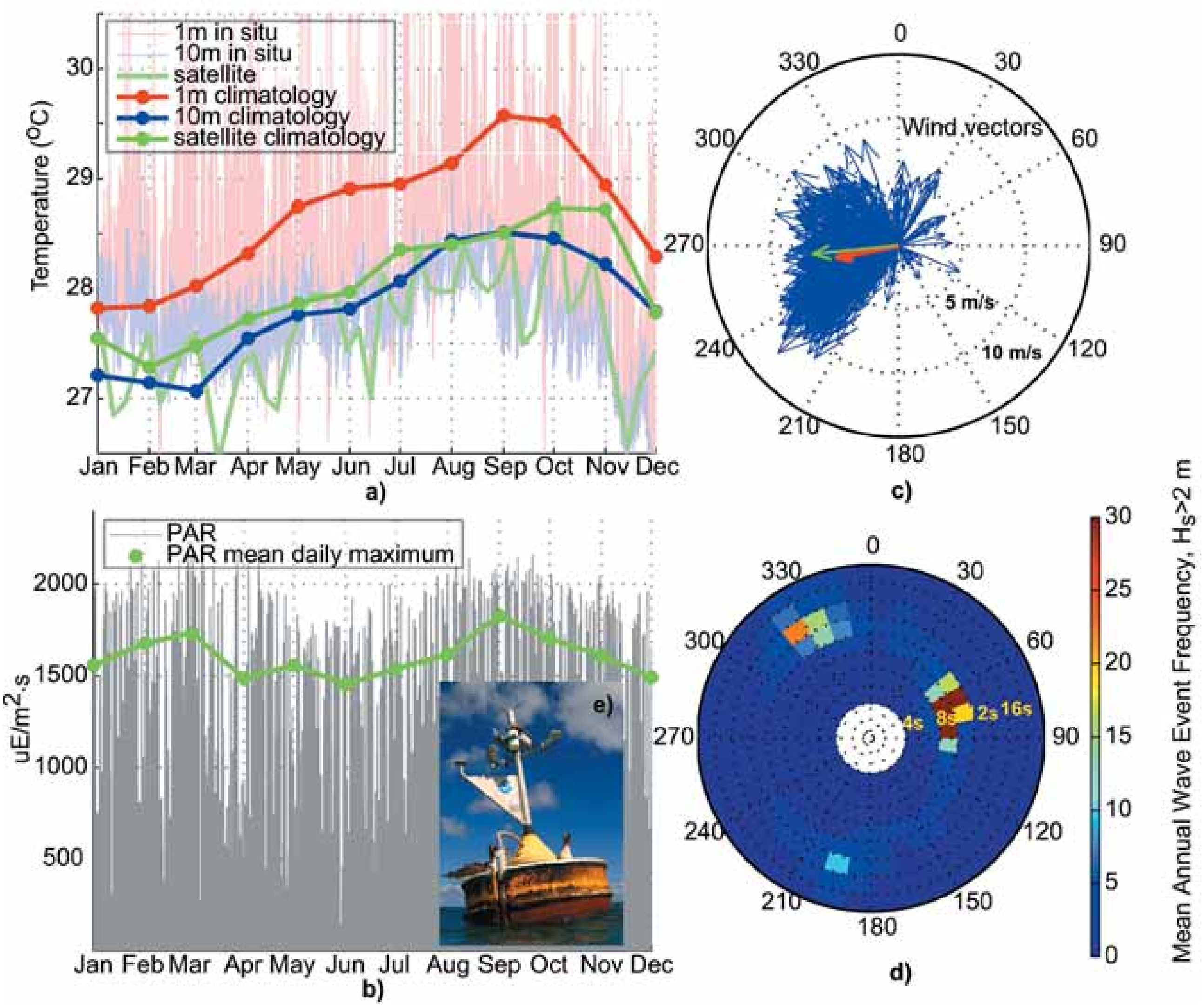

Fig 2: *In situ*, satellite, and model derived climatologies, Palmyra Atoll (5.87°N, -162.04°W): (a) Pathfinder satellite sea surface temperature (SST)[13] monthly climatology (thick green line) in 2007 compared with those derived from *in situ* CREWS Buoy sensor at 1m (thick red line) and 10m (thick blue line) water depths; thin red and blue lines represent *in situ* observation data during 2007 for 1m and 10m water depths, respectively; thinner green line (without points) represents weekly Pathfinder SST, from 2007. (b) Monthly daily maximum photosynthetically active radiation (PAR) climatology from the CREWS Buoy; grey lines are daily observations for 2007. (c) Compass rose of daily mean wind vectors from CREWS Buoy; red arrow represents mean; green arrow is vector mean of the Quickscat Seawinds[16] for the same period; both means show the dominance of NE trade winds. (d) Mean annual frequency of occurrence of significant wave heights over 2m. The yellow labels inside the directional plot identify wave period bins from 2-20s; the radial directions represent dominant wave direction. Shorter period (8-10s) waves arrive from the ENE (70-80°) most often, corresponding with NE trade wind dominance; while longer period episodes from the NW and SW from distant high northern and southern latitude storms occur with much lower frequency. (e) Photo of CREWS Buoy, topside instrumentation

purposes of using time series of physical oceanographic and meteorological data as correlating variables along with human mediated ecological observations to develop hypotheses and to monitor ecosystem level processes. For example, *in situ* water temperature observations, which are included at most of the CREIOS sites are typically measured using aged thermistors embedded in the titanium end cap of the instrument. These instruments (manufactured by Seabird Electronics Inc) have historically provided an initial accuracy of 0.002°C with drift typically less than 0.002°C per year. Post deployment calibration data is maintained for re-processing of raw datasets. Measurements of conductivity (used to infer salinity values), from an unattended instrument deployed for periods of up to 24 months, are necessarily subject to larger uncertainty. Mitigation efforts have included deploying a separate instrument prior to recovery of the target instrument in order to obtain overlapping observations to use as *in situ* end-point calibration values. Analysis of the time series data during the transition from one instrument deployed at a particular site to the replacement instrument deployed at the same site is also used to help bound the measurement error. The use of observations such as sub-surface PAR measurements necessarily have to be tempered by the data collection exigencies. (Sub-surface

PAR measurements have only been attempted at sites where local personnel were available to clean optical surfaces of the instrument. However, records indicate that the frequency of service is often quite variable depending on availability of boats, weather, staffing levels, etc)

The use of SCUBA, a primary method employed for instrument deployment/recovery, imposes limits on depth, duration of individual dives, and the number of repetitive dives allowed in a given time period. As an operational observing system, current and outyear efforts focus on maintaining the long-term (decadal scale) oceanographic and ecological data records at the existing CREIOS Pacific sites.

DISCUSSION

Example research applications

The CREIOS-Pacific *in situ* oceanographic observations were initiated in early 2001. Since that time, numerous connections between the observations and ecological changes have been identified at a variety of scales. A few of these are shown as examples in this section, and serve to demonstrate steps towards achieving ecosystem-based monitoring. The examples include: mass coral bleaching events in the Northwestern Hawaiian Islands (NWHI, reef-to-archipelago scale); exceptionally high fish biomass and distribution of this biomass around an island (reef to island/atoll scale); and the impact of an episodic storm wave event on the coral cover of a reef (reef to island/atoll scale).

During the late summer seasons of both 2002 and 2004, the NWHI experienced widespread mass coral bleaching. The extent of this bleaching was highly dependent not only on latitude within the archipelago, but also on morphological zone on the reef.[18,19,20] Analyses of *in situ* and satellite observations of temperature, wind, and insolation indicate a strong relationship between the severity of bleaching and local water-column mixing processes. CREIOS-Pacific observations provided both large-scale climatological and small-scale morphological indicators of coral bleaching susceptibly, both between reefs and islands and within individual reefs.[21,22] As shown in Fig 3, local habitat-associated (forereef, backreef, and lagoon) differences in temperature resulted in differences in the observed severities of bleaching.

Reef fish biomass around Jarvis Island, a small isolated island located within 40km of the equator in the central Pacific, has been documented to be exceptionally high, possibly the highest in the tropical Pacific.[23] Oceanographic observations have indicated not only higher productivity of the neighbouring oceanic water due to equatorial upwelling, but also locally intense, topographically induced upwelling caused by the interaction of the strong eastward flowing subsurface Equatorial Undercurrent striking the submarine portions of Jarvis Island.[24] This localised upwelling of nutrient-enriched waters supports a diverse and thriving reef fish community distributed around the island (Fig 4). Gove *et al*[24] utilised CREIOS observations to examine these processes in detail, resulting in an improved understanding of the role of large-scale oceanographic processes associated with the El Niño Southern Oscillation (ENSO) in modulating these local processes.

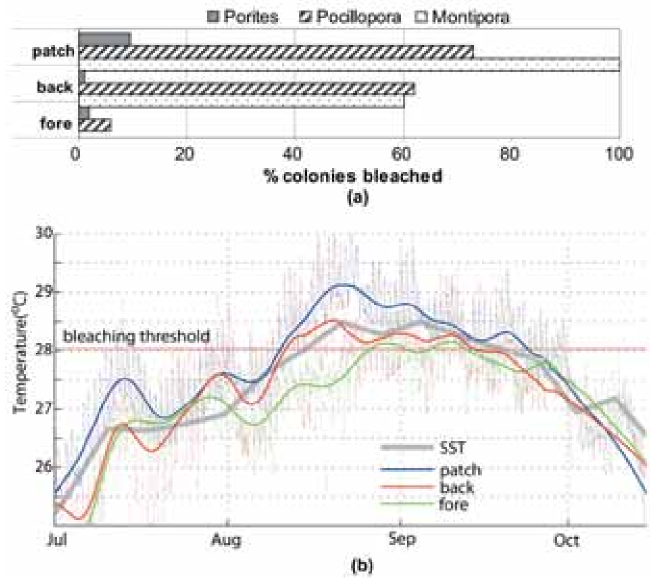

Fig 3: Mass coral bleaching event at Pearl and Hermes Atoll, NWHI (27.8°N, 178.5°W) in 2004. (a) Incidence of coral bleaching within REA belt transects by habitat and genus, September/October 2004, adapted from.[20] (b) Weekly Pathfinder SST[13] and *in situ* sea temperatures. Colored solid lines represent *in situ* data with diurnal variations smoothed out; small individual dots represent hourly observations. The bleaching threshold, 1°C above the maximum monthly climatological mean,[14] here derived from Pathfinder climatology, is included for reference. In both (a) and (b) 'patch', 'back', and 'fore' stand for observations on patch reefs within the atoll's lagoon, backreef habitats, and forereef habitats, respectively. Observed coral bleaching in the different habitats correlates well with *in situ* measurements of temperature magnitude and duration elevated above the bleaching threshold. Because of its large spatial footprint and much poorer temporal resolution, satellite SST alone does not provide such fine- scale measurements of temperature differences in local reef habitats

Percent live coral cover and overall benthic community structure, particularly biodiversity, are highly dependent on wave exposure at any particular location.[25,26,27] The community structure often represents the culmination of ecosystem response to multiple episodic disturbances.[28,29] Few studies on the overall response of a coral community to a single event exist, however. In 2004, Cyclone Heta, a large category 5 hurricane, passed approximately 300km west of Swains Island, American Samoa, and caused 8m storm waves to strike the reefs on the north and west sides of the island. Based on differences in coral cover from surveys in 2002 and those one month after the storm in early 2004, island-wide coral cover decreased by almost 25%, with a decrease of up to 60% in some areas[30] (Fig 5). Subsequent surveys in 2006 revealed a partial recovery of island-wide mean coral cover. The northwest corner where the coral breakage was highest in 2004 was observed to have macroalgae dominance in 2006 and dominance by an invasive

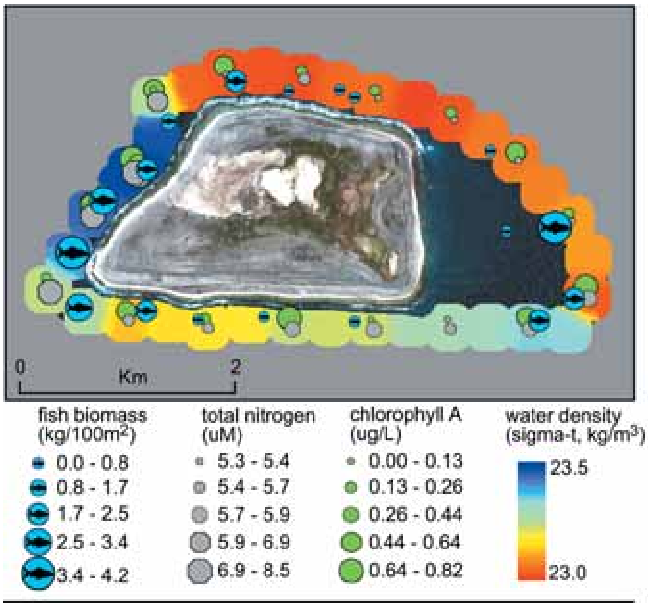

Fig 4: Jarvis Island (00.37°S, 160.0°W): biomass density of planktivorous fish from 2008 REA surveys; total nitrogen, chlorophyll-*a* concentrations, and *sigma-t* (water density) at the 10m depth level from water sampling and nearshore hydrographic surveys. Symbols represent geographic location of REA and water sample sites. Upwelled waters due to topographic interaction with the Equatorial Undercurrent are indicated by higher total nitrogen concentrations and *sigma-t* values. This is linked to exceptionally high biomass density and distributions of reef fish[23] as well as live coral cover, and a number of other components of the local coral reef ecosystem.[24]

didemnid tunicate in 2008.[31] These dynamic and far-reaching changes to the reef ecosystems of Swains highlight the complexity of recovery following a destructive wave event.

These examples are but a few of many currently being investigated using CREIOS observations, each highlighting connections between ecological and physical phenomena that would be difficult to make without a systematic and integrated ecosystem-based approach that concurrently collects biological and oceanographic information. As these time series observations are extended, efforts are continually made to improve the instruments and refine the methods to ensure that the observations cost-effectively address management issues. Continued data collection will provide an increasingly refined understanding of the impact of episodic events, anthropogenic impacts, and other biophysical mechanisms; this will lead to a drastically refined ability to predict ecosystem change in the face of climate variability and change.

Near real-time telemetry of subsets of these *in situ* data serves to alert resource managers and researchers of episodic events and emergent trends in the environment that could significantly affect the surrounding coral reef ecosystems, thereby allowing for responsive actions. CREWS buoys located at select coral reef sites provide highly useful up-to-date *in situ* environmental information for assessing local bleaching[19,22,20] and other biologically important manifestations like spawning and migrations.[5] Such telemetered data enable researchers to better document ecosystem changes and provide insight into ecological conditions that might be encountered during upcoming research cruises.

CRED's network of *in situ* instrumentation also provides

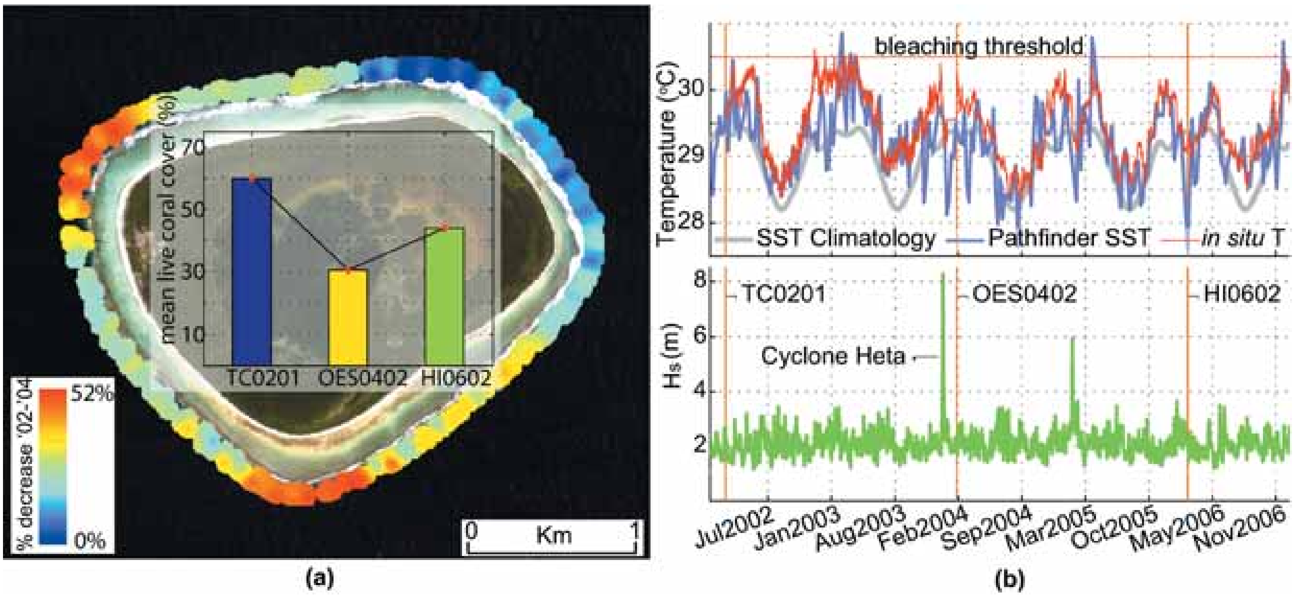

Fig 5: Swains Island, American Samoa (11.05°S, 171.08°W). Loss of coral cover associated with Cyclone Heta (category 5 hurricane), which passed to the west of the island. (a) The mapped data surrounding the island indicate the spatial decrease in percent live coral cover as measured by towed-diver surveys during research cruises in 2002 and 2004. The bar graph in the centre represents the island-wide mean coral cover during three research cruises in 2002, 2004, and 2006 (named TC0201, OES0402, and HI0602, respectively). An overall decrease between 2002 and 2004 and subsequent recovery are apparent. (b) Upper panel, Pathfinder (satellite) SST and *in situ* sea temperature. The bleaching threshold is defined as 1°C above the maximum monthly climatological mean temperature, here derived from Pathfinder SST climatology.[14] Lower panel: mean significant wave height derived from NOAA Wave Watch III,[17] showing the large wave heights generated by Cyclone Heta

important data used to augment and ground-truth satellite-based observations, particularly in the more remote Pacific Island areas where few, if any, other regular *in situ* observations are made. Groundtruthing of remotely sensed data products provides benchmark calibrations, maintains accuracy, removes bias, and compiles temporal statistics. CRED *in situ* SST instruments are actively used to ground-truth NOAA's Coral Reef Watch satellite SST products used for coral bleaching alerts and early warnings. They also improve the quality of Coral Reef Watch Hotspot, Degree Heating Week, and Trend Analyses.[14,15]

FUTURE DIRECTIONS

CREIOS methods have been designed to maximise the versatility, accessibility, and robustness of each data product while remaining cost-effective. The program will continue to build on existing infrastructure and outside expertise in an attempt to broaden and enhance the management applicability of the CREIOS-Pacific network. This will include increasing coordination with federal, state, and territorial resource management agencies, academic institutions, and nongovernmental organisations to better capitalise on the combination of data collection efforts and observing system assets. Future plans include reassessing the needs of resource managers regarding the quantity and types of near real-time information to be collected at each location, and assessing the extension of the CREIOS-Pacific network to the US Freely Associated States of Palau, the Federated States of Micronesia, and the Marshall Islands. Initiatives include broadening the suite of telemetered and archived meteorological and oceanographic parameters measured to include nutrients, chlorophyll, dissolved inorganic carbon, surface currents, humidity, precipitation, and other environmental variables of ecological significance.

While many physical variables are recorded by existing instrumentation, very few biological observations are available between visits of the biennial Pacific RAMP cruises. As extensive as these biennial biological surveys are, they may miss important ecological dynamics occurring on shorter timescales. Additionally, little is known of the frequency of human activities (eg, vessel traffic, blast-fishing), information necessary to assess their impact. To help fill these data gaps, the EAR has been developed to passively monitor the patterns of biological and anthropogenic acoustic activity in coral reef habitats.[32] In addition to providing nearly continuous monitoring of reef background noise (eg, snapping shrimp, fish vocalisations, cetacean activities), algorithms have been developed to identify the presence of vessel engine noise and acoustically identify and monitor certain marine mammals, fish, and invertebrates. EAR units have been co-located with other CREIOS *in situ* instruments at a number of marine protected areas, remote bays, underwater pinnacles and other marine areas of special concern. The number of units deployed is anticipated to increase, and research into EAR hardware and automated detection and identification algorithms continues. EAR data have shown, for example, that there is a correspondence between the sound level of snapping shrimp and diurnal temperature variations (Fig 6). Continuous monitoring of the acoustic activity of many of these animals is a promising approach for assessing patterns of change, stability, and seasonality in biological processes over time.

Understanding the effects of ocean acidification, caused by increasing levels of atmospheric CO_2, on the calcification rates of marine organisms, especially reef-building corals and crustose coralline algae, is an area of growing concern. It is projected that by the middle of this century, the drop in mean pH of surface waters will result in a decrease of the saturation state of carbonate minerals in the tropics by 30% and biogenic carbonate precipitation by 14–30%.[3,33] While the overall ecological implications are currently poorly understood, corals may be particularly threatened because they secrete metastable forms of carbonate minerals, but biogeochemical consequences on other calcifying marine ecosystems may also be severe.[33] CRED has

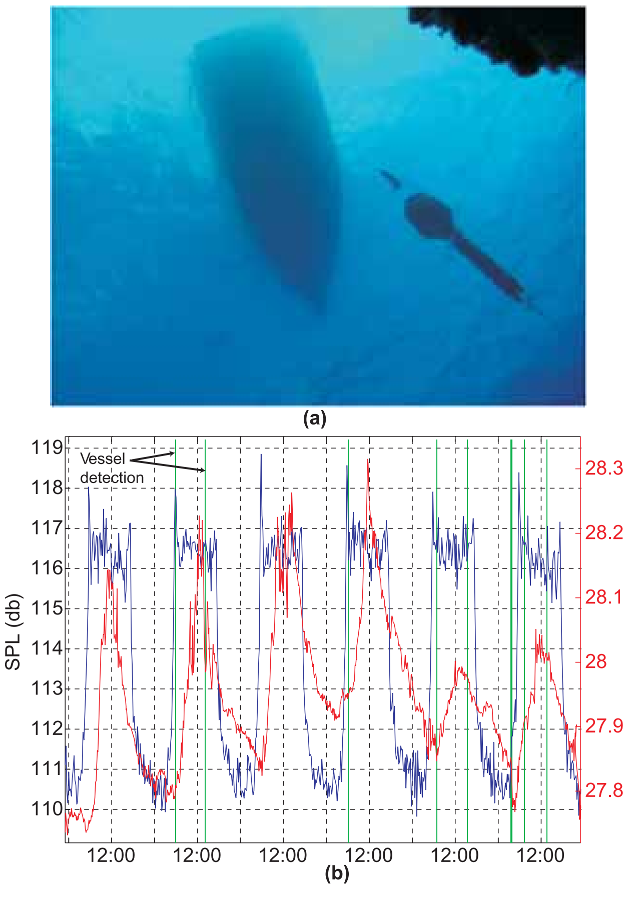

Fig 6: (a) An Ecological Acoustic Recorder (EAR) configured for deepwater (>40m) deployment with acoustic releases, aluminium housing, syntactic foam flotation collar and flag (to aid in recovery on the surface). Two acoustic releases are used for redundancy. Noise from vessel traffic can trigger the EAR's event detection hardware, providing a record of when and where anthropogenic activity occurred. (b) Synchronous diurnal variation of temperature (red line) and snapping shrimp sound pressure (acoustic) levels (SPL, blue line) recorded at the National Park of American Samoa over a 6-day period. The time 12:00 indicates local noon. Green lines indicate vessel traffic, including a surprising number of instances at night

collaborated with the University of Washington and NOAA's Pacific Marine Environmental Laboratory to undertake several pilot *in situ* seawater carbonate chemistry surveys. Additionally, specialised instrumentation to monitor shallow water carbonate chemistry and surveys to observe *in situ* calcification rate changes of corals and other reef-building organisms from select sites around the US Pacific Islands are being proposed. CREIOS-Pacific efforts to better assess the effects of ocean acidification on reef systems will increase significantly in the next few years.

Due to the complexity of coral reef ecosystems and the cost of observing them, a variety of statistical and numerical modelling approaches will be required to improve ecological and oceanographic data integration and understanding of reef processes.[5] Several numerical/hydrodynamic modelling pilot projects at a variety of scales are currently underway (Fig 7). The goals of these projects are to understand: larval dispersal and recruitment, the fate of land-based pollution and marine debris, the effect of episodic bed sheer stresses on benthic habitats, and other hydrodynamically linked processes important to ecosystem function and conservation. The outputs of these models will need to be statistically linked to ecosystem observations and are the necessary prerequisite to effective ecosystem modelling needed to support resource management decision-making.

CONCLUSIONS

The CREIOS-Pacific network combines an array of instrumented platforms with regular ecological field observations to create an IOS capable of providing resource managers, researchers, and other stakeholders with the ability to discern and assess responses of coral reef ecosystems to oceanographic processes. The network has enabled comparisons of heavily impacted and degraded reef systems with remote, relatively pristine reef systems on multiple spatial scales through comprehensive standardised data sets. Through these direct comparisons, researchers are rapidly improving their ability to assess both local ecological impacts, such as nutrient loading and sedimentation, extractive

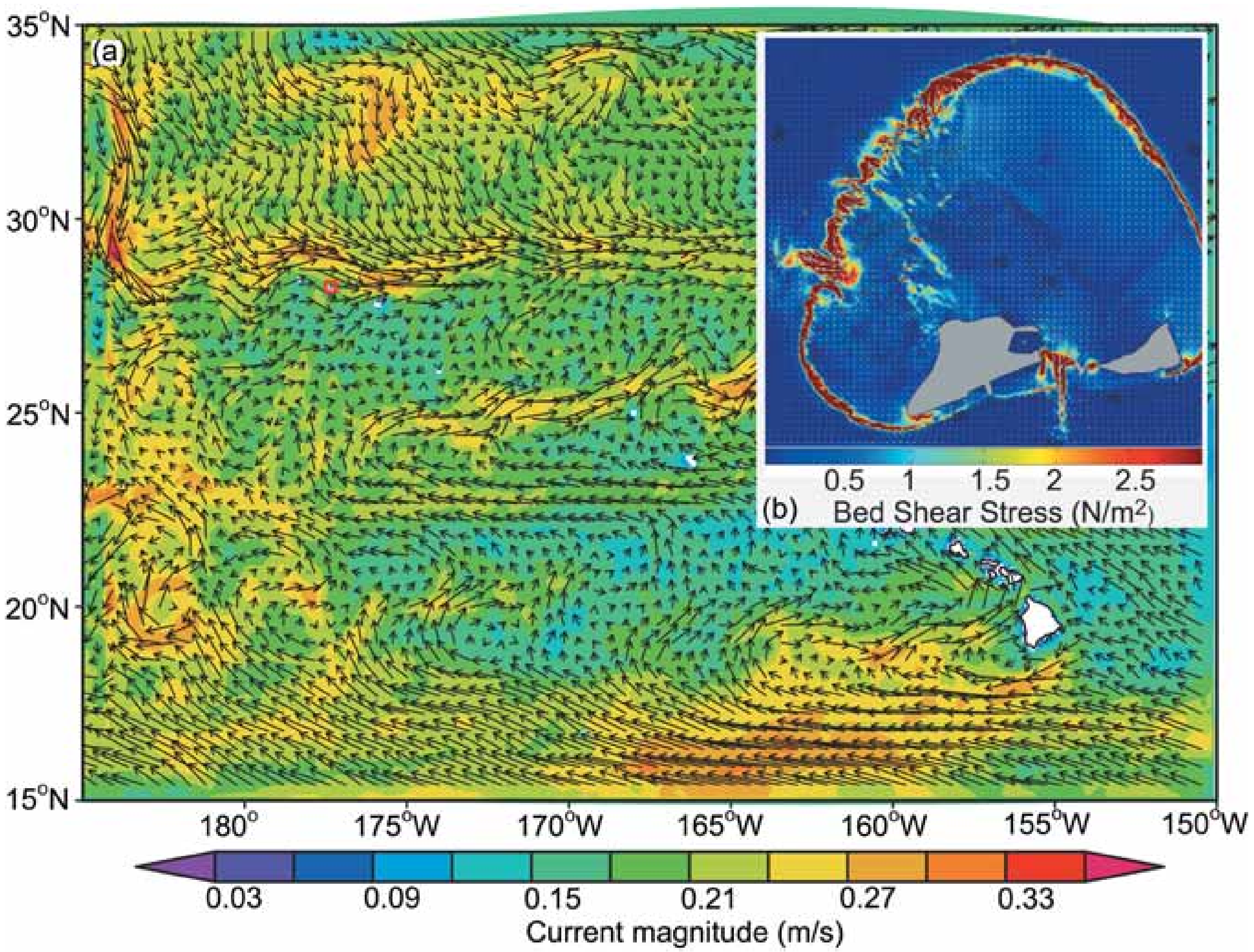

Fig 7: (a). Mean surface currents in the vicinity of the Hawaiian Archipelago from a HYbrid Coordinate Ocean Model (HYCOM) developed in partnership with the International Pacific Research Center (IPRC), University of Hawaii. (b). Maximum benthic shear stress (wave-induced + residual) during a typical NW swell event (3m wave height, 15-sec period) at Midway Atoll, NWHI (28.2°N, 177.35°W), from the Delft3D model. The small red box in the middle upper left of 7a indicates the location and approximate extent of 7b. Such hydrodynamic models, at such vastly differing scales, are necessary precursors to coral reef ecosystem modelling

activities such as fishing, and predicted global effects such as ocean warming and ocean acidification.

The CREIOS-Pacific network fulfills the UNESCO Strategic Design Plan for the Coastal Component of the Global Ocean Observing System (GOOS) mandate to 'increase in our ability to detect and predict the changes that are occurring in coastal ecosystems,'[4,6] particularly addressing the 'lack of spatially and temporally synoptic observations of key physical, chemical, and biological variables.'[5] While significant challenges and gaps in the CREIOS-Pacific network remain, the current network demonstrably fulfills the requirements of an operational, integrated, interdisciplinary, coastal component of GOOS. The network's continued support and further development will ensure the increasing value of its data holdings and the network's observational and predictive capacity.

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