IMOS Integrated Marine Observing System

IMOS National Reference Station (NRS) Network

Rationale, Design and Implementation Plan

August 2011

Prepared by: The NRS Scientific Steering Committee (Lynch T.P., Morello E.B., Middleton J. F., Thompson, P., Feng, M., Richardson A., Doherty P., Roughan, M, Morris B., Tilbrook B., Steinberg C., James, C., and S. Allen) and The IMOS Office (Moltmann T.C., Hill K.L.)

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IMOS, Australia's Integrated Marine Observing System, is investing heavily in a national network of reference stations designed to provide multi-decadal time series of the physical and biogeochemical properties of Australia's coastal oceans. These stations consist of both moored sensors and routine vessel-based sampling.

The importance of constructing long time series of ocean properties is now well-understood by the marine and climate science community. However the challenges in sustaining sampling programs across decades are significant, and the track record (globally) is not strong.

This document is intended to provide a sound, scientific and operational basis for long term investment in the IMOS National Reference Station (NRS) Network.

It has the following sections:

1. Background
2. Rationale
3. Design and Implementation Plan, covering
   - 3.1 location and number of reference stations,
   - 3.2 Standard sampling program (sensor-based and vessel-based), and
   - 3.3 Additional sampling using the network
4. Resourcing.

This document will inform higher-level IMOS strategy and science planning, and will also guide the more detailed planning of operators who are implementing and sustaining the NRS Network.

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1. Background

1.1 Context

IMOS has been established to provide sustained ocean observations that meet the broad needs of the marine and climate research community. The Node science and implementation planning that guides the observing system addresses five major research themes:

1. Multi-decadal ocean change,
2. Climate variability and weather extremes,
3. Major boundary currents and inter-basin flows,
4. Continental shelf processes, and
5. Biological responses.

IMOS has been designed in line with Global Ocean Observing System (GOOS) principles i.e.

- Linked global (ocean basin/climate) and coastal components.
- A coastal component integrated via national backbone and regional nodes.
- A national coastal backbone including reference stations, satellite remote sensing, and national information infrastructure.

International experience suggests that effective and efficient design of the coastal component is a particularly challenging task. As noted by a very respected international scientist who has reviewed the IMOS science plans, we must undertake "A national planning process for the coastal ocean" because "There is a tendency in large nations for coastal observing systems to be designed piecemeal, as the sum of what the participating coastal institutions would each like to do in their patch".

The National Reference Station Network, being a key element of both the national backbone and the regional nodes, has the potential to play a particularly important role in driving integration of marine observing within Australia's coastal oceans.

1.2 Australia's Coastal Oceans

Australia has the third largest ocean territory on earth. Approximately 77% is Exclusive Economic Zone (EEZ, outside three nautical miles), 20% Australian Antarctic Territory EEZ, and 3% within three nautical miles (under jurisdiction of State Governments rather than the Commonwealth)[1].

Being an island nation, Australia has one of the longest coastlines of any country – 36,000 kilometres for the mainland (including Tasmania), 60,000 kilometres including islands[2]. It is also a highly urbanised nation, with >90% of the population living in urban environments, the vast majority of which are on or within easy reach of the coast.

[1] http://www.environment.gov.au/coasts/oceans-policy/publications/policy-v1.html
[2] http://www.ga.gov.au/education/geoscience-basics/dimensions/coastline-lengths.jsp

As stated under Context, IMOS has been designed to have linked global and coastal components. For the NRS the term ‘coastal’ requires further definition:

> *The continental shelf, continental margin, coastal ocean and coastal zone are fuzzy concepts for which various definitions have been proposed. The continental shelf is the area extending from the coast to the shelf break, which is usually defined by the 200 metre depth isobath. The continental margin is the transition zone between the continental crust and the oceanic crust, including the coastal plain, continental shelf, slope and rise. The coastal ocean is the portion of the global ocean where physical, biological and biogeochemical processes are directly affected by land. It is either defined as the part of the global ocean covering the continental shelf or the continental margin. The coastal zone usually includes the coastal ocean as well as the portion of the land adjacent to the coast that influences coastal waters. It can readily be appreciated that none of these concepts has a clear operational definition.* [3]

For the purposes of IMOS planning and implementation, ‘coastal ocean’ is defined as the salt water mass from the high tide mark to the shelf break (200 metre isobath). This includes coastal waters to the three nautical mile limit.

The coastal oceans are clearly in scope for IMOS. To effectively address observing system requirements in the coastal zone more broadly, which includes “the portion of the land adjacent to the coast that influences coastal waters”, national collaboration between IMOS, State Governments (e.g. via MACC, COAG etc), TERN, BOM Water Division, NPEI, and other relevant institutions and programs will be essential. However the fundamental role of IMOS in observing linkages between the coastal ocean and the global ocean cannot be diminished or lost. There is no other mechanism within Australia by which to sustain this essential linkage.

The figure below represents Australia’s coastal oceans within a context of the coastline, the three mile limit, the 200 metre isobath and beyond[4]:

[3] http://www.eoearth.org/article/Coastal_zone

[4] AODN portal with ‘marine geo’ base layer, and coastal waters and 200 metre layers from GA added in.

1.3 History of coastal monitoring stations in Australia

Over the last 20 years[5], as climate change and variability, and the role of the ocean within the global climate system have become better understood, the value of long-term observations has become blindingly obvious. Unfortunately, many observing programs commenced across the world from the 1930's through to the 1980's were not able to be sustained over multiple decades. One exception is the Continuous Plankton Recorder Survey, which celebrates its 80th anniversary in 2011, but this is very rare exception to the rule. The dearth of sustained, biophysical observing programs is now widely noted (Le Quéré et al., 2009; Berghe et al., 2009).

Experience in Australia reflects this global trend. As an example, searching on 'coastal stations' in CSIRO's MARLIN meta-database returns 44 datasets commenced between 1942 and 1980. Of these, only three are still continuing today – Maria Island (from 1944), Port Hacking (1942), and Rottnest Island (1951). These three stations provide the foundation for the new expanded NRS network and are quite significant globally, as there are few if any other multi-decadal time series in the coastal oceans for the entire Southern Hemisphere.

The fact that Australia has managed to maintain these three, multi-decadal time series gives us hope, and provides a credible basis for establishing a National Reference Station Network within IMOS (Lynch et al., 2008). We know it can be done, and recent studies based on these datasets clearly demonstrate their utility in addressing major research themes of interest to the IMOS community e.g.

- At Maria Island, long-term observations of increasing salinity and temperature have been ascribed to increasing strength and extension of the East Australian Current (EAC) (Ridgeway 2007a; Hill et al, 2008).
- Similarly, repeat sampling over decades at Rottnest Island has helped demonstrate enhanced warming of the Leeuwin Current, especially during austral winter, as it moves down the WA coast (Pearce and Feng, 2007).
- Other studies have also used these two stations as well as data from the Port Hacking 100 NRS and Port Hacking 50 site to demonstrate regional declines in growth rates and biomass of phytoplankton (Thompson et al., 2009).
- The NRS data have been used, in part, to describe recent poleward range extensions of species (for a review see Poloczanska et al., 2007). A good example of how the Maria Island NRS has played this enabling role is a study of range extension of the habitat controlling the sea urchin *Centrosptephanous rogersii* (Ling et al., 2009). By using mean temperatures for August – the month *C. rodgersii* spawns – the long-term winter warming trend of coastal Tasmanian waters was plotted against the lower temperature limit for the development of the sea urchin's larvae. The NRS data set showed that the critical point when urchin larvae were able to successfully survive winter in Tasmanian waters was reached in the early 1990s. This range extension is a major factor in a catastrophic shift in the ecosystem occurring in Eastern Tasmania from a productive kelp-based community, to a much less diverse urchin barren habitat.

[5] The IPCC First Assessment Report was completed in 1990.

2. Rationale

The ocean regulates climate, weather and marine ecosystems on diurnal, seasonal and multi-decadal timescales. Patterns in large scale ocean circulation are connected to fine-scale ecosystem effects through the influence of major boundary currents, and through the distinctly regional features of Australia's continental shelf environment such as eddy encroachment, upwelling and downwelling, cross shelf exchange, coastal currents and wave climate.

The IMOS National Reference Station (NRS) Network is designed to provide the baseline information, at timescales relevant to human response, that are required in understanding how large-scale, long-term change and variability in the global ocean are affecting the ecosystems of Australia's coastal seas. The goal is to develop multi-decadal time series of the physical and biogeochemical properties of Australia's coastal seas, to inform research into ocean change, climate variability, ocean circulation and ecosystem responses. Moored instruments and repeated biogeochemical sampling at known points are the only viable strategy available, at the moment, for developing spatially explicit time series in relatively shallow continental shelf waters.

As determined by the major research themes addressed through IMOS the NRS collects observations of both physical and biogeochemical variables to characterise the ocean environment and to understand fundamental biological processes within the environment.

- Core physical variables observed are
  - temperature,
  - salinity
  - dissolved oxygen
  - nutrients
  - turbidity
  - carbon
  - phytoplankton (both direct, and via an optical proxy for chlorophyll a)
  - zooplankton

Understanding these variables necessitates observations at NRS sites being undertaken through the water column, from surface to seabed. Observations are sensor-based where possible and supplemented by vessel-based biogeochemical sampling (and laboratory analysis) at minimum frequencies required to provide appropriate resolution for core variables.
As the resources required to sustain physical and biogeochemical observations over the long term are significant, the NRS Network consists of the minimum number of sites necessary to provide a national multi-decadal baseline. At these timescales, ocean processes are operating at space scales in the thousands of square kilometres, and the IMOS NRS is hence a sparse network of well-instrumented, single-point, reference sites, strategically positioned around Australia's coastline.

The IMOS NRS Network is therefore designed to provide a framework for integrating both the national and regional components of the observing system:

- National - Components include:
    - integration of long-term time-series observations to more spatially-distributed and intensive shorter-term studies
    - establishing a coastal information infrastructure through development of national data standards
    - providing calibration and validation of coastal remote sensing

- Regional – NRS role in providing focal points within regional Nodes for integrating with
    - integrating with observations of other IMOS 'coastal ocean' Facilities : as components of various shelf arrays of the National Mooring Network and with observations from Ocean Gliders, Autonomous Underwater Vehicles, Ocean Radar, Animal Tagging and Monitoring and Wireless Sensor Networks
    - modelling of coastal processes
    - linking coastal process with offshore process

3. Design and Implementation Plan

Factors considered when designing and implementing the National Reference Station Network in Australia's coastal oceans included:

3.1 location and number of reference stations,
3.2 the standard sampling program, both sensor-based and vessel-based, and
3.3 additional sampling opportunities provided by the network.

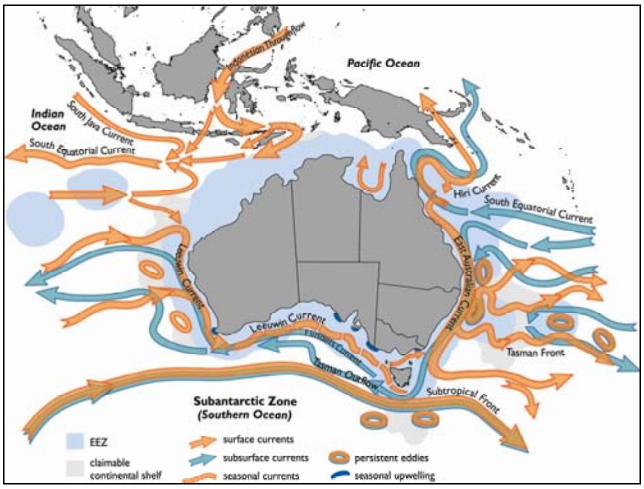
3.1 Location and Number of National Reference Stations

Australia's coastal oceans are characterised by:

1. broad, shallow, shelf seas in the tropical north, from North West Cape to Torres Strait,
2. the Great Barrier Reef lagoon
3. very narrow shelf on the sub-tropical east coast, from Fraser Island south to Tasmania,
4. narrow shelf along the sub-tropical west and south west coast, and
5. broader shelf in the Great Australian Bight, SA Gulfs and Bass Strait.

Two principal current systems bound Australia's coastal oceans, both of which flow poleward:

- The East Australian Current system forms off the GBR and flows south along the Queensland coast, separating in NSW to flow east as the Tasman Front, or south as the EAC Extension.
- The Leeuwin Current system flows south from North West Cape to southern Tasmania.



At broad scale, marine life in Australia's coastal oceans is influenced by the transition from tropics to sub-tropics, in addition to different oceanic influences on the east and west coasts outlined above.

Australia is divided into six phytoplankton provinces, four of which are coastal (based on work done by Jeffery & Hallegraeff, as used in Hayes et al., 2005):

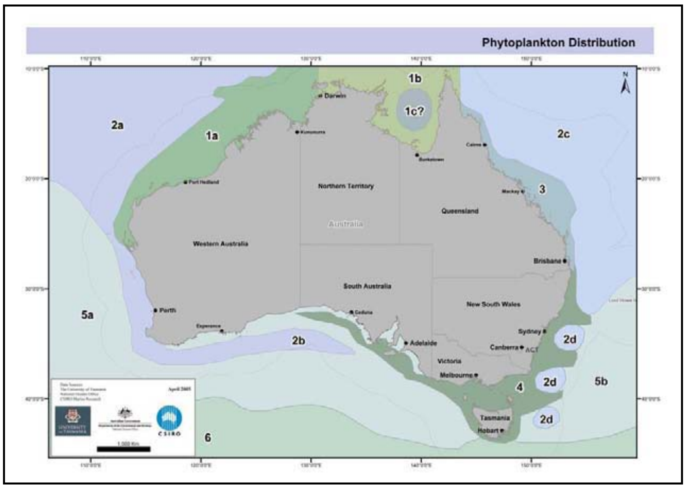
(1) The shelf waters of north-west Australia, the Gulf of Carpentaria, Arafura Sea and Timor Sea, with chlorophyll biomass discriminating the biomes **1 a, b, c.**

(2) The tropical neritic communities carried southwards by the Leeuwin Current (**2b**) and East Australian Current (**2d**), respectively.

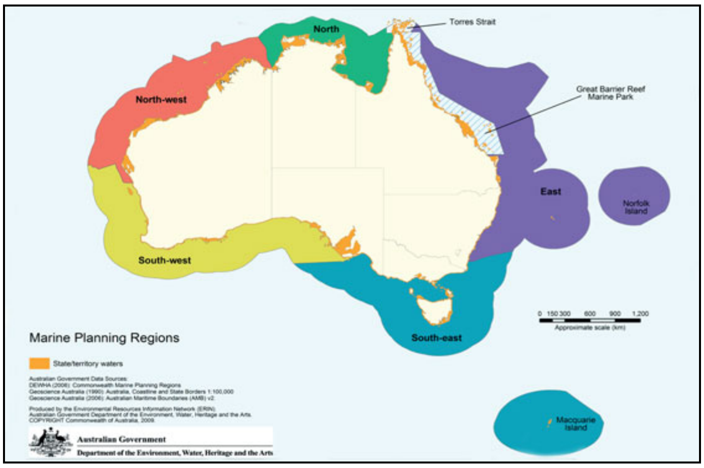
(3) The floristically distinct shallow waters of the Great Barrier Reef lagoon dominated by fast-growing nanoplankton diatoms.

(4) The productive temperate neritic province comprising coastal waters of New South Wales, Tasmania, Victoria and South Australia.

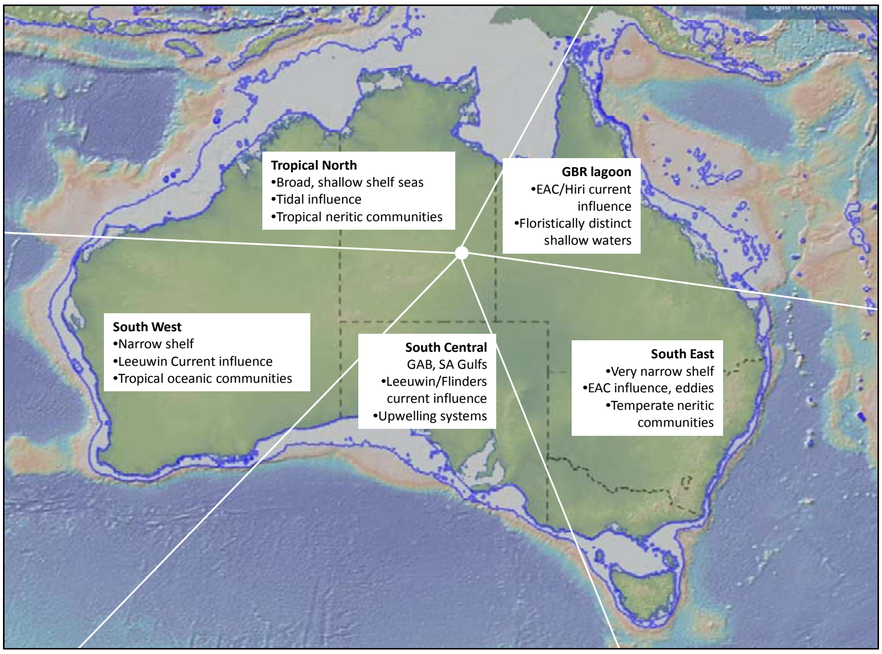
A highly variable oceanic transition zone (**5**) is bordered to the south by a Subantarctic phytoplankton province (**6**) where the coccolithophorid *Coccolithus pelagicus* is an indicator organism.



These provinces are also broadly reflected in Australia's Commonwealth marine planning regions i.e. North-west and North, South-west, East and South-east.

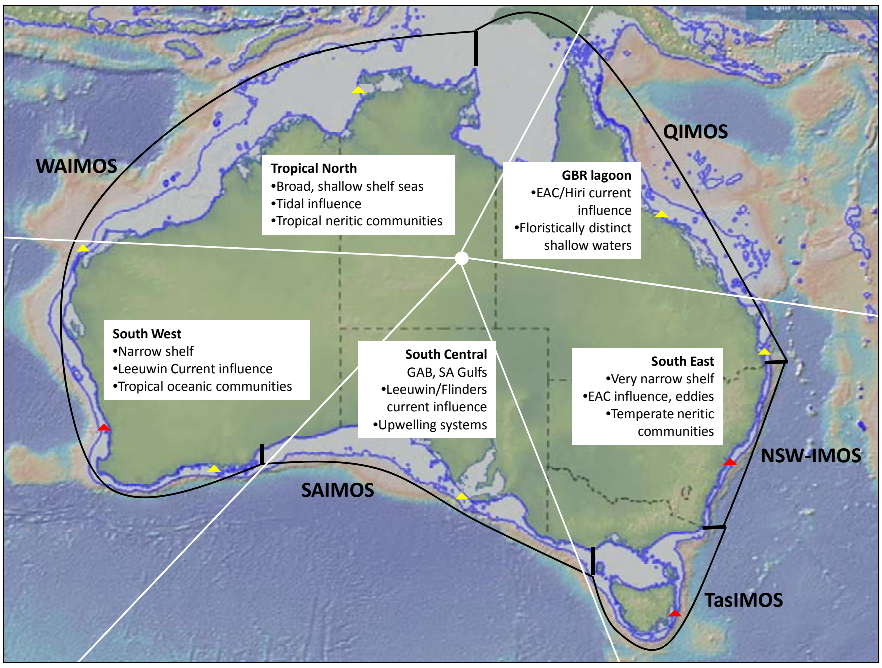


Based on these physical and biological features, it can be argued that there are at least five distinct regions of Australia's coastal oceans - tropical north, GBR lagoon, south east, south west, and south central (Great Australian Bight and SA Gulfs).



These regions align quite well with the areas of interest for the IMOS Regional Nodes, noting that WAIMOS covers both the tropical north and south west, and the SEQ component of QIMOS, along with NSW-IMOS and TasIMOS are all in the south east.

Building on the three long-term sites at Maria Island, Rottnest Island and Port Hacking (shown in red below), the NRS Network has been expanded by six extra sites at Darwin, Yongala, Kangaroo Island, Stradbroke Island, Ningaloo Reef and Esperance (all shown in yellow), making nine in total. Preliminary modelling (Oke pers. comm.) indicates that the NRS are well situated to describe inter seasonal and inter annual variation for a variety of oceanographic parameters (e.g. sea surface temperature, velocity and elevation) at national scales on the continental shelf. Further models should be run and observations analysed to confirm the adequacy of the network to achieve these roles.



Full details of the nine sites are provided in Appendix 1. A brief summary of the key features is as follows:

	Established, long-term			Regional gaps			Enhanced regional coverage		
	Maria Island	Port Hacking	Rottnest Island	Darwin	Yongala	Kangaroo Island	Stradbroke Island	Ningaloo Reef	Esperance
Region	SE	SE	SW	North	GBR	S/central	SE	SW	SW
Established	1944	1942	1951	2009	2007	2008	2008	2010 (1997)	2008
Lat/Long	42S 148E	34S 151E	32S 115E	12S 130E	19S 147E	36S 136E	27E 154S	21S 113E	34S 122E
Zone	Temperate	Subtropical	Subtropical	Tropical	Tropical	Subtropical	Subtropical	Tropical	Subtropical
Depth	90m	100m	50m	20m	27m	110m	67m	55m	50m
Current System	EAC/TO, LC	EAC	LC	-	EAC	LC	EAC	LC	LC
Shelf Processes	Connection zone	Eddies, upwelling	Eddies, upwelling. currents	Tidal	Currents, run-off	Upwelling, currents	Eddies, upwelling, currents	Upwelling, currents	Upwelling
Shelf array	No	Yes	Yes	No	No	Yes	Yes	No	No
Bioregion	Southeast	East	Southwest	North	GBR/East	Southwest	East	Northwest	Southwest
Phyto province	4	4	2	1	3	4	3	1	2

Points to note include the following:

- Of the three existing long-term stations, two are in the south east (Maria Island and Port Hacking) and one is in the south west (Rottnest Island).
- A station has been established in the tropical north, at Darwin.
- A station has been established in the GBR lagoon, at Yongala (off Townsville).
- A station has been established in south central, at Kangaroo Island.
- An additional station has been established in the EAC dominated south east, at North Stradbroke Island (making three in this region).
- Two additional stations have been established in the Leeuwin Current dominated south west, one 'upstream' at Ningaloo Reef and one 'downstream' at Esperance (making three in this region).
- The Ningaloo Reef location was chosen to continue a contiguous decadal mooring time series initiated by AIMS in 1997.

3.2 The Standard Sampling Program of the NRS Network

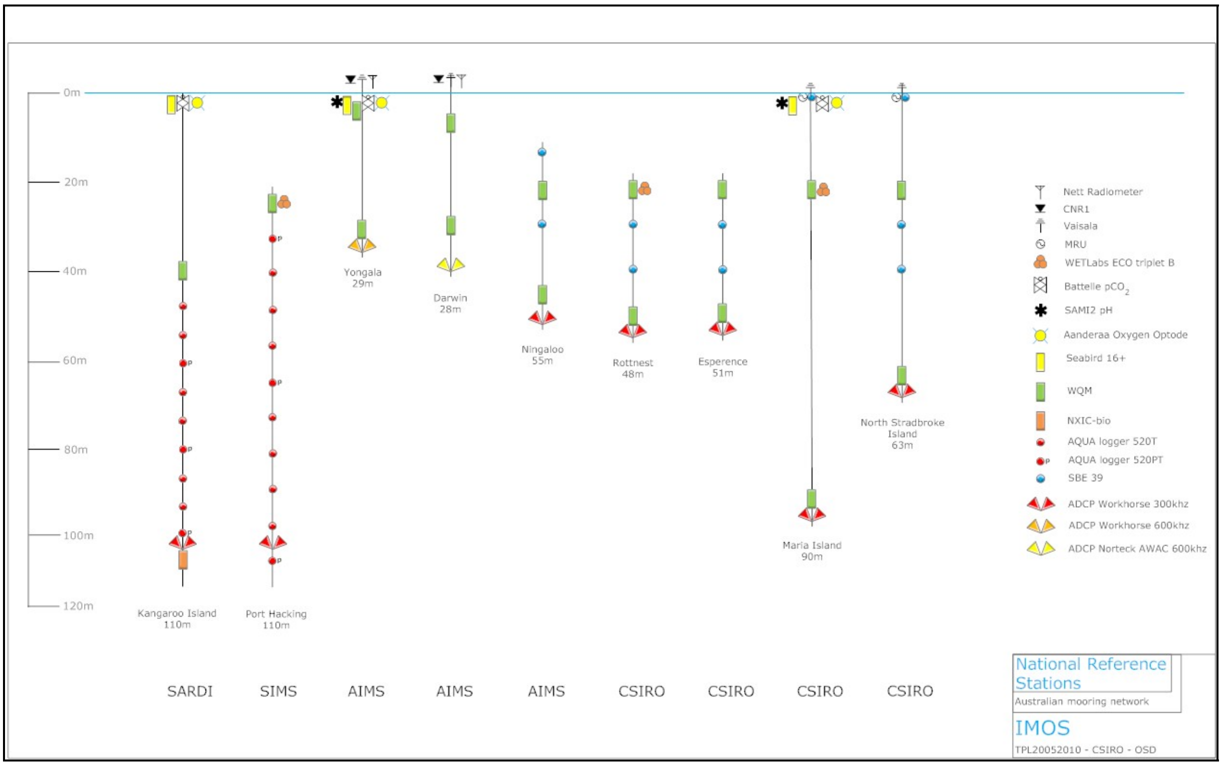
The NRS sampling program involves:

a) high temporal resolution data from a standard, moored sensor package,

b) where surface expression is logistically feasible, surface meteorology and delivery of sensor data in real time, and

c) vessel-based biogeochemical sampling and laboratory analysis.

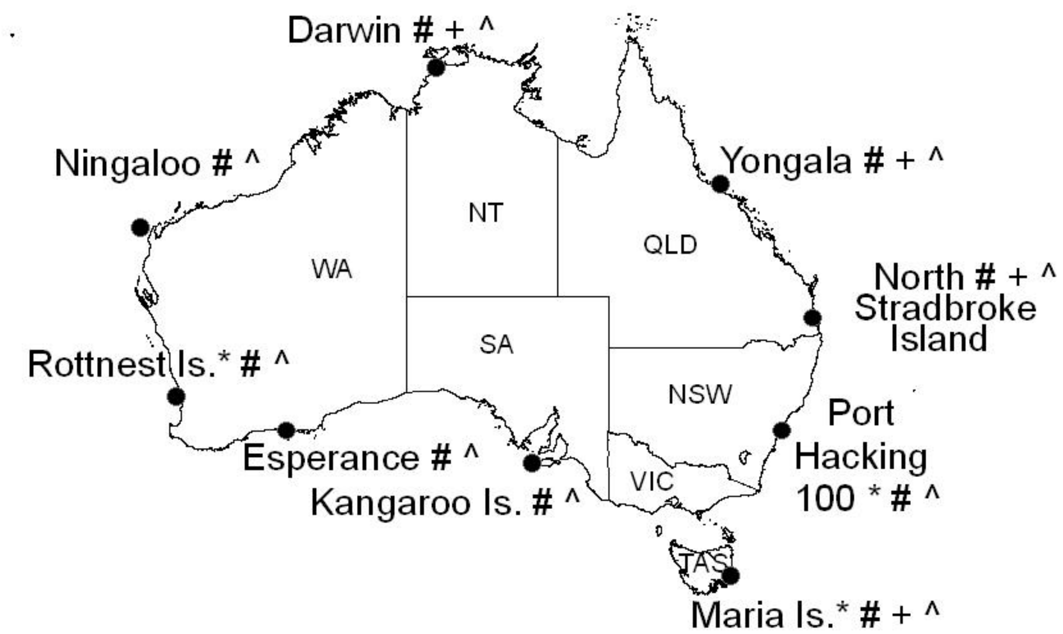
An overview of the moored sensor network is as follows, this is a schematic only with sensors often deployed on multiple moorings at the one NRS site:



A summary of the roll out of the NRS project by May 2011 is provided below.

Key: * - long term site; # - infrastructure deployed;

+ - Telemetry; ^ BGC sampling



A brief summary of the servicing and sampling program is as follows:

	Maria Island	**Port Hacking**	**Rottnest Island**	**Darwin**	**Yongala**	**Kangaroo Island**	**Stradbroke Island**	**Ningaloo Reef**	**Esperance**
Operator	CSIRO	SIMS	CSIRO	AIMS	AIMS	SARDI	CSIRO	AIMS	CSIRO
Mob time to site	2hr drive 1.5hr steam	3.5 hrs	35 min drive 1hr steam	1 hr steam	2hr 25kt or 5hr 10kt	12 hr steam	<5hrs	2hr flight 2hr steam	3hr drive/fly 1hr steam
Mooring turnaround	Quarterly	Quarterly	Quarterly	Quarterly	Six monthly	Quarterly	Quarterly	Quarterly	Quarterly
Sensor comm date	August 2008	November 2009	November 2008	August 2009	May 2010	August 2008	December 2010	January 2010	November 2008
Surface expression	Yes	No	No	Yes	Yes	No	Yes	No	No
Real time?	Yes	No	No	Yes	Yes	No	Yes	No	No
RT comm date	April 2009	-	-	July 2010	Aug/Sept 2010	-	December 2010	-	-
Physical sampling frequency	Monthly	Monthly	Monthly	Quarterly over 24 hr period	Monthly	8 times per annum	Monthly	Quarterly	Quarterly
Phys samp comm date	April 2009	February 2009	January 2008	October 2010	Sept 2009	October 2008	Sept 2008	November 2010	November 2008

The National Reference Stations codes, depths, locations (Degrees, minutes, and decimal seconds - WGS 84) * indicate long term monitoring sites.

Site	Station code	State	Depth (m)	Longitude	Latitude
Maria Island*	**MAI**	TAS	90	42° 35.80S	148° 14.00E
Kangaroo Is	**KAI**	SA	110	35° 49.93S	136° 26.84E
Esperance	**ESP**	WA	50	33° 56.00S	121° 51.00E
Rottnest Is*	**ROT**	WA	50	32° 00.00S	115° 25.00E
Ningaloo	**NIN**	WA	20	21° 51.991S	113° 56.822E
Darwin	**DAR**	NT	25	12° 24.00S	130° 46.083E
Yongala	**YON**	QLD	28.9	19° 18.508S	147° 37.105E
Port Hacking 100*	**PHB**	NSW	100	34° 05.00S	151° 15.00E
Moreton Bay	**MOR**	QLD	63	27° 18.00S	153° 06.00E

Points to note include the following:

- Moorings are turned around no more frequently than required to maintain quality data sets. Local conditions (e.g. degree of bio-fouling) can necessitate regional variation.
- Four of nine stations have surface expression and real time delivery i.e. Maria Island, Darwin. Yongala and Stradbroke Island. The other five stations do not currently have surface expression for the following reasons:
    - Port Hacking – risk of loss, due to population pressure

- Rottnest Island – not requested by regional node
    - Kangaroo Island - too energetic (although there will be a surface CO_2/acidification mooring here)
    - Ningaloo Reef – not requested by regional node
    - Esperance – not requested by regional node
- The standard frequency of vessel-based biogeochemical sampling is monthly, with regional variations. This is fully explained in section 3.2(c).
- Roll out of the network has been phased, and commencement dates for data streams vary.

(a) Moored sensor package

Observations of core variables are taken across the network using standard water quality monitors and acoustic current doppler profilers.

(i) Water Quality Monitors (WQM)

The Wetlabs Water Quality Monitor (WQM) is a multi-sensor with on-board processing and inbuilt bio-fouling controls. The WQM measures: oxygen, fluorescence proxies for chlorophyll a (as a proxy for phytoplankton biomass), turbidity and conductivity, temperature and pressure (CTD) which can be converted into salinity. Sampling is standardised across the network at 60 samples over a one minute bursts every 15 minutes.

Details of data streams are as follows:

Data stream type	Units	Depths	Sensor
Conductivity	Mmho	~20m, seafloor	WQM
Temperature	°C	~20m, seafloor	WQM
Pressure	Dbar	~20m, seafloor	WQM
Salinity	PSU	~20m, seafloor	WQM
Dissolved oxygen (ml)	$ml{\cdot}l^{-1}$	~20m, seafloor	WQM
Dissolved oxygen (mg)	$ml{\cdot}l^{-1}$	~20m, seafloor	WQM
Oxygen saturation	%	~20m, seafloor	WQM
Chlorophyll (raw)	CHL	~20m, seafloor	WQM
Chlorophyll	$\mu g\ l^{-1}$	~20m, seafloor	WQM
Turbidity (raw)	units	~20m, seafloor	WQM
Turbidity*	m^{-1}	~20m, seafloor	WQM
Scatter at wavelength red	m^{-1}	~20m, seafloor	WQM
Site	code	~20m, seafloor	WQM
Time	Mm/dd/yy	n/a	WQM
Date	Hh:mm:ss	n/a	WQM

*scattering and turbidity sensors (FTU/NTU) should be calibrated and reported as SI units (m-1)

WQM's are deployed at subsurface and bottom depth. Exceptions are:

- Port Hacking, which is being slowly instrumented as risk from trawling was thought to be high. Preliminary investigation of the current data streams will also indicate whether a WQM is required on the bottom of the mooring.
- Kangaroo Island, where an NXIC-bio multisensor (CTD with Aanderraa Optode and FLNTU) is deployed at bottom depth to measure important cross-shelf exchange, which occurs during both summer (bottom upwelling) and winter (bottom dense water outflows). A NXIC has been generally used due to continuing problems with the two WQM's purchased.

Climatologies are being developed for the WQM data streams both for quality control (QC) purposes (Morello et al 2011) and to guide future adjustment of the sampling strategy.

(ii) Acoustic Current Doppler Profilers (ADCP)

All NRS sites also have bottom-mounted, upward-looking ADCP's to provide structure of currents and backscatter proxies for zooplankton and mid trophic level species.

Data stream type	**Units**	**Depths**	**Sensor**
tba	$m \cdot s^{-1}$	seafloor	Workhorse300khz

The standard instrument is a Teledyne 300 khz workhorse ADCP. Exceptions are:

- Yongala and Darwin, where 600 khz is used because of the shallower water depth.

(b) Stations with surface expression

Four stations of the nine stations have surface expression - Maria Island, Yongala, Darwin and Stradbroke Island. These sites include a Vaisala weather station for surface meteorology, producing the following data streams:

Data stream type	**Units**	**Depths**	**Sensor**
Barometric pressure	hPa	1 metre	WXT520 Met St.
Wind speed	$m \cdot s^{-1}$	1 metre	WXT520 Met St.
Wind direction	$0 - 360^{o}$	1 metre	WXT520 Met St.
Air temperature	°C	1 metre	WXT520 Met St.
Liquid precipitation	mm	1 metre	WXT520 Met St.
Relative Humidity	%	1 metre	WXT520 Met St.

Data telemetry is also provided at these four sites, to enable delivery of sensor data in real time and to monitor the infrastructure.

For some stations without surface expression, surface meteorology is available from other sources as follows:

- Rottnest Island – Daily surface meteorology conditions have also been measured at Rottnest Island by the Bureau of Meteorology.
- Ningaloo Reef – Ancillary weather station data is available from the AIMS automatic weather station located to the South at Milyering.
- Kangaroo Island – The Bureau operates a real time automatic weather station at near-bye Neptune Island.
- Port Hacking – The Bureau operates a real time automatic weather station at Sydney Airport
- Esperance - The Bureau operates a real time automatic weather station at Esperance

(c) Vessel-based biogeochemical sampling and laboratory analyses

The vessel-based biogeochemical sampling and laboratory analysis program includes:
i. CTD and secchi disk sampling, to ground truth sensor data and other measurements,
ii. Hydrochemistry and plankton sampling of variables required to monitor nutrients, phytoplankton and zooplankton (NPZ),
iii. Water sampling of variables required for carbon monitoring i.e. total dissolved inorganic carbon, total alkalinity, and salinity,
iv. Log sheets for metadata such as UTC time and date.

An Operations Manual has been developed for the sampling and analysis program – see http://imos.org.au/fileadmin/user_upload/shared/ANMN/IMOS_NRS_BIOGEOCHEMICAL_SAMPLIN/IMOS_NRS_BIOGEOCHEMICAL_OPERATIONS_PRACTICAL_HANDBOOK.v2.pdf

A summary of the data streams produced by each component of the program is as follows:

(i) Seabird SBE19 + CTD and Secchi Disk stations

Data stream type	**Units**	**Depth**
Site	Code	n/a
Time	24:00	n/a
Date	dd/mm/yyyy	n/a
Secchi Disk	m	n/a
Conductivity	mmho	Profile 0-2.5m sonic depth
Temperature	°C	Profile 0-2.5m sonic depth
Depth	m	Profile 0-2.5m sonic depth
Fluorescence*	$mg \cdot m^{-3}$	Profile 0-2.5m sonic depth
Turbidity*	NTU	Profile 0-2.5m sonic depth
Dissolved oxygen*		
* at selected stations		

- The standard instrument for CTD profiles is a Seabird SBE19*plus*.

- Files appear on the IMOS Ocean Portal as ‘CTDPRO’.
- The Secchi disc data appears is recorded on the field sheet.
- Fluorescence, Turbidity and Dissolved Oxygen sensor additions to the SBE19+ are being rolled out to all stations.

(ii) Nutrients, phytoplankton and zooplankton

Nutrients		
Data stream type	**Units**	**Depth**
Nitrites/Nitrate	$\mu mol \cdot l^{-1}$	0,10,20,30,40,50m*
Nitrite	$\mu mol \cdot l^{-1}$	0,10,20,30,40,50m
Silicates	$\mu mol \cdot l^{-1}$	0,10,20,30,40,50m
Orthophosphate	$\mu mol \cdot l^{-1}$	0,10,20,30,40,50m
Ammonia	$\mu mol \cdot l^{-1}$	0,10,20,30,40,50m
Salinity		
Dissolved oxygen**	$\mu mol \cdot l^{-1}$	
* Except Darwin and Yongala, where depth <50m ** Laboratory analysis is only at selected stations		

- Files appear on the IMOS Ocean Portal as ‘HYDNUT’ and ‘HYDSAL’. The sampled depths give coverage through the photic zone and provide a combined sample for the phytoplankton. There is some debate that this sampling rate is excessive with 3 -4 depths being adequate. A more efficient systems could be to sample depths at the surface, 40m and below the Chlorophyll maximum layer (about 50m during summer and then within 10 m of surface in summer). Further analysis of the preliminary data is required to identify potential efficiencies.
- Maria Island, Port Hacking and Kangaroo Island are sampled deeper to categorise the water column. For instance The Kangaroo Is NRS is deployed in 110m of water and to resolve the bottom upwelled and down welled plumes sampling is conducted every 10 m.
- Only selected stations have Dissolved Oxygen (DO) as this measure needs to be analysed quickly as it degrades. Hence also sites with short travel distances have DO chemical analysis. A rollout of DO sensors for all BGC sampling CTDs is underway across the network.

Phytoplankton		
Data stream type	**Units**	**Depth**
Phytoplankton count	$Cells \cdot l^{-1}$	Water column
HPLC pigments	$\mu g \cdot l^{-1}$ (or $mg \cdot m^{-3}$)	Water column
Phytoplankton biomass	$ml \cdot l^{-1}$	Water column
Flow cytometry	$Cells \cdot l^{-1}$	Water column

- Files appear on the IMOS Ocean Portal as ‘PHYNUM’, ‘PHYPIG’, ‘PHYBIO’ and ‘PHYCYT’.
- A whole-of-water column measure of phytoplankton is being trialled.

Zooplankton		
Data stream type	**Units**	**Depth**
Zooplankton dry weights	$mg \cdot m^{-3}$	Water column
Zooplankton community	Species $nos \cdot m^{-3}$	Water column
Zooplankton size class	µm +/- SE	Water column

- Files appear on the IMOS Ocean Portal as 'ZOONUM' and 'ZOOBIO'.

(iii) Carbon, acidification and suspended matter

Carbon and acidification		
Data stream type	**Units**	**Depth**
Total CO2 (TCO2)	$\mu mol \cdot kg^{-1}$	4-7 depths at each site
Total alkalinity (TALK)	$\mu mol \cdot kg^{-1}$	4-7 depths at each site
Salinity	Unit less	4-7 depths at each site
pH – DIC*	Ratio	0,10,20,30,40,50m,
* Calculated from TCO2 and TA		

- Files appear on the IMOS Ocean Portal as 'CARBON'.

Suspended matter		
Data stream type	**Units**	**Depth**
Total	$mg \cdot l^{-1}$	Water column
Organic	$mg \cdot l^{-1}$	Water column
Inorganic	$mg \cdot l^{-1}$	Water column

- Files appear on the IMOS Ocean Portal as 'SUSMAT'.

(iv) Frequency of sampling

Sampling frequency at the three pre-existing long term stations (Maria Island, Rottnest Island and Port Hacking) was based around monthly sampling trips, where single point measures were taken by physically sampling the water column from a small boat. In most cases, annual sampling rates of less than once per month occurred, due to adverse weather conditions or other factors.

With the advent of IMOS and creation of an enhanced and extended NRS Network, moored sensor packages were deployed insitu at each site and are now sampling every 15 minutes. This has a number of advantages:

- A much higher likelihood that an unbroken record for various parameters can be maintained.
- The opportunity for analysis at all temporal scales. Daily or weekly events which would not be detected by monthly samples can be studied, such as tides, respiration over daily cycles, diurnal migrations of the plankton and stratification of the water column.

- On larger temporal scales, events, which had the potential to be missed with single samples per month, can also be detected.
- Bias for low sampling in bad weather can be overcome, and events associated with bad weather, such as re-suspension of sediments, can be sampled.
- Important ecosystem relationships and changes that are missed with monthly, seasonal or annual sampling can be resolved. This is particularly important for coastal systems that can be highly influenced by catchment events such as floods causing sediment plumes. Events are particularly important for plankton, which have lifecycles of weeks to months. Frequent sampling is thus needed to obtain the timing of peak abundance and avoid aliasing of the signal. Phytoplankton blooms, upwelling events and eddies can all occur at rates that make them unlikely to be detected by a single monthly sample.
- Remotely sensed ocean colour sensor products can be better calibrated by matching sampling to satellite over-flights.

For the monitoring of coastal pelagic ecosystems, another important consideration for sampling frequency is phenology. This is the timing of repeated seasonal activities such as migrations or reproduction. It has been shown in Northern Hemisphere studies that phenology is highly sensitive to global warming with marine groups, such as zooplankton, showing changes at significantly greater rates than terrestrial groups (Richardson, 2008). Phenological changes have profound implications for the functioning of marine ecosystems (Edwards and Richardson, 2004). Over the past 45 years, many groups of plankton are peaking in their abundance earlier, in some cases by up to 23 days. This differential response of phytoplankton and zooplankton may lead to a mismatch between successive trophic levels and a change in the synchrony between primary, secondary, and tertiary production. Successful fish recruitment is highly dependent on synchronization with pulsed planktonic production (Hjort, 1914; Cushing, 1990; Beaugrand et al., 2003). To detect these phenological changes, at least monthly sampling is required.

Sensors, however, have technological limitations, and a vessel-based biogeochemical sampling and laboratory analysis program clearly needs to be continued for IMOS to address its major research themes effectively. The purposes of the field sampling program are:

- Cross validation of the sensor observations,
- Collection of data streams that cannot yet be collected via the sensors, such as the diversity of zooplankton and nutrient concentrations, and
- Sampling of the whole water column, which is not currently possible from *in situ* fixed point instruments.

In determining the minimum field sampling frequency, we can look at the three pre-existing long term stations to determine whether the monthly sampling interval used has been sufficient.

All parameters (temperature, salinity, nitrate, phosphate, silicate and dissolved oxygen) showed significant long term (> 10y) trends in one or more parameters at one, or more, coastal stations. Unless otherwise indicated in the table below, probabilities for all trends were < 0.001, though blank cells indicate non-significant results. The last row shows the linear regression results for surface nitrate concentrations as a function of surface temperature in July with the intercept in brackets and slope italicised (Adapted from Thompson et al., 2009).

Long-term (> 10 y) linear trends in surface (0 m) ocean properties after seasonally detrending data by removing monthly means.

	Maria Island	Port Hacking (100 m)	Port Hacking (50 m)	Rottnest Island
Maximum span (years analysed)	1944-2005	1953-2005	1944-2004	1951-2001
Maximum total # observations*	3273	9263	9882	2736
Temperature (°C·century^{-1})	2.02	0.746	0.744	1.23
Salinity (psu·century^{-1})	0.346	0.232	0.269	0.407
Nitrate (µM·century^{-1})		0.556		0.400 P = 0.008
Phosphate (µM·century^{-1})	0.530	††	0.611††	0.313
Silicate† (µM·century^{-1})	-5.84	-1.97	-2.30	
dissolved oxygen (µM·century^{-1})			-12.9	-49.1
Relationship between July temperature (°C) and July nitrate concentration (µM) at surface	*-1.04* (15.3) P < 0.004	*-0.31* (6.95) P < 0.001	*-0.45* (9.57) P < 0.001	*0.22* (-4.0) P = 0.048

*for any parameter. † silicate measurements commenced in 1970 at all sites.
†† gap in PO_4 measurements from 1985 to 2003

From this we can conclude that monthly sampling is sufficient to detect multi-decadal change.

The standard frequency of vessel-based biogeochemical sampling will therefore be monthly. Exceptions are:

- Darwin - Quarterly Biogeochemical sampling occurs over a 24 hour period in order to take into the account the significant aliasing caused by the suspended sediments over a tide cycle. Sampling over at least one tide cycle is required. Due to the tidal inequalities that exist in this macro mixed tide environment, if a 12 hour cycle is chosen then the timing has to be chosen carefully so the inequalities are at a minimum. A 24 hr cycle eliminates a large component of the inequality. Quarterly sampling is undertaken for sediment and nutrients representing a Dry and Wet season, spring and neap tide. The sampling should be undertaken hourly for a minimum of 12 hours. At least one set of these samples (mid tide for example) is sent to CSIRO for analysis, and the remaining samples for flux calculations processed at the AIMS ATRF laboratory. When the AIMS/ATRF aquaria are constructed it will be utilised to determine rates and exchanges of nutrients to/from sediments under a range of conditions experienced in the coastal water of the NT. In this way essential flux measurements and sediment/nutrient processes will be understood, allowing us to develop and test coastal shelf transport models.

- Kangaroo Island - As part of the NRS and coastal mooring program, eight, 5-6 day field surveys are also conducted each year and water samples obtained from 6 biological stations and, like the NRS station at Kangaroo Island are analysed for nutrients, phytoplankton species and abundance, chlorophyll-a, suspended matter, but also for nano and pico plankton populations and bacteria and virus population . These samples have been collected since February 2008 and will provide baseline time series to understand the biophysics of the upwelling ecosystem, and how it responds to inter-annual and longer (climate) variability.
- Ningaloo Reef – Quarterly sampling because of current cost constraints.
- Esperance - Quarterly sampling because of current cost constraints.

3.3 Additional Sampling Using the NRS Network

(a) Bio-optics

Notwithstanding the strengths of the NRS biogeochemical sampling program, is it relatively infrequent, limited in scope, labour-intensive and costly. In recent years, the bio-optical research community has begun to benefit from increased observations of variables with biogeochemical and ecosystem relevance such as chlorophyll a, and optical backscattering or attenuation coefficients which are proxies of Particulate Organic Carbon (POC) and Coloured Dissolved Organic Matter (CDOM) (Claustre et al., 2010).

Inclusion of Chlorophyll fluorescence and RED scattering measurement on the WQM sensors is a step towards enhanced, sensor-based sampling of biogeochemical variables. IMOS plans to make greater use of bio-optical observations in the future so as to increase temporal resolution, control quality and lower cost, with the aim of improving the availability and utility of biogeochemical observations from the NRS network and related IMOS Facilities such as the Lucinda Jetty Coastal Observatory in tropical Australia (Brando et al 2010).

To progress this strategy, Wetlabs ECO Triplet Pucks, measuring CDOM fluorescence and BLUE and GREEN scattering, will be added to a subset of the NRS sites. Priority has been given to the three long term sites i.e. Maria Island, Rottnest Island and Port Hacking, plus Yongala to provide a tropical site. Subject to evaluation and affordability, these sensors may be added to other sites over time.

Details of data streams are as follows:

Data stream type	Units	Depths	Sensor
CDOM flourometer	m^{-1}	20m*	ECO triplet puck
Scatter at wavelength blue	m^{-1}	20m*	ECO triplet puck
Scatter at wavelength green	m^{-1}	20m*	ECO triplet puck

* co-located with WQM

Points to note include the following:

- Sustained observation of bio-optical variables for Australia's shelves will be used for the assessment of various satellite ocean colour products. These include accuracy of algorithms foRretrieval of optical properties from Ocean Colour data (i.e. absorption and scattering, apportioned to phytoplankton, CDOM and non-algal particulate matter), which will be assessed by using the data from the ECO triplets combined with other IMOS data.
- The combined bio-optical observations will also be useful for a variety of process studies such as particle and phytoplankton temporal dynamics (e.g. assessing diurnal to seasonal variability), modelling of the underwater light climate for primary production, and identifying optical proxies linking optical observations to biogeochemical properties. These studies will benefit from the broad range of environmental conditions at the NRS sites where sources of particulate and dissolved matter substantially vary during the tidal and seasonal cycles due to the interaction of river discharge, shelf currents and continental circulation patterns.

(b) Ocean Acidification

The acidification of the global ocean's surface waters is driven by CO_2 uptake form the atmosphere and carbonate chemistry. This process poses one of the most significant threats to the health and sustainability of Australia's marine ecosystems in the next few decades, with environmental and economic consequences for Australia. Evidence is already emerging of declines in calcification of tropical and polar marine species, but a lack of data on the changes in carbonate chemistry is making any link to acidification tenuous. A network of moorings, combined with some underway observations in the SOOP program, will provide key observations to address this problem (Borges et al 2010; Feely et al 2010 and Monteiro et al 2010).

The IMOS NRS Network provides an excellent platform on which to begin building an ocean carbon and acidification network for Australia. Priority sites are

- Yongala and Maria Island, to characterise changes down the east coast of Australia and the influence of the EAC on CO_2 uptake and acidification from the GBR to Southern Ocean, and
- Kangaroo Island, to monitor deeper waters upwelled on the SA shelf which are expected to have higher CO_2 and thus could accelerate the exposure of ecosystems to acidification earlier than in other regions.

Subject to evaluation and affordability, further sites may be added to the network over time.

Each of the three NRS sites is equipped with surface CO2 systems, using proven and robust technology. Three sensors will determine surface CO2, dissolved oxygen, temperature and salinity. The hydrochemistry sampling at the National Reference Sites will also provide total alkalinity data, allowing for a complete determination of the carbonate system and pH. The pH sensors on the Yongala and Maria Island moorings will also provide data, but are not yet considered robust enough to deploy more widely without further development and testing. However, the CO2 sensors and alkalinity data from monthly samples will provide enough information to characterise pH and carbonate chemistry.

Data products will be delivered in near real time (daily), and as a delayed mode product (within 3-6 months) when final calibrations have been applied and more extensive data checking completed.

Details of data streams are as follows:

Data stream type	Units	Depths	Sensor
pCO2	ppm	Surface	Battelle pCO_2
Dissolved oxygen	$um \cdot kg^{-1}$	Surface	Aanderra Oxygen Optode
temperature	°C	Surface	Seabird 16+
Salinity	unitless (PSU)	Surface	Seabird 16+
pH	unitless (pH)	Surface	SAMI2 pH

(c) Additional Sensors and Sampling

Region by region, additional sensors have been added to the NRS moorings as follows:

	Maria Island	**Port Hacking**	**Rottnest Island**	**Darwin**	**Yongala**	**Kangaroo Island**	**Stradbroke Island**	**Ningaloo Reef**	**Esperance**
	CSIRO	**SIMS**	**CSIRO**	**AIMS**	**AIMS**	**SARDI**	**CSIRO**	**AIMS**	**CSIRO**
Sea surface temp	SBE 39						SBE 39		
Waves	MRU						MRU		
Net radiation				Radiometer /CNR1	Radiometer /CNR1				
Water column temp		10 x Aquatech thermistor	2 x SBE39			9 x Aquatech thermistor	2 x SBE39	2 x SBE39	2 x SBE39

It is valid for the NRS Network to provide a platform for the marine and climate science community to add additional sensors, increasing the value of the observing system in a cost effective manner. However the cost of acquiring additional sensors and maintaining quality controlled and quality assured data streams from these sensors across decades is not part of the NRS sampling program, and are not supported from the NRS network budget.

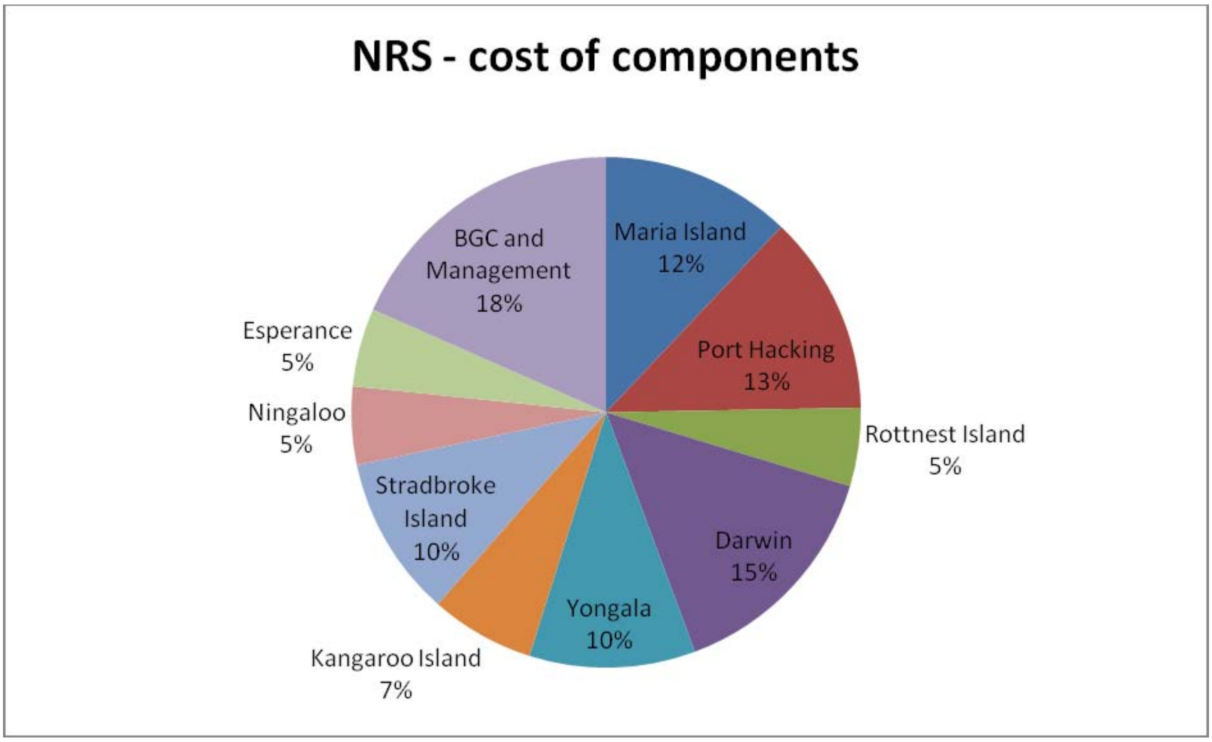
The biogeochemical sampling program was originally planned to include genomic analysis of zooplankton, phytoplankton and microbial samples. This has not progressed as planned due to resourcing constraints, and the fact that the proposed Marine Molecular Observatory Facility was not funded. However zooplankton genomics samples are being drawn from the towed net sample for zooplankton, shipped to CSIRO (Pru Bonham) in a cryofreezer with the pigment and picoplankton samples and stored for use by CSIRO (Stan Robert). This is not part of the NRS sampling program, and is not supported from the NRS network budget.

4. Resourcing

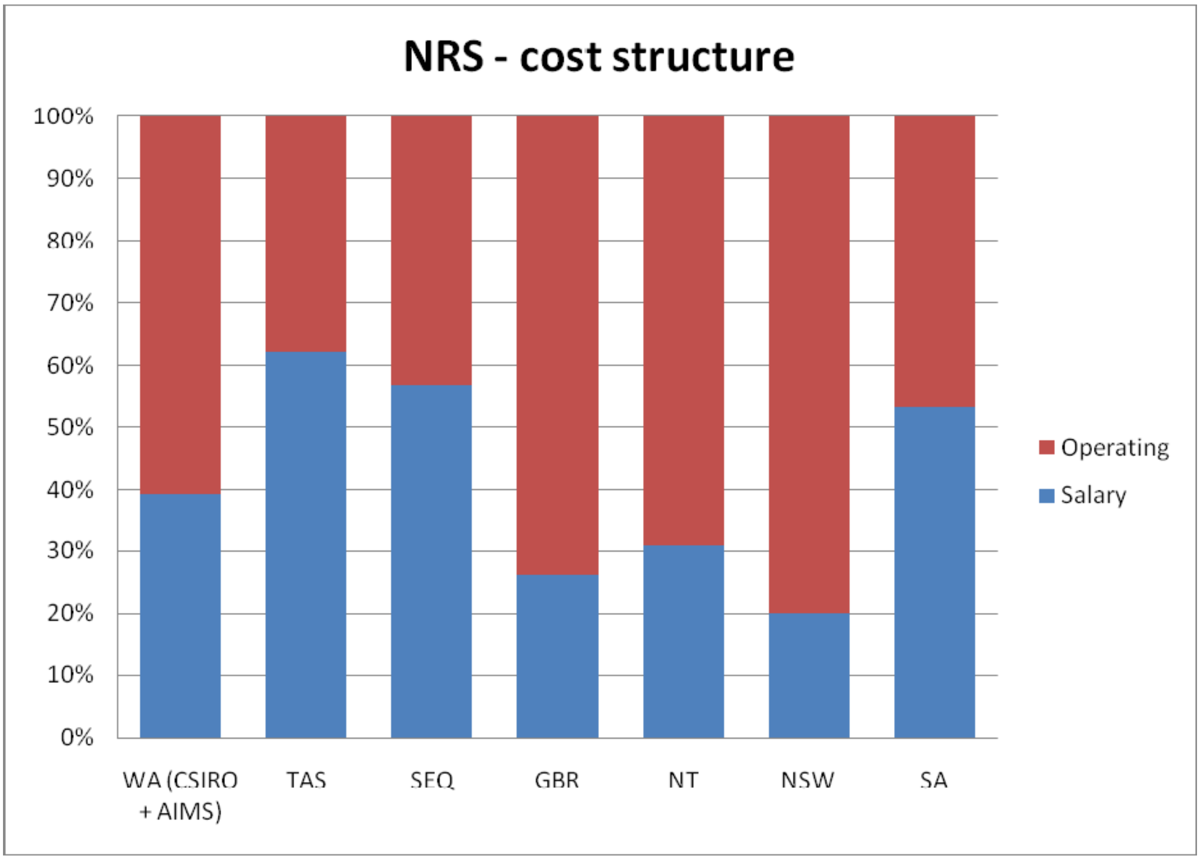
The integrated nature of IMOS means that it can be difficult to separate the resources required to operate particular components, such as the NRS. Integration of some NRS sites with regional mooring arrays is a particular complication in this instance. That said, it is important for IMOS to have some understanding of the resources required to operate various components of the system if

we are to assess the scientific benefits of the data streams to be delivered against the cost of creating and developing those data streams.
Current indications are that the NRS consumes ~$1.9M (11%) of IMOS core funding per annum. This does not include the investment required to refresh capital investment in moorings/sensors in future years.

This investment is currently quite heterogeneous across sites. In particular, WA sites (Rottnest, Ningaloo, and Esperance) appear relatively under-invested, at least in part due to quarterly vs. monthly sampling at Ningaloo, and Esperance. This requires further investigation.



Cost structure of NRS operation across sites also needs to be looked at more closely, with the ratio of salary to operating ranging from 20:80 to 62:38. While there are valid reasons for difference, there may also be gains in efficiency/effectiveness to be generated from more explicit attention to structuring of NRS costs in the future.



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6. APPENDIX 1 – Description of NRS sites

Maria Island NRS

The oceanography of the Tasmanian region is complex. It is one of the few oceanic connection zones between major ocean basins, providing access for the waters of the Pacific Ocean to interchange with the eastern Indian Ocean. This connection is unusual, as the local bathymetry means most exchange occurs across relatively shallow depths (Ridgway 2007b). The region is also historically influenced by two boundary currents, the EAC and the Zeehan Current (ZC). Interestingly, a recent additional complexity to the system has been an extension of the Leeuwin Current, which reached Tasmania during the summer of 2009/10 (Hill pers. comm.).

Although most of the EAC's transport separates from the coast north of Sydney near 30oS, forming the Tasman Front, the remainder continues southward towards Bass Strait and can reach the east coast of Tasmania to form the EAC Extension (Cresswell, 2000; Ridgway and Dunn, 2003). The EAC flow then turns southwestward around South East Cape and creates a zonal jet, the Tasman Outflow, into the southeast Indian Ocean.

Complexity to the region is added by a second warm, saline boundary current, the ZC which flows south along the West Coast of Tasmania before turning north as it rounds the southern tip of the island. There is a sharp division between the EAC and ZC influence adjacent to the Tasman Peninsula off southeast Tasmania (Ridgway, 2007b) and although both currents are seasonal they are also diametrically opposed in their intensity with the EAC strongest in Austral Summer (Cresswell, 2000). With such a complex oceanographic situation it is opportune that the oceanographic data collection at the Maria Island NRS, located immediately north of the Tasman Peninsula, is one of the longest operational time series in the Southern Hemisphere, having been established in 1944 (Hill et al, 2008). Comparisons with satellite observations confirm that the data are representative of the core of the EAC Extension (Ridgway, 2007b). These long-term observations show that the southward penetration of the East Australian Current (EAC) has increased over the past 60 years (Ridgway, 2007a). The station also samples the northward flow of cool, fresh subantarctic water that occurs over winter but is thought to be too far north to be strongly influenced by the winter ZC inflows (Ridgway 2007b).

Port Hacking NRS

The marine environment off NSW is dominated by the presence of the EAC and the eddy field it produces. The EAC sporadically stimulates upwelling and transports the resulting phytoplankton blooms and larvae in multiple directions (Roughan and Middleton, 2002). Depending on the configuration of the eddy field, the EAC can transport waters poleward to Tasmania, or east toward New Zealand (Cresswell, 2000; Ridgway and Dunn, 2003).

The natural variability of the EAC is driven largely by the mescoscale eddy field downstream of the separation point consisting of both warm and cold core eddies that can periodically encroach on the continental shelf and affect coastal waters. The Port Hacking NRS is an integral part of a cross shelf array of moorings and water sampling locations across the continental shelf downstream of the EAC separation point, and adjacent to the NSW-IMOS Sydney oceanographic mooring line. The data collected provides sustained observations of the biochemical response to key oceanographic processes on the SE Australian continental shelf.

Further, through its industry partners (Oceanographic Field Services, Sydney Water, Manly Hydraulics Laboratory, NSW DPI and NSW DECCW), the Port Hacking NRS is integrated with historical oceanographic observations off Port Hacking at 50 and 100m dating back to 1942; nearly 3 decades of wave climate observations at 7 locations along the NSW coast; the Ocean Reference Station's oceanographic data off Sydney (since 1992), as well as an existing array of 70 acoustic telemetry listening posts for tagged sharks along the NSW coast.

Rottnest Island NRS

Rottnest Island is located 18 km off the lower west coast of Western Australia, near Fremantle. The CSIRO Rottnest station was established in 1951 to measure upper ocean temperature and salinity at 55 m water depth to the west of Rottnest Island. The Rottnest NRS is under the direct influence of the Leeuwin Current and eddies; the current produces strong cross-shelf exchanges of waters, heat, nutrient, plankton and fish larvae. ENSO has a strong influence on the Leeuwin Current and eddy field. The Leeuwin Current transports warm and less saline waters southward along the west coast, so that sea surface temperature off the lower west coast of Western Australia is warmer during a La Nina event and cooler during an El Nino event (Feng et al., 2008). Inter annual variations of the water properties of the Leeuwin Current is reflected in the Rottnest time series due to the strong cross-shelf exchanges. Over the past half century, temperature at Rottnest have demostrated a relatively fast rising trend, mostly during the austral winter (Pearce and Feng, 2007; Caputi et al., 2009).

Due to the existence of the Leeuwin Current, shelf regions off the west coast are generally oligotrophic and nutrient is largely depleted in the upper ocean. Sporatic summer upwelling and Leeuwin Current eddies may lift the nutracline and cause enhancement of primary production. Another process that could drive cross-shelf processes is Perth Canyon induced upwelling events, which has not been quantified in previous studies.

The Rottnest NRS station, in conjunction with the shelf mooring array to the north, at Two Rocks, monitors the strength of the Leeuwin/shelf current. The NRS also supports the Perth Canyon mooring array, which will provide the first quantitative study of key processes that controlling the biogeochemical processes on the shelf off the west coast.

Darwin NRS

Darwin is the capital of the Northern Territory, Australia, and is the Darwin NRS is located in the cities harbour. The harbour is an inverse estuary that imports oceanic water during the dry season, but the area can be a stratified for a few days to a few weeks during the wet season, and a vertically well-mixed the rest of the time (Williams et al., 2006). Annual average rainfall is 1500 mm falling mainly between the months of December to April, while the remainder of the year is dry. From May to October the dry, south easterly trade winds prevail, and in the wet season the wind blows moisture-laden air from the northwest. The Northern Territory waters also experience several tropical cyclones.

At the NRS site, macro-tides range up to 8 m, producing severe tidal currents of up to 2ms-1. As a result, sediment re-suspension is a key parameter of interest as it dominates the character of the water throughout the NT and NW Shelf coastal waters. Turbidity is so high that phytoplankton growth is constrained by light attenuation by the sediment and nutrient availability (Burford et al., 2008). Hence sampling on a quarterly or even monthly basis as a single time point sample gives no indication of trend or transport. Time series sampling, however, allows flux calculations to be made. As there are no distinct net coastal currents in the coast off the Northern Territory (NT), flux measurements represent a measure of the balance being imported from offshore and the export from nearshore.

The NRS is located at Channel Marker buoy 5 in Beagle Gulf at the approach to Darwin Harbour off the Cox Peninsula. The location is within a reasonable distance from Darwin where the Australian Timor Research Facility, a joint venture between AIMS and the Australian National University and the adjacent Charles Darwin University provide the necessary local personnel and infrastructure. The Darwin Ports Corporation also regularly monitors the buoy as pilot boats traverse the region daily.
The Department of Natural Resources, Environment and the Arts undertake coastal research in the NT and have underwritten the development of a coastal hydrodynamic model in conjunction with AIMS (Wolanski et al., 2006). The Ecosystems Research Group within the Darwin Harbour Advisory Committee will promote the use of the mooring as a facility for marine science. The Darwin NRS is located on the wide continental shelf and provides a boundary condition for coastal and harbour models being developed by the NT government. The real time data is also expected to assist the Ports Corporation with their shipping operations and overall understanding of the environment.

Yongala NRS

The Yongala NRS is located in the centre of the Great Barrier Reef lagoon, between the mainland and the reef itself. This mid-shelf location is representative of a large region of the Continental Shelf between the predominantly outer shelf reef matrix and the coastal waters. The Yongala NRS is hence well located to sample the competing influences of the south-eastward lagoonal branch of the East Australian Current (EAC) (Brinkman et al., 2002) and the opposing south-easterly trade wind forced coastal current (Burrage et al., 1991). The location complements the larger GBROOS Moorings array, which is focussed on monitoring the major boundary currents along the continental slope and outer shelf-ocean exchanges. Occasionally, during the monsoonal wet season flooding, the Burdekin river plume will occupy a large portion of the shelf and impinge on the site. The Burdekin is Australia's 4th largest river by volume, largest in Queensland and second to the Murray in terms of economic importance. Since European settlement, changed land use practises have meant increased sediment, nutrients and pesticide delivery to the coastal and reef waters (Brodie et al 2001 & 2009, McCulloch et al 2003, Furnas, 2003).

Constraints on the site were twofold: Firstly the location had to be reasonably readily accessible by a small vessel to allow the monthly Biogeochemical (BGC) sampling. Secondly, due to the multiple use zoning of the Great Barrier Reef Marine Park (GBRMPA) it was best sited in a protected zone free of trawling. The presence of the Yongala Wreck meant that an isolated green zone was established by GBRMPA as it supports a recreational diving and tourism industry and it is in the middle of commercial shipping lanes. AMSA required the installation of an IALA Isolated Danger Mark (IDM) which provided the ideal platform upon which the NRS instrumentation could be installed. The IDM is a co-investment between the following stakeholders: Museum of Tropical Queensland (MTQ), Department of Environment and Resource Management (DERM), Department of Environment, Water, Heritage and the Arts (DEWHA), IMOS, Australian Institute of Marine Science (AIMS) and Australian Maritime Safety Authority (AMSA).

The Yongala NRS not only forms the mid shelf link between the outer shelf focussed GBROOS moorings array but also a number of coastal monitoring programmes focussed on water quality. It is being integrated in to the Reef Rescue Marine Monitoring Program funded by Reef and Rainforest Research Centre and GBRMPA (Schaffelke, et al., 2009). The site will also be part of an observing array sampling pesticide levels. The data will be used to also validate remotely sensed SST and ocean colour products and provide validation of a number of hydrodynamic and biogeochemical modelling efforts: Bluelink, OceanMAPS and a new near-real time whole of GBR model under development. The NRS is also in the region of a recreational sailfish and marlin sport fishery and when added to the large.scale dive tourism at the site the real time mooring is expected to attract significant local interest.

Kangaroo Island NRS

The Kangaroo Island NRS is located at a choke point in isobath convergence and is thus an ideal sampling point for: detecting low-frequency flows driven by winds, modulation by ENSO events, the eastward Leeuwin Current during winter and indirectly, the westward Flinders Current (FC). The importance of the Antarctic Circumpolar Wave (ACW) in the area is currently unknown but analyses suggest 0.5 C variations in Sea-surface Micro layer (SML) temperature may occur over a four year time scale. In addition, the Kangaroo Island NRS is also located where upwelling occurs during summer and dense Spencer Gulf water is expelled during winter. The degree of upwelling is modulated by both local winds, ENSO events and possibly canyon-induced upwelling by the slope FC (Middleton and Bye, 2007).

Currents measured at the Kangaroo Island NRS are influenced not only by the Leeuwin Current but also the FC. This current is forced by the large scale wind stress curl in the Southern Ocean and a bifurcation of the Tasman Outflow, the latter a remnant of the EAC. In the west, the FC also acts as driver of the Leeuwin Undercurrent. The relative importance of this local and large-scale forcing is to be determined using the data streams from the NRS site (deployed in August 2008) and those from the regional mooring array. These include a cross-shelf mooring array made up of the NRSKAI, a 200 m (SAM3MS) and a 600 m deep mooring (SAM7DS): all three will each have ADCP's and 25 temperature loggers to resolve the FC and variations in thermocline depth that may arise from ENSO events or the ACW.

The NRS data are also being supplemented locally by: HF RADAR current data, CTD data from gliders and sea-lions, ARGO CTD and SVP data and satellite SST and altimetry. These data (and those from WAIMOS and TASIMOS) will enable the relative importance of both local- and large-scale forcing of this complex system of currents to be determined.

North Stradbroke Island NRS

The North Stradbroke NRS provides a coastal point in one of the world's most ambitious aquatic and marine transects. With the IMOS partner the Terrestial Ecosystem Research Network (TERN) and the IMOS facilities of the ANMN and the Australian Benthic Observing System (ABOS) a transect of instrumented monitoring points are being deployed from the top of the region's major terrestrial catchment, through Morton Bay, out across the continental shelf and into the deep ocean.

The North Stradbroke Island NRS is also in an important location to monitor the coastal environment. SEQ, with cities such as Brisbane and the Gold Coast merging into one metropolis, is a fast growing region in Australia. With this population growth there are associated increased pressures of eutrophication, pollution and overfishing on the coastal environment. The sites location - just north of North Stradbroke Island - is at an opening of Moreton Bay and as such, is well situated to assess the physical, chemical and biological environment entering and leaving the Bay. Water quality is an important issue in the Bay and there is an extensive monitoring program in the area. The National Reference Station will provide a measure of nutrients entering and leaving the Bay, as well as providing an oceanic context for evaluating local eutrophication in the Bay.

Southeast Queensland (SEQ) is an important point along the EAC as the current passes south here at it's most intense. South of this region, eddy activity in the EAC increases, so dynamics of EAC flows in this area are important to the understanding overall EAC variability. Because eddies in the EAC initiated in SEQ are important to fisheries productivity and weather in SEQ and NSW, a better understanding of the eddy dynamics in SEQ is necessary for validating physical models such as BlueLink. An example of a industrial application of the information generated by modelling observations provided by the NRS and the associated shelf and deepwater arrays is informing commercial companies interested in generating renewable power using ocean turbines driven by the strong and consistent EAC flow off Brisbane.

The North Stradbroke Island NRS is also at a biogeographic boundary between tropical and subtropical species of fish and invertebrates. Macroalgae is at its northernmost extent on the east coast here, as the region experiences periodic upwelling of cooler, nutrient-rich water that sustains coastal macro-algal populations. Cyclonic (cold-core) eddies are formed where the EAC separates from the GBR. These eddies feed back onto their selves and propagate southward to SEQ. Cold-core eddies generate increased productivity in their cores due to shallowing of the mixed layer depth. These biologically-rich cold-core eddies are important for fish recruitment, whereas the warm-core eddies are considered to be relatively unproductive. For example the cold water upwellings are responsible for the SEQ relatively high productivity and supports local bay fisheries such as for King Prawns. Other EAC features off SEQ can also promote upwelling, including interactions of current flow with bottom topography as well as upwelling at the shelf break due to Coriolis force. Enrichment processes lead to regular coastal and oceanic algal blooms in the region. In particular, harmful and nuisance algal blooms can be initiated offshore and approach the coast through onshore currents and nutrients from coastal regions undoubtedly feed offshore zones.

The North Stradbroke NRS is an important piece of infrastructure to understand and observe currents to the west of the EAC. The effect of the EAC on these coastal currents is likely to have a substantial influence upon on coastal processes such as benthic productivity and sand transport. They are also likely to be extremely important in the context of connectivity through both larval transport and active north-south migrations along the coast.

Ningaloo NRS

The circulation off the coast of Western Australia (WA) is anomalous compared to currents along other eastern ocean margins. In most other parts of the world these currents tend to be wind-driven equatorward producing cold upwelling leading to high productivity. While these equatorward winds are still prevalent off WA, the circulation along this extensive 5000 km long coastline is, for the most part, dominated by the Leeuwin Current, a unique poleward-flowing eastern boundary current. Flowing strongest during the winter, the Leeuwin is forced by a sea-level gradient between the North West continental shelf and the Southern Ocean (Cresswell and Golding, 1980). The inter-annual variability of the Leeuwin is controlled by the Indonesian Through Flow via the Pacific/Indian ocean wave guide. Here, the El Niño-Southern Oscillation (ENSO) signals propagate from the western Pacific Ocean to the north of the Western Australia and are then transmitte with the Leeuwin Current along the west and southern coasts of Australia. This results in a stronger Leeuwin Current during La Niña events and a weaker current during El Niño years (Pattiaratchi and Buchan, 1991; Feng et al., 2003). The presence of the Leeuwin tends to suppress upwelling along the WA coast throughout most of the year, leading to the sea surface temperature off WA to be 4-5° C warmer than upwelling systems at similar latitudes elsewhere on the globe.

With its flow opposing the dominant southerly winds that are present along WA, the Leeuwin is not a stable ocean boundary current, and generates the strongest eddy kinetic energy of any eastern boundary current system (Feng et al., 2005, Waite et al., 2007). During summer months, when southerly winds are strong enough to oppose it, the Leeuwin can be pushed offshore, often leading to the formation of an inshore coastal currents that is northward flowing and wind-driven. These coastal currents generate episodic and transient upwelling along some regions of WA where the continental shelf is relatively narrow, such as between Capes Leeuwin and Cape Naturaliste and along the North West Cape region of Ningaloo Reef (Gersbach et al., 1999, Woo et al., 2006). The summer wind-driven northward surface current present adjacent to the Ningaloo coast during some

months of the year, has previously been termed the Ningaloo Current and the existence of this current has been thought to have profound impacts on the ecology of coral reef communities living among Ningaloo Reef (Taylor and Pearce, 1999). It has been suggested that the presence of the upwelling-favourable Ningaloo Current can enhance dissolved and particulate nutrient levels adjacent to Ningaloo Reef, thereby triggering local increases in primary production and increasing nutrient fluxes to coral communities (Feng and Wild-Allen, 2010). Further, it has been hypothesized that presence of the NC and associated upwelling may make Ningaloo less vulnerable to bleaching compared to other Indian Ocean reefs (Pattiarachi , 2007), however, the role that upwelling plays in mitigating coastal temperatures has never been quantified.
The Whale shark, Rhincodon typus, also seasonally aggregate in coastal waters off Ningaloo Reef and are the basis of a regional tourist industry. A link between the abundance of aggregating whale sharks and the physical and biological oceanography of the region has been established with greater whale shark numbers in La Nina years (Wilson et al., 2001). The complexity of the interaction between the physical and biological oceanography of the region means, however, that this response by the R. typus to the oceanography is not well understood.

The Ningaloo NRS is located offshore from Tantabiddi on the North West Cape inside the Ningaloo Marine Park, and detects the presence of the poleward Leewuin Current and the wind forced Ningaloo Current and associated upwelling. The site is just south of the NW Cape tip, where the Leeuwin Current becomes well formed and the sea surface temperature signal is more easily seen from satellite imagery.

The data from the Ningaloo NRS is contributing to the outcomes of WAMSI node 'Climate Variability and Prediction' and the regional IMOS node of WAIMOS . Data from the NRS is being used by researchers from AIMS, CSIRO and the UWA, to develop a system wide understanding of circulation in the Ningaloo Reef region and its response to variability of the Leewuin Current system through the development of a validated numerical coastal circulation model nested within a larger scale data assimilating ocean circulation model. This suite of models is being employed to investigate the spatial and temporal variability of transient upwelling along the Ningaloo Coast, with the ultimate aim of better understanding the vulnerability of the coral reef to adverse impacts of climate change.

These models require a suite of data, at various spatial scales, for validation in order to build confidence in model performance. An ARC UWA internal wave study by Ivey and Lowe has also integrated data from the NRS into its experimental plan by providing long term background ocean properties as a context their study of higher frequency internal waves and transient upwelling.

Esperance NRS

Southwest Western Australia has experienced a significant decrease in winter rainfall since the late 1960s. The existence of links between rainfall and both mean sea level pressure (MSLP) and sea-surface temperature (SST) are suggestive of coupled air-sea interactions over the southern Indian Ocean which may be relevant at decadal or multi-decadal timescales. A major difficulty with defining any such processes is the relative sparseness of data (Smith et al., 2000). The Esperance NRS will help establish a baseline to monitor impacts of climate variability on coastal process in the Southwest Western Australia region.

Of further interest, while the Esperance NRS experiences the influence of the Leeuwin Current during austral winter, it also experiences unpredictable upwelling in response to favourable winds during austral summer.