National Environmental Research Program

TROPICAL ECOSYSTEMS hub

Final Report

Tracking GBR water clarity over time and demonstrating the effects of river discharge events Progress Report: Southern and Northern NRM Regions

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Australian Government
Department of the Environment

Reef & Rainforest RESEARCH CENTRE

Tracking GBR water clarity over time and demonstrating the effects of river discharge events

Progress Report: Southern and Northern NRM Regions

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Australian Government

Department of the Environment

Supported by the Australian Government's
National Environmental Research Program

Project 4.1 Tracking GBR water clarity over time and demonstrating the effects of river discharge events

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National Library of Australia Cataloguing-in-Publication entry:

978-1-925088-69-4

This report should be cited as:

Logan, M., Fabricius, K., Weeks, S., Rodriguez, A., Lewis, S., Brodie, J. (2014) *Tracking GBR water clarity over time and demonstrating the effects of river discharge events. Progress Report: Southern and Northern NRM Regions.* Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (53pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Research Program (NERP) Tropical Ecosystems (TE) Hub.

The Tropical Ecosystems Hub is part of the Australian Government's Commonwealth National Environmental Research Program. The NERP TE Hub is administered in North Queensland by the Reef and Rainforest Research Centre Limited (RRRC). The NERP Tropical Ecosystem Hub addresses issues of concern for the management, conservation and sustainable use of the World Heritage listed Great Barrier Reef (GBR) and its catchments, tropical rainforests including the Wet Tropics World Heritage Area (WTWHA), and the terrestrial and marine assets underpinning resilient communities in the Torres Strait, through the generation and transfer of world-class research and shared knowledge.

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Cover photographs: Water clarity is an important ecological factor for marine ecosystems on continental shelves. Examples of water clarity changes from the Wet Tropics, as seen from space and under water in clear and turbid waters. Landsat, Modis Aqua, K. Fabricius

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June 2014

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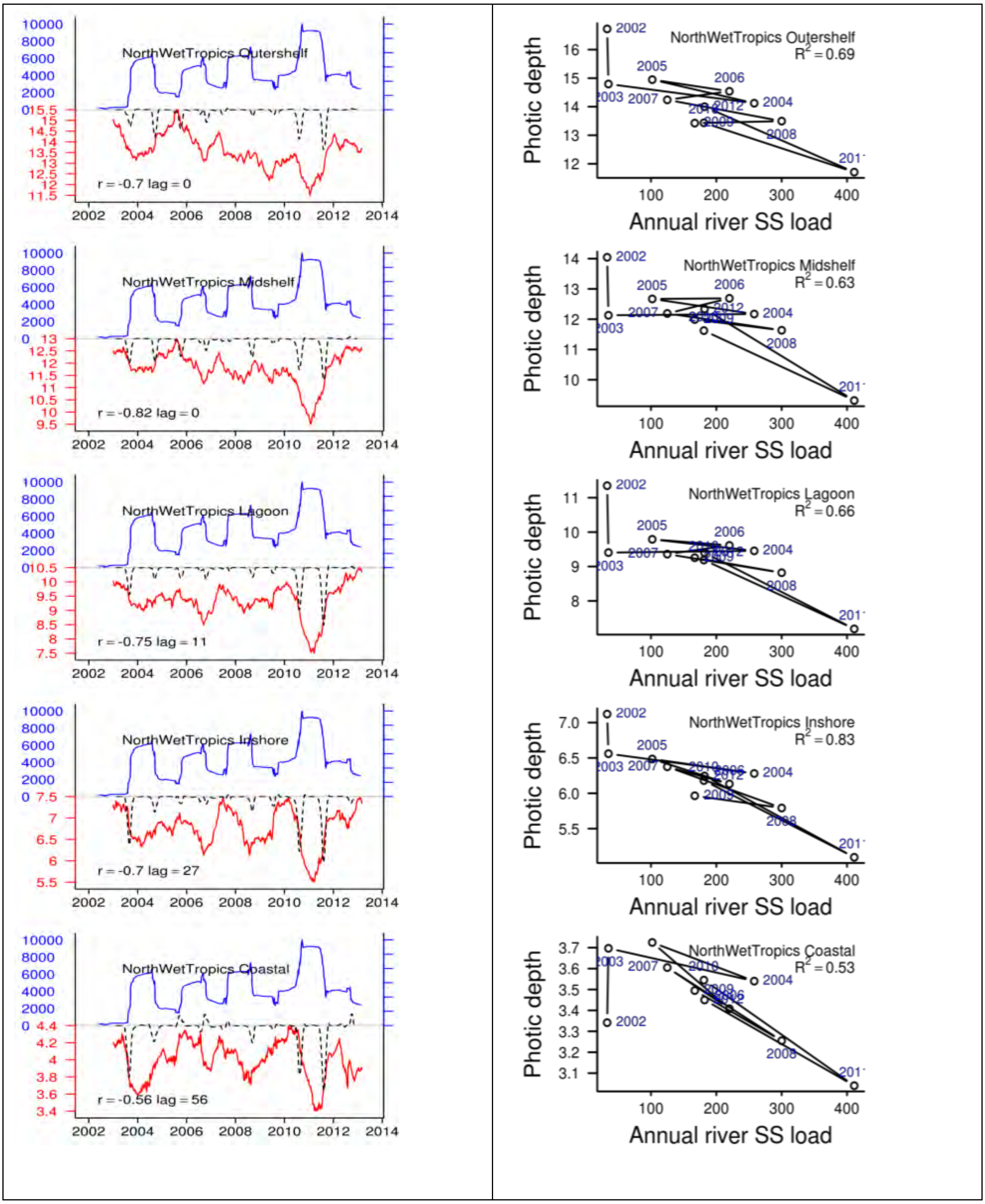
Acronyms Used In This Report

COTS .... Crown of Thorns Starfish
GBR .... Great Barrier Reef
NERP .... National Environmental Research Program
NRM .... Natural Resource Management
TSS .... Total Suspended Solids

Acknowledgements

We thank the State of Queensland's Department of Environment and Heritage Protection for providing the wave rider buoy data, and the river flow and river nutrient load data. The Bureau of Meteorology provided the wind and rainfall data, and the Australian Navy provided modelled estimates of tidal ranges. We also thank the NASA Ocean Biology Processing Group for both the SeaWiFS and MODIS-Aqua matchups of the satellite-to-in situ Secchi depth data. The study was funded by the Australian Government's National Environmental Research Program (NERP) Tropical Ecosystems (TE) Hub, and the Australian Institute of Marine Science (AIMS).

Graphical Summary: Standardized photic depth (left panel: red lines) strongly declines with increasing river flows (blue lines), and with annual sediment and nutrient loads (right panel, black lines) in all GBR regions except Cape York. Of all GBR regions, the Northern Wet Tropics (Cairns to Lizard Island, the initiation area of outbreaks of crown-of-thorns starfish) had the strongest correlation between photic depth and rivers. In this region, the relationship was strong across the whole shelf, including the Mid- and Outershelf Zone, and only slightly weaker in the turbid Coastal Zone. The conclusion that runoff only affects the inshore of the GBR has to be revised for the Central and Northern GBR.



Executive Summary

Water clarity is a key factor for coastal marine systems. Here we show preliminary results of our study to investigate the relationship between water clarity in the Fitzroy, Whitsundays, Wet Tropics and Cape York NRM Regions of the Great Barrier Reef and the discharges of their major rivers. We used 11-years (2002-2013) of daily 1 km^2 MODIS-Aqua remote sensing data to investigate time scales and processes affecting water clarity in these regions. As in our previous analysis of water clarity in the Burdekin Region (Fabricius et al. 2014), the Week et al. (2012) algorithm quantifying 'photic depth' from MODIS-Aqua was chosen as a measure of water clarity. It defines the penetration depth for 10% of surface irradiance. Photic depth was standardised for wave height, wave period and tidal range, using boosted tree models. In all coastal, inshore and lagoonal regions, photic depth was strongly negatively related to the freshwater discharge of the main rivers. The declines started with the onset of river floods, and typically took 150 – 260 days until complete recovery. Relationships between photic depth and rivers were strong in most regions of the GBR but weaker in the Cape York region. The strongest relationship was found in the Northern Wet Tropics region (Cairns to Lizard Island), the initiation area of outbreaks of crown-of-thorns starfish. Here, the correlations of photic depth to river flows, and to annual sediment and nutrient loads, were very strong all the way across the shelf, from the Inshore to the Midshelf and Outershelf zones. They were slightly weaker in the turbid coastal zones. Previous conclusions that river runoff predominantly affects the inshore of the GBR are confirmed for the southern GBR. However these conclusions are incorrect and have to be revised for the Central and Northern GBR (14.5 – 19^{o} latitude South, i.e., Burdekin River to Lizard Island) where the correlations between photic depth and river loads are strong within much of the main reef matrix, possibly due to the narrowness of its continental shelf combined with relatively high anthropogenic contributions to river nutrient loads.

Introduction

This study investigates the relationship between long-term patterns in water clarity of the GBR and the terrestrial runoff of nutrients and sediments. In the first year of this NERP Project, we have developed a novel approach to assess the relationships between the terrestrial runoff of freshwater and its associated fine sediments and nutrients and the daily to inter-annual variation in water clarity, using the central section of the shallow GBR continental shelf as a model system (Logan et al. 2013, Fabricius et al. 2014). That study was based on 10 years of remote sensing and environmental data (2002–2012), a new GBR-validated photic depth algorithm for MODIS-Aqua data (Weeks et al. 2012) and statistical models. The study showed that mean annual water clarity in the central GBR is strongly related to discharges by the large Burdekin River. The study then assessed the spatial extent (inshore to offshore) and duration of reduction in water clarity beyond the duration of the flood plumes. The results suggest that reductions in the sediment and nutrient loads of the Burdekin River will likely result in significantly improved water clarity downstream of the river mouth and across much of the central GBR, both during the wet season and throughout the following dry season (Logan et al. 2013, Fabricius et al. 2014).

We extended the methods developed by Logan et al. (2013), and applied them to the other four large NRM Regions of the GBR, namely the Fitzroy and Whitsundays regions in the south, and the Cape York and Wet Tropics regions in the north. Here we present the results of these large, memory intensive and complex analyses.

Methods

Turbidity data

The daily 1 km^2 MODIS-Aqua remote sensing data were processed as described previously (Weeks et al. 2012, Logan et al. 2013, Fabricius et al. 2014). New masks were generated to excise optically shallow waters (reefs and very shallow sections of the seabed) optically shallow waters. The full gridded daily data series for each region at 1 km^2 resolution is too large to reside in memory (Fitzroy and Whitsundays regions: 91,082 grid points per day (Fig. 1), Cape York and Wet Tropics 36,474 grid points per day, over 11 years). We therefore spatially aggregated the data into 15 zones for the Fitzroy and Whitsundays region (Fig. 2, Table 1), and 15 zones for the Cape York and Wet Tropics regions (Table 1). For the Whitsundays, Wet Tropics and Cape York regions, five bands were defined parallel to the coastline, as previously used for the Burdekin region:

Coastal: 0 – 0.1 fractional units across the GBR
Inshore: 0.1 – 0.25 fractional units across the GBR
Lagoon: 0.25 – 0.45 fractional units across the GBR
Midshelf: 0.45 – 0.65 fractional units across the GBR
Outer shelf: 0.65 – 1 fractional units across the GBR

The Fitzroy region cannot be partitioned up into simple coast-parallel bands, due to its geomorphology around the Capricorn-Bunkers and Swains complex, and the estuarine Keppel Bay. Consequently, the Fitzroy region was partitioned according to a combination of geomorphological regions and boundary rules (based on distances from coastlines and bioregions) so as to reflect its oceanographic and geomorphological characteristics.

The Broad Sound was analyzed separately, as its high tidal range and distance from the major Whitsundays and Fitzroy Rivers make this area unrepresentative of the more intensely used and populated areas of the Whitsundays and Fitzroy NRM Regions. The boundaries were chosen to best match those of both the Whitsundays and Fitzroy areas.

The Cape York and Wet Tropics NRM regions were subdivided into three long-shore bands, with the 'Cape York' band extending to 14.5° latitude (Lizard Island), and a northern Wet Tropics region, split at Cape Grafton (south of Cairns), and the southern Wet Tropics to best capture their differences in geomorphology, rainfall, agricultural use patterns, and population outbreak dynamics of crown-of-thorns starfish.

Data were aggregated to water years (1st October to 30th September) rather than calendar years. As the data were provided and stored by calendar year, the most convenient pathway was to join all years together and then aggregate on water year. However, as the collective data sources were too large to fit into memory, two consecutive years were loaded at a time, only retaining the middle water year data each time (except for the first and last years in the sequence). As the data processing was very memory intensive, it was necessary to process each of the yearly files individually and then remove the yearly object from memory before proceeding.

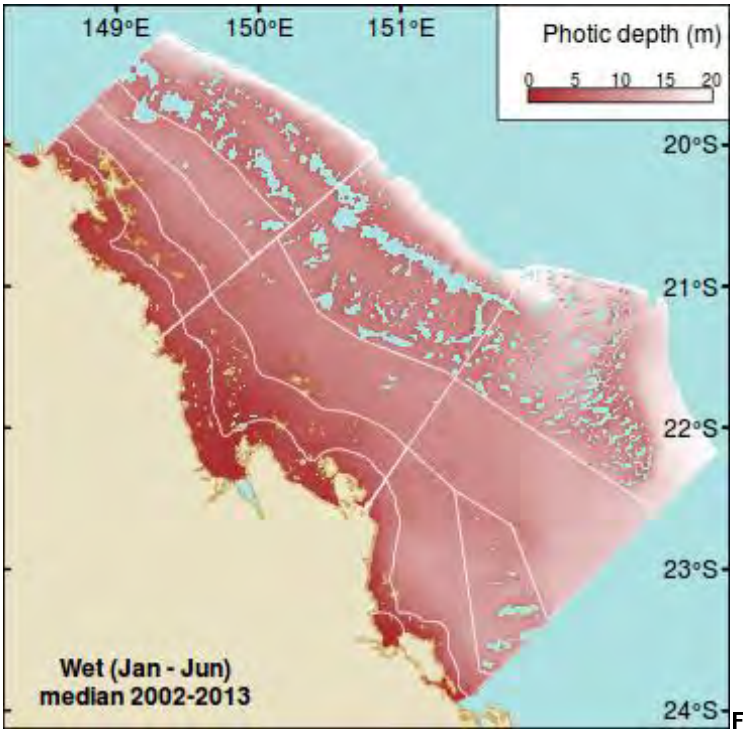


Figure 1: Example of gridded data of photic depth from the Fitzroy and Whitsundays region (here: medians across the wet seasons). This southern data series consists of 91,082 daily grid points, over 11 years.

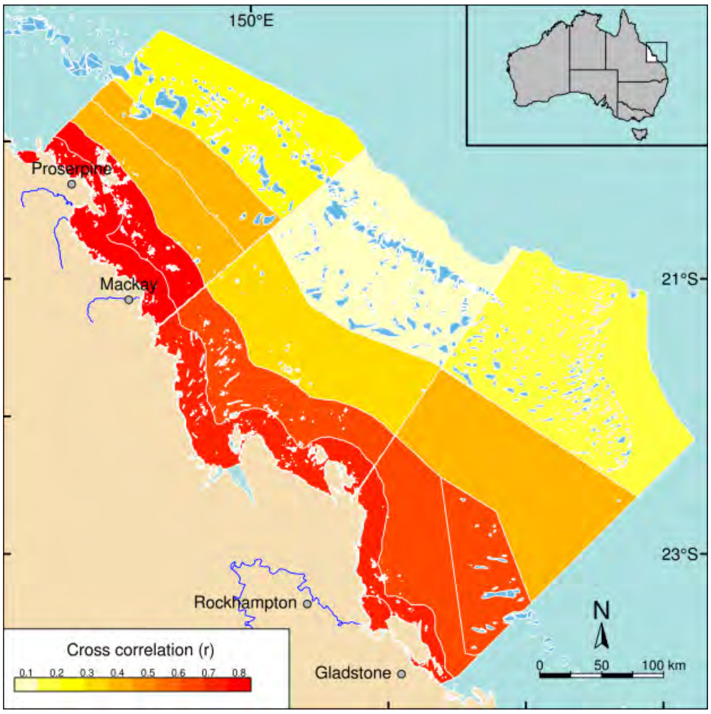


Figure 2: Map of the southern GBR illustrating the boundaries of the fifteen defined data aggregation zones of the Fitzroy and Whitsundays regions. The colour scheme represents the strength of correlation of photic depth (seasonally detrended, and standardised by waves and tides) to intra- and inter-annual changes in river discharges in each zone (see Results section below, Fig. 13).

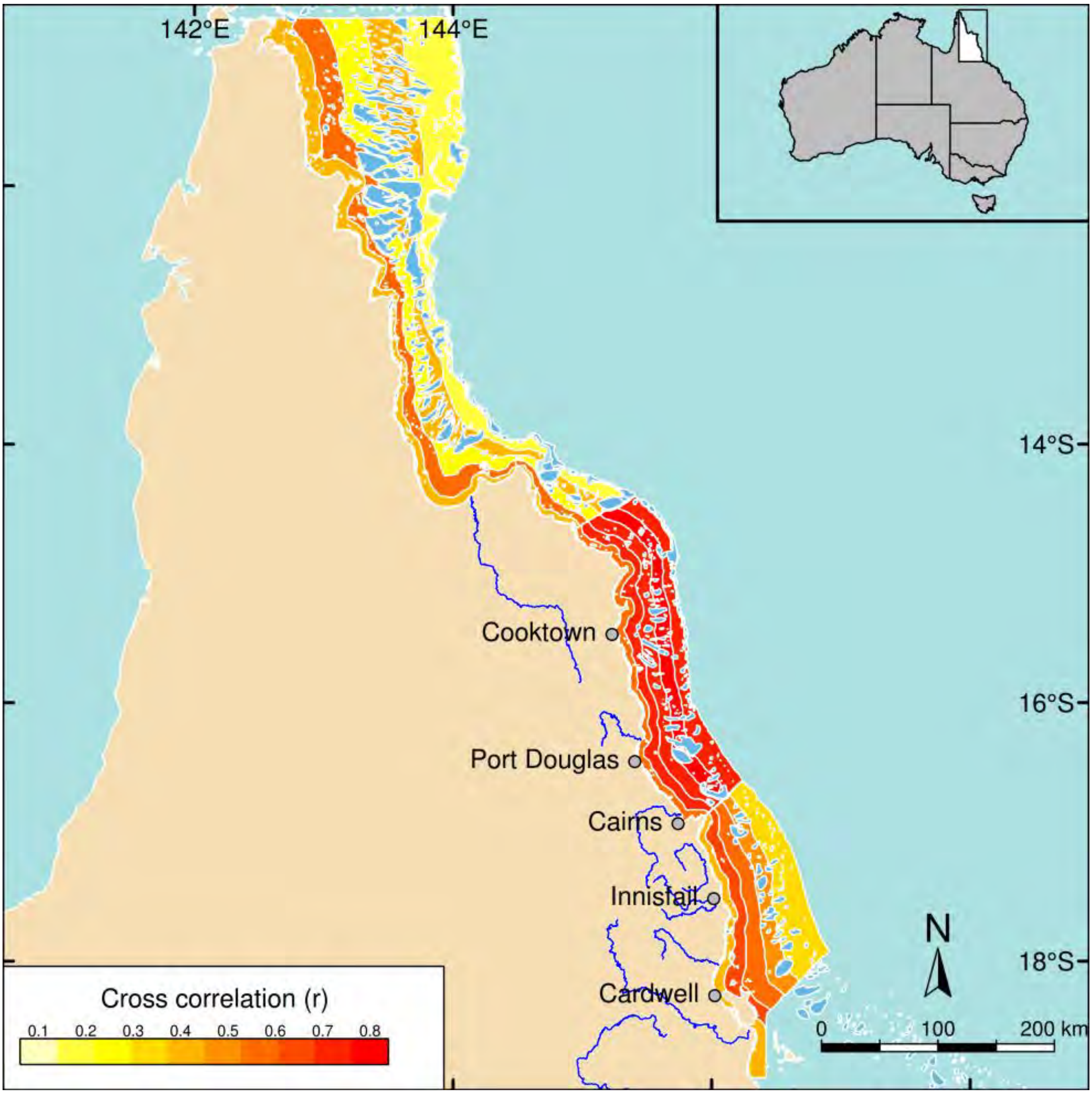


Figure 3: Map of the northern GBR illustrating the boundaries of the fifteen defined data aggregation zones of the Cape York and Wet Tropics regions. The colour scheme represents the strength of correlation of photic depth (seasonally detrended, and standardised by waves and tides) to intra- and inter-annual changes in river discharges for the Wet Tropics zones, and rainfall for the Cape York zones (see Results section below, Fig. 14). In the lagoon and midshelf zones of the Cape York region, the reef matrix is too dense to provide sufficient information for plotting.

Environmental data

Bathymetry, oceanographic and wind data

Bathymetry data (metres below mean sea level) for each grid point were obtained from a high-resolution digital elevation model for the GBR at a resolution of 0.001-arc degrees (about 100 m) (Beaman 2012).

Oceanographic data

Daily tidal amplitudes as a proxy for tidal currents: Rather than using measured tidal levels, modelled/predicted tidal data by the Australian Navy were used. Previous correlations between actual and harmonic tides have shown them to be very similar. Modelled estimates exist for many locations throughout the coast of eastern Australia (thanks to the Australian Navy, Supplementary Table 1 - 2, Fig. 4). For each zone, a single tidal location or a set of 'representative' tidal locations was chosen, and the mean tidal range per day was calculated across these locations, to reduce computational exhaustion. This approach is justified since it is predominantly the relative tidal range (rather than absolute tidal range) that we are most interested in, and the relative tidal ranges within each zone should remain relatively homogeneous. Furthermore, photic depth is also one daily value, and all grid points within a zone were treated as being equal with respect to their photic depth to determine means per zone.

Hourly data on wave heights and wave frequencies were obtained from the Queensland State Government, Department of Environment and Heritage Protection (DEHP), from the 3 only wave rider buoys available in the study region (Supplementary Table 1; Fig. 4): Emu Point for the southern zones, Mackay for the Whitsunday zones, and Cairns Buoy for the Northern and Southern Wet Tropics. For the Cape York zones, wind data from Lockhart River were considered more representative than the wave data from the Cairns buoy.

Wind data

Wind data were obtained from the Bureau of Meteorology (http://www.bom.gov.au/oceanography/projects/abslmp/data/index.shtml) for a number of coastal stations (Supplementary Table 3). For each wind station, we generated different lags:

- no lag (wind speed at each time)
- three day back lag (the wind speed for a given day is the mean of that day and the two days previous)
- three day attenuated back lag (the wind speed for a given day is the weighted mean of that day and the two previous - where the weights are 1,0.5,0.25)
- five day back lag (the wind speed for a given day is the mean of that day and the four days previous)
- five day attenuated back lag (the wind speed for a given day is the weighted mean of that day and the four previous days - where the weights are 1/1,1/2,1/3,1/4,1/5)

A little experimenting suggested that the mean over five days (four previous and current) was generally best - although only marginally so.

The wind data in the Cape York zones seem to have an interesting cyclical pattern (Supplementary Fig. 1, 2). Whilst it would be good to be able to use Lucinda wind data, the station was damaged in Tropical Cyclone Yasi and offline for 851 days (Supplementary Table 3, 4). As the wind recorded at this station was different to the other stations in the region, its inclusion causes the data to present a change in wind patterns following Yasi, likely an artifact of the missing Lucinda data. Similarly, Rundle Island is missing 877 consecutive days. Hence, it will also be regrettably omitted. Many of the other stations have also experienced some down time; however, they were typically only down for 10 or fewer days at a time. There are also still clearly issues with the Cairns wind data which alter dramatically mid-2010.

River data

Daily data of freshwater discharge volumes of the main rivers were provided by the State of Queensland, Department of Environment and Heritage Protection (DEHP; Figs. 5, 6). To assess the effects of river discharge on water clarity in each region, the main rivers for each region were identified based on proximity and predominant northerly current directions near the shore (Fig. 4, Table 2). The main rivers in the Whitsundays and Fitzroy are relatively unambiguous. For Broad Sound with its high tidal range and the absence of major rivers, only the large Fitzroy River was assumed to be of influence. The Southern and Northern Wet Tropics have a large number of rivers directly discharging into the regions. Both regions are probably also affected by rivers further south (esp. the Burdekin River for the Southern zones, and the Russell-Mulgrave and Johnston Rivers for the Northern zones), with unknown time lags. At this stage, the analyses focused on the main rivers that directly discharged within each of the regions. For the Cape York, only the Stewart, Endeavour and Normanby River data are available, and the discharge station for the latter only came online late 2005. Therefore, the better part of the first four years of daily discharge data for the main river in this region are missing (Stewart and Endeavour Rivers are much smaller than the large Normanby), and also missing are any form of river discharge information for the whole northern half of the region.

For the Cape York region, we also used daily rainfall data from the Lockhart River rainfall gauge as an alternative to river discharge data. This gauge is located relatively centrally in this ~400 km long band and extends throughout the observation period. Daily rainfall data were obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/oceanography/projects/abslmp/data/index.shtml).

Annual loads of total suspended solids (TSS), total nitrogen and total phosphorus / or, PP, PN, DIN and DIP of the main rivers were estimated (Table 5). Note that nutrient loads were all highly correlated - suggesting that three of them are derived from one of them (or else they are all derived from a common proxy). Figs 7 and 8 show time series of TSS loads across the years; the patterns for the other variables are almost identical and therefore not shown. The last two years for the PP, PN, DIN and DIP data were missing. Since all are highly correlated to TSS loads, we used a fairly simple Bayesian regression model to assess the relationship between X and TSS and to impute the missing values (and their uncertainty). A regression model was then used to relate annual photic depth to the nutrient loads.

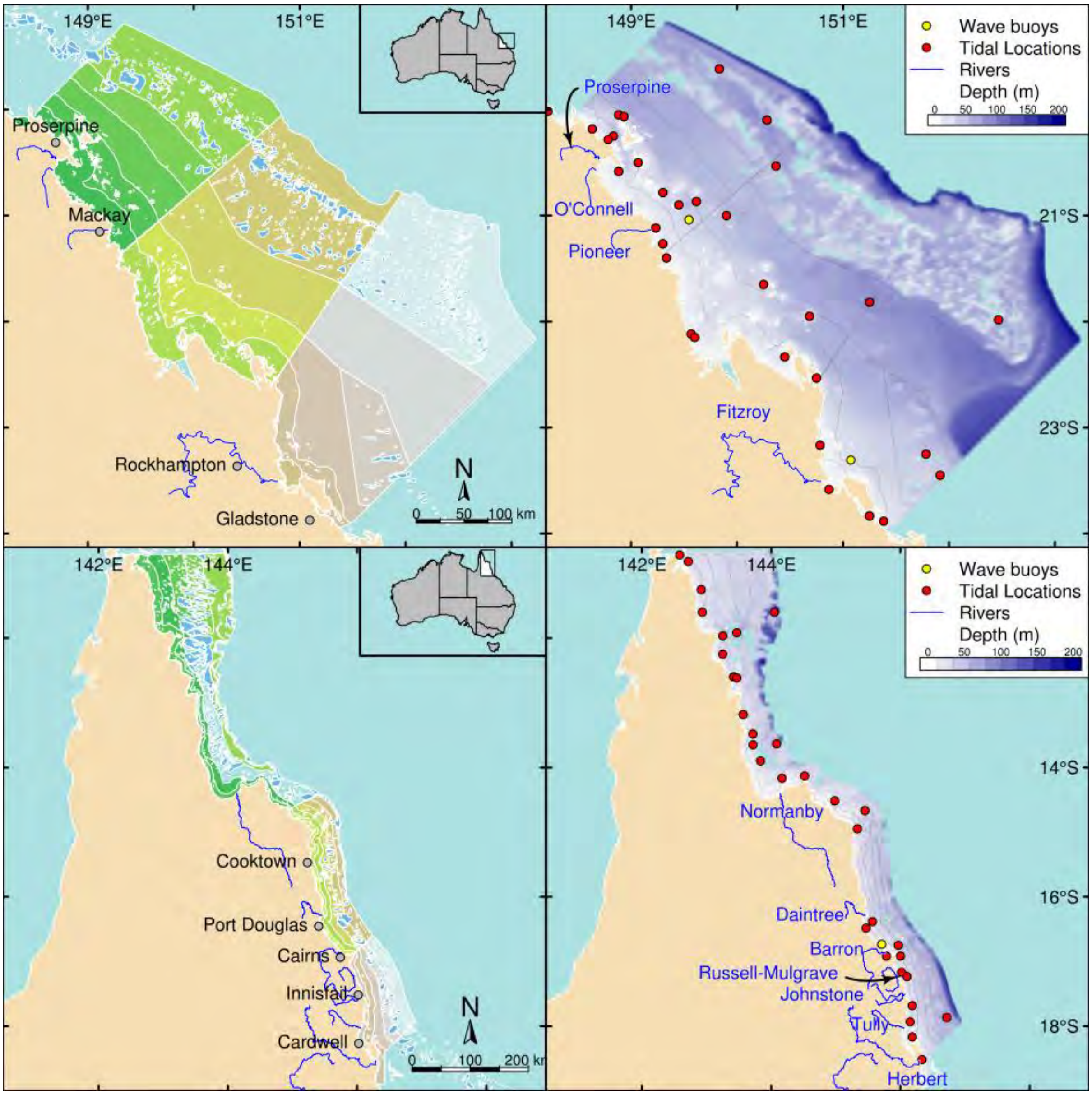


Figure 4: Map of the southern and northern GBR illustrating bathymetry and covariate capture stations (red symbols: tidal stations, yellow symbols: wave buoys) throughout the 30 defined data aggregation zones as well as the locations of the major rivers.

Table 1: Names, mean photic depth (m), tidal range (m), wave height (m) and wind speed (m/s) of the 30 zones across all years (2002-2013).

Region	Zone	Photic depth	Tidal range	Wave height	Wind speed
Whitsundays	Coastal	3.99	02.74	00.88	21.86
	Inshore	6.22	03.23	00.88	21.86
	Lagoon	10.73	02.89	00.88	21.86
	Midshelf	11.99	02.20	00.88	21.86
	Outershelf	10.68	01.91	00.88	21.86
Broad Sound	Coastal	3.62	04.84	00.86	22.42
	Inshore	5.98	03.88	00.86	22.62
	Lagoon	9.95	03.75	00.86	22.62
	Pompeys	10.29	02.56	00.86	22.62
Fitzroy	Keppel Bay	1.34	03.53	00.84	15.94
	Coastal	05.97	03.13	00.84	16.39
	Inshore	10.88	02.87	00.84	19.16
	Capricorn Bunkers	11.32	02.13	00.84	22.45
	Swains Bluewater	13.09	02.28	00.84	22.45
	Swains Reef	13.05	01.73	00.84	22.45

Region	Zone	Photic depth	Tidal range	Wave height	Wind speed
Cape York	Coastal	3.72	02.08	00.50	17.88
	Inshore	5.30	01.86	00.50	17.88
	Lagoon	7.89	01.96	00.50	15.51
	Midshelf	10.63	01.81	00.50	15.51
	Outershelf	10.81	01.60	00.50	15.51
North Wet Tropics	Coastal	4.00	01.73	00.50	19.04
	Inshore	6.73	01.68	00.50	19.04
	Lagoon	9.43	01.68	00.50	19.04
	Midshelf	11.82	01.68	00.50	19.81
	Outershelf	13.75	01.68	00.50	19.81
South Wet Tropics	Coastal	3.62	01.77	00.50	15.91
	Inshore	6.68	01.75	00.50	15.91
	Lagoon	10.81	01.68	00.50	15.91
	Midshelf	11.85	01.73	00.50	17.69
	Outershelf	14.49	01.73	00.50	17.69

Table 2: The major rivers included in the models for each of the zones, based on the location of their river mouth, and assuming predominant northerly current direction.

Zone	**Rivers**
Whitsundays (all zones)	Proserpine River O'Connell River Pioneer River
Broad Sound Coastal, Inshore, Lagoon, Pompeys Keppel Bay	Fitzroy River
Fitzroy Coastal	Fitzroy River Burnett River
Fitzroy Inshore	Fitzroy River Burnett River
Capricorn-Bunkers	Fitzroy River Burnett River
Swains Bluewater	Fitzroy River Burnett River
Swains Reef	Fitzroy River Burnett River
Cape York (all zones)	Normanby River Endeavour River Stewart River *Alternative:* Rainfall Lockhart River
North Wet Tropics (all zones)	Daintree River Barron River
South Wet Tropics (all zones)	Russell River Mulgrave River North Johnstone River South Johnstone River Tully River Herbert River

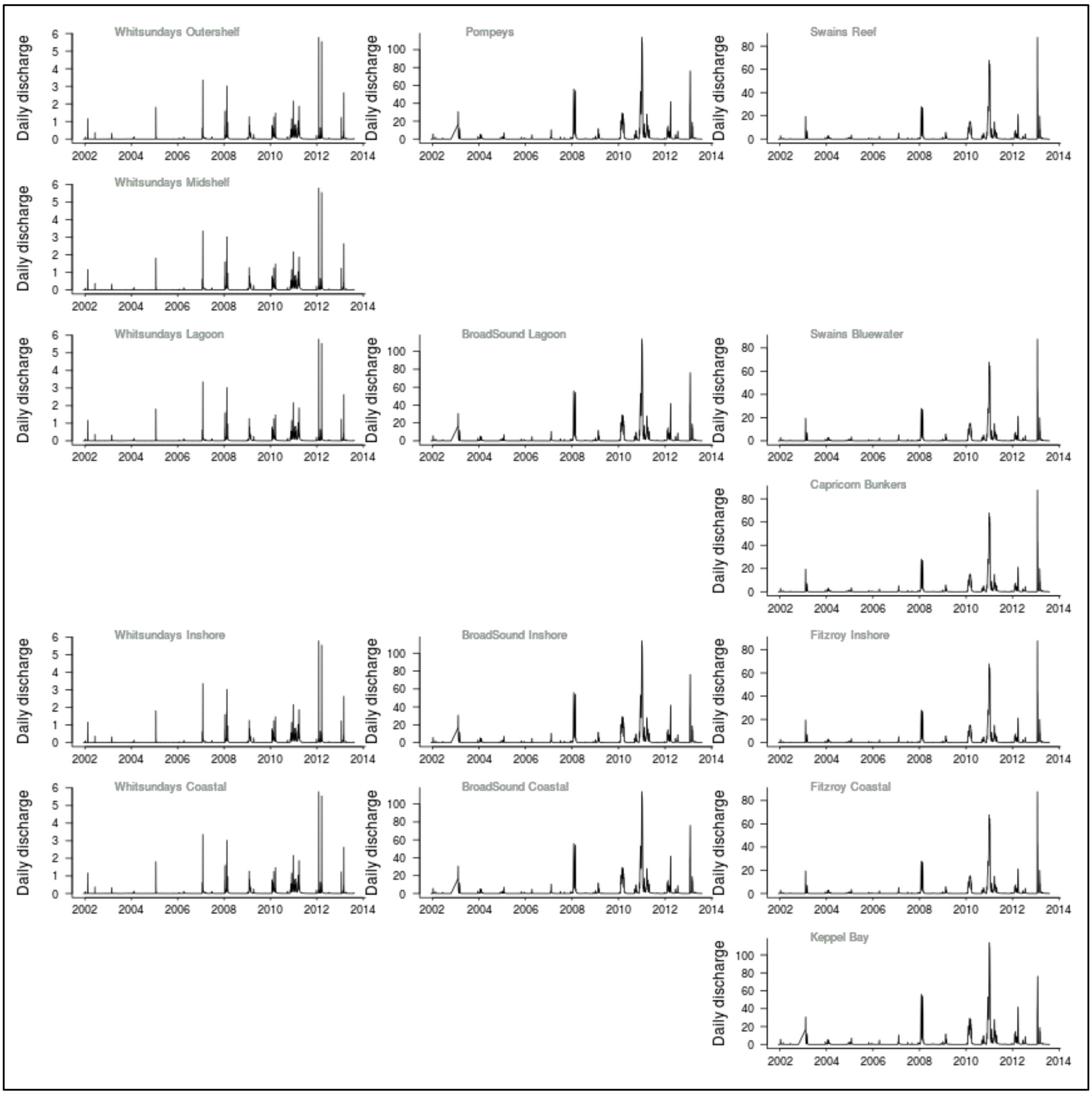


Figure 5: Freshwater discharges of the major rivers included in the models for each of the 15 southern zones over the 11 years.

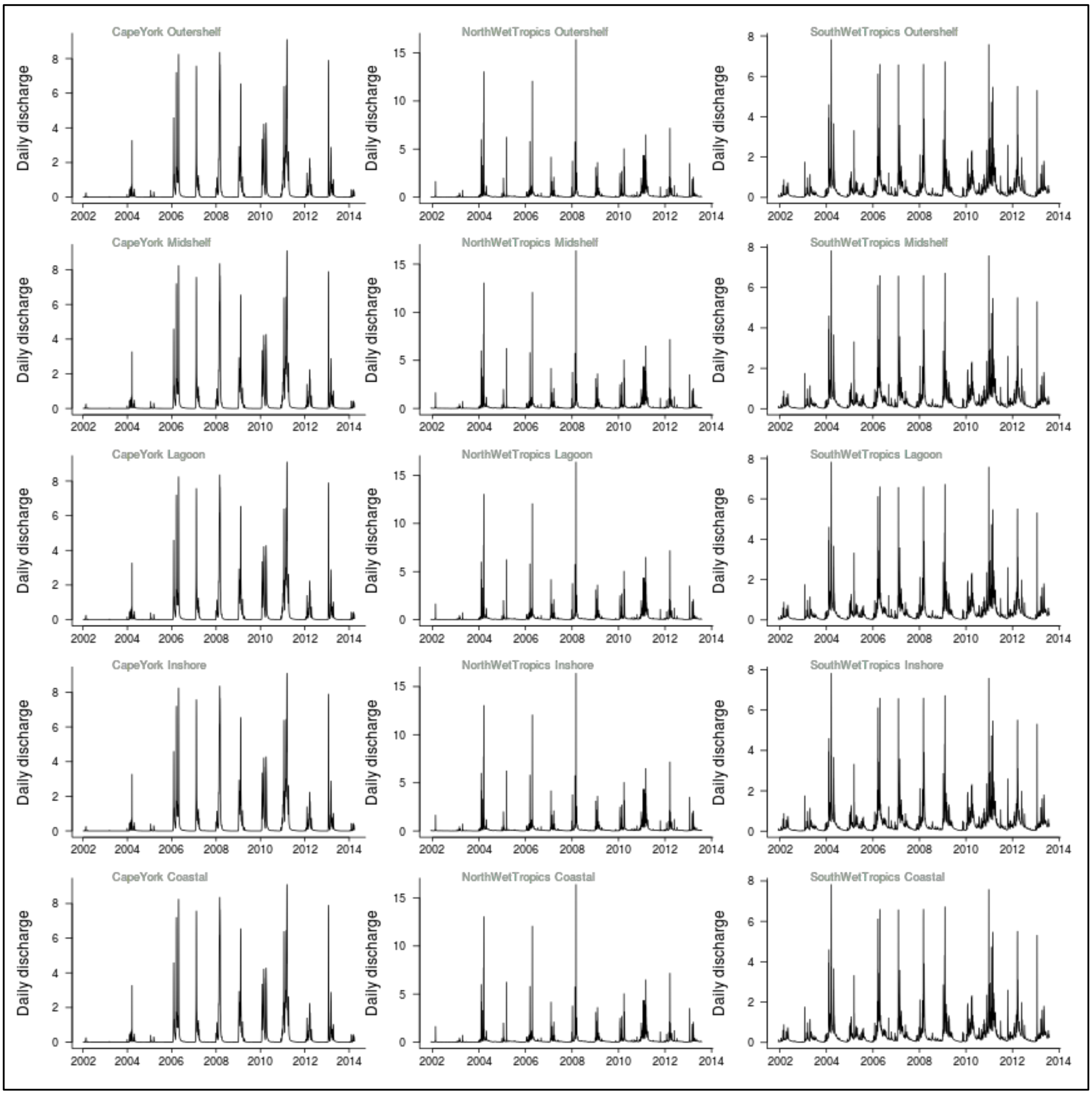


Figure 6: Freshwater discharges of the major rivers included into the models for each of the 15 northern zones over the 11 years.

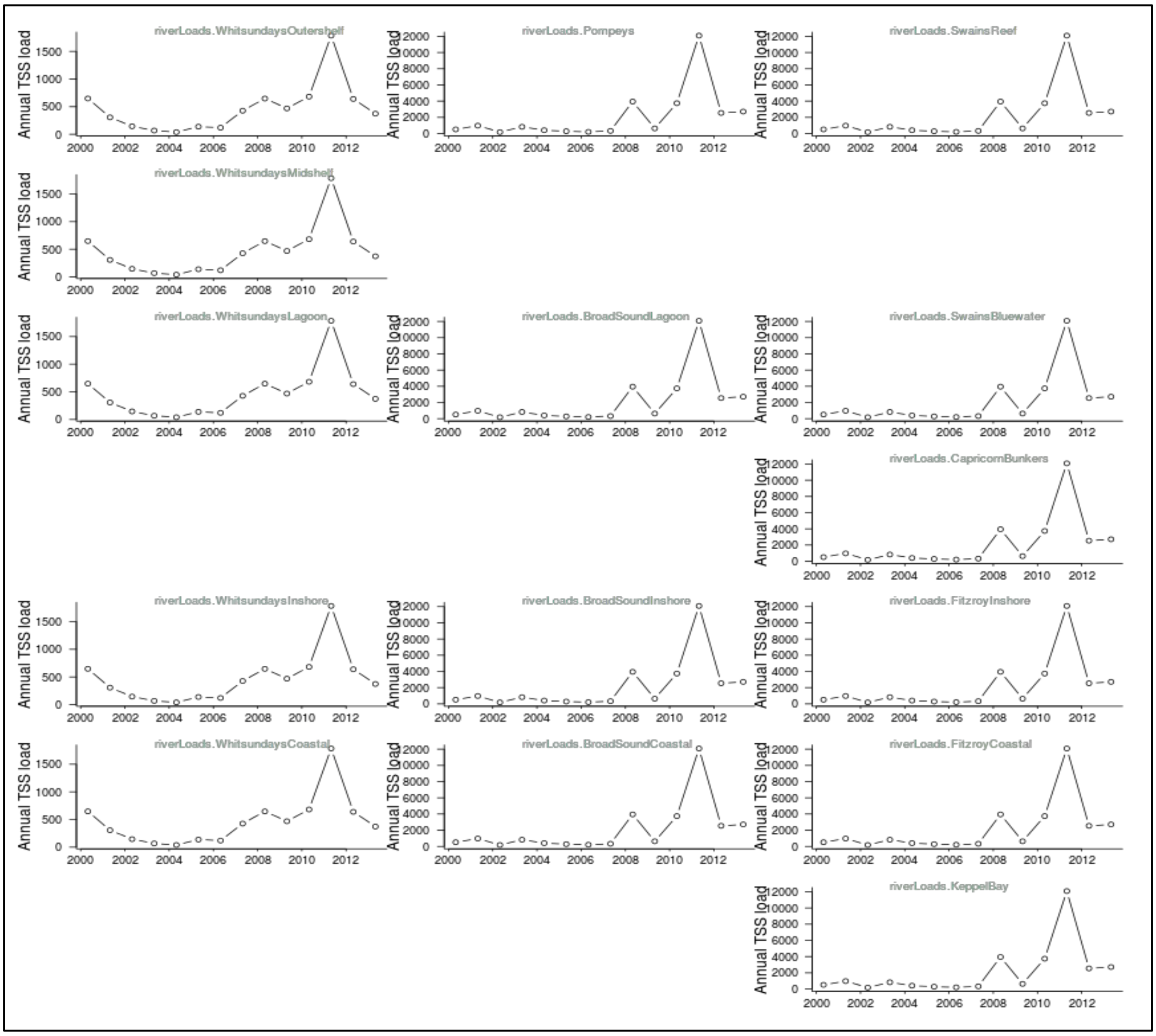


Figure 7: Annual loads of total suspended solids of all rivers included into the models for each of the southern zones over the 11 years.

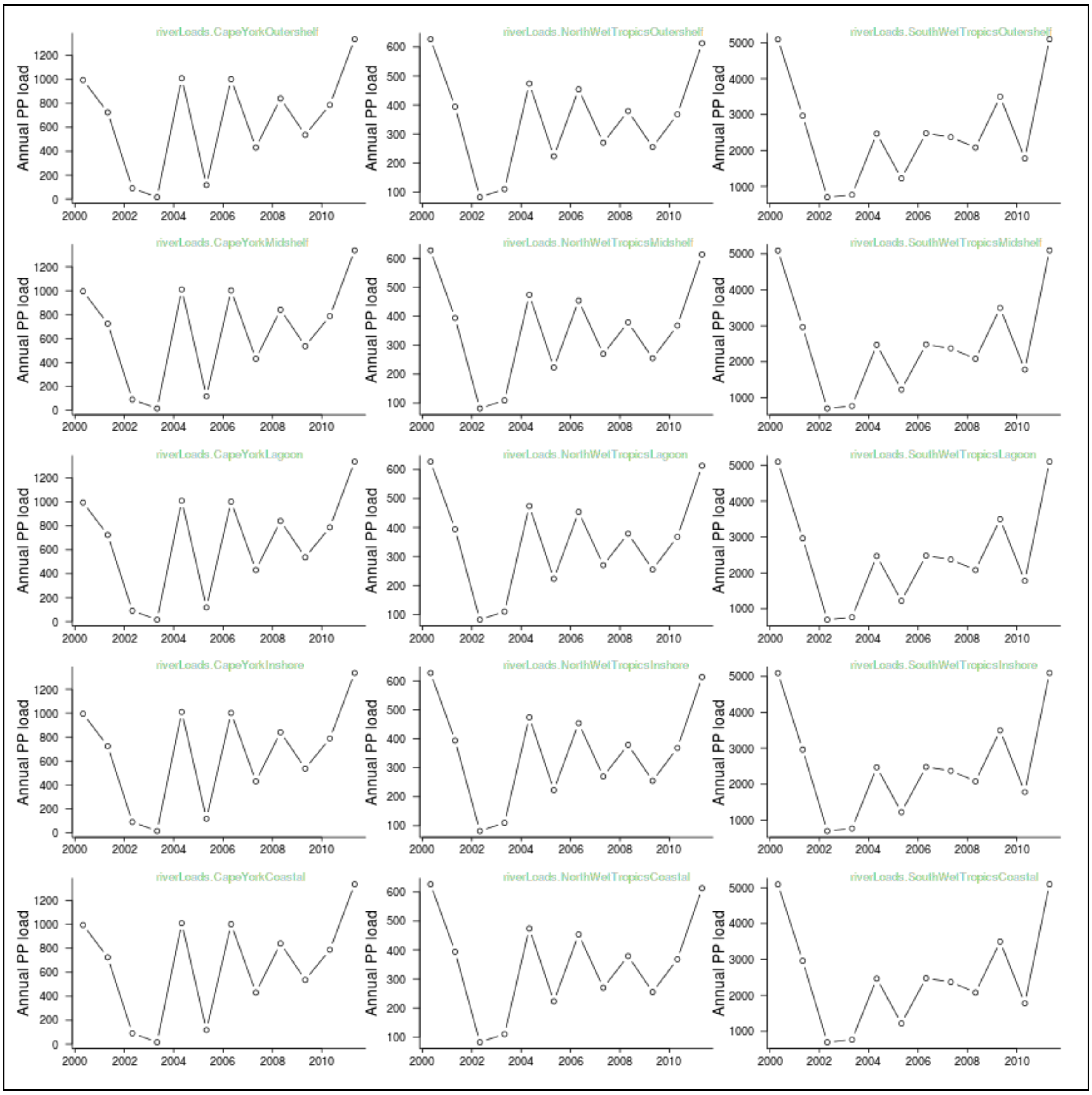


Figure 8: Annual loads of total suspended solids of all rivers included into the models for each of the northern zones over the 11 years.

Table 3a: Estimated loads of freshwater, TSS, PP, PN, DIN and DIP in the main southern rivers, and the classification into 'wet' and 'dry' years.

	TSS				
Year	**Fitzroy**	**O'Connell**	**Pioneer**	**Proserpine**	**Wet vs Dry**
2000	515.57	212.87	342.55	92.60	
2001	977.13	121.07	163.65	22.53	
2002	182.34	69.83	44.66	31.04	Dry
2003	832.75	19.04	19.91	28.94	Dry
2004	410.34	19.65	04.44	16.05	Dry
2005	287.76	62.28	39.30	36.94	Dry
2006	212.75	73.57	14.74	31.70	Dry
2007	330.81	150.86	206.89	69.54	Wet
2008	3,953.68	210.30	317.99	118.86	Wet
2009	637.78	156.69	210.33	101.93	Wet
2010	3,744.92	268.53	332.34	81.29	Wet
2011	12,087.06	481.54	765.82	538.14	Wet
2012	2,546.29	228.15	330.69	80.70	Wet
2013	2,716.43	87.51	230.76	55.18	Wet

	PN				**PP**			
Year	**Fitzroy**	**O'Connell**	**Pioneer**	**Proserpine**	**Fitzroy**	**O'Connell**	**Pioneer**	**Proserpine**
2000	880.00	429.90	540.72	218.69	670.00	163.35	246.95	70.61
2001	1,605.00	244.96	259.34	53.16	960.00	99.75	130.56	17.86
2002	360.00	136.75	67.44	72.28	460.00	46.17	26.05	21.84
2003	3,900.00	37.40	30.73	67.70	870.00	12.89	12.29	20.73
2004	700.00	38.50	06.94	37.62	415.00	12.64	02.58	11.22
2005	280.00	120.21	60.83	86.20	140.00	38.03	21.49	25.18
2006	300.00	141.96	23.21	74.23	140.00	54.67	11.11	24.45
2007	645.00	294.57	309.98	160.54	400.00	118.75	155.90	53.60
2008	8,460.00	412.72	450.07	270.23	4,250.00	129.31	151.75	77.31
2009	1,070.00	340.25	332.57	239.12	750.00	159.73	194.81	86.02
2010	4,291.27	540.24	435.95	181.47	3,862.82	214.01	204.51	57.80
2011	16,833.86	1,046.96	1,083.92	1,225.62	8,724.69	401.57	471.26	382.80
2012	NA	NA	NA	NA	NA	NA	NA	NA
2013	NA	NA	NA	NA	NA	NA	NA	NA

	DIN				DIP			
Year	**Fitzroy**	**O'Connell**	**Pioneer**	**Proserpine**	**Fitzroy**	**O'Connell**	**Pioneer**	**Proserpine**
2000	420.00	378.67	672.17	138.16	350.00	26.83	16.00	18.29
2001	570.00	217.31	323.20	33.89	500.00	15.17	07.74	04.41
2002	162.00	119.00	83.25	45.72	250.00	08.52	01.98	05.97
2003	674.00	32.75	38.14	43.50	94.00	02.31	00.88	05.51
2004	382.00	33.78	08.65	24.47	72.00	02.35	00.19	03.02
2005	363.00	104.79	75.72	56.29	62.00	07.34	01.69	06.87
2006	135.00	124.22	29.02	49.15	34.00	08.70	00.67	05.86
2007	176.00	256.26	383.69	103.72	34.00	18.59	09.35	12.95
2008	1,580.00	355.23	550.19	169.93	912.00	26.39	13.28	22.11
2009	367.00	309.96	416.22	155.85	221.00	21.14	09.96	19.34
2010	2,061.00	460.35	523.36	109.69	1,142.54	36.67	14.45	15.39
2011	3,859.00	931.05	1,325.02	757.64	5,079.84	68.09	33.30	102.60
2012	NA	NA	NA	NA	NA	NA	NA	NA
2013	NA	NA	NA	NA	NA	NA	NA	NA

Table 3b: Estimated loads of freshwater, TSS, PP, PN, DIN and DIP in the main northern rivers. Flows and loads were too similar between years to justify classification into 'wet' and 'dry' years.

	SS							
Year	**Normanby**	**Daintree**	**Barron**	**Russell**	**Johnstone**	**Tully**	**Herbert**	**Burdekin**
2000	454	157	220	297	456	278	1,203	5,122
2001	331	99	114	175	269	184	598	3,151
2002	42	11	22	38	112	59	119	1,624
2003	07	20	15	69	102	61	88	766
2004	461	131	127	236	141	162	424	617
2005	54	51	51	110	177	93	172	1,607
2006	458	120	100	195	331	194	513	915
2007	197	70	55	154	289	188	512	3,688
2008	384	84	216	202	259	160	429	9,927
2009	245	63	104	154	338	197	1,206	10,732
2010	360	114	67	161	238	141	406	2,958
2011	610	152	259	327	526	369	1,471	12,589
2012	98	78	104	226	307	204	531	5,783

	PN							
Year	**Normanby**	**Daintree**	**Barron**	**Russell**	**Johnstone**	**Tully**	**Herbert**	**Burdekin**
2000	427	599	813	1,714	9,767	1,303	2,563	7,907
2001	311	393	423	1,000	5,864	875	1,355	3,738
2002	39	83	83	201	2,231	300	273	2,032
2003	07	121	57	334	1,780	350	195	959
2004	433	474	490	1,156	2,517	828	843	1,127
2005	51	228	200	518	3,078	555	340	2,281
2006	430	467	394	905	5,636	926	1,003	1,776
2007	185	281	217	711	4,789	990	1,000	5,266
2008	361	304	820	843	4,730	759	803	11,532
2009	230	232	392	654	7,217	867	2,352	13,728
2010	338	390	248	637	5,592	690	742	4,283
2011	573	557	970	1,437	14,468	1,489	2,916	15,098
2012	NA	NA	NA	NA	NA	NA	NA	NA

	PP							
Year	**Normanby**	**Daintree**	**Barron**	**Russell**	**Johnstone**	**Tully**	**Herbert**	**Burdekin**
2000	199	118	283	387	9,024	292	1,044	2,311
2001	145	80	146	236	5,673	203	687	1,257
2002	18	16	28	42	2,004	65	123	659
2003	03	25	20	75	1,732	81	85	312
2004	203	87	165	241	2,363	183	310	313
2005	24	44	67	114	3,079	128	126	736
2006	201	96	132	219	6,178	231	405	470
2007	86	51	71	149	4,922	227	386	1,604
2008	169	44	265	133	4,669	148	237	3,828
2009	108	42	125	137	8,299	201	1,133	4,365
2010	158	69	78	132	6,672	160	334	1,296
2011	268	97	294	288	17,265	336	1,158	5,151
2012	NA	NA	NA	NA	NA	NA	NA	NA

	DIN							
Year	**Normanby**	**Daintree**	**Barron**	**Russell**	**Johnstone**	**Tully**	**Herbert**	**Burdekin**
2000	995	505	122	1,438	4,574	1,069	2,585	5,170
2001	725	331	63	840	2,761	720	1,404	2,019
2002	91	70	12	169	1,047	247	283	1,121
2003	16	102	08	280	839	289	198	547
2004	1,010	402	72	970	1,185	686	814	784
2005	118	194	29	434	1,451	461	327	1,372
2006	1,002	397	57	760	2,647	770	950	1,245
2007	431	239	31	597	2,261	824	951	3,164
2008	841	259	120	707	2,226	631	743	5,965
2009	537	197	58	549	3,382	721	2,227	7,798

	DIN							
Year	**Normanby**	**Daintree**	**Barron**	**Russell**	**Johnstone**	**Tully**	**Herbert**	**Burdekin**
2010	788	331	37	534	2,615	573	674	2,673
2011	1,336	471	142	1,205	6,751	1,240	2,651	7,876
2012	NA	NA	NA	NA	NA	NA	NA	NA

	DIP							
Year	**Normanby**	**Daintree**	**Barron**	**Russell**	**Johnstone**	**Tully**	**Herbert**	**Burdekin**
2000	41	22	19	45	175	45	120	657
2001	30	15	10	27	109	31	62	395
2002	04	03	02	05	39	10	12	207
2003	01	04	01	09	34	12	09	96
2004	42	17	11	30	47	27	42	83
2005	05	08	05	14	61	18	17	213
2006	41	17	09	26	122	31	53	127
2007	18	10	05	19	98	32	52	483
2008	35	10	19	20	92	24	42	1,251
2009	22	09	09	18	158	29	125	1,359
2010	33	15	06	18	125	24	42	379
2011	55	20	24	39	319	48	167	1,626
2012	NA	NA	NA	NA	NA	NA	NA	NA

Statistical methods

The statistical analyses largely followed those outlined in Logan et al. (2013), and Fabricius et al. (in press). A flow chart summarises the analyses step-by-step (Fig. 9).

Given the degree of short term fluctuation in photic depth, identifying long-term trends from raw daily data is almost impossible. Daily fluctuations are likely to be due to the mixing influences of waves and tides, and thus partialling these influences out is likely to reduce the amount of noise layered onto the underlying long-term signals.

Moreover, photic depth fluctuates seasonally. Whilst a component of such seasonal fluctuations could also be seasonal wind patterns, the majority of seasonal fluctuations are likely to be driven by river discharge patterns or changes in the East Australian Currents. Although the regular seasonal discharge influences on photic depth are of some interest, this project is primarily concerned with relating long-term photic depth patterns to variations in long-term discharge and river sediment loads.

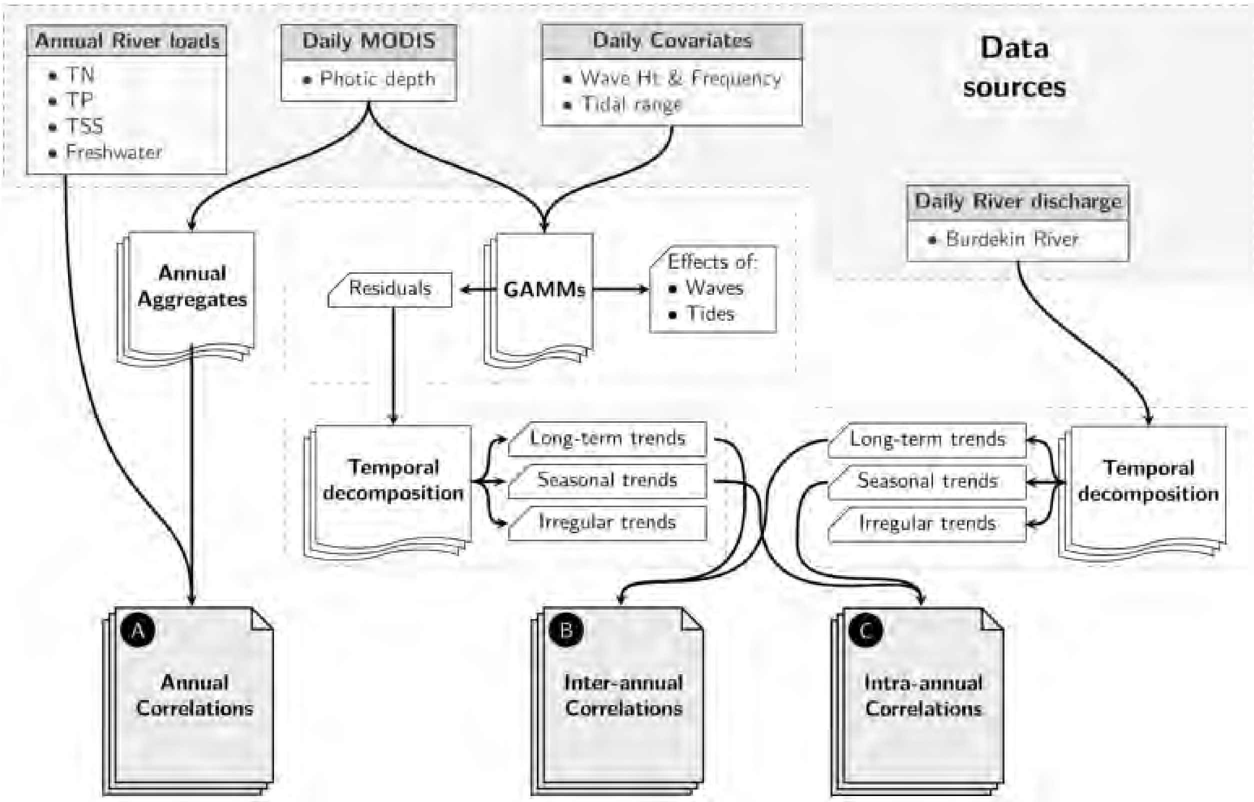


Figure 9: Summary of the main steps taken for data processing and statistical analyses.

The first set of analyses was based on daily values. Gradient boosted model (GBM) and generalized additive mixed effects models (GAMM) were fitted to remove the effects of tides and wind/waves (GAMMs; Wood 2006), using the mgcv (Wood 2006; Wood 2011) package in R 2.15.1 (R Development Core Team, 2014). A methods comparison showed that for partialling out the wind, waves and tide effects, simple multiple regression, GAM or GBM all yielded very similar residuals. Although the GBM is substantially slower, it yielded slightly lower sum-square residuals and importantly, it is able to impute missing values (of which there are many for wind speed). Consequently, we used this method of partialling. The residuals from these GBM (which thus reflect the photic depth signal after the extraction of wave, tidal and bathymetry signals) were then decomposed to derive both the inter-annual (2003-2012) and intra-annual trends (i.e., seasonal based on 365.25 day cyclicity) in photic depth.

There are numerous ways of extracting trend and seasonal cycles (seasonal detrending) from a regular time series. Seasonal decomposition was chosen which applies a smoother (typically either a moving average or locally weighted regression smoother) through a time series to separate periodic fluctuations due to cyclical reoccurring influences and long-term trends (Kendall and Stuart 1983). This approach does not tend to oversmooth with the same severity as the GAM approach. However, as it is not possible to incorporate covariates into this approach, the time series must already have the effects of waves and tides partialled out. So prior to seasonally detrending, it was necessary to model photic depth against wave height and tidal range via GBM, extract the resulting residuals and return the residuals to the original response scale (since residuals are always zero centered).

Following temporal decomposition, seasonal cycles and long-term trends were re- centered around mean GBM fitted values, and transformed back into the original photic depth scale via exponentiation. Patterns in daily river discharge values were also decomposed both for seasonal and long-term trends. Long-term water clarity trends were hence cross-correlated against long-term river discharge trends.

To explore spatial differences in the associations of photic depth and river discharges, GBMs and seasonal decompositions were performed separately for each zone. To explore temporal differences in photic depth between wet and dry years, the analyses were also performed separately for dry (2003-2006) and wet (2007-2012) years.

The second set of analyses focused on annual (water year) values. Annual mean photic depth for each zone was correlated against the annual total river freshwater discharge volume (summed across the several rivers per region), and the total river loads of suspended solids (TSS), as a proxy for relationships to the other, highly correlated river loads of nitrogen and phosphorus.

Results

Inter-annual trends in photic depth and river freshwater discharges

Mean photic depth varied greatly been zones, ranging from a mean of 1.3 m in Keppel Bay to 14.5 in the Southern Wet Tropics Outershelf (Table 1, Figs. 10 and 11). Cross-shelf gradients were pronounced in all zones.

In the southern zones, many of the inshore data showed severe declines in photic depth throughout the decade after detrending over time. Such a decline was not detected in the Outershelf zones, however there is a relatively dramatic decline/spike in photic depth present itself, which was likely to be associated with Cyclone Hamish in 2009. This impact was lessened, yet still detectable in the Midshelf and Lagoon zones.

In the northern zones, no consistent long-term trend was detected, with periods of steep declines following times of steep recovery. The variability between years was greater in the Wet Tropics compared with the Cape York zones. In the mid- and Outershelf bands, photic depth varied by <1.5 m in Cape York, and by ~2.5 m in the Wet Tropics. In the lagoon, the variation was 1.2 m vs 2 – 3 m, and inshore, the variation was 0.5 vs 1 – 1.5 m. Only in the coastal zone was the variation similar in both regions (~0.5 m).

River discharges also varied greatly between years. The 11-years temporal trend in the combined river discharge within the southern regions (Fig. 12) showed a period of relative dry years (2002 to 2006), followed by periods with high freshwater discharges (2007 – 2013). In Cape York, the river data for the first 4 years are unreliable due to the missing Normanby River data. Rivers in the Northern Wet Tropics show slightly higher discharges in the years 2004, 2006, 2008 and 2011, and dryer years in between, while rivers in the Southern Wet Tropics show high flows in most years.

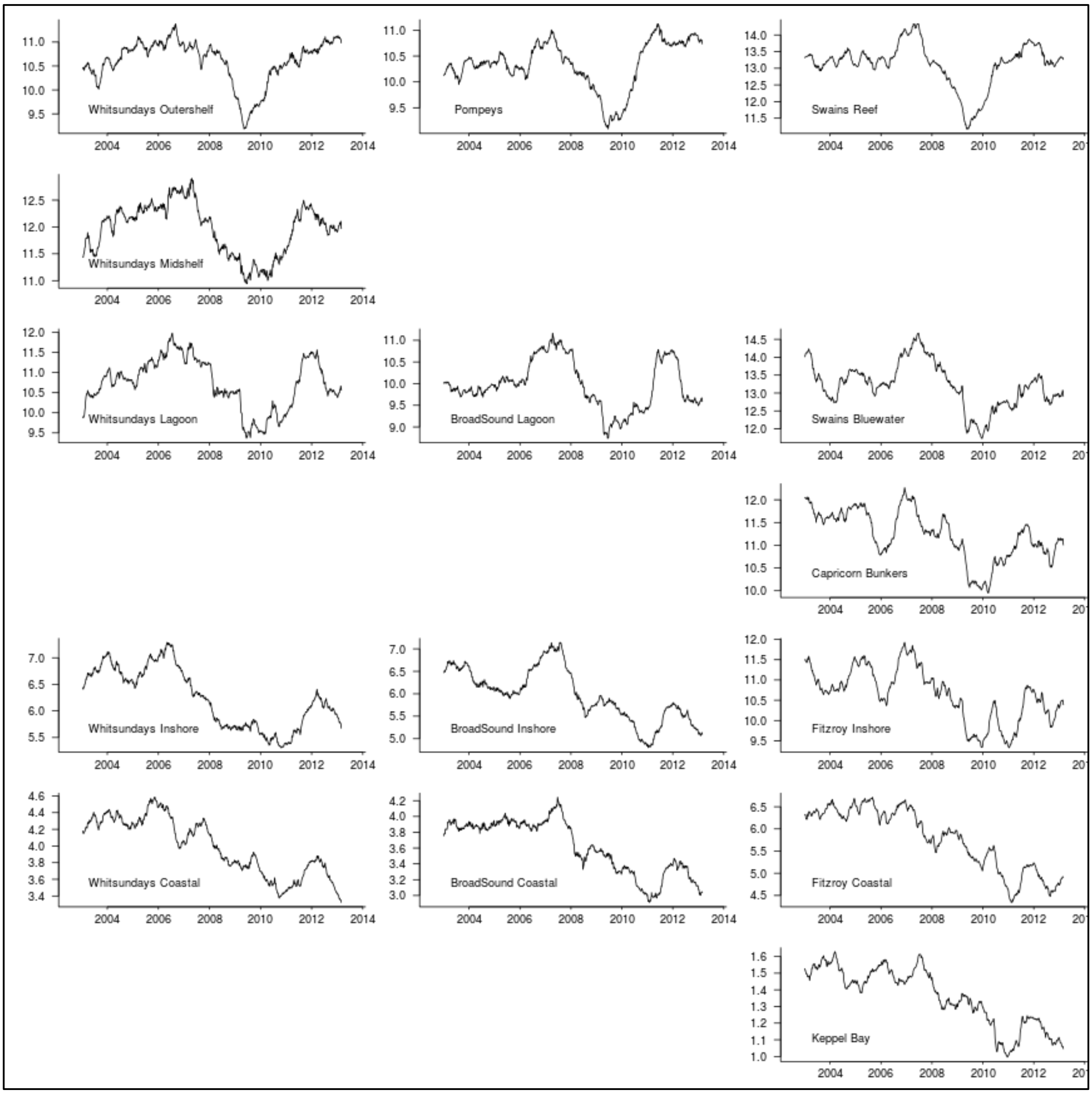


Figure 10: Eleven-year temporal trend in photic depth within each of the fifteen zones partitioned from the Whitsundays and Fitzroy Regions of the GBR.

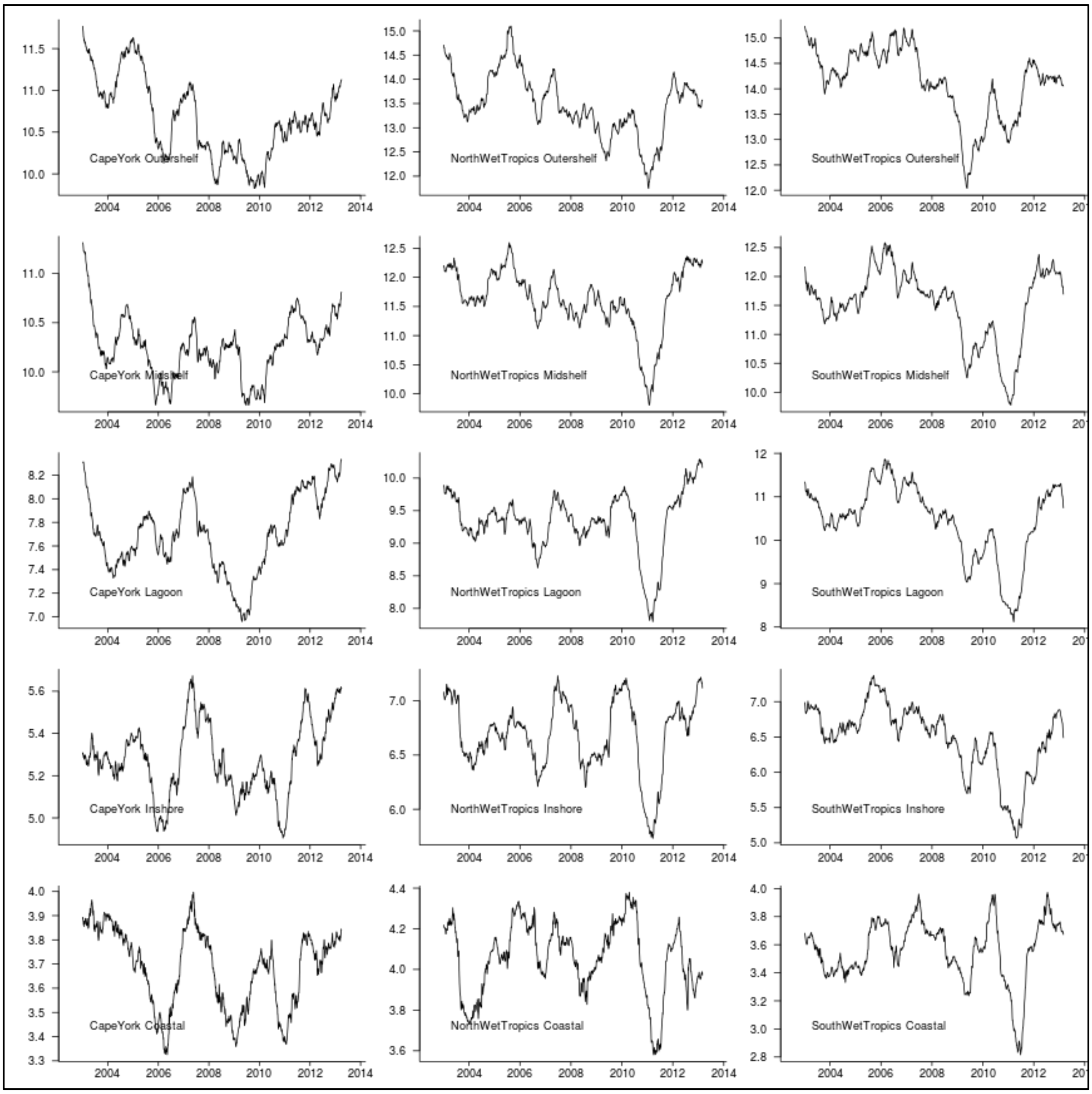


Figure 11: Eleven-year temporal trend in photic depth within each of the fifteen zones partitioned from the Cape York and Wet Tropics Regions of the GBR.

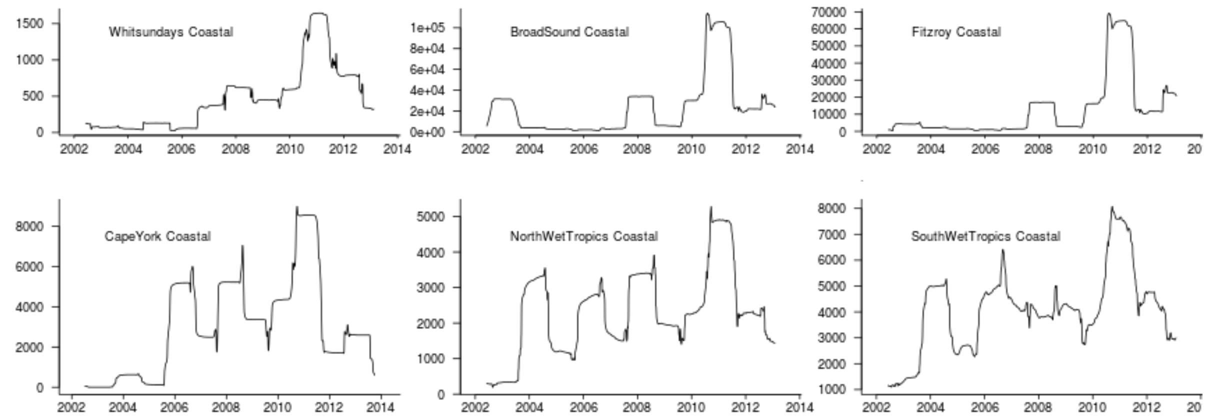


Figure 12: Eleven year temporal trend in combined river discharge within the Whitsundays, Broadsound and Fitzroy/Swains Regions, and the Cape York, Northern and Southern Wet Tropics. Only the coastal stations are shown, however the data are the same for the zones further offshore.

Relationships between inter-annual trends in photic depth and river freshwater discharges

Whitsundays/Broad Sound/Fitzroy

Correlations between long-term photic depth and discharges were very pronounced close to the shore (Coastal and Inshore zones: r = 0.61 to 0.79; Fig. 13) and very weak on the Outer-shelf (r = 0.18 to 0.27). In all cross-shelf bands (Whitsundays, Broad Sound, Fitzroy), the correlations declined steeply and systematically across the shelf. For example, in the Whitsundays, correlations declined from r = 0.79 in the coastal zone to r = 0.27 in the Outershelf zone, with photic depth in the coastal, inshore and lagoonal zones being very highly correlated to the combined discharges of the Pioneer, Proserpine and O'Connor Rivers. Whitsundays Inshore and Coastal zones had the highest overall correlations between photic depth and discharge of all 15 zones of the southern regions ($\overline{0.59}$=0.7681 and $\overline{0.61}$=0.781 respectively). In the Fitzroy Region, the correlations were strong for the Keppel Bay, Fitzroy Coastal, Fitzroy Inshore and Capricorn Bunkers zone (r = 0.74 to 0.61), moderate for the Swains Bluewater and extremely weak for the Swains Reefs zones. The correlations in the Broad Sound to the Fitzroy River discharges were also surprisingly strong for the coastal and inshore zones, despite their distance from the river and the high tidal ranges.

The black dashed lines in Fig. 13 represent a running covariance between photic depth and discharge. They essentially highlights moments (as spikes) when both trends show rapid shifts. For Keppel Inshore, Coastal and Bay zones, some rapid losses in photic depth were linked to rapid increases in river discharge, and interestingly, the same was true for the Broad Sound Inshore and Coastal zones. The Whitsundays Inshore and Coastal zones (which have the highest overall correlation between photic depth and discharge) did not present substantial spikes, possibly suggesting that discharge effects are somewhat more prolonged and less spikey than they are in the Broad Sound and Keppel Coastal and Inshore zones. The lags in the Whitsundays and Broad Sound Inshore and Coastal zones were 40 to 51 days, whereas in the Keppel Coastal and Inshore zones, the lags were only 2 to 13 days.

The lag in Fig. 13 indicates the number of days either the blue (discharge) or the red (photic depth) line would need to be shifted in order to have the highest correlation between discharge and photic depth. It is the lag of the cross-correlation. This analysis shows that for Keppel Bay, the Coastal and Inshore Fitzroy zones, photic depth declined within 2 to 13 days after the rivers started flooding. For the Broadsound Coastal and Inshore zones, the lag was 40 to 45 days. In the Whitsundays Coastal and Inshore zones, the lags are more difficult to interpret, being 51 and -40 days respectively. In all zones further away from the coast (where photic depth was more weakly correlated to the rivers), a negative half year lag would have improved the correlations, which may be an artifact related to the massive loss in photic depth after cyclone Hamish in 2011, which was followed by very large river flows in 2011.

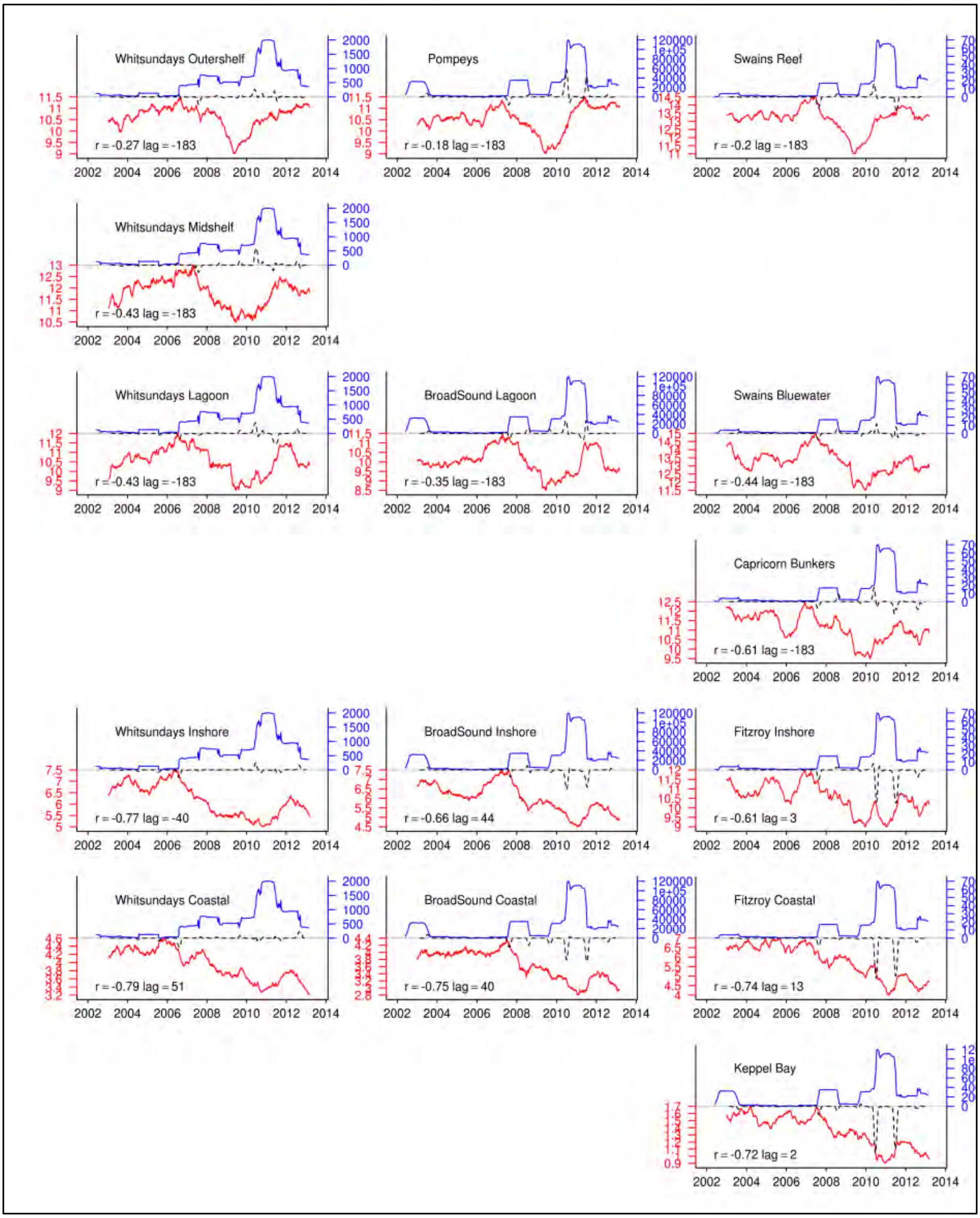


Figure 13: Eleven year temporal trend cycle in river discharge (blue lines) and photic depth (red lines) within each of the fifteen zones partitioned from the Whitsundays and Fitzroy regions of the GBR. The r values indicate the strength of the correlations between the two trend cycles. Black dashed lines represent a running covariance between photic depth and discharge, highlighting moments (as spikes) when both trends show rapid shifts (negative spikes: rapid increases in discharge and reductions in photic depth).

Cape York and Wet Tropics

In Cape York, the correlations between photic depth and river discharges did not systematically decay across the shelf (Fig. 14). Changes between the maximum and minimum observed photic depths were typically <12% (<1.5 m), while variations in river flows were >5-fold (<2000 to >10,000 ML/yr.). Some of the correlations were strong (r = 0.11 to 0.64), with some high correlations on the Outershelf. Along the coast, the lag time was zero and correlation between river and photic depth was moderate (r = 0.64), however all other zones had 'negative lags (i.e., low photic depth preceding high river flows). Both negative and some positive 'spikes' in the patterns (black dashed lines) occurred across the shelf, suggesting some fast losses and relatively rapid recoveries in photic depth. The lagoon seemed to have a much lower correlation than the surrounds (r = 0.11).

In the Cape York region, the cross-correlations of photic depth to rainfall (Lockhart) did not improve the fits compared to the fits for the combined river discharges, except on the inshore (r = 0.58 vs 0.42; Fig. 15). In the other zones, the correlation between the combined rivers discharges and Lockhart rainfall was poor, with the fits to the rainfall data being even worse than the ones to the rivers.

In the Northern Wet Tropics, the correlations between photic depth and river discharges were the strongest ones observed in any zone of the GBR (r = up to 0.84; Fig. 14). The correlation was lowest for the coastal zone, which was chronically turbid (mean photic depth: 4.0 m). Interestingly, the mid-shelf and outer shelf zones had much higher correlations to rivers than were seen in Whitsundays, Broadsound, Fitzroy and Cape York regions, and models with almost no time lags between rivers and loss in photic depth represented the best fits, possibly reflecting the narrowness of the continental shelf, and/or lesser influence of the East Australian Currents. Changes between the maximum and minimum observed photic depths were up to 30%, while variations in river flows were <3-fold. Only negative 'spikes' in the patterns (black dashed lines) were observed across the shelf, suggesting some fast impacts yet relatively slow recoveries.

In the Southern Wet Tropics, the correlations between photic depth and river discharges were moderate (r = up to 0.67 in the inshore). As in the Northern Wet Tropics, changes between the maximum and minimum observed photic depths were up to ~30%, while variations in river flows were <3-fold. Lags were typically relatively short. Again, the chronically turbid Coastal zone (mean photic depth: 3.7 m) had a poorer fit than the zones further offshore. Only negative 'spikes' in the patterns were observed, suggesting some fast impacts yet relatively slow recoveries across the shelf. There were no visible signals from Cyclones Larry in 2006 and Cyclone Yasi in 2011, the latter possibly masked by the additional discharges in this very wet year.

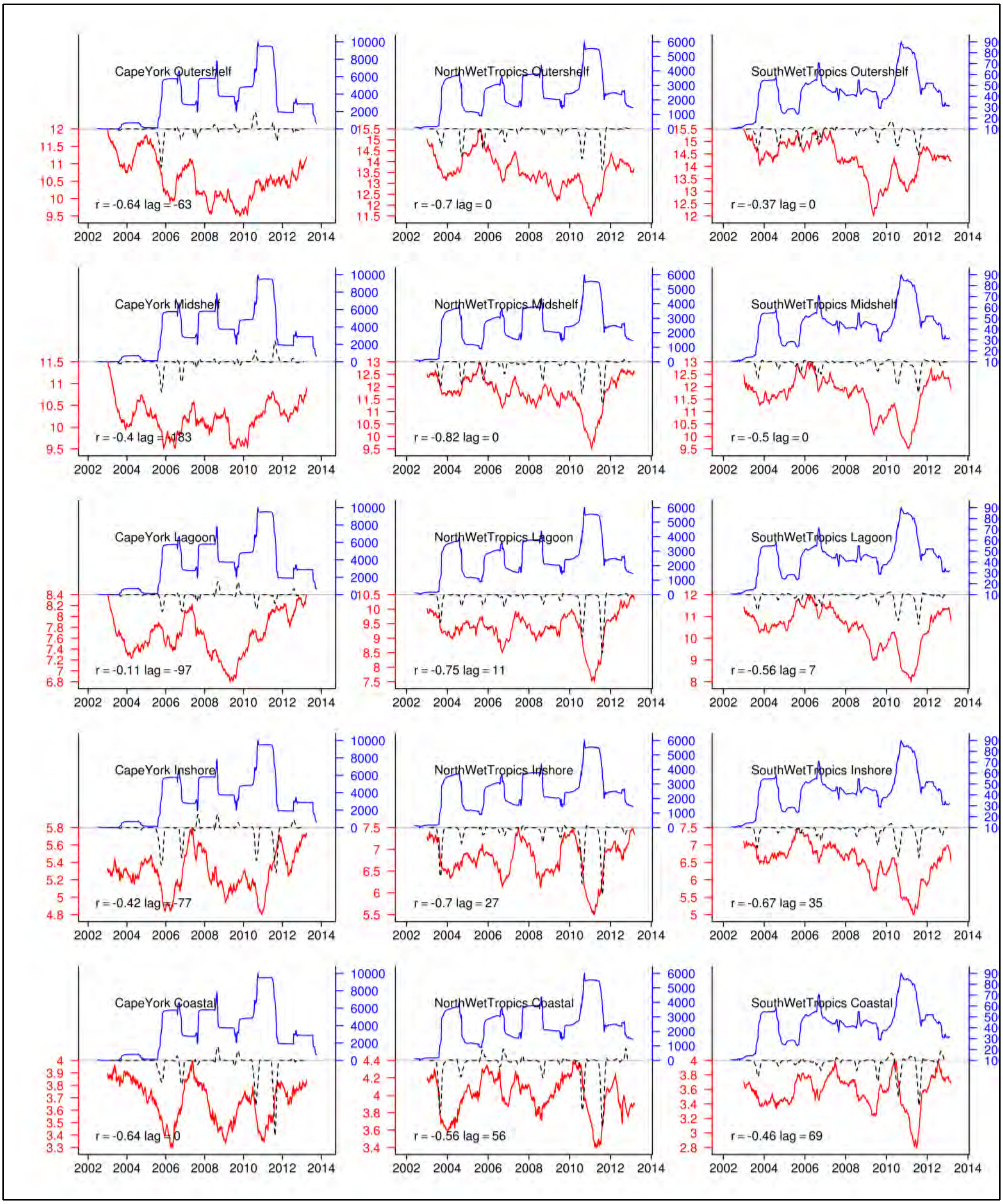


Figure 14: Eleven year temporal trend cycle in river discharge and photic depth within each of the fifteen zones partitioned from the Cape York and Wet Tropics regions of the GBR. The r values indicate the strength of the correlations between the two trend cycles.

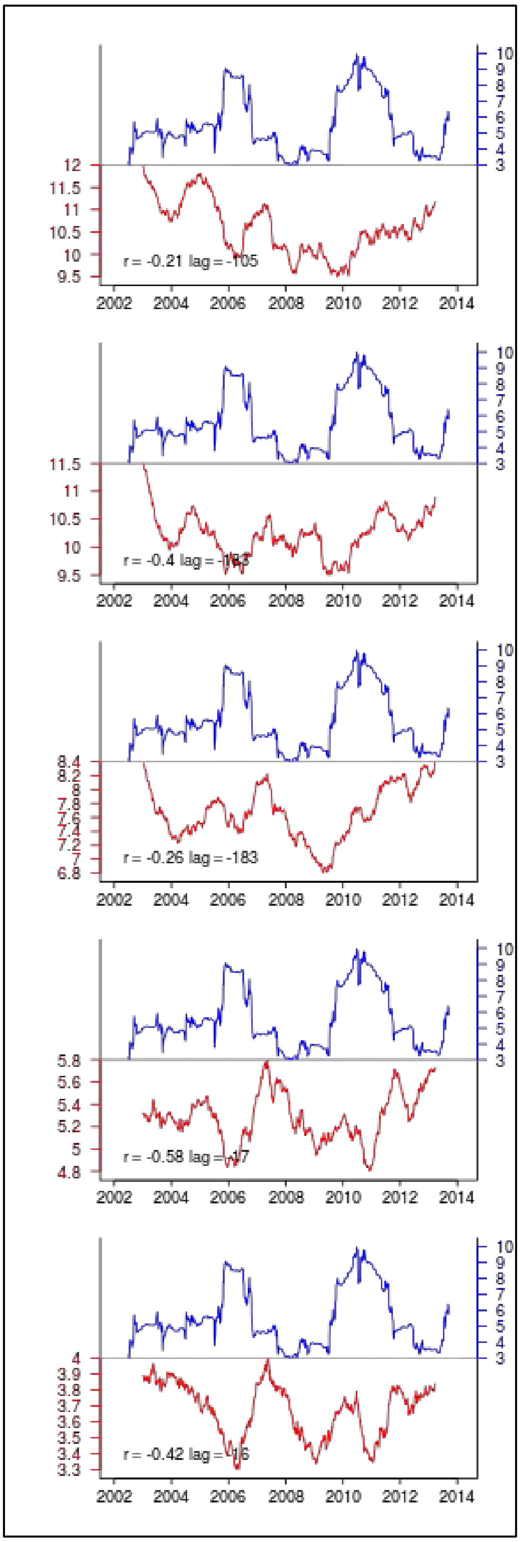


Figure 15: Eleven year temporal trend cycle in rainfall (blue line: Lockhart BOM station) and photic depth (red lines) within the five Cape York zones of the GBR. The r values indicate the strength of the correlations between the two trend cycles.

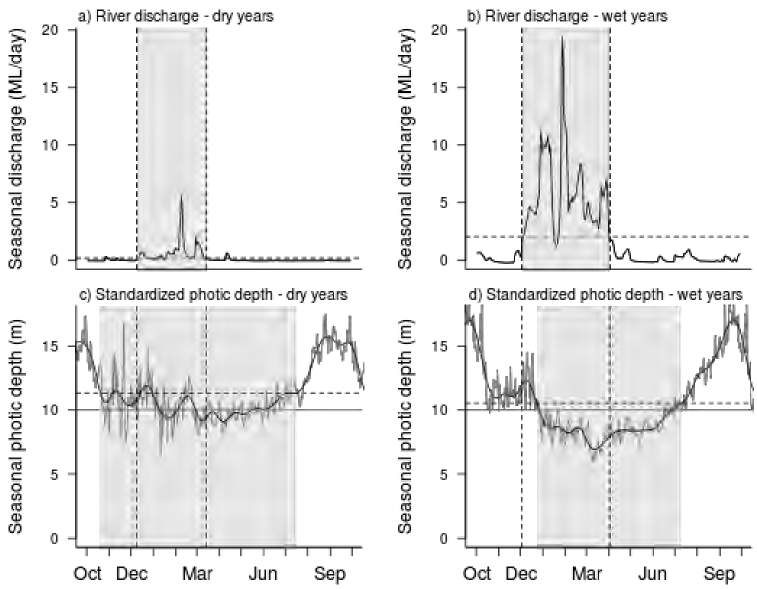
Intra-annual changes in water clarity and river discharges

Seasonal decomposition allowed us to tease out the seasonal components of the time series. Whilst the previous subsection focused on the long-term trends, this current subsection will explore patterns in seasonal trends for wet and dry sequences of years (Fig. 16, Table 4). The southern regions were split into wet and dry years, whereas for the northern regions all years were combined. Fig. 16 shows, as examples, the six 'Inshore' zones within the six regions. The main seasonal changes for these and the other zones are quantified in Table 4.

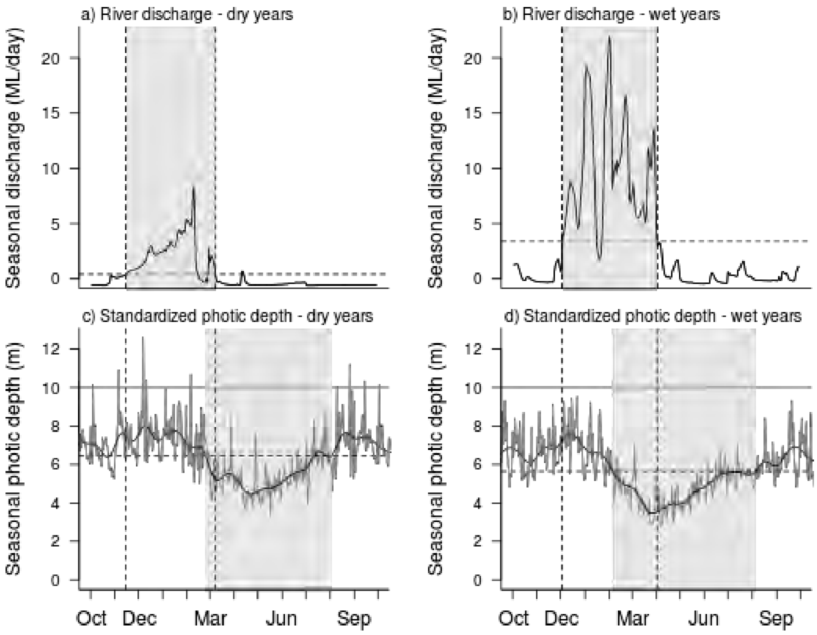
In the southern regions, standardised maximum photic depth varied between 15.7 m (Swains Blue Water) and 1.9 m (Keppel Bay, wet years) across the zones, while the minima ranged from 11.1 to 0.7 m. Typically, the maxima were encountered in August to December, while most of the minima occurred between March and May.

In the northern regions, standardised maximum photic depth varied between 16.9 and 6.4 m across the zones, while the minima ranged from 9.9 to 2.6 m. Typically, the maxima were encountered in September to December, while the minima occurred typically between March and May.

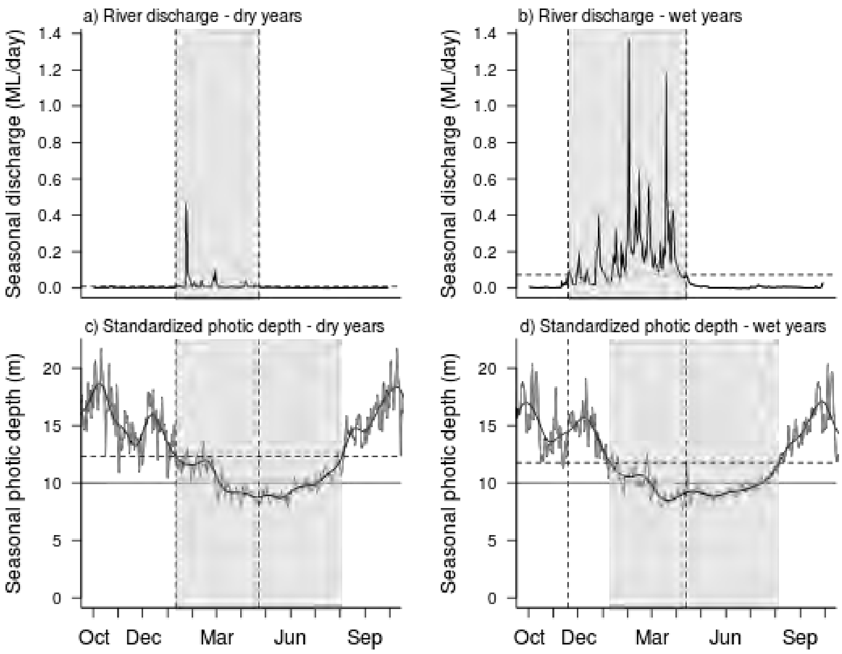
Fitzroy Inshore:



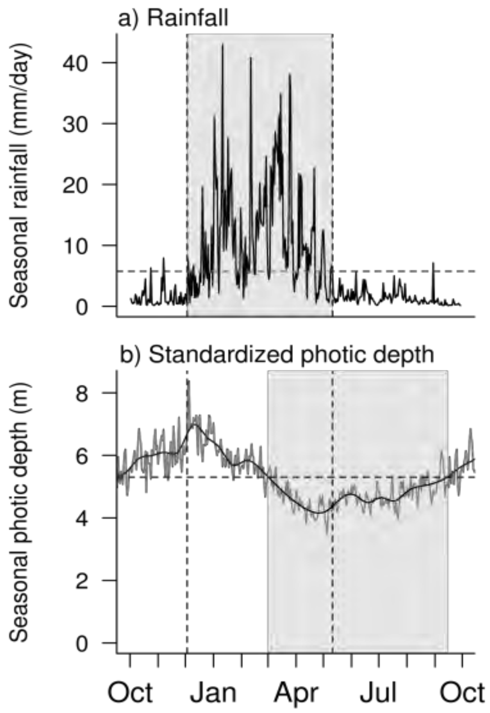
Broad Sound Inshore:



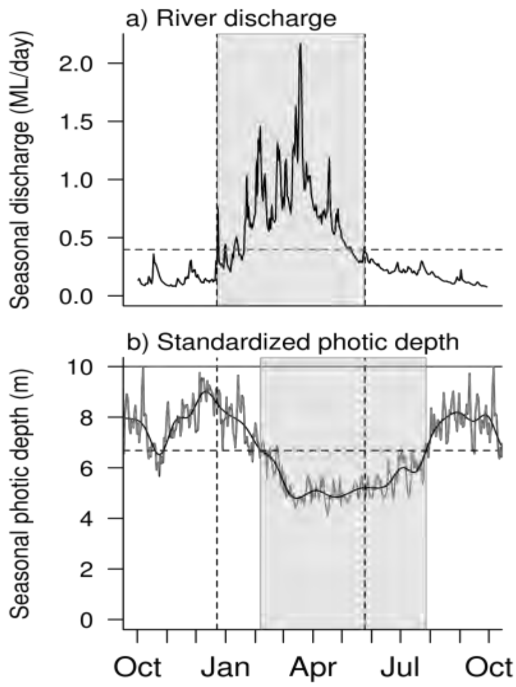
Whitsundays Inshore:



Cape York Inshore:



South Wet Tropics Inshore:



North Wet Tropics Inshore:

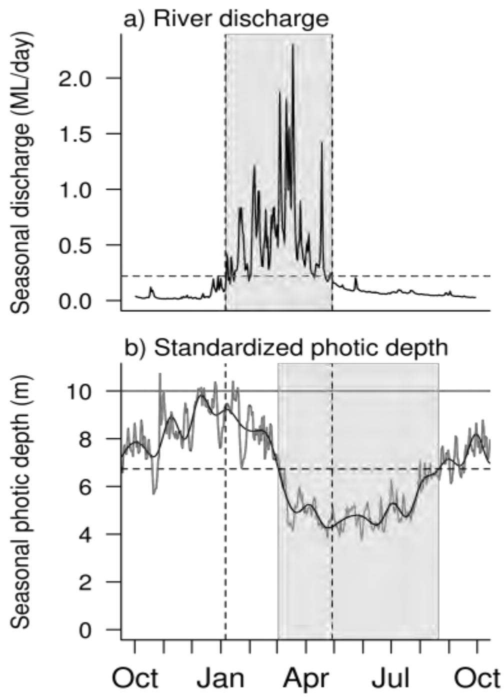


Figure 16: Seasonal cycles of river discharges and photic depth following decomposition of the seasonal components of the time series. Here, as examples, the 'Inshore' zones within the Fitzroy, Broad Sound, Whitsundays, separated for dry years (2002 - 2006) and wet years (2007 – 2012), and the Wet Tropics and Cape York regions (all years combined).

Table 4: Dynamics in water clarity in the different zones of the three Southern (A) and three Northern (B) regions. Tabulated parameters:

- Period: wet or dry season
- Maximum: the maximum smoothed photic depth over the season
- MaxDate: date within a year cycle corresponding to the maximum photic depth
- Minimum: the minimum smoothed photic depth over the season
- MinDate: date within a year cycle corresponding to the minimum photic depth
- DeclineTime: duration of time elapsed between the max photic depth and the NEXT minimum photic depth (in the continuous cycle)
- Decline: difference (in units of photic depth) between max and min photic depth
- **PercentDecline: the decline expressed as a percentage of the max photic depth**
- DeclineRate: rate of decline (Decline/DeclineTime) - I might make this a positive number??
- RecoveryTime: duration of time elapsed between the min photic depth and the NEXT max photic depth (in the continuous cycle). Note, DeclineTime and RecoveryTime complete the 365(ish) day cycle.
- RecoveryRate: rate of recovery (Decline/RecoveryTime)
- Recovery95Date: date within a year cycle corresponding to a recovery of 95% (up to max - decline*0.05)
- **Recovery95Time: duration of time elapsed between the min photic depth and the NEXT 95% recovery in photic depth (in the continuous cycle).**
- Recovery95Rate: same as RecoveryRate, yet based on 95% recovery

A) Whitsundays, Broad Sound and Fitzroy:

Zone	Period	Maximum	Max Date	Minimum	Min Date	Decl Time	Decline	**Perc Decline**	Decline Rate	Recov Time	Recov Rate	Recov 95Date	**Recov Time95**	Recov Rate95
Whit. Outersh.	Dry	13.20	19 Sep	9.24	25 Mar	187	3.96	**30.02**	-0.02	178	0.02	08 Sep	**167**	0.02
Whit. Outersh.	Wet	13.03	15 Sep	8.73	03 Apr	200	4.30	**33.01**	-0.02	165	0.03	08 Sep	**158**	0.03
Whit. Midshelf	Dry	18.69	09 Oct	8.68	19 May	223	10.01	**53.55**	-0.04	142	0.07	03 Oct	**137**	0.07
Whit. Midshelf	Wet	17.09	28 Sep	8.47	22 Mar	175	8.62	**50.44**	-0.05	190	0.05	21 Sep	**183**	0.05
Whit. Lagoon	Dry	15.07	29 Sep	7.83	21 May	234	7.25	**48.07**	-0.03	131	0.06	20 Sep	**122**	0.06
Whit. Lagoon	Wet	15.87	23 Sep	6.65	22 Mar	180	9.22	**58.09**	-0.05	185	0.05	17 Sep	**179**	0.05
Whit. Inshore	Dry	8.56	20 Aug	5.48	18 Apr	241	3.08	**35.97**	-0.01	124	0.02	15 Aug	**119**	0.03
Whit. Inshore	Wet	8.08	19 Dec	3.54	23 Mar	95	4.54	**56.16**	-0.05	270	0.02	11 Dec	**263**	0.02
Whit. Coastal	Dry	5.45	09 Dec	3.23	22 Apr	135	2.22	**40.73**	-0.02	230	0.01	01 Dec	**223**	0.01
Whit. Coastal	Wet	5.38	10 Dec	2.47	25 Mar	106	2.91	**54.06**	-0.03	259	0.01	02 Dec	**252**	0.01
Pompeys	Dry	13.37	17 Sep	8.02	21 Mar	185	5.35	**40.03**	-0.03	180	0.03	10 Sep	**173**	0.03
Pompeys	Wet	12.39	11 Dec	8.39	20 Apr	131	4.00	**32.30**	-0.03	234	0.02	09 Sep	**142**	0.03
BSnd Lagoon	Dry	13.17	29 Sep	6.78	06 May	219	6.39	**48.49**	-0.03	146	0.04	28 Aug	**114**	0.06
BSnd Lagoon	Wet	14.00	29 Sep	6.35	21 Mar	173	7.65	**54.63**	-0.04	192	0.04	26 Sep	**189**	0.04
BSound Insh	Dry	7.99	09 Dec	4.45	22 Apr	135	3.55	**44.37**	-0.03	230	0.02	04 Dec	**226**	0.02
BSound Insh.	Wet	7.59	13 Dec	3.46	27 Mar	105	4.14	**54.50**	-0.04	260	0.02	05 Dec	**253**	0.02

BSound Coast	Dry	5.48	20 Jan	2.48	20 Apr	91	3.00	**54.71**	-0.03	274	0.01	13 Jan	**268**	0.01
BSound Coast	Wet	5.11	18 Dec	2.04	27 Mar	100	3.07	**60.13**	-0.03	265	0.01	09 Dec	**257**	0.01
SwainsReef	Dry	15.10	28 Sep	11.11	26 Jun	271	3.98	**26.39**	-0.01	94	0.04	16 Sep	**82**	0.05
SwainsReef	Wet	15.75	08 Dec	10.29	05 Jul	210	5.45	**34.62**	-0.03	155	0.04	01 Dec	**149**	0.04
Swains Bluew	Dry	19.86	08 Oct	8.58	27 May	232	11.28	**56.81**	-0.05	133	0.08	29 Sep	**125**	0.09
Swains Bluew	Wet	19.09	28 Sep	8.19	22 May	236	10.89	**57.08**	-0.05	129	0.08	23 Sep	**124**	0.09
Cap. Bunkers	Dry	16.85	29 Sep	9.74	15 May	228	7.11	**42.20**	-0.03	137	0.05	26 Sep	**134**	0.05
Cap. Bunkers	Wet	16.80	24 Sep	8.40	16 Mar	173	8.40	**49.99**	-0.05	192	0.04	18 Sep	**186**	0.05
FitzroyInshore	Dry	15.73	28 Aug	9.08	06 Apr	221	6.64	**42.23**	-0.03	144	0.05	20 Aug	**136**	0.05
FitzroyInshore	Wet	17.08	20 Sep	6.94	12 Mar	173	10.14	**59.38**	-0.06	192	0.05	13 Sep	**185**	0.05
FitzroyCoastal	Dry	10.06	24 Aug	4.32	09 Mar	197	5.74	**57.03**	-0.03	168	0.03	15 Aug	**159**	0.04
FitzroyCoastal	Wet	7.88	31 Aug	2.81	25 Mar	206	5.08	**64.38**	-0.02	159	0.03	21 Aug	**149**	0.03
KeppelBay	Dry	2.23	07 Oct	1.03	23 Apr	199	1.21	**54.05**	-0.01	166	0.01	01 Oct	**161**	0.01
KeppelBay	Wet	1.90	13 Dec	0.70	02 Apr	111	1.20	**63.06**	-0.01	254	0.00	29 Nov	**241**	0.00

b) Cape York and Wet Tropics

Zone	Period	Maximum	Max Date	Minimum	Min Date	DeclineTime	Decline	**Perc Decline**	DeclineRate	RecoveryTime	RecoveryRate	Recov 95Date	**Recovery Time95**	Recovery Rate95
CapeYorkOutershelf	All	13.26	23-Sep	8.51	26-Jan	125	4.75	**35.82**	-0.04	240	0.02	16-Sep	**233**	0.02
CapeYorkMidshelf	All	13.45	22-Sep	7.67	7-Mar	166	5.78	**43**	-0.03	199	0.03	15-Sep	**192**	0.03
CapeYorkLagoon	All	9.21	25-Sep	6.62	12-Apr	199	2.6	**28.18**	-0.01	166	0.02	17-Sep	**158**	0.02
CapeYorkInshore	All	6.99	11-Dec	4.16	26-Apr	137	2.83	**40.5**	-0.02	228	0.01	5-Dec	**223**	0.01
CapeYorkCoastal	All	5.21	15-Dec	2.69	24-Mar	100	2.52	**48.31**	-0.03	265	0.01	7-Dec	**258**	0.01
NorthWet-T-Outer	All	17.35	18-Sep	9.93	25-Apr	219	7.42	**42.77**	-0.03	146	0.05	4-Sep	**132**	0.06
NorthWet-T-Mid	All	15.94	24-Sep	7.61	3-May	221	8.33	**52.27**	-0.04	144	0.06	16-Sep	**136**	0.06
NorthWet-T-Lagoon	All	12.62	13-Dec	6.05	29-Apr	138	6.57	**52.07**	-0.05	227	0.03	24-Sep	**148**	0.04
NorthWet-T-Inshore	All	9.83	11-Dec	4.26	25-Apr	136	5.56	**56.62**	-0.04	229	0.02	6-Dec	**225**	0.02
NorthWet-T-Coastal	All	6.35	5-Feb	2.55	18-Jul	164	3.81	**59.91**	-0.02	201	0.02	31-Jan	**197**	0.02
SouthWet-T-Outer	All	19.4	21-Sep	11.4	23-Mar	183	8.03	**41.37**	-0.04	182	0.04	15-Sep	**176**	0.05
SouthWet-T-Mid	All	16.88	19-Sep	9.06	4-May	227	7.83	**46.36**	-0.03	138	0.06	12-Sep	**131**	0.06
SouthWet-T-Lagoon	All	15.19	17-Sep	7.77	10-Mar	174	7.42	**48.85**	-0.04	191	0.04	5-Sep	**179**	0.04
SouthWet-T-Inshore	All	9.01	11-Dec	4.8	15-Mar	95	4.22	**46.79**	-0.04	270	0.02	5-Dec	**265**	0.02
SouthWet-T-Coastal	All	5.16	11-Dec	2.56	17-Apr	128	2.6	**50.46**	-0.02	237	0.01	4-Dec	**231**	0.01

Across the shelf, mean photic depth increased from the Coastal to the Mid- or Outershelf zones in all 3 northern regions, while in the 3 southern regions, photic depth plateaued at maximum values in the Lagoon, and was similar on mid- and outer-shelf reefs (Fig. 17).

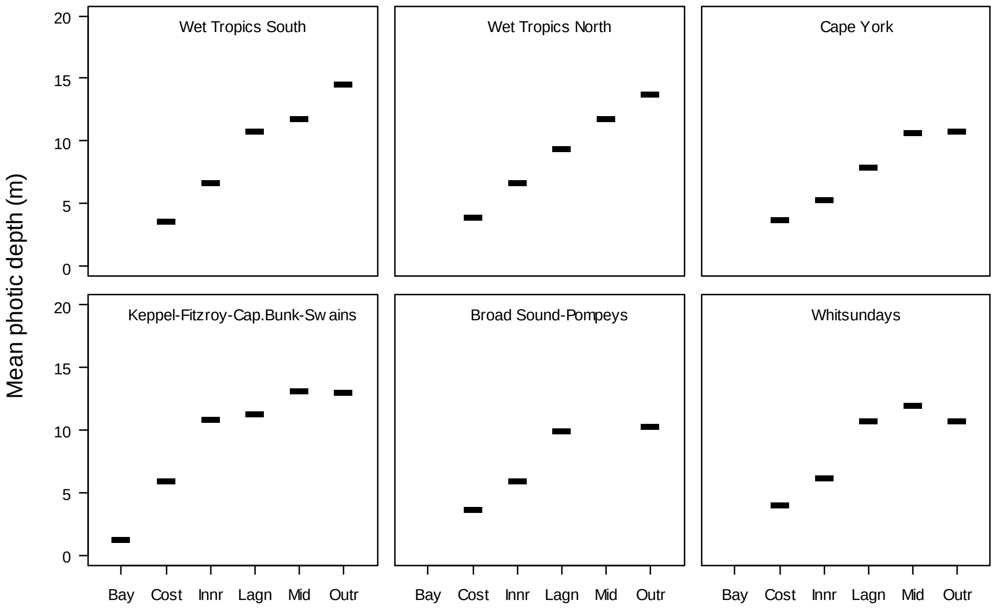


Figure 17: Mean photic depth averaged across all grid points and days (11 years) within each of the 15 northern and 15 southern zones.

Neither the seasonal maximum nor the seasonal minimum standardized mean photic depths were significantly different across the six regions (Fig. 18). However, the absolute mean decline in photic depth varied between regions: it was greatest in the two Wet Tropics Regions (>7.5 m difference between maximum and minimum mean photic depths), and lowest in Broad Sound and Cape York regions (Fig. 18). As a percentage of mean photic depth, the losses were smallest in Cape York (~40%), and greatest in the Northern Wet Tropics (~55%). However, Cape York took the longest time to recover from the seasonal lows (~220 days), while the Fitzroy Region, which has the strongest dynamics of the East Australian Currents, recovered the fastest (150 days).

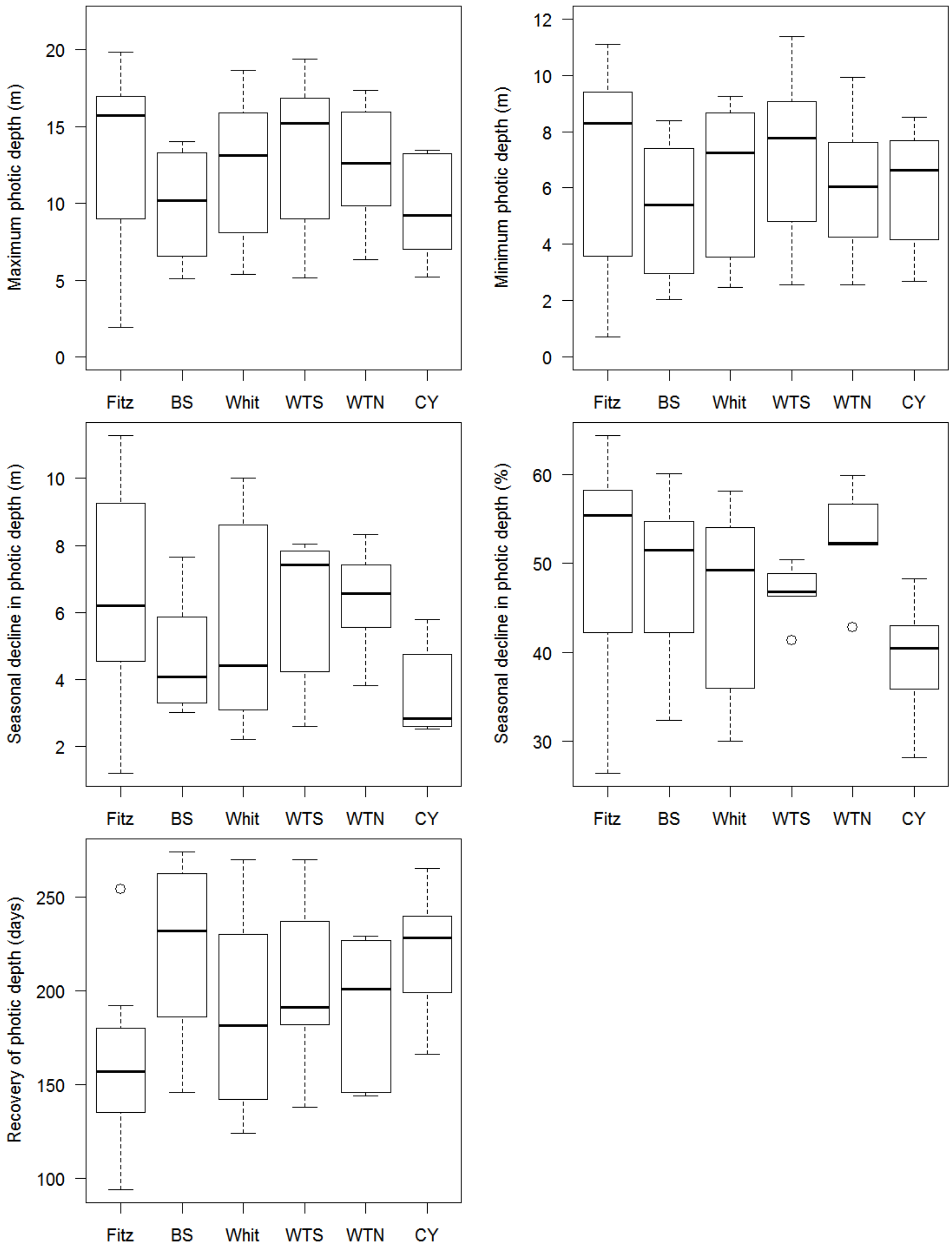


Figure 18: Summary of data presented in Table 4: Absolute and relative seasonal decline in photic depth (long-term detrended), and days of recovery of photic depth after their seasonal minima, over the 6 regions (from south to north: Fitzroy, Broad Sound, Whitsundays, Southern and Northern Wet Tropics, and Cape York).

Within individual zones, the seasonal decline in photic depth ranged from 30 to 70% of mean values (Table 4, Fig. 19). The decline was greatest in the Northern Wet Tropics, with highest values near the coast and declining towards to the outer-shelf zone. In the Coastal and Inshore Zone, these values were 57% to 70%, but even in the Mid- and Outershelf zones, the decline was still 46 to 55% between the highest and lowest values observed in that region.

In the southern regions, the percent decline in photic depth ranged from ~30 to 60% across the zones (Fig. 19). For the inshore zone of the Whitsundays, the seasonal decline averaged 36.0% for the dry years, and 56.2% for the wet years (Table 4). Similar differences between dry and wet years were encountered in the inner zones of the Fitzroy Regions, while in the outer zones and in the Broad Sound, the differences between dry and wet years were less steep. In the northern regions, the percent decline in photic depth ranged from 28 to 48% in Cape York, while in the Northern and Southern Wet Tropics it was 43 to 60%, and 41 to 50%, respectively. In the Wet Tropics, seasonal declines always diminished from high values near the coast to lower values away from the coast, whereas in Cape York the patterns were more complex (Fig. 19).

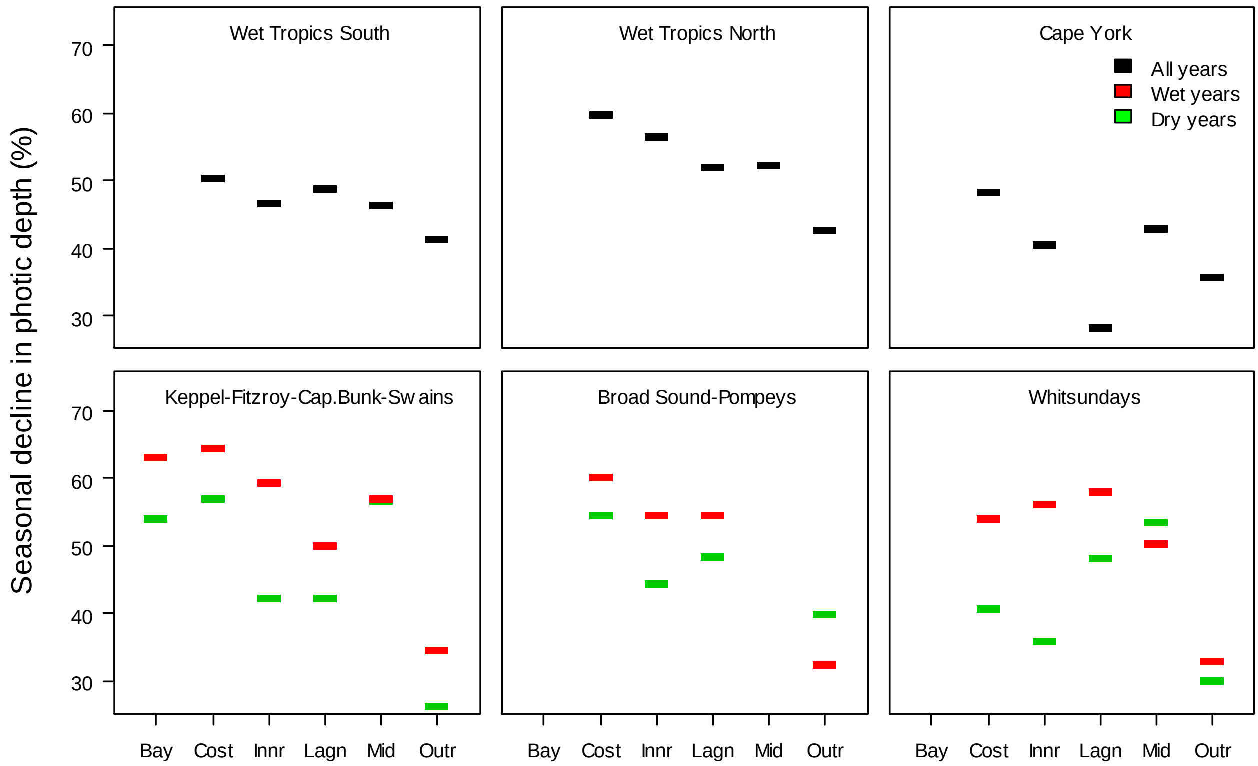


Figure 19: Mean photic depth averaged across all grid points and days (11 years) within each of the 15 northern and 15 southern zones. (b) Percent seasonal decline in mean photic depth in the 30 zones. Long-term detrended data from the wet and dry seasons.

The correlation coefficient of the loss in photic depth and river discharge volume in the Mid- and Outershelf zones of the Northern Wet Tropics was 0.82 and 0.7, respectively, again the highest of all regions (Figs. 13, 14, 20a). In the southern regions, such high correlations were typically only found in the Bay, Coastal and Inshore Zones.

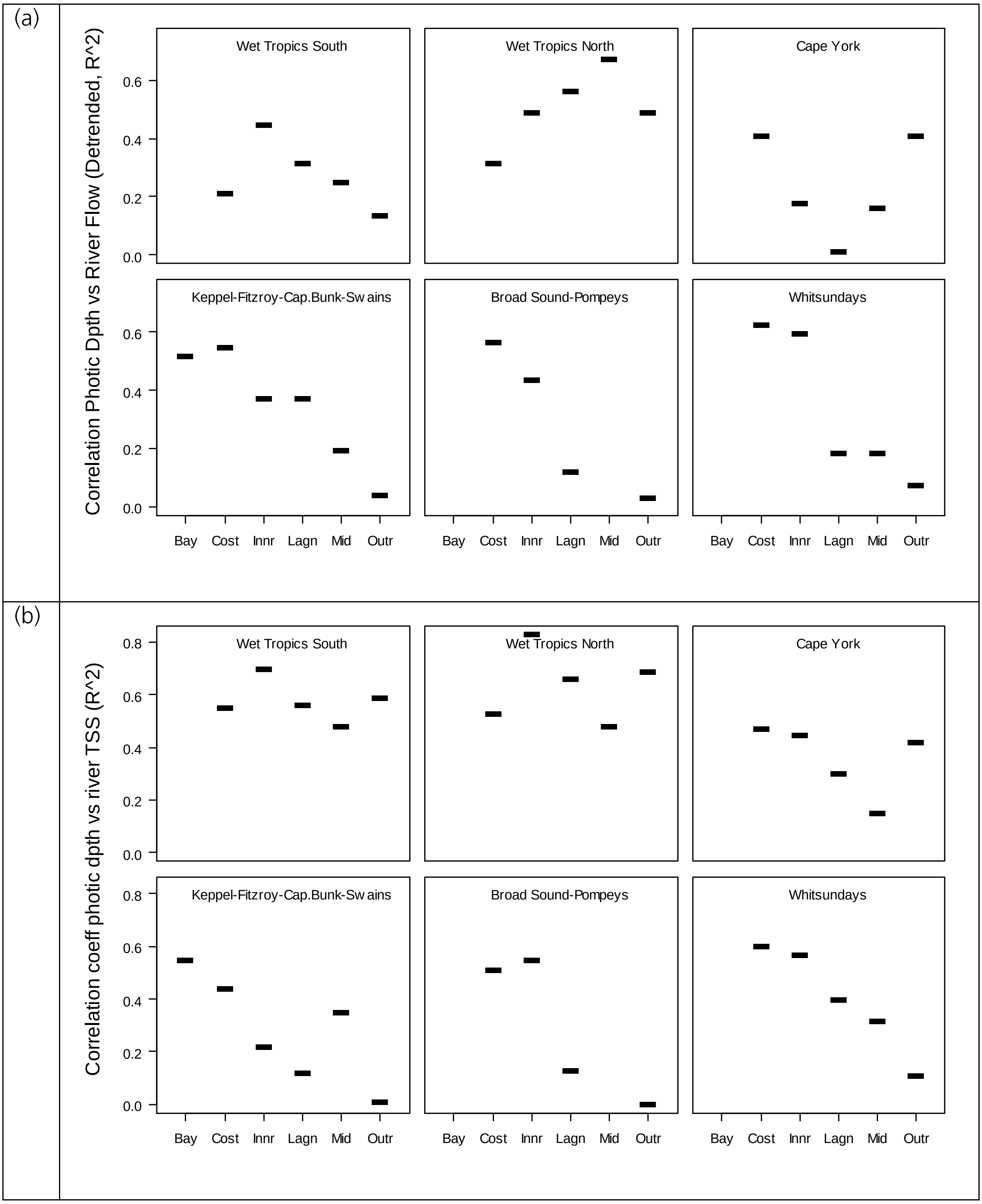


Figure 20: Correlation coefficient of loss in photic depth and river freshwater discharge volume (a), and river loads of TSS (b).

The number of days between the seasonal minima in photic depth to recovery to 95% of the seasonal maxima varied over 2-fold between zones, between 114 and 268 days (Table 4, Fig. 21). Recovery was typically slower near the coast than away from the coast, but there were exceptions to this pattern (e.g. slow recovery throughout the Cape York region). Recovery was also typically 10 to >100 days slower in wet years compared to dry years (Fig. 21).

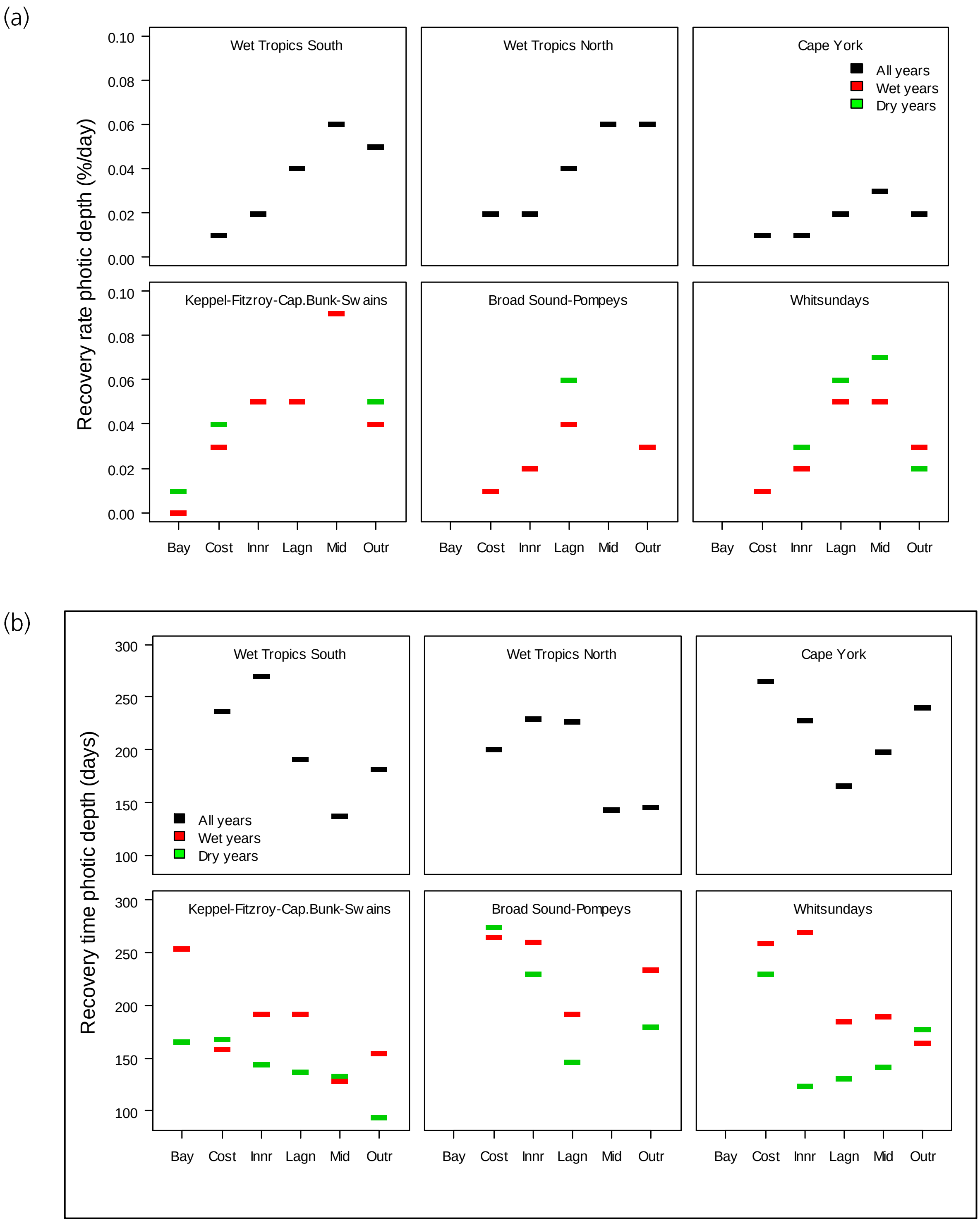


Figure 21: (a) Recovery rate (percent per day) to return to 95% of photic depth after the seasonal minima in the 30 zones. (b) Number of days until recovery to 95% of photic depth after the seasonal minima in the 30 zones.

Annual photic depth vs annual river loads

In the southern regions, the relationship between annual loads of TSS (and equally, all other forms of dissolved and particulate nutrients, the changes of which are numerically identical) and annual photic depth was typically strong in the Coastal and Inner-shelf Zones, and declined with increasing distance from the coast (Figs. 20b, 22). Typically, rates of recovery of photic depth were substantially lower than rates of decline. The only exceptions were the Inshore and Coastal Zones of the Whitsundays, when annual photic depth showed some recovery after the major wet years. The relationships between each of the river load metrics (TSS, PN, PP, DIN and DIP) were so strong that their associations between annual photic depth and annual river loads were almost identical; it is therefore impossible to conclude from these data what materials contribute to what proportion to the loss in photic depth.

In the northern regions (Figs. 20b, 22), the correlation coefficients between TSS and photic depth averaged 0.36, 0.64 and 0.58 for the Cape York, Northern and Southern Wet Tropics, respectively. Of all 30 zones, the correlation was highest for the Inshore zones of the Northern and Southern Wet Tropics (R^2 = 0.83 and 0.7, respectively). In the Northern Wet Tropics, relationships remained strong all the way across the shelf to the Outershelf zone (R^2 = 0.69). Again, it has to be emphasised that TSS should be understood as a proxy for the river loads of other nutrients rather than the main cause for the loss in photic depth, as the loads of PP, DIP, PN and DIN resulted in almost identical patterns.

Discussion

This analysis showed consistently strong relationships between the photic depth in the GBR and the freshwater volumes and river loads of TSS (and/or particulate and dissolved nutrients). Effects typically declined from the coast to zones further offshore, but in the Northern Wet Tropics (the zone where COTS outbreaks are assumed to originate), the relationships are strong all the way across the continental shelf.

The results are clearly relevant for our understanding of main drivers of water clarity in the GBR. They show that rivers exert a strong influence on water clarity both within and between years. Reductions in river loads all along the GBR coastline should lead to improvements in GBR water clarity, which should be measurable at time scales relevant for Reef Report Card reporting.

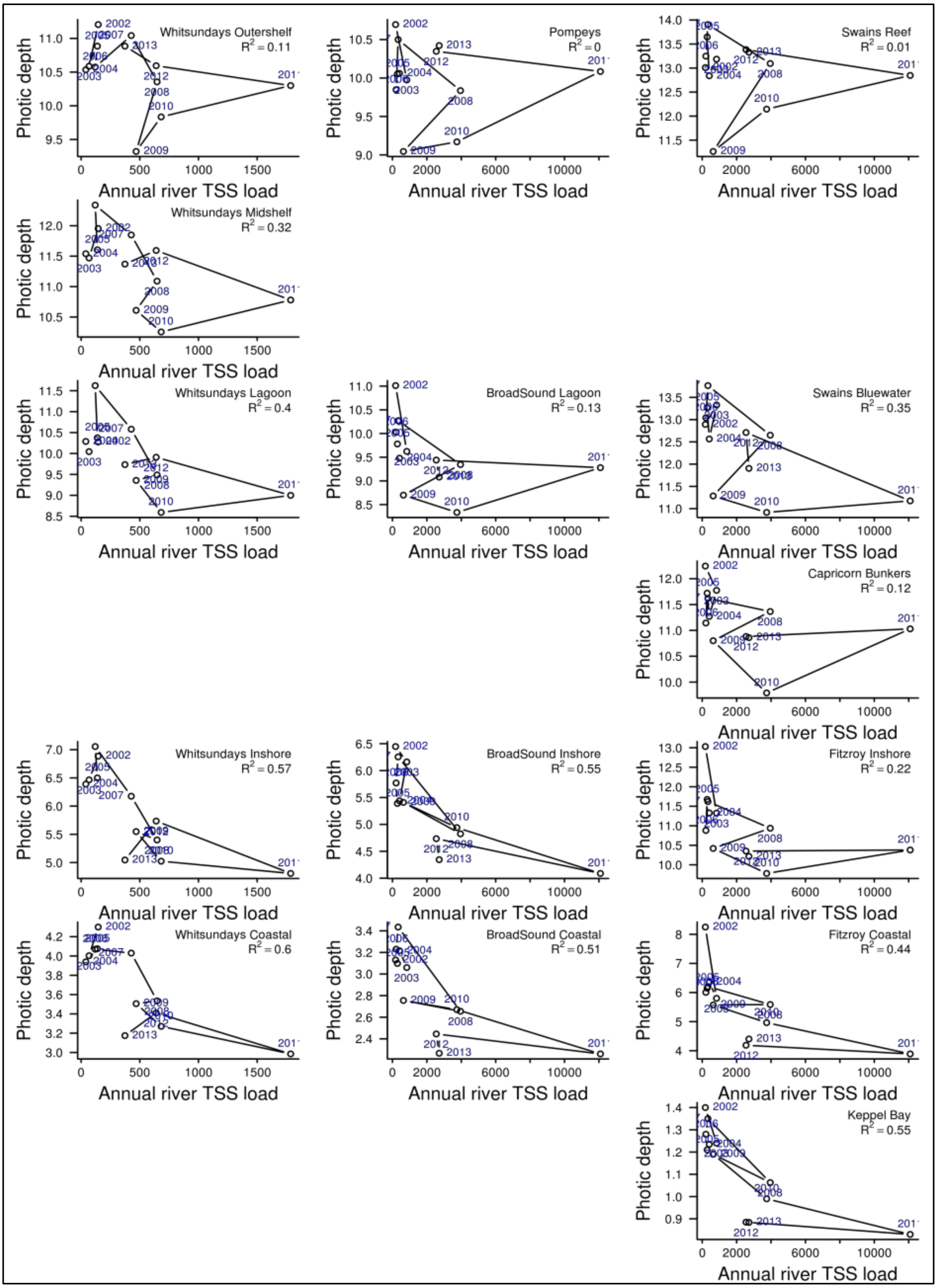


Figure 22: Relationships between annual mean photic depth and annual river loads of TSS in the southern Regions (Whitsundays, Broadsound and Fitzroy). (Note TSS is just a proxy for all forms of particulate and dissolved nutrients).

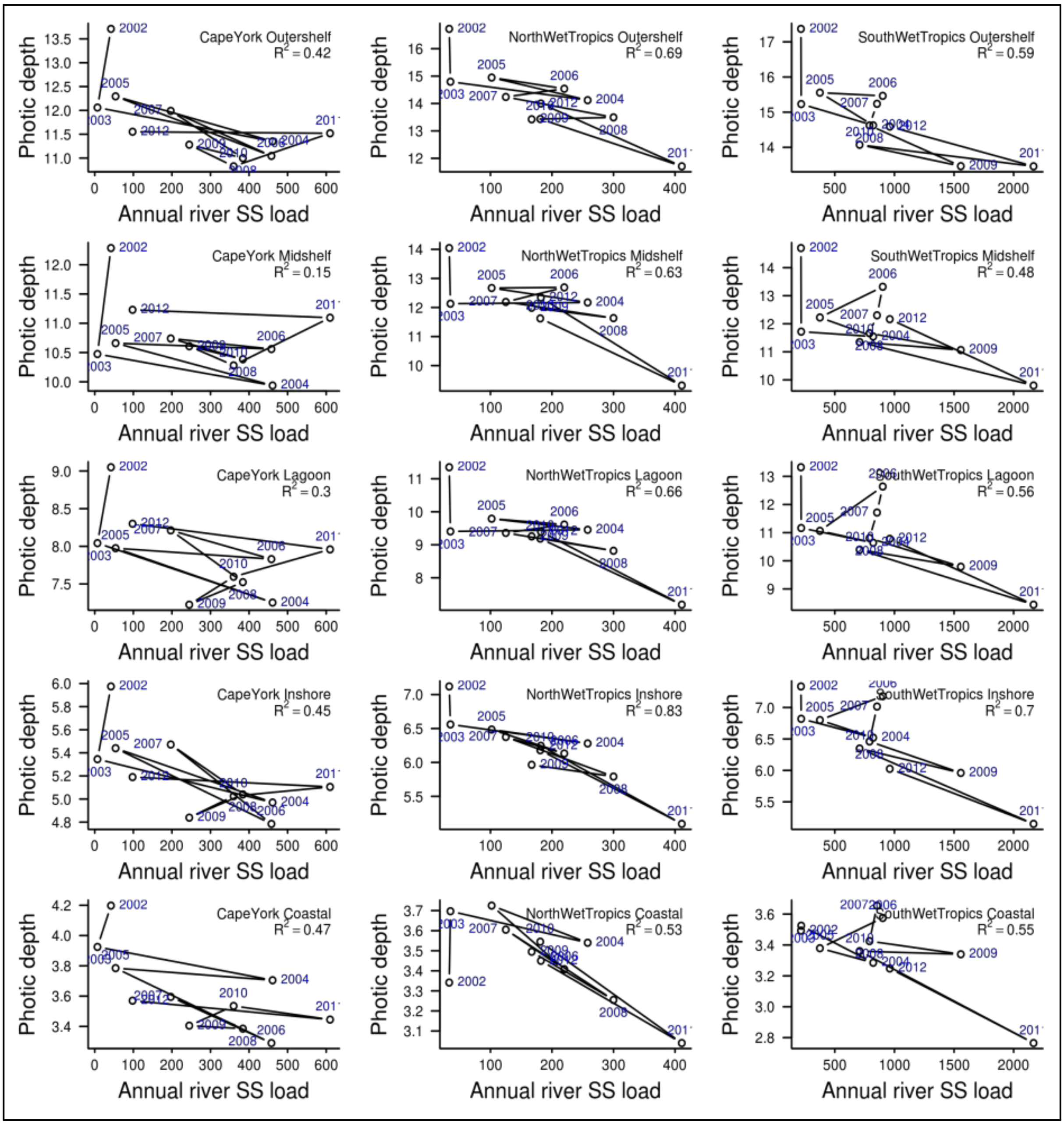


Figure 23: Relationships between annual mean photic depth and annual river loads of TSS in the northern regions. (Note TSS is just a proxy for all forms of particulate and dissolved nutrients).

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Appendix 1

Supplementary Table 1: Temporal summaries: mean photic depth (m), tidal range (m), wave height (m) and wind speed (m/s), broken down by calendar years, water years (1st Oct - 30 Sept), and wet/dry seasons.

(A) Southern Regions (Whitsunday-Broadsound-Fitzroy zones) combined:

Year	Photic depth	Tidal range	Wave height	Wind speed
2002	10.075	2.911	0.756	20.58
2003	8.918	2.910	0.858	21.70
2004	9.017	2.901	0.830	20.93
2005	9.172	2.894	0.859	21.79
2006	9.119	2.901	0.926	21.79
2007	9.560	2.902	0.836	20.99
2008	8.819	2.902	0.846	21.06
2009	8.007	2.908	0.843	20.92
2010	8.267	2.927	0.892	21.36
2011	8.715	2.938	0.854	21.20
2012	8.590	2.934	0.855	20.14
2013	7.772	2.911	0.938	20.84

Water year	Photic depth	Tidal range	Wave height	Wind speed
2002	9.660	2.803	0.702	18.90
2003	9.103	2.926	0.852	21.73
2004	8.791	2.911	0.858	21.38
2005	9.169	2.886	0.894	22.31
2006	8.997	2.894	0.846	20.95
2007	9.630	2.910	0.857	21.23
2008	8.856	2.907	0.882	21.35
2009	8.311	2.897	0.822	20.79
2010	8.233	2.921	0.841	20.98
2011	8.378	2.939	0.886	21.43
2012	8.884	2.939	0.855	20.35
2013	8.290	2.927	0.908	20.71

Water year	Season	Photic depth	Tidal range	Wave height	Wind speed
2002	Dry	9.660	2.803	0.702	18.90
2003	Wet	7.940	2.904	0.959	22.47
2003	Dry	9.847	2.941	0.776	21.20
2004	Wet	8.087	2.870	0.967	22.64
2004	Dry	9.250	2.940	0.777	20.48
2005	Wet	8.212	2.888	1.038	24.15
2005	Dry	9.837	2.884	0.792	20.84
2006	Wet	7.890	2.927	0.973	21.98
2006	Dry	9.717	2.870	0.755	20.22
2007	Wet	8.514	2.889	1.006	22.70
2007	Dry	10.405	2.925	0.755	20.21
2008	Wet	7.687	2.866	1.081	23.42
2008	Dry	9.611	2.935	0.728	19.88
2009	Wet	7.109	2.900	1.052	23.17
2009	Dry	9.021	2.895	0.664	19.11
2010	Wet	7.182	2.947	1.024	22.61
2010	Dry	8.880	2.902	0.730	19.85
2011	Wet	7.118	2.914	0.960	22.55
2011	Dry	9.292	2.957	0.836	20.63
2012	Wet	7.552	2.896	0.980	21.50

2012	Dry	9.758	2.969	0.766	19.52
2013	Wet	7.274	2.932	1.057	22.44
2013	Dry	8.913	2.923	0.781	19.49

(B) Northern Regions (Cape York, Wet Tropics South and Wet Tropics North) combined:

Year	Photic depth	Tidal range	Wave height	Wind speed
2002	10.129	1.739	0.492	16.16
2003	8.876	1.765	0.488	16.08
2004	8.822	1.775	0.470	16.23
2005	9.101	1.776	0.499	17.57
2006	8.621	1.778	0.541	18.21
2007	9.160	1.776	0.486	17.58
2008	8.554	1.775	0.501	18.18
2009	8.286	1.767	0.486	16.39
2010	8.467	1.761	0.520	18.50
2011	8.036	1.751	0.482	17.71
2012	8.973	1.741	0.493	18.04
2013	8.434	1.715	0.528	18.70

Water year	Photic depth	Tidal range	Wave height	Wind speed
2002	10.338	1.671	0.486	15.69
2003	8.998	1.773	0.492	16.12
2004	8.581	1.779	0.488	16.66
2005	9.022	1.770	0.495	17.26
2006	8.842	1.770	0.510	17.25
2007	9.167	1.785	0.508	18.28
2008	8.551	1.779	0.497	18.26
2009	8.320	1.762	0.480	16.19
2010	8.590	1.758	0.528	18.56
2011	7.901	1.759	0.482	17.81
2012	8.857	1.745	0.481	17.59
2013	8.844	1.724	0.525	18.70

Water year	Season	Photic depth	Tidal range	Wave height	Wind speed
2002	Dry	10.338	1.671	0.486	15.69
2003	Wet	8.489	1.780	0.464	14.42
2003	Dry	9.331	1.768	0.511	17.31
2004	Wet	7.646	1.773	0.490	16.11
2004	Dry	9.143	1.784	0.487	17.06
2005	Wet	7.995	1.794	0.510	16.86
2005	Dry	9.676	1.754	0.483	17.54
2006	Wet	7.419	1.809	0.507	15.26
2006	Dry	9.606	1.742	0.512	18.66
2007	Wet	7.973	1.789	0.494	16.44
2007	Dry	9.903	1.782	0.518	19.58
2008	Wet	7.356	1.768	0.485	16.45
2008	Dry	9.286	1.787	0.506	19.54
2009	Wet	7.147	1.779	0.472	14.90
2009	Dry	8.996	1.750	0.485	17.11
2010	Wet	7.755	1.790	0.504	15.97
2010	Dry	9.093	1.735	0.547	20.39
2011	Wet	6.341	1.752	0.457	15.39
2011	Dry	8.875	1.764	0.501	19.52

2012	Wet	7.715	1.724	0.459	16.57
2012	Dry	9.489	1.759	0.493	18.30
2013	Wet	8.039	1.736	0.505	17.26
2013	Dry	9.339	1.716	0.541	19.72

Supplementary Table 2: Tidal data used to create zonal summaries

(A) Southern Regions:

Zone	Tide Location	Latitude	Longitude
Whitsundays Coastal	Bowen	-20.0167	148.2167
	Double Bay	-20.1833	148.6333
	Shute Harbour	-20.2833	148.7833
	Molle Island	-20.2500	148.8330
	East Repulse Island	-20.5833	148.8833
	Hay Point	-21.2667	149.3000
	Mackay Outer Harbour	-21.1167	149.2333
Whitsundays Inner	Hayman Island	-20.0500	148.8833
	Hook Island	-20.0667	148.9333
	Shaw Island	-20.5000	149.0667
	Carlisle Island	-20.7833	149.3000
	St. Bees Island	-20.9000	149.4500
Whitsundays Lagoon	Hook Island*	-20.0667	148.9333
	Scrawfell Island	-20.8667	149.6167
Whitsundays Midshelf	Hook Island*	-20.0667	148.9333
	Scrawfell Island*	-20.8667	149.6167
	Unnamed Reef No. 2*	-19.6167	149.8333
	Bugatti Reef*	-20.1000	150.2833
Whitsundays Outershelf	Unnamed Reef No. 2	-19.6167	149.8333
	Bugatti Reef	-20.1000	150.2833
Broad Sound Coastal	Sarina Inlet	-21.4000	149.3333
	Flock Pigeon Island	-22.1167	149.5667
	McEwin Islet	-22.1500	149.6000
	Marquis Island	-22.3333	150.4500
	Port Clinton	-22.5333	150.7500
Broad Sound Inner	St. Bees Island*	-20.9000	149.4500
	High Peak Island*	-21.9500	150.6833
	Middle Island Anchorage*	-21.6500	150.2500
Broad Sound Lagoon	Penrith Island	-21.0000	149.9000
	Middle Island Anchorage	-21.6500	150.2500
	Bell Cay	-21.8167	151.2500
Pompeys	Creal Reef	-20.5333	150.3667
Keppel Bay	Port Alma	-23.5833	150.8667
Fitzroy Coastal	Port Clinton*	-22.5333	150.7500
	Rosslyn Bay	-23.1667	150.7833
	Port Alma*	-23.5833	150.8667
	Gladstone	-23.8333	151.2500
	Gatcombe Head	-23.8833	151.3833
Fitzroy Inshore	Port Clinton*	-22.5333	150.7500
	Rosslyn Bay*	-23.1667	150.7833
	Gatcombe Head*	-23.8833	151.3833
	Heron Island*	-23.4500	151.9167
Capricorn-Bunkers	Heron Island	-23.4500	151.9167
	Tryon Islet	-23.2500	151.7833
Swains Bluewater	Bell Cay*	-21.8167	151.2500
	Gannet Cay*	-21.9833	152.4667
Swains Reef	Gannet Cay	-21.9833	152.4667

(B) Northern Regions:

Zone	Tide location	Latitude	Longitude
Cape York Coastal	Albany Island	-10.7167	142.5833

	Harrington Reef	-10.8167	142.7167
	Cairncross Island	-11.2500	142.9167
	Hannibal Island	-11.6000	142.9333
	Cape Grenville	-11.9667	143.2500
	Portland Roads	-12.6000	143.4167
	Night Island	-13.1833	143.5667
	Pipon Island	-14.1333	144.5167
Cape York Inshore	Albany Island	-10.7167	142.5833
	Harrington Reef	-10.8167	142.7167
	Cairncross Island	-11.2500	142.9167
	Hannibal Island	-11.6000	142.9333
	Cape Grenville	-11.9667	143.2500
	Portland Roads	-12.6000	143.4167
	Night Island	-13.1833	143.5667
	Pipon Island	-14.1333	144.5167
	Restoration Island	-12.6167	143.4667
	Morris Island	-13.4833	143.7167
	Flinders Island	-14.1667	144.1667
	Howick Island	-17.1667	146.0167
Cape York Lagoon	Albany Island	-10.7167	142.5833
	Harrington Reef	-10.8167	142.7167
	Cairncross Island	-11.2500	142.9167
	Hannibal Island	-11.6000	142.9333
	Sir Chas Hardy Island	-11.9167	143.4667
	Night Island	-13.1833	143.5667
	Morris Island	-13.4833	143.7167
	Fife Island	-13.6500	143.7167
	Pelican Island	-13.9000	143.8333
	Pipon Island	-14.1333	144.5167
	Howick Island	-17.1667	146.0167
Cape York Midshelf	Albany Island	-10.7167	142.5833
	Harrington Reef	-10.8167	142.7167
	Cairncross Island	-11.2500	142.9167
	Raine Island	-11.6000	144.0500
	Sir Chas Hardy Island	-11.9167	143.4667
	Creech Reef	-13.6333	144.0833
	Pipon Island	-14.1333	144.5167
	Howick Island	-17.1667	146.0167
Cape York Outershelf	Raine Island	-11.6000	144.0500
	Sir Chas Hardy Island	-11.9167	143.4667
	Creech Reef	-13.6333	144.0833
	Pipon Island	-14.1333	144.5167
	Howick Island	-17.1667	146.0167
North Wet Tropics Coastal	Cape Flattery	-14.9500	145.3333
	Port Douglas	-16.4833	145.4667
	Cairns	-16.9167	145.7833
	Fitzroy Island	-16.9167	146.0000
North Wet Tropics Inshore	Cape Flattery	-14.9500	145.3333
	Low Isles	-16.3833	145.5667
	Green Island	-16.7500	145.9667
	Fitzroy Island	-16.9167	146.0000
North Wet Tropics Lagoon	Lizard Island	-14.6667	145.4500
	Low Isles	-16.3833	145.5667
	Green Island	-16.7500	145.9667

North Wet Tropics Midshelf	Lizard Island	-14.6667	145.4500
	Low Isles	-16.3833	145.5667
	Green Island	-16.7500	145.9667
North Wet Tropics Outershelf	Lizard Island	-14.6667	145.4500
	Low Isles	-16.3833	145.5667
	Green Island	-16.7500	145.9667
South Wet Tropics Coastal	Cairns	-16.9167	145.7833
	Fitzroy Island	-16.9167	146.0000
	High Island	-17.1667	146.0167
	Dunk Island	-17.9333	146.1500
	Lucinda	-18.5167	146.3333
South Wet Tropics Inshore	Green Island	-16.7500	145.9667
	Fitzroy Island	-16.9167	146.0000
	Russell Island	-17.2333	146.1000
	Dunk Island	-17.9333	146.1500
	Goold Island	-18.1667	146.1833
	Lucinda	-18.5167	146.3333
South Wet Tropics Lagoon	Green Island	-16.7500	145.9667
	Fitzroy Island	-16.9167	146.0000
	Russell Island	-17.2333	146.1000
	Unnamed Reef No. 1	-17.8667	146.7167
South Wet Tropics Midshelf	Green Island	-16.7500	145.9667
	Unnamed Reef No. 1	-17.8667	146.7167
South Wet Tropics Outershelf	Green Island	-16.7500	145.9667
	Unnamed Reef No. 1	-17.8667	146.7167

Supplementary Table 3: Wind data used to create zonal summaries

Southern Regions:

Zone	BOM station	Latitude	Longitude
Whitsundays Coastal	Hamilton Island	-20.4	149.0
	Mackay	-21.1	149.2
Whitsundays Inner	Hamilton Island	-20.4	149.0
	Mackay	-21.1	149.2
Whitsundays Lagoon	Hamilton Island	-20.4	149.0
	Mackay	-21.1	149.2
Whitsundays Midshelf	Hamilton Island	-20.4	149.0
	Mackay	-21.1	149.2
Whitsundays Outershelf	Hamilton Island	-20.4	149.0
	Mackay	-21.1	149.2
Broad Sound Coastal	Hay Point	-21.3	149.3
	Middle cy Island -21	.7 150	.3
Broad Sound Inner	Middle Percy Island	-21.7	150.3
Broad Sound Lagoon	Middle Percy Island	-21.7	150.3
Broad Sound Midshelf	Middle Percy Island	-21.7	150.3
Pompeys	Middle Percy Island	-21.7	150.3
Keppel Bay	Yappon	-23.1	150.8
	Rundle Island	-23.5	151.3
Fitzroy Coastal	Yappon	-23.1	150.8
	Rundle Island	-23.5	151.3
	Glastone	-23.9	151.3
Fitzroy Inshore	Yappon	-23.1	150.8
	Rundle Island	-23.5	151.3
	Heron Island	-23.4	151.9
Capricorn-Bunkers	Heron Island	-23.4	151.9
Swains Bluewater	Heron Island	-23.4	151.9
Swains Reef	Heron Island	-23.4	151.9

Northern Regions:

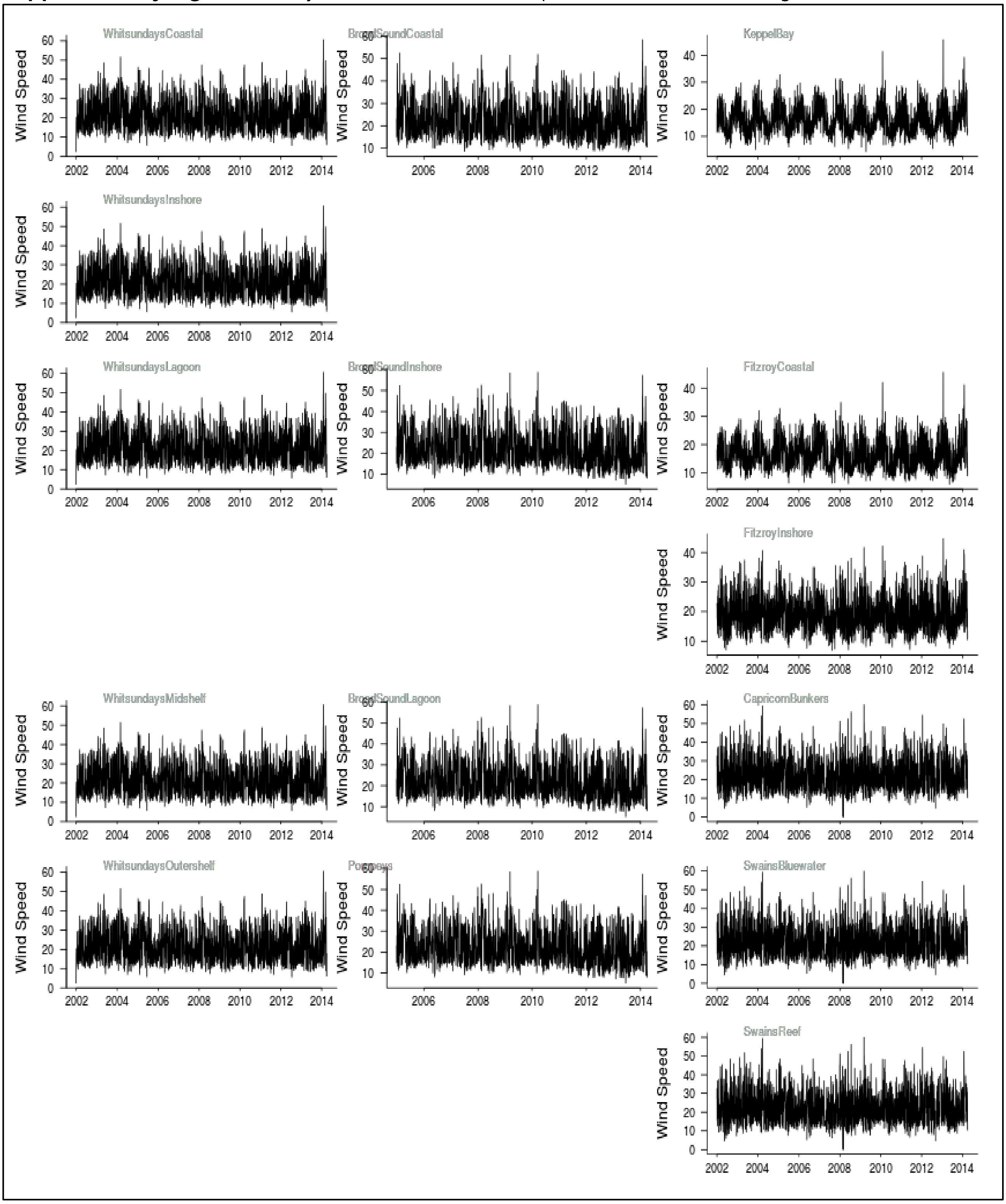
Zone	BOM station	Latitude	Longitude
Cape York Coastal	Horn Island	-10.6	142.3
	Lockhart River	-12.8	143.3
	Cape Flattery	-15.0	145.3
Cape York Inshore	Horn Island	-10.6	142.3
	Lockhart River	-12.8	143.3
	Cape Flattery	-15.0	145.3
Cape York Lagoon	Horn Island	-10.6	142.3
	Lockhart River	-12.8	143.3
Cape York Midshelf	Horn Island	-10.6	142.3
	Lockhart River	-12.8	143.3
Cape York Outershelf	Horn Island	-10.6	142.3
	Lockhart River	-12.8	143.3
North Wet Tropics Coastal	Cape Flattery	-15.0	145.3
	Cooktown	-15.4	145.2
	Low Isles	-16.4	145.6
	Cairns	-16.9	145.7
North Wet Tropics Inshore	Cape Flattery	-15.0	145.3
	Cooktown	-15.4	145.2
	Low Isles	-16.4	145.6
	Cairns	-16.9	145.7

North Wet Tropics Lagoon	Cape Flattery	-15.0	145.3
	Cooktown	-15.4	145.2
	Low Isles	-16.4	145.6
	Cairns	-16.9	145.7
North Wet Tropics Midshelf	Cape Flattery	-15.0	145.3
	Cooktown	-15.4	145.2
	Low Isles	-16.4	145.6
	Cairns	-16.9	145.7
	Arlington Reef	-16.7	146.1
North Wet Tropics Outershelf	Cape Flattery	-15.0	145.3
	Cooktown	-15.4	145.2
	Low Isles	-16.4	145.6
	Cairns	-16.9	145.7
	Arlington Reef	-16.7	146.1
South Wet Tropics Coastal	Cairns	-16.9	145.7
	Cardwell	-18.3	146.0
	Lucinda	-18.5	146.4
South Wet Tropics Inshore	Cairns	-16.9	145.7
	Cardwell	-18.3	146.0
	Lucinda	-18.5	146.4
South Wet Tropics Lagoon	Cairns	-16.9	145.7
	Cardwell	-18.3	146.0
	Lucinda	-18.5	146.4
South Wet Tropics Midshelf	Cairns	-16.9	145.7
	Cardwell	-18.3	146.0
	Lucinda	-18.5	146.4
	Arlington Reef	-16.7	146.1
South Wet Tropics Outershelf	Cairns	-16.9	145.7
	Cardwell	-18.3	146.0
	Lucinda	-18.5	146.4
	Arlington Reef	-16.7	146.1

Supplementary Table 4: Number of missing data for the main wind stations used to create zonal summaries

STATION_NAME	min	max	MaxConsecutiveMissingDays
Adele Island	2013-08-18	2014-03-31	0 days
Alva Beach	2000-01-01	2014-03-31	7 days
Arlington Reef	2010-05-04	2014-03-31	0 days
Barrow Island	2005-01-01	2014-03-31	0 days
Browse Island	2013-08-18	2014-03-31	0 days
Cairns	1989-01-01	2014-03-31	2 days
Cape Flattery	2003-06-20	2014-03-31	5 days
Cape Wessel	2013-08-18	2014-03-31	0 days
Cardwell	2013-08-13	2014-03-30	0 days
Centre Island	2005-02-07	2014-03-31	289 days
Cooktown	2000-07-24	2014-03-31	4 days
Darwin	2005-01-01	2014-03-31	0 days
Darwin Harbour	2012-08-16	2014-03-31	6 days
Double Island Point	2005-01-04	2014-03-31	7 days
Gladstone	2000-01-01	2014-03-31	2 days
Gove Airport	2005-01-01	2014-03-31	0 days
Groote Eylandt Airport	2005-01-30	2014-03-31	317 days
Hamilton Island	2002-07-19	2014-03-31	9 days
Hay Point	2005-11-24	2014-03-31	9 days
Heron Island	2000-01-01	2014-03-31	17 days
Horn Island	2005-01-01	2014-03-31	3 days
Jabiru	2005-01-01	2014-03-31	1589 days
Lady Elliot Island	2000-03-12	2014-03-31	460 days
Learmonth	2005-01-01	2014-03-31	0 days
Lockhart River	2001-06-26	2014-03-31	10 days
Low Isles	1998-11-07	2014-03-31	22 days
Lucinda	2000-01-01	2014-03-31	851 days
Mackay	2000-01-01	2014-03-31	2 days
McCluer Island	2005-01-01	2014-03-31	504 days
Middle Percy Island	2005-01-01	2014-03-31	0 days
Northeast Island	2010-10-13	2014-03-31	865 days
Rockhampton	2000-01-01	2014-03-31	2 days
Rowley Shoals	2008-12-24	2014-03-31	901 days
Rundle Island	2000-01-01	2014-03-31	877 days
Townsville	2000-01-01	2014-03-31	2 days
Troughton Island	2005-01-01	2014-03-31	0 days
Wadeye (Port Keats)	2005-01-11	2014-03-31	379 days
Yeppoon	2000-01-01	2014-03-31	2 days

Supplementary Figure 1: Daily zonal means of wind speed for the southern regions.



Supplementary Figure 2: Daily zonal means of wind speed for the northern regions.