The Centre for Australian Weather and Climate Research

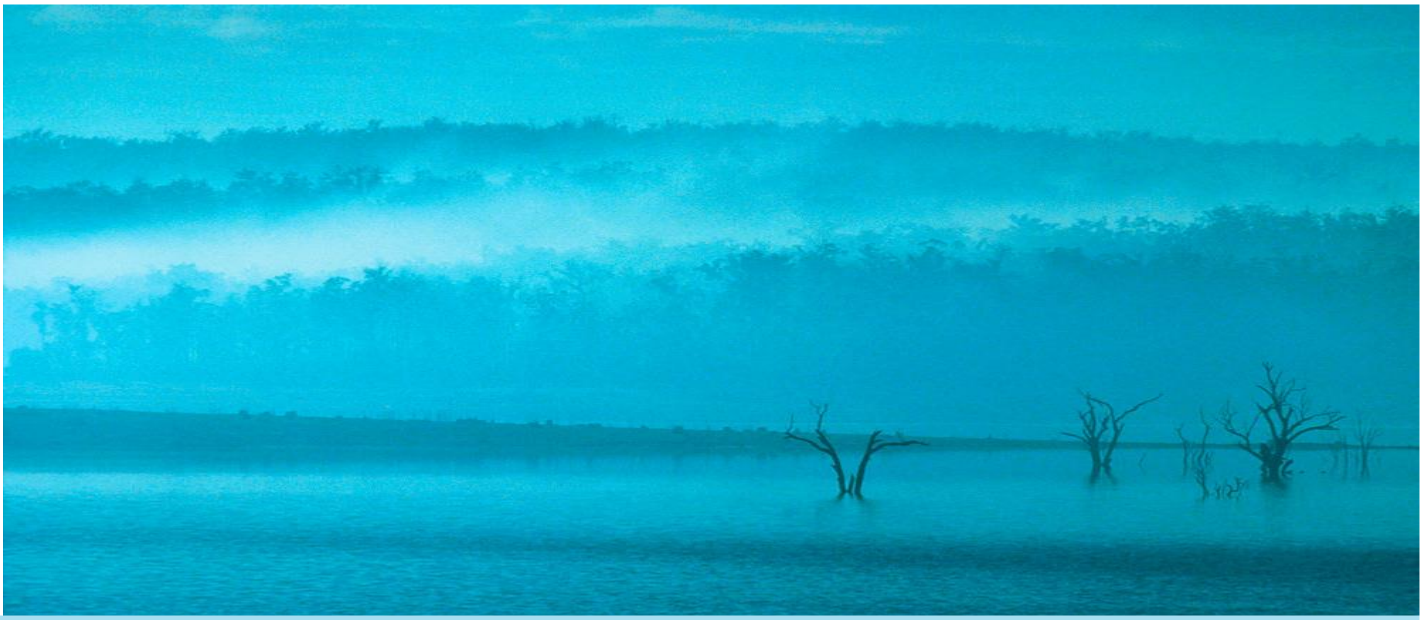
A partnership between CSIRO and the Bureau of Meteorology

ReefTemp Next Generation

L.A. Garde, C.M Spillman, L. Majewski, C. Griffin, G. Kruger and H. Beggs

CAWCR Technical Report No. 063

July 2013



www.cawcr.gov.au

ReefTemp Next Generation

L.A. Garde[1], C.M Spillman[1], L. Majewski[2], C. Griffin[2], G. Kruger[1, 2] and H. Beggs[1]

[1] Centre for Australian Weather and Climate Research (CAWCR)
- a partnership between CSIRO and the Bureau of Meteorology

[2]Observations and Engineering Branch

CAWCR Technical Report No. 063

July 2013

ISSN: 1835-9884

National Library of Australia Cataloguing-in-Publication entry

Author: L.A. Garde, C.M Spillman, L. Majewski, C. Griffin, G. Kruger and H. Beggs

Title: ReefTemp Next Generation

ISBN: 978-1-4863-0123-2

Series: CAWCR technical report CRT 063

Enquiries should be addressed to:

Luke Garde
Climate and Water Division | Climate Information Services | Climate Prediction
Bureau of Meteorology
GPO Box 1289, Melbourne
Victoria 3001, Australia

l.garde@bom.gov.au

Copyright and Disclaimer

All images reproduced in grayscale. A colour version of CAWCR Technical Report No.063 is available online: http://www.cawcr.gov.au/publications/technicalreports.php

Contents

List of Figures

List of Tables

1. ABSTRACT

Mass coral bleaching events are primarily triggered by elevated ocean temperatures. ReefTemp produces high resolution satellite based nowcasts of sea surface temperature (SST), thermal stress and associated bleaching risk for the Great Barrier Reef (GBR). The ReefTemp Next Generation (RTNG) system is based on new state-of-the-art Integrated Marine Observing System (IMOS) Level 3 super-collated (L3S) multi-sensor composite satellite SST products. Derived SST products are delivered daily online via static images, Google Earth™ and a sophisticated data portal, providing an improved ability to monitor thermal stress over the Great Barrier Reef.

The original ReefTemp system was a collaborative project between Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research, the Great Barrier Reef Marine Park Authority and the Australian Bureau of Meteorology (the Bureau). The ReefTemp Next Generation system has been developed and operationalized within the Bureau and is funded by eReefs, under the National Plan for Environmental Information (NPEI).

Continuous SST monitoring provides researchers and management with necessary tools to inform decisions and plan in advance for the complex interactions leading to coral bleaching. When bleaching conditions occur, this tool can be used to support both bleaching response plans and strategic reef management decisions. Development of real-time reef-scale monitoring systems with 24/7 support is extremely important as the frequency and severity of coral bleaching is expected to increase under future climate change.

2. INTRODUCTION

Coral reefs are among the most diverse ecosystems in the world and are often referred to as the 'rainforests of the sea' (Liu et al. 2006). The Great Barrier Reef (GBR) is the largest coral reef system in the world, composed of over 2,900 individual reefs and 900 islands stretching 2500 km, covering an area of approximately 344,400 km^2. The GBR is managed by the Great Barrier Reef Marine Park Authority (GBRMPA) and is a World Heritage Site. However, despite best management practices, climate change is expected to have serious impacts on the reef in the coming decades (Hennessy et al. 2007). Coral bleaching in particular is expected to increase in frequency and severity as ocean temperatures rise under global warming (Hoegh-Guldberg 1999; Donner et al., 2005; Frieler et al. 2012), presenting many challenges for reef management worldwide (Hoegh-Guldberg et al., 2007; Donner et al., 2009).

Coral bleaching has been observed sporadically since 1982 on the GBR, with mass bleaching events occurring in 1997/1998 and 2002 and a more localised but severe event in 2006, affecting the southern GBR (Hoegh-Guldberg 1999; Berkelmans et al. 2004; Weeks et al. 2008). No mass coral bleaching events were observed prior to 1979 (Glynn 1993; Hoegh-Guldberg 1999). Mass coral bleaching events are caused primarily by anomalously warm sea temperatures (Brown 1997; Hoegh-Guldberg 1999; Lesser 2004) and have caused significant damage and mortality when thermal stress has been prolonged and/or severe.

As water temperatures increase, coral bleaching can occur. This process is characterised by the expulsion of zooxanthellae from the coral host. Zooxanthellae are microscopic photosynthetic organisms which live within the coral tissues and provide the coral with nutrients and, due to their pigments, give corals their vibrant colours. In addition to protection, coral provide zooxanthellae with metabolic and respiratory by-products. The loss of zooxanthellae often results in coral turning white, hence the term 'coral bleaching' (Jones et al. 1998). Corals become white because their tissue without zooxanthellae is nearly transparent, revealing the coral skeleton. Loss of reef-building corals, changes in benthic habitat and reef fish populations are just a few of the long-term impacts as a result of severe bleaching events. Anomalously high sea surface temperature (SST) conditions have also been linked to coral disease frequency (Hoegh-Guldberg 1999; Beeden et al. 2011; Heron et al., 2012). Although corals can re-establish themselves under favourable conditions, it can take one to two decades for severely bleached reefs to fully recover (Baker et al., 2008; Wilkinson, 2008).

ReefTemp is a customised remote sensing application for the monitoring of local SST conditions that may lead to coral bleaching (Maynard et al., 2009) and was first developed in 2007 through a collaboration between GBRMPA, Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Bureau of Meteorology (the Bureau; Maynard et al., 2008). The system is utilised on a daily-to-weekly time scale throughout the year by GBRMPA, with particular attention to the summer months, to monitor the current SST conditions and associated thermal stress across the GBR. Continuous near-real time monitoring of the SST conditions provides reef management with the capability to effectively employ limited resources for the best outcome of both individual reefs and the entire reef system. As part of a broader early warning system, these monitoring tools can indicate the levels of likely impact across the entire reef and, in conjunction with other observations, support response plans and management decisions (Maynard et al. 2009).

However, the ReefTemp system (herein now referred to as RT1) is essentially an experimental system, run in research mode at CSIRO and not operationally supported by the Bureau. RT1 derived products are based on the Bureau legacy 14-day Advanced Very High Resolution Radiometer (AVHRR) Mosaic SST product (Rea 2004). This product is soon to be superseded by new satellite SST products developed under the Integrated Marine Observing System (IMOS; Paltoglou et al. 2010). Additionally, the legacy software has not been updated since its initial development in 2007, nor has the system been kept in line with the latest scientific developments. Furthermore, the RT1 codebase uses legacy tools and methods that are not appropriate for operational implementation within the Bureau.

During 2012, with funding from eReefs under the National Plan for Environmental Information (NPEI), a new operational version of RT1, known as ReefTemp Next Generation (RTNG), was designed, developed and launched at the Bureau. There were several motivations behind the development of the new RTNG system. The first was to deliver a nowcast system based on the latest scientific advances and new state-of-the-art, multi-sensor composite AVHRR SST products. The second was to run the system in an operational environment (i.e. 24/7 supported) using a modern portable programming language suitable for operational deployment, within the National Meteorological and Oceanographic Centre (NMOC) at the Bureau. The third was to rethink both the design and delivery of the thermal stress products to best address the needs of the reef managers. Table 1 and Table 2 directly compares the RT1 and RTNG systems and their products.

Table 1: Comparison between ReefTemp coral bleaching thermal stress monitoring systems: Legacy (RT1) and ReefTemp Next Generation (RTNG).

Item	Legacy ReefTemp (2007)	ReefTemp Next Generation (2012)
SST Input Product	Bureau Legacy 14-day mosaic SST	IMOS 1-day L3S SST product
Grid Resolution	0.018° x 0.018°	0.02° x 0.02°
SST Dataset	14-day (day+night) composite	1-day night-time
Climatology Dataset	CSIRO SST (Griffin et al. 2004)	IMOS L3S SST (Paltoglou et al., 2010) CSIRO SST (Griffin et al. 2004)
Climatology Baseline	1993 – 2003	2002 – 2011
Climatology Calculation	65^{th} percentile, day + night	Monthly means, night only
Climatology Resolution	0.042° x 0.036°	0.02° x 0.02°
Degree Heating Day Calculation	Monthly climatologies	Monthly climatologies: • IMOS • CSIRO
Degree Heating Day analysis period	1 Dec to 28 Feb	1 Dec to 31 Mar
System Deployment	Experimental at CSIRO	Operational at the Bureau (24/7)

Table 2: Comparison between ReefTemp coral bleaching thermal stress products: Legacy (RT1) and ReefTemp Next Generation (RTNG).

<table>
<tr><th>Legacy ReefTemp
(2007)</th><th colspan="2">ReefTemp Next Generation
(2012)</th></tr>
<tr><td rowspan="4">• Sea Surface Temperature (SST)
• SST Anomaly
• Degree Heating Days (DHD)
• Heating Rate</td><td>1-day IMOS SST
(IMOS climatology)</td><td>1-day IMOS SST
(CSIRO climatology)</td></tr>
<tr><td>• SST
• Quality Level (QL)
• Gap analysis
• Single Sensor Error Statistics Bias

• SST anomaly
• Degree Heating Day (DHD)
• DHD count
• Mean Positive Summer Anomaly</td><td>• SST anomaly
• Degree Heating Day (DHD)
• DHD count
• Mean Positive Summer Anomaly</td></tr>
<tr><td>14-day mosaic IMOS SST
(IMOS Climatology)</td><td>14-day mosaic IMOS SST
(CSIRO climatology)</td></tr>
<tr><td>• SST
• Grid Age

• SST anomaly
• Degree Heating Day (DHD)
• DHD count
• Mean Positive Summer Anomaly</td><td>• SST anomaly
• Degree Heating Day (DHD)
• DHD count
• Mean Positive Summer Anomaly</td></tr>
</table>

3. THE REEFTEMP NEXT GENERATION SYSTEM

The new RTNG system has been developed using the Python programming language (specifically Python 2.7.2), which is a high-level, open-source cross platform programming language. This choice of language supersedes the original experimental RT1 system which is based on a mixture of outdated software. RTNG module dependencies and functions are summarised in Table 3 and Table 4 respectively.

One of the advantages of RTNG is that the whole system is contained within the one programming environment to aid in the transition to an operational environment. Figure 1 provides an overarching view of how each of the RTNG products is calculated. RTNG has been developed to operate in two execution modes, '*Real-time*' and '*Hindcast*'. By developing the code in this way, users are able to run RTNG in an operational real-time mode or run for a period in the past, targeting a specific date range.

Once created, RTNG products are then output to three netCDF files (CF1.5 compliant). For each analysis date, the SST, error and thermal stress gridded data is plotted for both the web and visualisation within Google Earth™. Additionally, the RTNG netCDF files are also served online in real-time to the eReefs Marine Water Quality Dashboard via an OPeNDAP (Open-source Project for a Network Data Access Protocol) server. This provides end users with a user friendly interface where the grids from RTNG can be visualised with other eReefs products such as Marine Water Quality. The contents of the RTNG netCDF files are listed in Table 5.

Table 3: ReefTemp Next Generation module dependencies

Module (version)	Description
Basemap (1.0.2)	Module for plotting data on maps with matplotlib
Matplotlib (1.1.0)	A Python plotting library.
netCDF4 (0.9.6)	Python interface to the netCDF version 4 library.
NumPy (1.6.1)	A fundamental package used for scientific computing within Python.

Table 4: ReefTemp Next Generation running scripts and user developed functions. Note that functions indicated by * are not used in the daily execution of the RTNG suite

Method/Script	**Description**
run-reeftempNG.py	Main execution script for the RTNG system. Calculation periods, paths, ID codes and general settings are adjusted within this script.
reeftemp_savegrids.py	Saves RTNG grids to netCDF4 (with zlib compression enabled).
reeftemp_plotting.py	Plotting routine to produce images for the web and Google Earth^{TM}.
reeftemp_calcs2.py	Series of functions to calculate RTNG thermal stress products.
reeftemp_domains.py	Dictionary of bounding coordinates and settings used in plotting and in the generation of the netCDF.
reeftemp_mosaicSST.py	Function to generate 14-day SST mosaic data.
reeftemp_generateKML.py	Function to generate KML and KMZ files - thermal stress variables included.
reeftemp_generateKML_noDHD.py	Function to generate KML and KMZ files - thermal stress variables not included.
reeftemp_KMLsettings.py	Dictionary of settings used in generating the KML and KMZ Google Earth^{TM} files.
reeftemp_utils.py	Series of utilities used in calculating RTNG products.
reeftemp_read_netcdf.py	Functions used to read the IMOS gridded SST data.
nc_plot.py	Function which plots the gridded data as high quality images which are displayed on the RTNG website.
ge_plot.py	Function which produces transparent borderless images which are called within the Google Earth^{TM} KMZ files.
epalettes.py	Colour palette container.
reeftemp_climatology.py*	Function to calculate IMOS monthly climatologies.
reeftemp_climplotter.py*	Function to plot IMOS monthly climatologies.
reeftemp_maxgap.py*	Function to plot maximum gap counts for each month

Syntax to execute RTNG: `shell prompt> python run-reeftempNG.py`

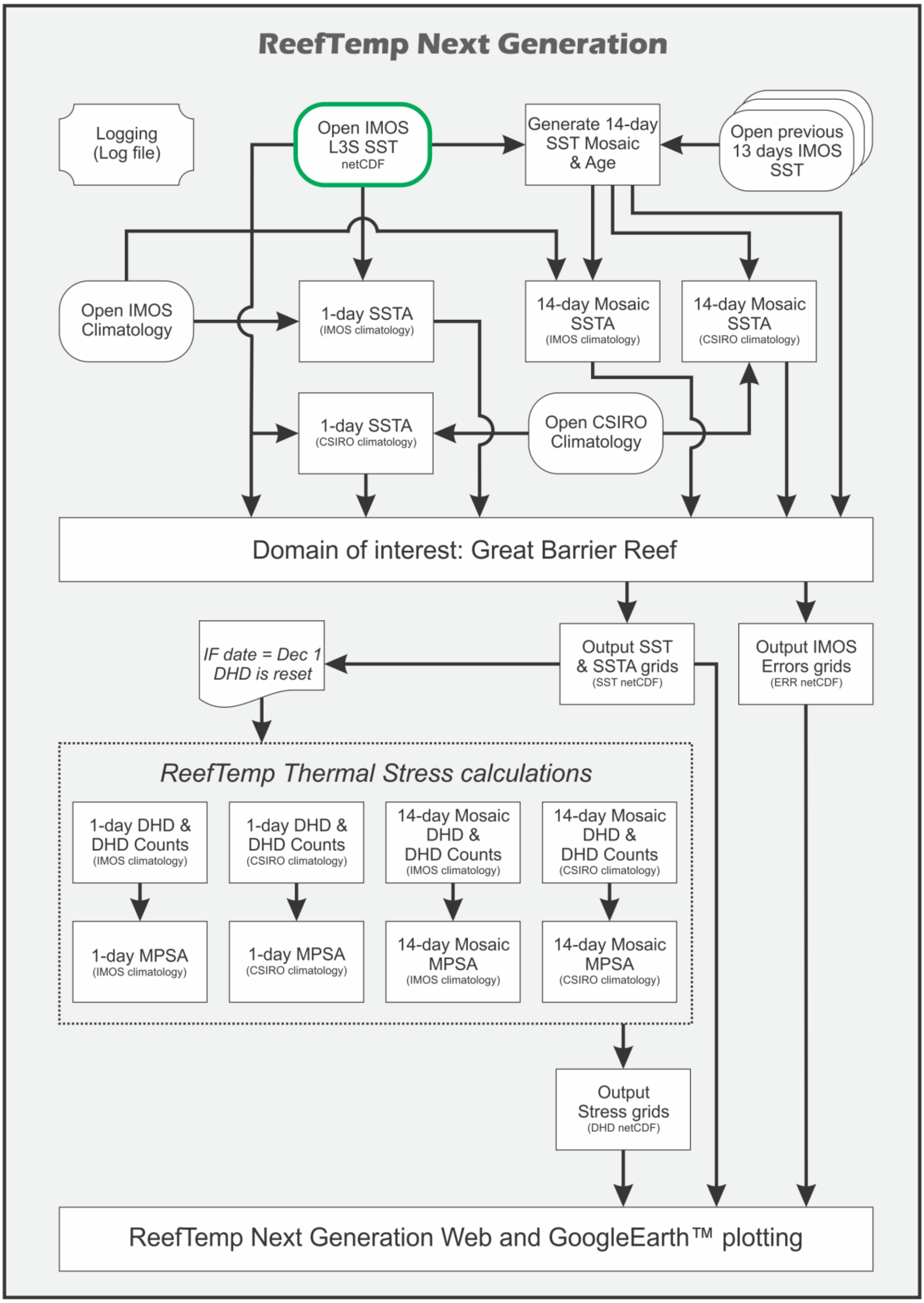


Fig. 1 Schematic overview of the ReefTemp Next Generation program. Calculation of thermal stress is only conducted during the extended summer period (1 Dec – 31 March inclusive). IMOS SST data has been used to generate RTNG products.

Table 5: ReefTemp Next Generation netCDF output configuration (yyyy = year, mm = month, dd = day)

NetCDF file name	NetCDF file variable contents	
	Variable Long name	Short name
RT2_yyyymmdd_SST.nc4	1-day IMOS SST	sst1day
	14-day SST Mosaic	sst_mosaic
	1-day IMOS SSTA	ssta1day
	1-day Legacy SSTA	ssta_leg1day
	14-day SSTA IMOS Mosaic	ssta_mosaic_imos
	14-day SSTA Legacy Mosaic	ssta_mosaic_leg
RT2_yyyymmdd_DHD.nc4	1-day IMOS DHD	dhd1
	1-day Legacy DHD	dhd1_leg
	14-day DHD IMOS Mosaic	dhd_mosaic_imos
	14-day DHD Legacy Mosaic	dhd_mosaic_leg
	1-day IMOS DHD counts	dhdc1
	1-day Legacy DHD counts	dhdc1_leg
	14-day DHD IMOS Mosaic counts	dhdc_mosaic_imos
	14-day DHD Legacy Mosaic counts	dhdc1_mosaic_leg
	1-day IMOS MPSA	mpsa1
	1-day Legacy MPSA	mpsa1_leg
	14-day MPSA IMOS Mosaic	mpsa_mosaic_imos
	14-day MPSA Legacy Mosaic	mpsa_mosaic_leg
RT2_yyyymmdd_ERR.nc4	Persistence Gap counter	gap_counter
	IMOS L2P mask flags	l2p_flags
	14-day SST IMOS Mosaic Pixel Age	mosaic_age
	1-day IMOS QL	ql_1day
	1-day IMOS SSES Bias	sses_bias_1day

3.1 Data Acquisition

The SST analyses produced by RTNG show the ocean skin temperatures for that day. The Group for High Resolution Sea Surface Temperature (GHRSST) define SST skin temperatures as the temperature within the conductive diffusion-dominated sub-layer at a depth of approximately 10-20 µm (see www.ghrsst.org/ghrsst-science/sst-definitions for details). These temperatures are measured by an infrared radiometer typically operating at wavelengths of 3.7-12 µm.

SST processing upgrades implemented by the Bureau now adhere to international best practices and comply with GHRSST data processing specification v2.0 (Paltoglou et al., 2010; Casey et al., 2011). By measuring brightness temperatures in five spectral bands, National Oceanic and Atmospheric Administration (NOAA) satellites (NOAA-11, 12, 14, 15, 16, 17, 18, 19) are used to produce state-of-the-art multi-sensor composite High Resolution Picture Transmission (HRPT) AVHRR skin SST products (Paltoglou et al., 2010), from 1992 to present. Raw HRPT data, received by ground receiving stations across Australia and Antarctica, are used to generate a level 2 pre-processed (L2P) geolocated, single swath dataset. This is then re-mapped to a standard Level 3 un-collated gridded product (L3U). A new level 3 collated product (L3C) is created from a combination of multiple swaths from a single sensor. Finally a multi-sensor, multi-swath (L3S or 'super-collated') product is produced. An overview of the Bureau's GHRSST-format products is provided at http://imos.org.au/sstproducts.html (accessed 2 March 2013) and Casey et al. (2011) provides detailed information regarding the content and format of these products.

The L3S SST product is a super-collated, multi-sensor gridded product at 0.02° x 0.02° spatial resolution, with no spatial or temporal smoothing to fill in missing data. Daily L3S data used in RTNG are produced by the Bureau as a contribution to the Integrated Marine Observing System (IMOS; www.imos.org.au). During 2012, the Bureau's Observations and Engineering Branch (OEB) were storing daily, day-time and night-time grids at the following FTP location:

ftp://aodaac2-cbr.act.csiro.au/imos/GHRSST/L3S-01day/night/

Currently, the RTNG system is based on the L3S 1-day night-time only product (Table 1). The night-only SST limitation was chosen to avoid observations that are affected by daily surface warming caused by solar heating and/or solar glare effects (Gentemann et al., 2003). Satellite retrievals measure temperatures at the surface layer and thus these warming effects will have strong influences in their measurements (Gentemann et al., 2003). The relationship with deeper bulk temperature, is the same on average during the night and during the day for wind speed conditions of > ~6 m s^{-1} (Donlon et al., 2002; Minnett, 2003). But under low winds the relationship is very variable vertically, horizontally and temporally (Ward, 2006). Night-time SSTs also correlate with in situ SSTs at one meter depth (Montgomery and Strong, 1995).

An important stage in the creation of the L3S grids is in the identification of clouds. Following an extensive study, clouds are identified using a carefully calibrated set of radiance, uniformity and 2-channel thresholds (Paltoglou et al., 2010). Paltoglou et al., (2010) state that cloud contamination will result in a negative temperature bias at affected grid cells in the dataset because observations contaminated by cloud have lower temperatures than the ocean surface. Consequently, particular effort has been made to ensure that all suspect pixels are identified and masked out. Conversely, it is also important to ensure that pixels are not needlessly masked out during this process, as spatial coverage is also a factor for consideration (Paltoglou et al., 2010).

To illustrate how cloud may affect the L3S 1-day product, Fig. 2 compares the night-time SST analysis for 1 January 2012 with an infrared satellite image captured by the MTSAT-2 platform for the same date. From this comparison it can be seen that large portions of the north-eastern Coral Sea are covered in cloud, which is shown as light blue, green-yellow and red colours (Fig. 2b), corresponding to brightness temperatures ranging from 190 to 285 K. The regions which depict these colours coincide with white regions or missing data points in the RTNG GBR SST product (Fig. 2a).

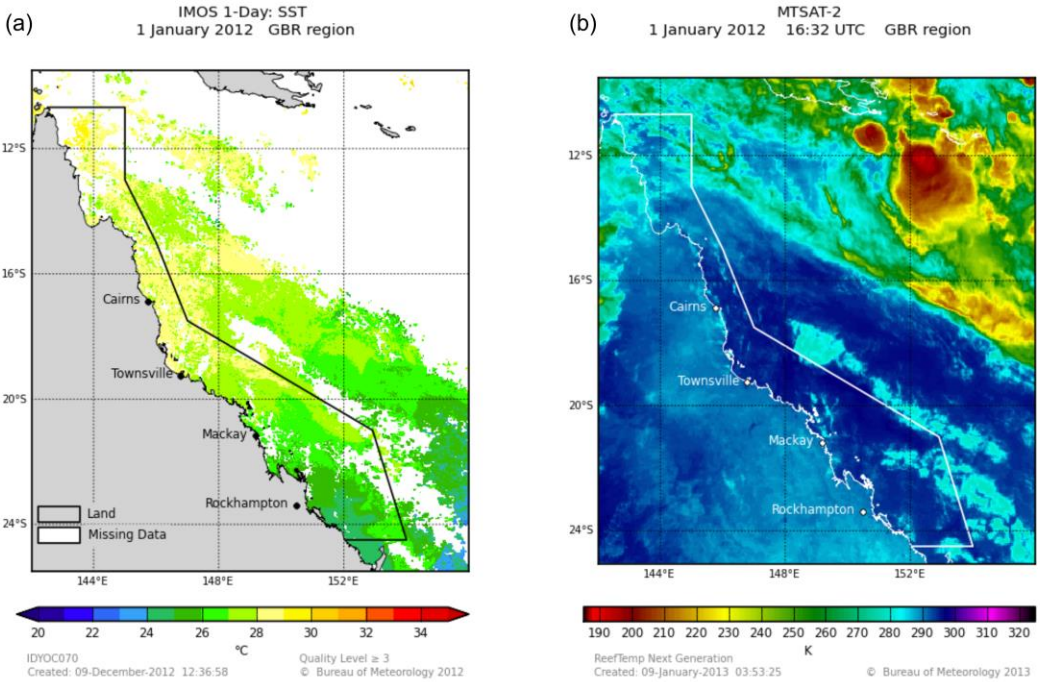


Fig. 2 (a) GBR night-time L3S-01day SST data for the 1 January 2012. (b) Infrared satellite image taken from the MTSAT-2 platform for 1 January 2012 (16:32 UTC), highlighting cloud cover in the north-eastern parts of the Coral Sea. Note that in (a) gray regions represent land and white regions represent missing data, or data of insufficient quality. GBR Marine Park boundary is illustrated as a solid black line (a) and a white line in (b).

3.1.1 L3S Spatial Coverage and SST Mosaic

As IMOS L3S daily SST data does not contain any smoothing to fill spatial gaps, there was a concern that poor coverage would lead to an underestimate of the total accumulated thermal stress. This is of major concern to GBRMPA management as this would prevent appropriate and timely action regarding a current bleaching episode. This underestimate is further compounded when SST data is restricted to higher quality levels (will be discussed in Section 3.1.2).

To address this issue, a gap-filled SST mosaic product was developed based on the IMOS L3S 1-day product. The SST mosaic generation followed the methodology of the Bureau legacy SST mosaic (Rea 2004); i.e., filling each missing-data grid cell in the current day using the most-recent daily SST for that grid cell from up to 13 days ago. Figure 3 is a simple representation of the RTNG mosaic generation process. Initially, the scheme determines the locations of all missing or insufficient data. Data from the previous day are then selected to fill in those locations. If grids are still missing data, an additional preceding day is sourced for data. This process is repeated until all grids are filled, or historical data has been sourced from as far back as 13 days. If data is still missing, these locations remain empty.

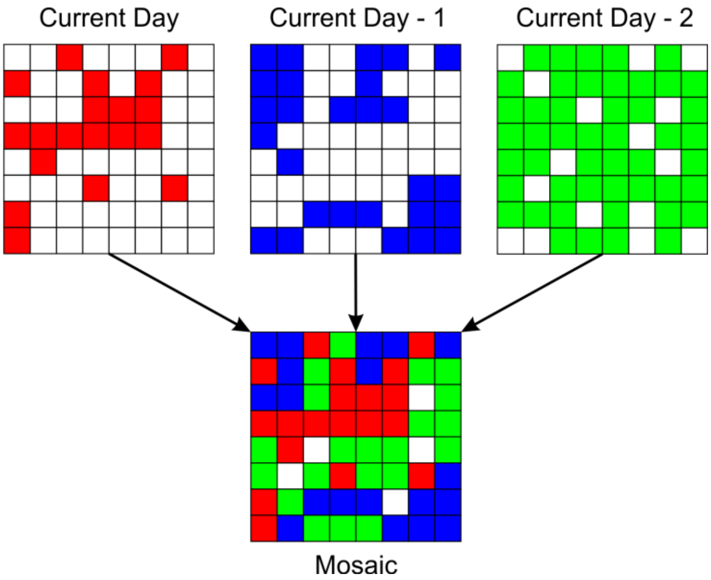


Fig. 3 Simple representation of how the ReefTemp Next Generation SST mosaic is generated. In this example, only the data from 3 days is shown.

Figure 4 illustrates the data coverage for two example dates, 8 January and 24 January 2012 with varying spatial coverage due to monsoonal cloud cover. Figures 4a and 4b represent the output from the 1-day IMOS SST product, whilst Fig. 4c and 4d represent the output from the 14-day IMOS SST mosaic product for the two dates respectively. It can be seen that the mosaic product has markedly improved spatial coverage.

Whilst a more complete SST image is available using the mosaic method, the generated SST field can be spatially inhomogeneous as data recorded over the space of up to 14 days is mixed in a single image. It is possible that neighbouring pixels within the final mosaic grid may contain SST variations which do not represent current conditions. However, this product serves to improve spatial coverage, ensuring that the thermal stress is accumulated and not simply masked due to cloud. Although not representing the real world, this product meets the needs of reef management who are more concerned by under prediction of bleaching events than over prediction.

To quantify this effect, a new product which accounts for when missing data points were filled was developed. This is known as Pixel Age and can be thought of as temporal error bars for each SST grid value. This product represents the age of the SST data at each grid cell, with an age of zero days representing current data (Figs 4e-f; indicated by light tones). Figure 4e illustrates that the SST mosaic that was generated for 8 January 2012, contains more current day data as compared to the mosaic generated for 24 January 2012, which contains SST data from up to 13 days previously in the northern GBR region.

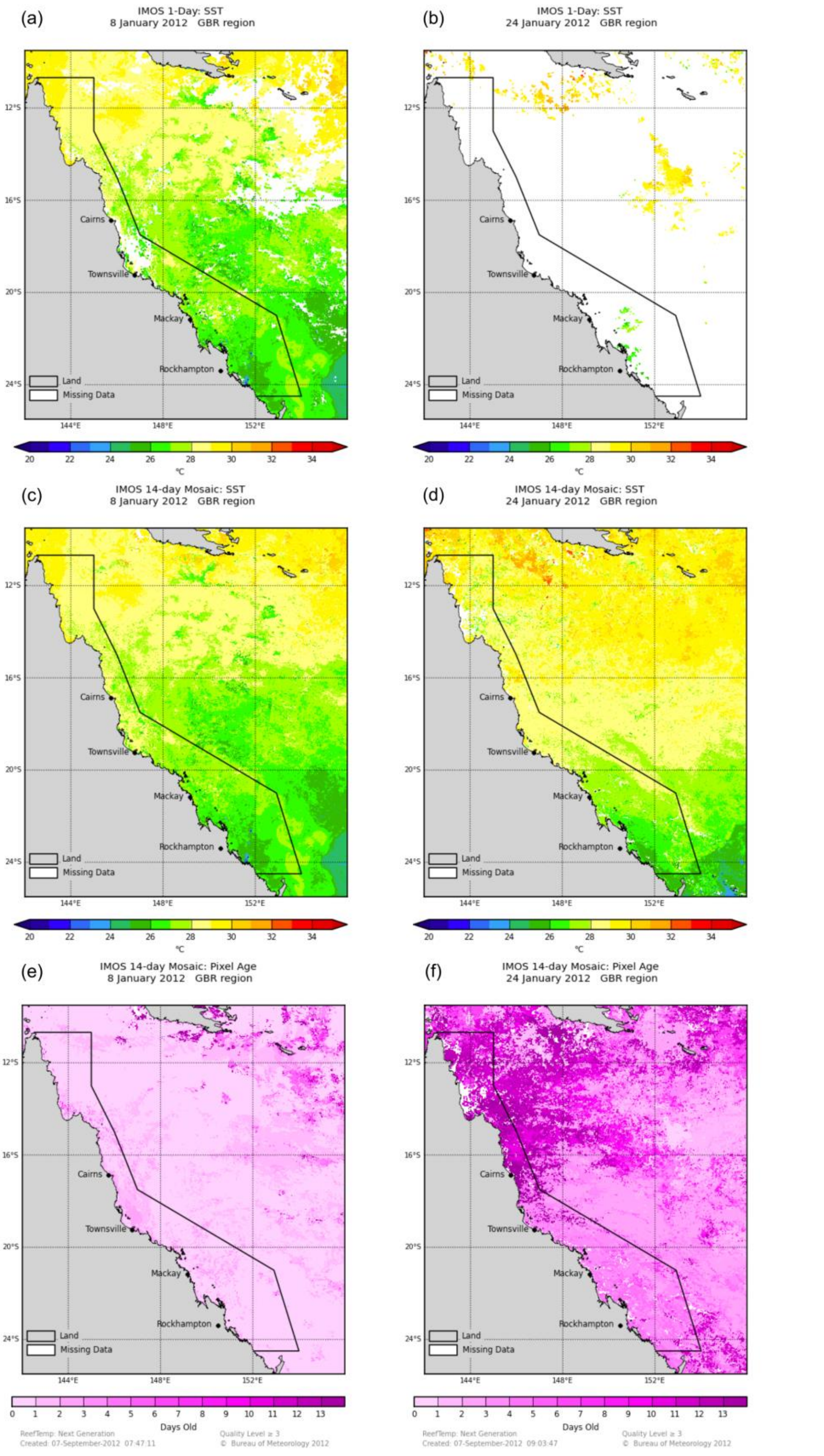


Fig. 4 Example GBR region IMOS L3S-01day SST grids for (a) 8 January and (b) 24 January 2012. (c) and (d) represent the 14-day SST mosaic and (e) and (f) represent the mosaic pixel age for the two dates 8 and 24 of January respectively.

3.1.2 IMOS L3S Quality Level and Error Bias

The IMOS L3S satellite data files contain information regarding the quality level (QL) and sensor specific error statistics (SSES) for each SST value by pixel. The QL is based on proximity to cloud (distance to cloud), satellite zenith angle and day/night. The SSES comprise bias and standard deviation estimates for each QL based on rolling 60 day match-ups with drifting buoy SST observations (Paltoglou et al., 2010).

IMOS L3S metadata states that pixels at QL 3, 4, and 5 are of low, acceptable and best quality respectively (Paltoglou et al. 2010). To ensure the best spatial coverage, RTNG uses all QL pixels (QL 3, 4 and 5). Figure 5 illustrates the contribution of each QL and SSES for the dates shown in Fig. 2 (8 and 24 January 2012 respectively). Even when cloud cover is minimal and data coverage is good as for 8 January (Fig. 5a), resulting in improved data coverage, some pixels may still be of low quality. For this specific date, the likely explanation for the swath of low quality data is a result of high satellite sensor viewing angle. These would be removed if specific QL threshold was set to acceptable or above only.

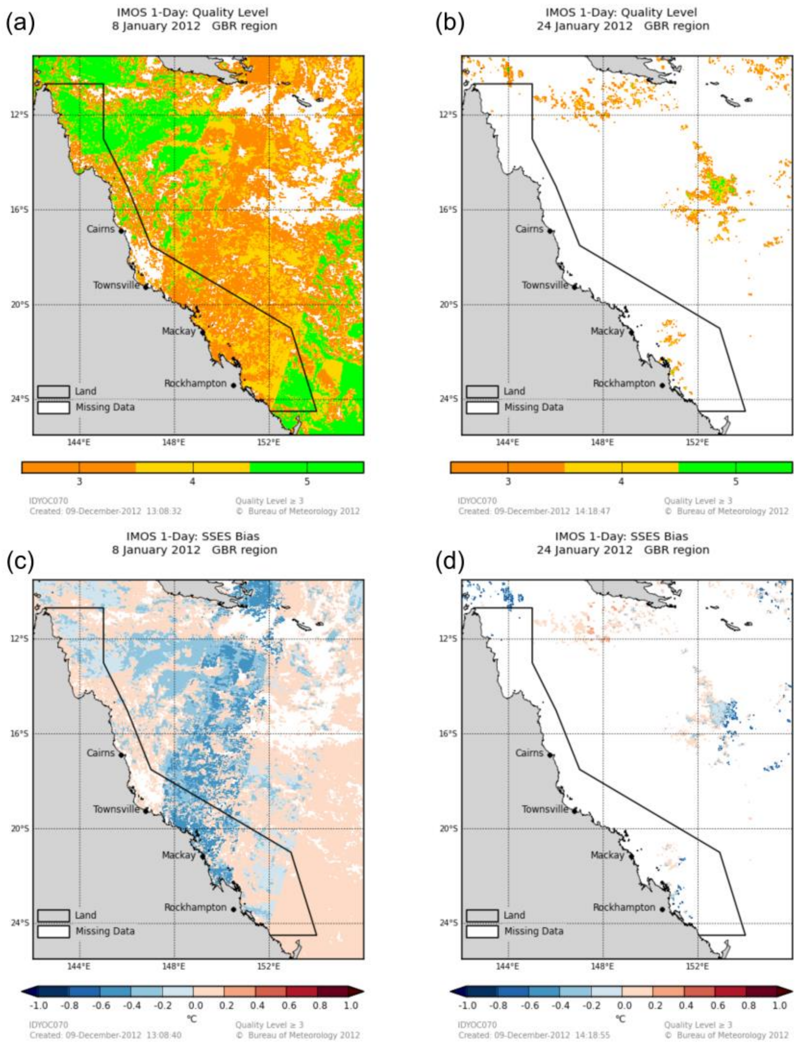


Fig. 5 Example Quality Level (QL) images for (a) 8 January and (b) 24 January 2012. SSES Bias images for (c) 8 January and (d) 24 January 2012.

3.2 Calculation of Climatologies

The RTNG SST anomaly (SSTA) and thermal stress products are calculated using new monthly IMOS climatologies. These climatologies use the L3S-01day nightly grids covering the 2002 to 2011 period. A monthly climatology refers to the long term monthly mean, i.e. January climatology is the average of all January monthly means within a specified period. First, monthly means were calculated for all months within 2002 – 2011, before an average was calculated across the 10 years for each month. To ensure consistency with the real-time SST data, all QL data (QL 3, 4 and 5), as described in Section 3.1.2, were included.

To assess the impact of using a new climatology on RTNG products, the IMOS and CSIRO legacy climatologies were compared for December, January and February (Fig. 6). The RT1 system utilises the CSIRO SST climatology for 1993 – 2003, generated using day and night HRPT AVHRR SST data from NOAA polar-orbiting satellites, calibrated to around 20 – 30 cm depth by using observations from global drifting buoys (Griffin et al., 2004; Maynard et al., 2008). The IMOS HRPT AVHRR SSTs forming the IMOS climatology were calibrated to the ocean skin at around 10 – 20 micron depth by first regressing the AVHRR brightness temperatures against drifting buoy SST observations over the Australian region, followed by conversion from buoy depths to the cool skin by subtraction of 0.17°C (Paltoglou et al., 2010). In the CSIRO SST processing system, the removal of anomalous values caused by cloud and diurnal surface warming is achieved by removing all the SST values above the 65^{th} percentile of the cumulative frequency distribution (Maynard et al., 2008). In contrast, the IMOS processing system uses a set of brightness temperature, uniformity and 2-channel thresholds to identify cloud (Paltoglou et al., 2010).

Generally, the IMOS climatology is warmer than the CSIRO climatology across most of the GBR region (Fig. 6), with the exception of the far northern GBR and inshore regions. This is in spite of the 0.17°C cold offset between the IMOS skin SST and CSIRO sub-skin SST and the use of night-time only data for the IMOS climatology. Two possible explanations which help explain why the IMOS climatology is warmer on average as compared to the CSIRO climatology are:

1. The climatologies are calculated for two different decades. SSTs in the Australian region were the warmest on record during the recent decade as compared to the 1961 – 1990 average using NOAA Extended Reconstruction SSTs (Australian Bureau of Meteorology, 2011). Lough (2008) showed that the trend in SST of coastal waters off north-eastern Australia was to increase at 0.12°C/decade for the period 1950-2007.

2. The cloud quality control methods differ between the IMOS and CSIRO products. The CSIRO SST product utilises a cloud detection mask which is generated using the Saunders and Kribel (1998) algorithm. Griffin et al. (2004) states that approximately 40% of thin cloud at night is not detected by the Saunders and Kribel algorithm. This would result in a cooler SST for the CSIRO SST climatology although the effect is at least partially offset by using the 65^{th} percentile median SST. For the IMOS SST and climatology, Paltoglou et al. (2010) states that a new threshold test based on brightness temperature measured from thermal infrared channels was found to be very effective at identifying cloud.

We postulate that the observed differences could be due to these combined factors. However, it is worth highlighting that the GBR had shown very little difference (± 0.5°C) between climatologies, which is of importance to the primary management users of the RTNG product.

The number of available data points for each 0.02° x 0.02° grid cell in the period 2002-2011 was assessed for each IMOS monthly climatology. Expressed as a percentage of the theoretical number of data points (*n = 10 years x days per month = 282–310*) that could form the climatological value, Fig.7 shows that large portions of the GBR domain are infrequently populated by valid data. At best, the southern regions of the GBR have 30 – 40 % data coverage whilst northern and inshore regions show as little as 0 – 10 % coverage for the period. The lack of SST data is of concern, as regions with minimal temporal coverage could contain a temperature bias (either above or below the true mean SST) and therefore not be an accurate representation of the climatological temperature for that month in that region.

Future updates to the RTNG system could utilise a SST climatology which allows for a linear change in the monthly climatology (e.g. from 31 November to 1 December). This would ensure that a step change in the climatological SST value between months was avoided. In addition, when the L3S 3-day or 6-day composite products are developed, RTNG would need to use a weighted climatology. For example a 3-day SST composite produced on 1 December 2012 would incorporate data from 31 November 2012 to 2 December 2012. Consequently, the climatology used would need to take into account both November and December SST climatological values.

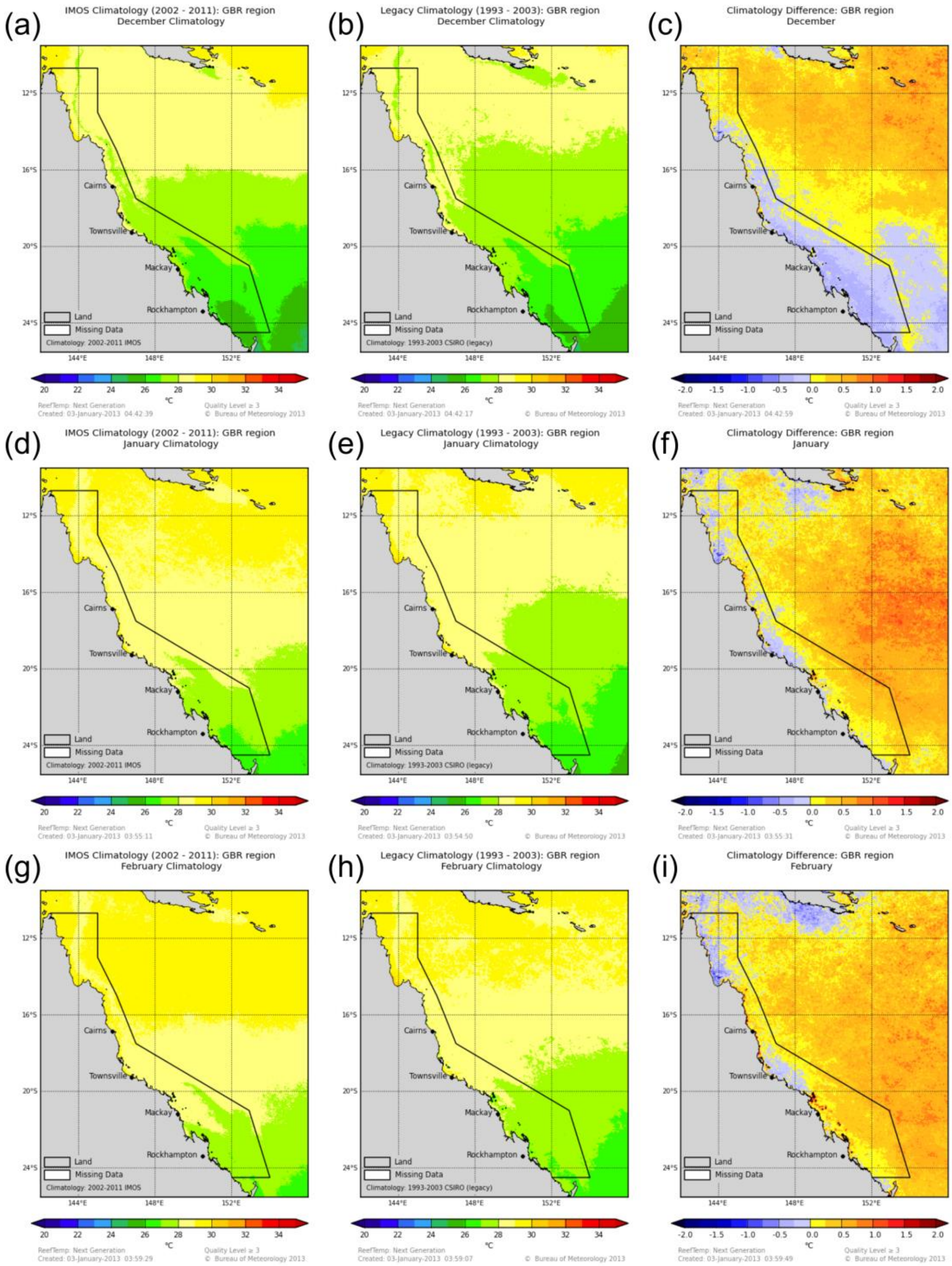


Fig. 6 December climatology using (a) IMOS L3S-01day (2002-2011) and (b) CSIRO SST data (1993-2002), and the (c) difference (IMOS – CSIRO). January climatology using (d) IMOS L3S-01day (2002-2011), and (e) CSIRO SST data (1993-2002) and the (f) difference. February climatology using (g) IMOS L3S-01day (2002-2011) and (h) CSIRO SST data (1993-2002), and the (i) difference.

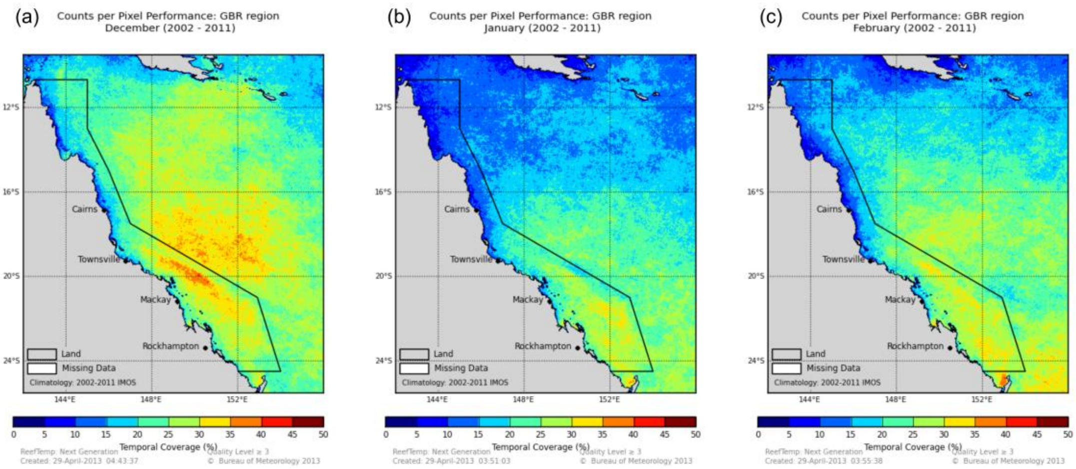


Fig. 7 Number of data points per grid cell, expressed as a percentage of the total number of days that form the climatological period for (a) December (n=310), (b) January (n=310) and (c) February (n=282) IMOS climatologies. Note that the colour scale is limited to 50%.

3.2.1 L3S Maximum Gap Persistence

Given the sparse spatial nature of the IMOS L3S dataset, the temporal coverage at each grid cell was assessed. The gap persistence count represents the longest consecutive period with no data at each grid cell. The gap persistence counts are shown for three summer periods over the GBR region (Fig. 8). This analysis is vital, as it highlights which specific regions will be potentially underestimate the accumulated thermal stress due to lack of data.

Measured in days, Fig. 8 shows that there are regions where the maximum gap counts exceed 14 consecutive days, meaning no data for over two weeks. Some regions of the GBR can experience gaps which exceed 20 days. Black shaded regions represent gap persistence values in excess of 28 days. The most likely cause of missing values is persistent cloud cover, which prohibits the radiometer from measuring the brightness temperature (Section 0). Regions where SST data is missing for more than 14 consecutive days will result in missing data within the 14-day mosaic SST grid (Section 3.1.1).

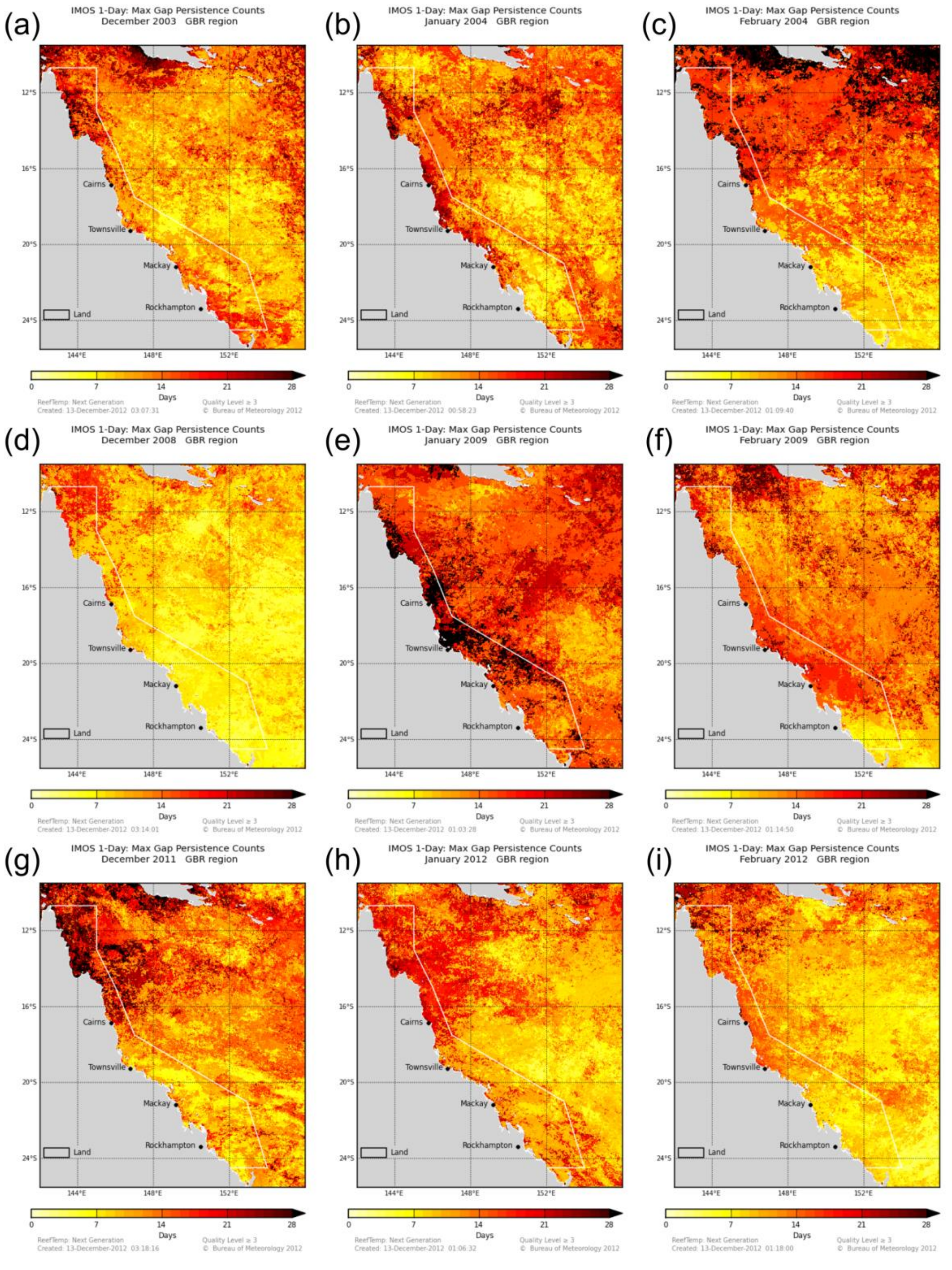


Fig. 8 Example night-time L3S-01day gap persistence counts (days) for (a) December 2003, (b) January 2004, (c) February 2004, (d) December 2008, (e) January 2009, (f) February 2009, (g) December 2011, (h) January 2012 and (i) February 2012. The Australian coastline and GBR marine park boundary are indicated by solid white lines.

3.3 Product Development

There are four primary products that comprise *ReefTemp Next Generation (RTNG)*. These are:

1. Sea Surface Temperature (SST)
2. Sea Surface Temperature Anomaly (SSTA)
3. Degree Heating Days (DHD)
4. Mean Positive Summer Anomaly (MPSA)

These products are each generated using both IMOS-based 1-day L3S SST data and 14-day SST mosaic products. Furthermore, all RTNG products are generated from daily night-time only observations as discussed in Section 3.1.

3.3.1 Sea Surface Temperature

Daily SST values, derived directly from IMOS L3S 1-day products, are shown spatially over the GBR, using the range 20-35°C in 1°C increments (Fig. 9). During the climatological period of 2002-2011, SST values tend to peak around 29°C in the northern GBR and 26°C in the southern GBR during the summer months. Temperatures in the low to mid-twenties (°C) are common during the winter months.

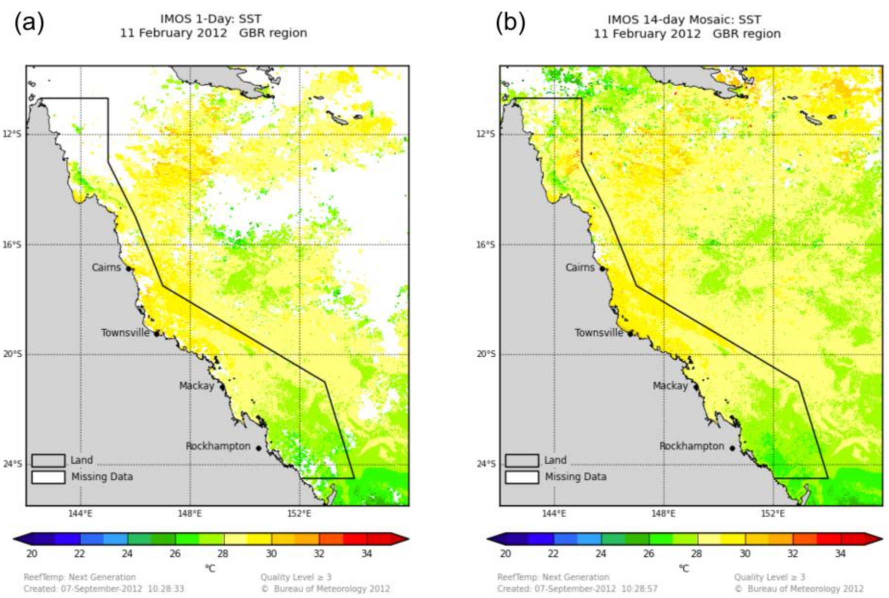


Fig. 9 Example of the IMOS (a) L3S-01day and (b) 14-day mosaic SST products generated by RTNG for 11 February 2012.

3.3.2 Sea Surface Temperature Anomaly

SSTA is calculated at each grid cell as the difference between the current SST condition and the relevant monthly climatology. Figure 10 shows the four RTNG SSTA products, which utilise IMOS 1-day and 14-day mosaic input SST grids, as well as IMOS and CSIRO climatologies. The SSTA product temperature range is from -4°C to 4°C in increments of 0.5°C.

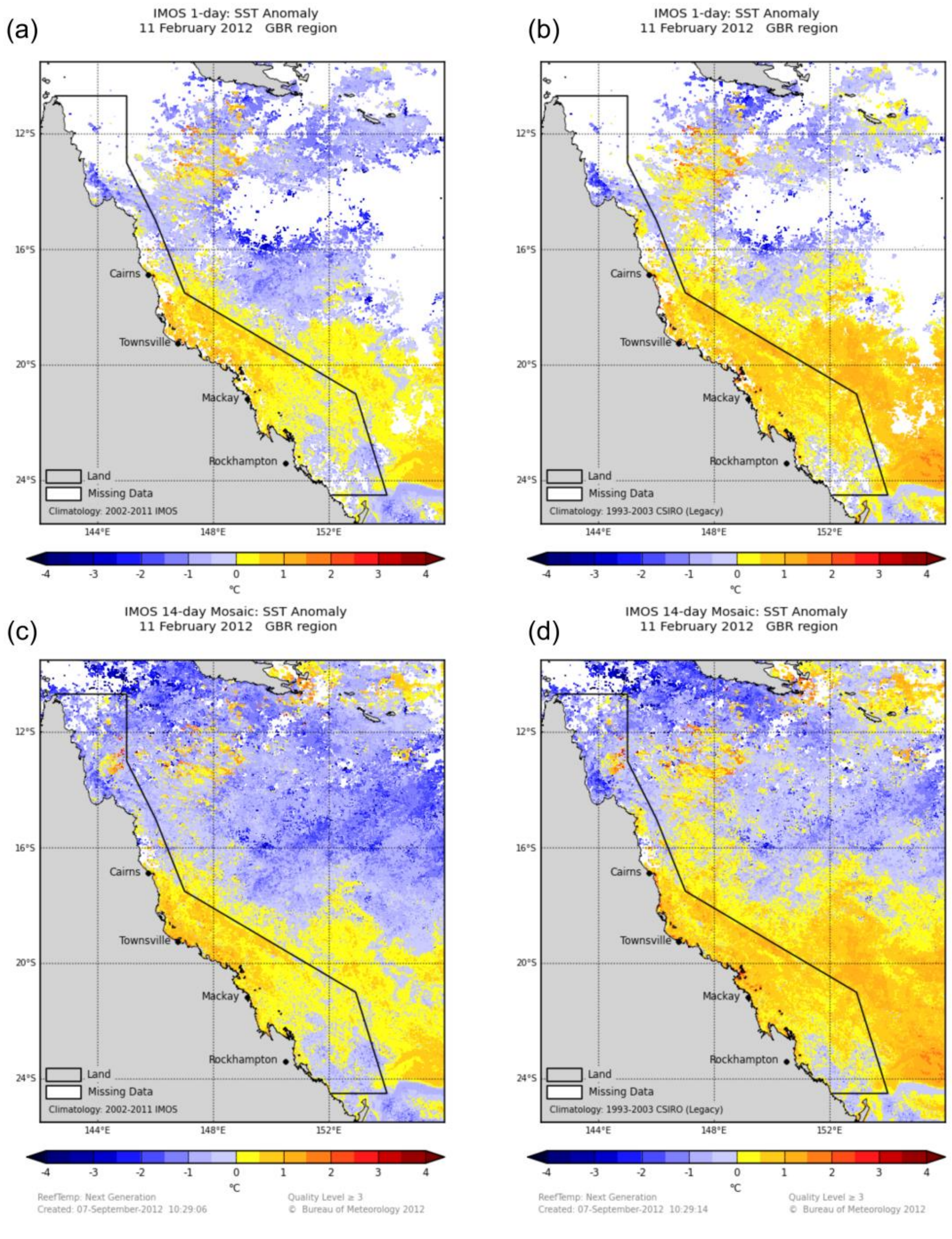


Fig. 10 Example RTNG SSTA products for 11 February 2012. IMOS 1-day SST referenced to (a) IMOS climatology and (b) CSIRO climatology. 14-day SST mosaic referenced to (c) IMOS climatology and (d) CSIRO climatology.

3.3.3 Degree Heating Days

Degree Heating Days (DHD) is a measure of the accumulation of heat stress from 1 December, to 31 March each year. One DHD is calculated as 1°C above the relevant monthly climatology for one day at a particular grid point (x, y). DHD can represent a broad range of heat stress, in that 3 weeks at 1°C above the local long-term average results in the same number of DHDs as 1 week at 3°C, the latter representing more severe stress to corals. Mathematically, DHD can be written as the following:

$$DHD_{x,y} = \sum_{t_0 = 1^{\text{st}}\ \text{Dec}}^{t_1 = today} SSTA_{x,y} \quad \text{where } SSTA > 0°\text{C} \qquad \text{(Equation 1)}$$

Figure 11 illustrates the logic underlying the DHD (and Mean Positive Summer Anomaly) calculation which starts by determining whether the current month is a summer month. If no SST is available at a particular pixel, there is no accumulation to the relevant DHD value (i.e., it remains the same as the previous day). If current date is December 1, DHD grids are reset to 0°C days.

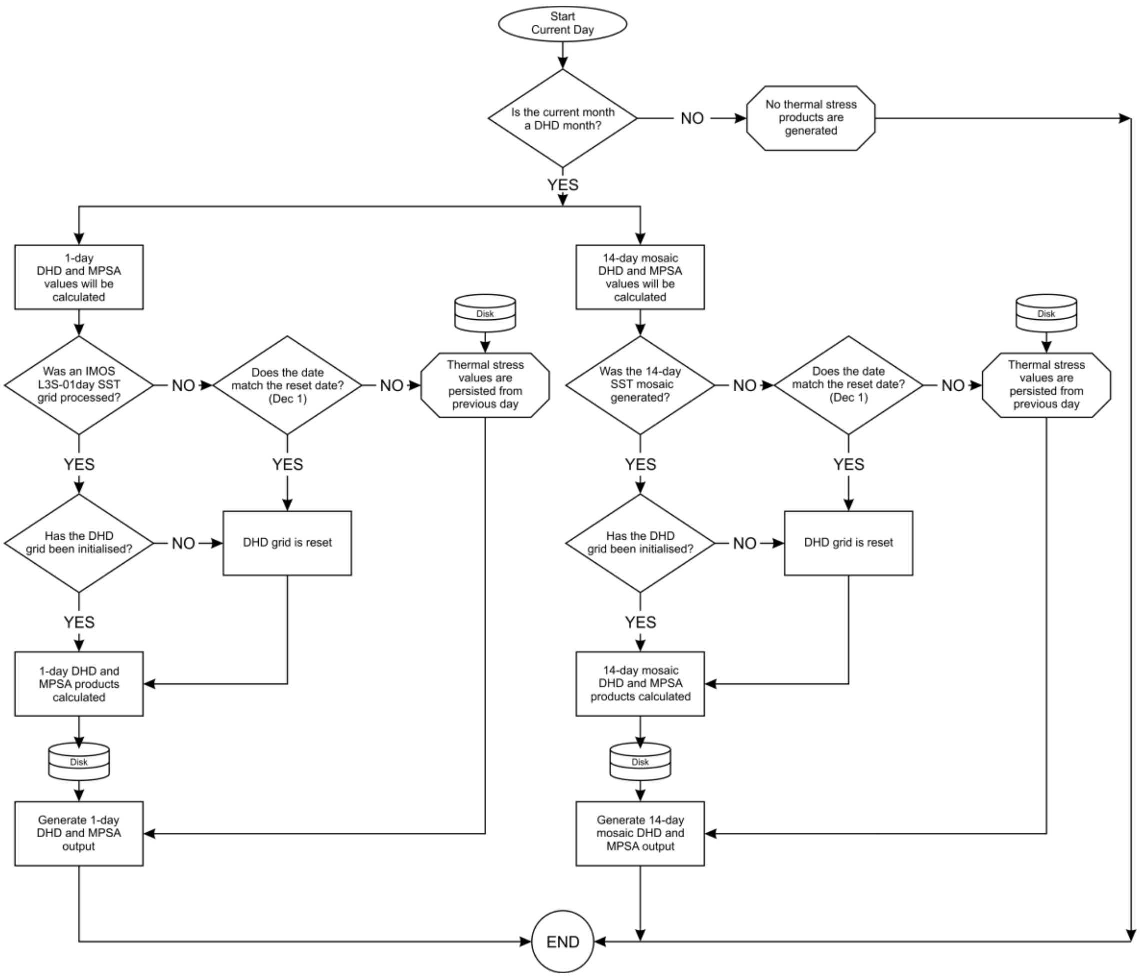


Fig. 11 Flow diagram representing how the IMOS 1-day and 14-day mosaic DHD grids are calculated.

RTNG also produces a complementary product which illustrates occurrences, called DHD counts. This product represents the number of days where the SSTA is greater than 0°C. As a guide, DHD values above 60 generally are a cause of concern for GBRMPA, and are linked to moderate-to-severe bleaching observations (Maynard et al., 2008). Figures 12 and 13 present example DHD values using the L3S-01day and 14-day SST mosaic products respectively. DHD value visualisation range is 0 – 240°C days in increments of 20°C days and DHD counts range from 0 – 120 days in increments of 10 days.

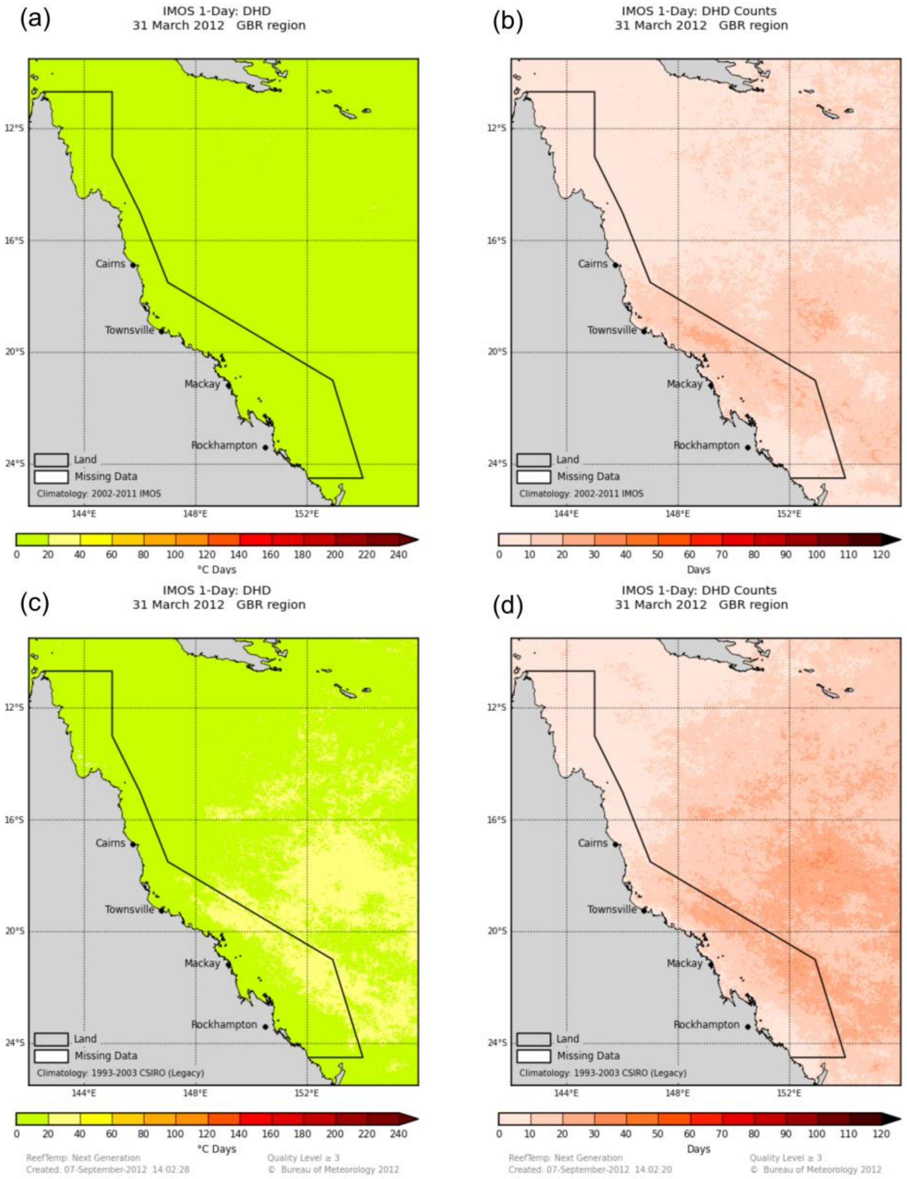


Fig. 12 Example L3S-01day DHD stress index products for 31 March 2012 using (a) IMOS climatology, (b) IMOS climatology DHD counts, (c) CSIRO climatology and (d) CSIRO climatology DHD counts.

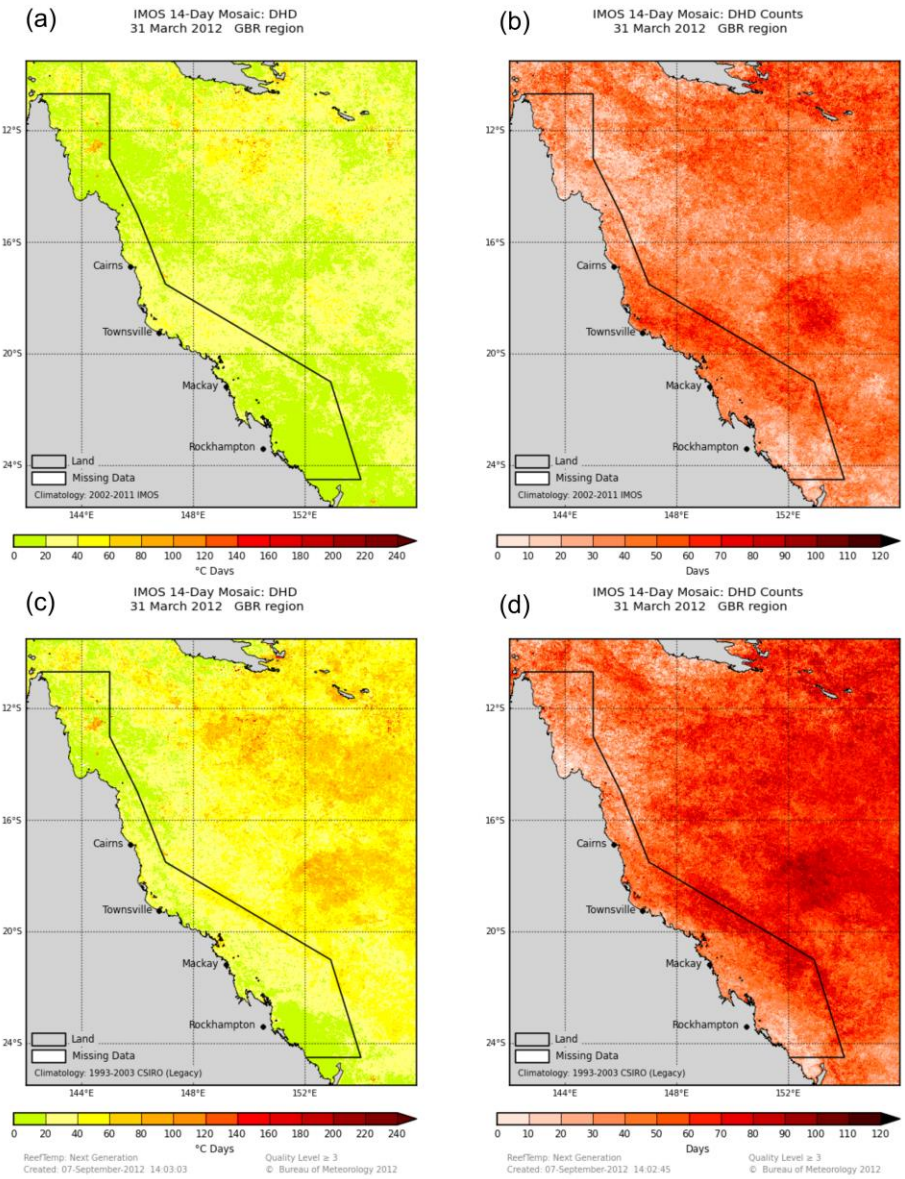


Fig. 13 DHD stress index products using 14-day SST IMOS mosaic for 31 March 2012: (a) IMOS climatology, (b) IMOS climatology DHD counts, (c) CSIRO climatology and (d) CSIRO climatology DHD counts

3.3.4 Mean Positive Summer Anomaly

RTNG also displays the Mean Positive Summer Anomaly (MPSA; formerly known as Heating Rate; Maynard et al 2008), calculated as the number of DHD divided by the number of days in which temperatures have exceeded the monthly climatology, i.e. positive SSTA values (when data was available). Mathematically MPSA can be written as the following:

$$MPSA_{x,y} = \frac{DHD_{x,y}}{DHDcount_{x,y}} \qquad \text{(Equation 2)}$$

MPSA visualisation range is 0-5°C in increments of 0.5°C. Close inspection of Fig. 14 reveals small isolated regions of high MPSA values (orange to red colours). These values represent specific regions of thermal stress which can then be targeted by reef management for further investigation.

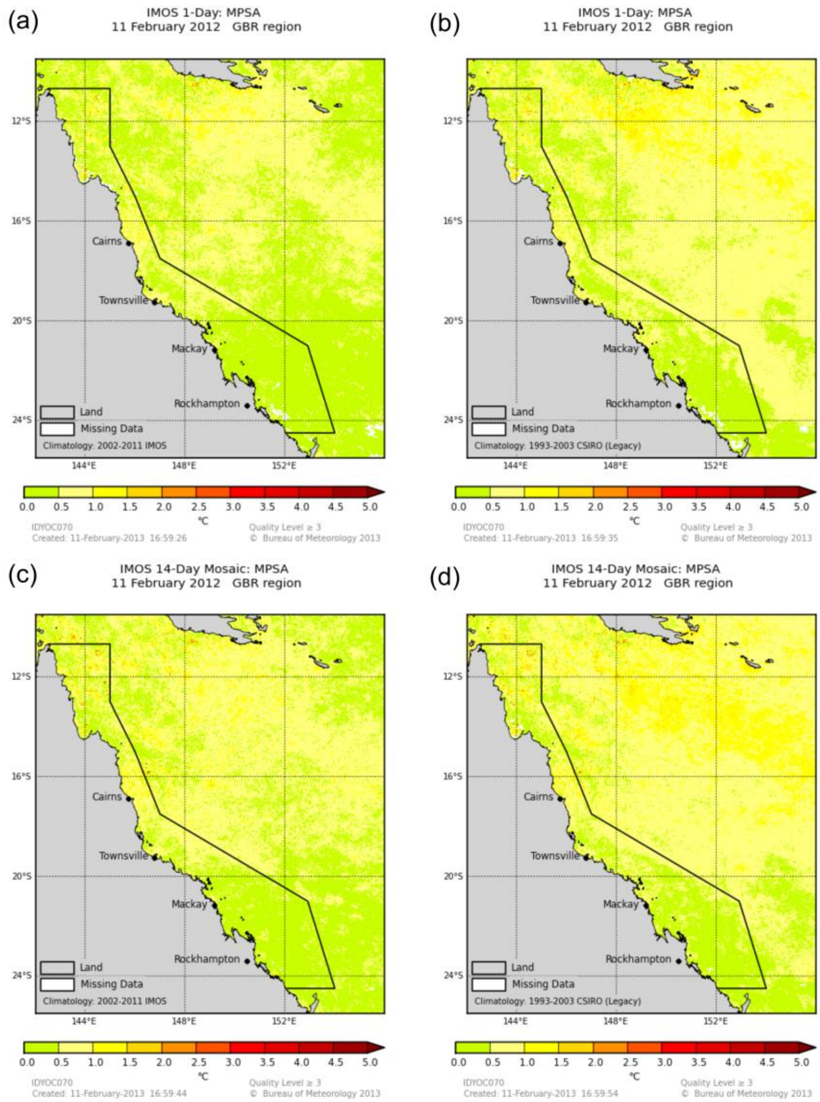


Fig. 14 Example MPSA products for 11 February 2012 for (a) IMOS climatology, (b) CSIRO climatology, 14-day SST mosaic product using (c) the IMOS climatology and (d) the CSIRO climatology

3.3.5 Thermal Stress Product Interpretation

In comparing Figures 12 and 13, it is apparent that DHDs calculated based on the IMOS 1-day SST product do not accumulate to the same magnitude as compared to the 14-day SST mosaic SST product. As shown in Fig. 11, in the event that a daily SST grid is missing, the DHD values remain the same. However, as the 14-day SST mosaic has historical data to draw on and so better spatial coverage, its DHD are allowed to continue accumulating. As stated previously, care must be taken when using the mosaic DHD products as the accumulated DHD may not be a true representation of the current thermal stress.

The observed changes in baseline between the monthly climatologies have implications in the way the thermal stress indices are calculated and how they should be interpreted. As discussed in Section 3.2 (Fig. 6), for most of the GBR region, the IMOS climatology is warmer than the CSIRO climatology. It is therefore not surprising that the DHD values will be higher when using the CSIRO climatology, as it is more likely to observe a positive SSTA and therefore accumulate DHD.

Given the inhomogeneous mosaic concerns raised in Section 3.1.1, it is advised that further research could be targeted at developing a more accurate back-filled daily SST product. Spatial interpolation techniques could be employed which would result in improved spatial coverage. To complement this, at times where no daily SST data are available, the SSTA could be persisted and damped from the previous day. This method would allow DHD values to continue to accumulate instead of being persisted from the previous analysis. However, sensitivity and performance evaluations are needed to measure the accuracy of such a technique.

3.4 Product Visualisation and Delivery

RTNG real-time and historical SST, SSTA and thermal stress products can be viewed online in multiple ways. Delivery methods include:

1. Static images through specific RTNG web pages and Google Earth™ displays
2. eReefs – Marine Water Quality dashboard and OPeNDAP server

1. RTNG website and Google Earth™

As shown in Fig. 15, the RTNG website (development site) provides an introduction to the system as well as a simple user interface. By selecting a date from the top-left calendar, current or historical RTNG products can be viewed. Multiple parameters can be viewed for a selected product by selecting each parameter. In addition, Google Earth™ KMZ files can be downloaded by clicking on the ‘Download KMZ’ button. Useful links, references and product information can be viewed by clicking on the respective link under ReefTemp on the left hand side.

Viewing RTNG products in Google Earth™ provides an interface in which users are able to search, zoom and navigate to specific locations, change the viewing angle, and bookmark favourite locations. Google Earth’s built in ocean layers also allow users to toggle GBR Marine Park boundaries and reef outlines.

To view these products in Google Earth™ (example screenshot shown in Fig. 16), a user must first have downloaded and installed Google Earth™ on a computer. Once installed, RTNG analysis can be viewed by downloading and launching one of the KMZ files. Once open, the following instructions will display a selected product.

1. In the 'Places' panel on the left side of the Google Earth™ window, find the RTNG product folder under 'Temporary Places.'
2. Click on the radio button next to the desired product and parameter for display within the viewing window.
3. Details on each product can be found by clicking on the link 'About These Products' below the product folders.
4. If the full Google Earth™ display cannot be seen (including logos or colour bars), please modify your screen resolution (minimum 1280x1024).

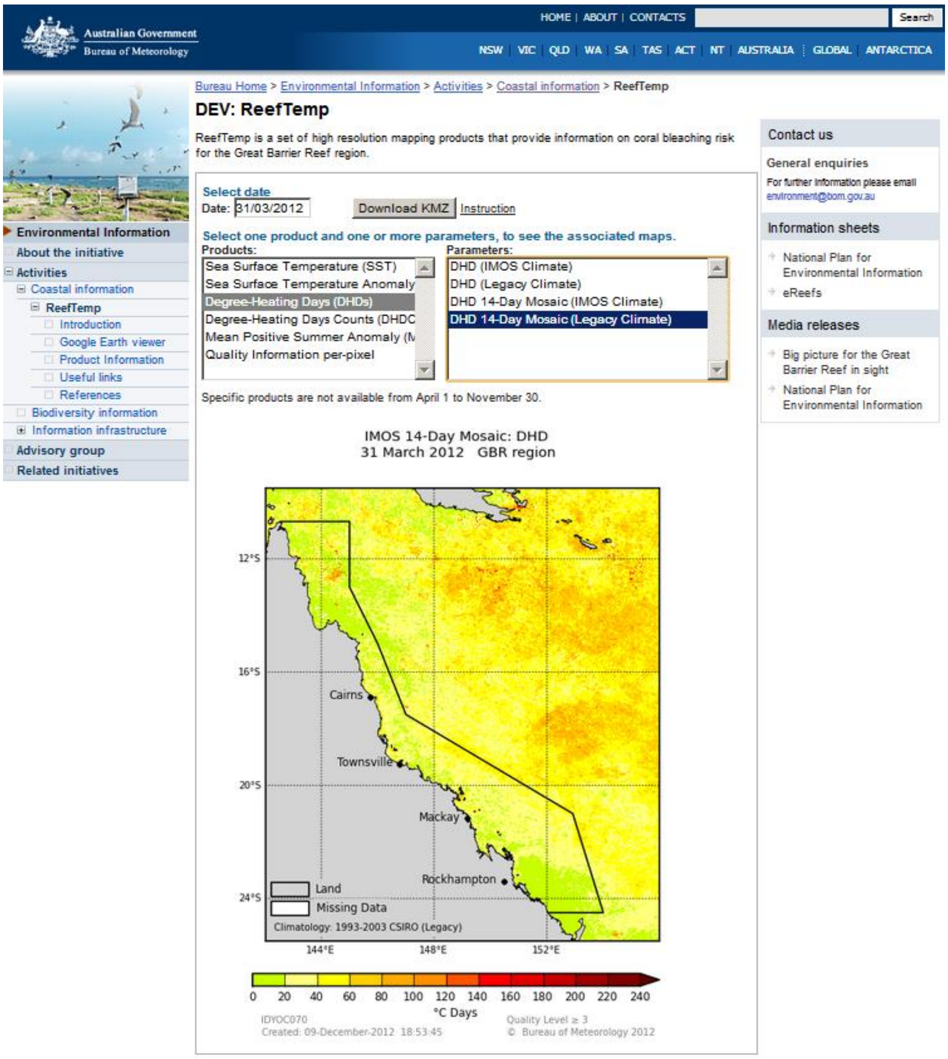


Fig. 15 Screenshot of the ReefTemp Next Generation webpage (screenshot captured during the development phase). DHD data for 31 March 2012 shown.

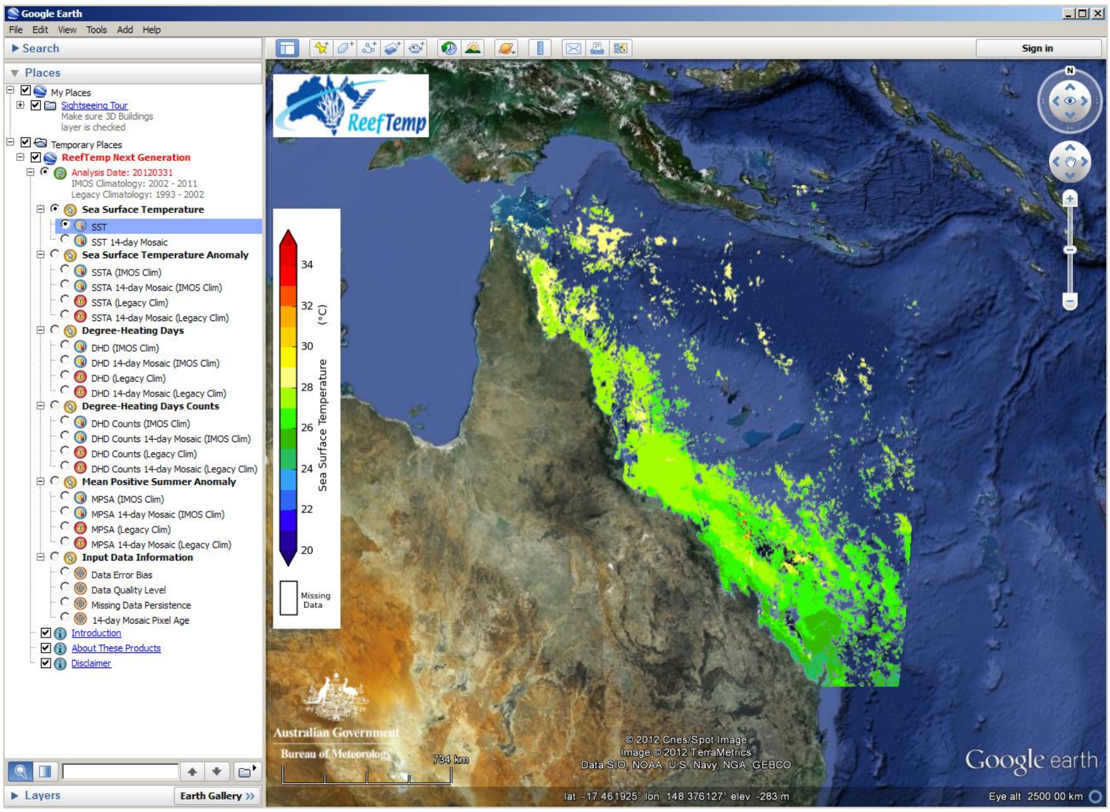


Fig. 16 Screenshot of the RTNG Google Earth™ display illustrating the IMOS 1-day SST product for 31 March 2012.

2. *Dashboard and OPeNDAP server*

The eReefs – Marine Water Quality dashboard visualises products from the RTNG system. By selecting 'Reef Temp Next Gen' from the Browse Panel, a RTNG product can be selected by clicking on the appropriate checkbox (Fig. 17). Once selected, the user can overlay GBRMPA management zones, additional layers or change the map background. In addition, a user can select a GBR region of interest which is then highlighted on the map. The dashboard backend has the ability to source the netCDF data and calculate an area average of a parameter for that region. A time series is generated and displayed. Animations can also be controlled via the dashboard which is important as it allows users to visualise the accumulation of thermal stress. This user interface will see major development throughout 2013.

RTNG netCDF files are also being served via the Bureau OPeNDAP (Open-source Project for a Network Data Access Protocol) server which allows users to use data which are stored remotely with visualisation client software. This server architecture is widely used within the earth sciences community. To use this service, the OPeNDAP URL is simply entered into the client's software.

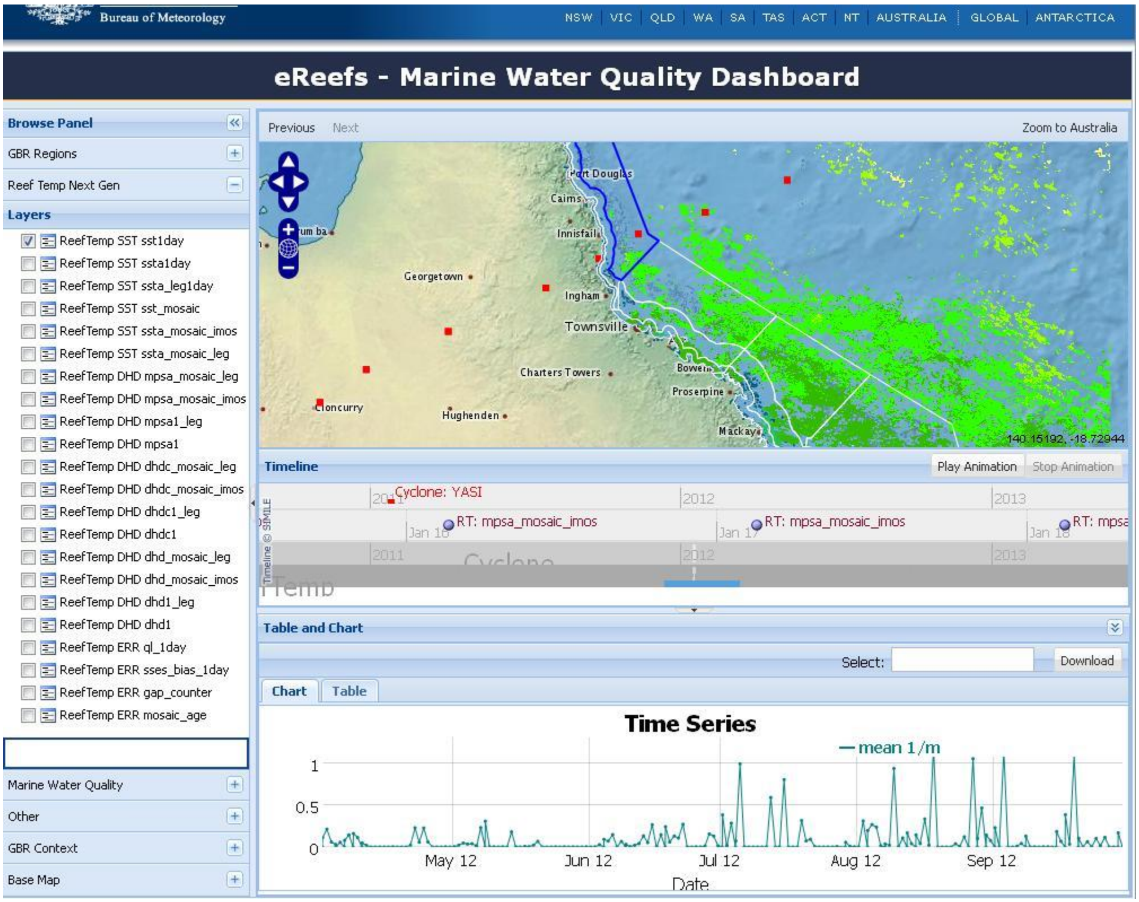


Fig. 17 Screenshot of the eReefs Marine Water Quality Dashboard, highlighting the RTNG layers (screenshot captured during the development phase). Red squares on the map represent the trajectory of TC Yasi (2011). GBRMPA boundaries are also indicated by the wide (and blue) outlines.

4. FUTURE DEVELOPMENT

The development of RTNG has provided the launching pad for additional research. Reef managers are particularly interested in products that document risk of coral disease (e.g. White Syndrome, Black Band disease) as well as cross validation of current RTNG products with coral bleaching data. Additional requests included increased spatial coverage, extension of the RTNG geographical domain beyond the GBR and the facilitation of virtual stations, which are analyses that are targeted at specific reef locations.

Enhancements to this system could include new products for diurnal warming and coral bleaching risk. In its current form, RTNG utilises night-only IMOS L3 1-day data to produce SST products. The capability to capture diurnal warming (warming over the course of the day) would create more refined functionality and provide the first real-time products documenting diurnal warming over the GBR. Coral disease risk can be estimated using SST conditions and coral cover and would be valuable information for management. New RTNG disease risk products could facilitate quick response reef management teams to attend locations of concern within the GBR. The product would also provide an historical overview of disease risk as related to temperature to aid climate change research.

Additional products could include 6-10 day composite and day+night products for greater spatial coverage. Currently a mosaic product has been built to provide a gap-filled SST product for managers, using the L3S 1-day data over the past 14 days. However whilst effective, this approach can produce spatially inhomogeneous results. The next step would be to utilise new IMOS L3S 6-day or 10-day products which provide a more sophisticated weighted average of SST values over the past 6 or 10 days. Likewise, day+night products would incorporate a greater volume of data and would increase the spatial coverage currently possible in the RTNG products.

The RTNG domain is currently limited to the GBR. The geographic region covered could be expanded to the wider Australian region, [70-190°E; 20-70°S], including Ningaloo Reef, Scott Reef, Lord Howe Island, the Coral Sea and the Western Pacific. The expansion of the RTNG domain will significantly increase both functionality and the number of users and applications of RTNG. It will also facilitate comparison with complementary NOAA Coral Reef Watch satellite products over a wider geographic domain.

Nowcasts from RTNG present high resolution SST, SSTA and thermal stress distributions over the GBR at the daily timescale. These nowcasts show current conditions at a 2 km spatial scale, allowing assessment of the current risk of bleaching in particular reef regions. Linking in seamlessly with the daily nowcasts, would be multi-week and seasonal forecasts of coral bleaching risk, generated using the dynamical prediction system POAMA (Prediction Ocean Atmosphere Model for Australia). Seasonal POAMA forecasts of bleaching risk for the GBR are currently already produced operationally at the Bureau and are the first in the world to utilise a dynamical GCM (General Circulation Model) in the prediction of coral bleaching conditions (Spillman 2011a; 2011b) . They are an important component in management plans and strategic frameworks for the GBR, including the GBRMPA Early Warning System for coral bleaching (Maynard et al. 2009).

This multi-scale reef information presentation would allow reef managers to assess the current thermal conditions at the reef scale then move forward in time to predicted regional temperatures to enable them to plan their activities for the upcoming season. The provision of both the observation-based nowcasts and forecasts on different spatial scales in real-time provides reef management to the most up-to-date information and hence facilitates proactive management. Forecasts on a weekly to seasonal timescale are particularly useful for reef managers as they provide advance notice of potential bleaching conditions, allowing for implementation of management strategies prior to bleaching onset (Spillman and Alves 2009). This would also synergise with other projects looking at intra-seasonal to seasonal climate risk products.

5. SUMMARY

RTNG is a sophisticated new state-of-the-art nowcast remote sensing system that monitors ocean temperature and associated coral bleaching risk over the GBR. The development and operational support for these types of systems is extremely important as the frequency and severity of coral bleaching is expected to increase due to climate change.

RTNG is based on the new multi-sensor composite AVHRR SST L3S 1-day night-only product developed as part of IMOS. RT1 products have been reconfigured in the new system to use this new data stream and updated climatologies. These products include SST, SSTA, DHD and MPSA. New 14-day SST mosaic products have also been developed to address the issue of missing data. Additionally, new products have been created to provide complementary information as to the number of data points used to construct climatologies, length and persistence of data gaps and data errors. Products are available online as static images through tailored RTNG web pages, in Google Earth™ and in the new Marine Water Quality dashboard.

This research also presented an opportunity to rethink both the design and delivery of the thermal stress products to best address the needs of the reef managers. This was undertaken in close consultation with end users, such as the GBRMPA and NOAA, to ensure that the new system addressed user needs. RTNG provides reef management with the means of better monitoring thermal stress events and when coral bleaching is likely, targeting both response actions and in-situ observations of stress impacts.

6. ACKNOWLEDGMENTS

The authors would like to acknowledge Dr. Oscar Alves, Dr. Debbie Hudson, Aurel Griesser, Elaine Miles, Griffith Young, Kevin Keay (Centre for Australian Weather and Climate Research, Australian Bureau of Meteorology), Dr. Scott Heron (National Oceanic and Atmospheric Administration), Roger Beeden (Great Barrier Reef Marine Park Authority) and Dr. Jeffrey Maynard (Maynard Marine Consulting) for their guidance, helpful discussion and suggestions given to the authors during the preparation of this manuscript. Thanks is also extended to the staff at GBRMPA for their support and feedback during the ReefTemp Next Generation development process. The authors also thank the reviewers of this document for the comments and suggestions.

Data was sourced from the Integrated Marine Observing System (IMOS). IMOS is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and the Super Science initiative. Raw HRPT AVHRR SST data was collected by the Australian Bureau of Meteorology in collaboration with Australian Institute of Marine Science (AIMS) and CSIRO Marine and Atmospheric Research. Finally, thanks also to the reviewers of this manuscript. Funding provided by eReefs/NPEI.

REFERENCES

Australian Bureau of Meteorology 2011: Annual Climate Summary 2010. January 2011. pp 20

Baker, A., Glynn, P.W. and Riegl, B. 2008: Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuar. Coast. Shelf Sci.* **80**, 435–71

Beeden, R.J., Maynard, J.A., Marshall, P., Heron, S. and Willis, B. 2011: A framework for responding to coral disease outbreaks that facilitates adaptive management. *Environmental Management*, 1-11-11. http://dx.doi.org/10.1007/s00267-011-9770-9

Berkelmans, R., De'ath, G., Kininmonth, S. and Skirving, W. J. 2004: A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. *Coral Reefs*, **23**, 74–83. doi:10.1007/s00338-003-0353-y

Brown, B.E. 1997: Coral bleaching: causes and consequences. *Coral Reefs*. **16**, doi:10.1007/s003380050249

Casey, K., Donlon, C. and the GHRSST Science Team. 2011. The recommended GHRSST Data Specification (GDS) 2.0, Revision 4 [online], 7 November 2011, 123 pp. https://www.ghrsst.org/documents/q/category/gds-documents/operational/

Donlon, C.J., Minnett, P.J. Gentemann, C. Nightingale, T. J. Barton, I. J. Ward, B. and Murray, J. 2002: Toward improved validation of satellite sea surface skin temperature measurements for climate research. *Journal of Climate*, **15,** 353-69

Donner S.D., Skiving, W., Little C.M., Oppenheimer M. and Hoegh-Guldberg O. 2005: Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology,* 11, 1-15, doi: 10.1111/j.1365-2486.2005.01073.x

Donner S. D. 2009: Coping with Commitment: Projected Thermal Stress on Coral Reefs under Different Future Scenarios. *PLoS ONE* **4**(6): e5712. doi:10.1371/*journal.pone*.0005712

Frieler, K., Meinshausen, M., Golly, A., Mengel, M., Lebek, K., Donner, S.D. and Hoegh-Guldberg, O. 2012: Limiting global warming to 2°C is unlikely to save most coral reefs. *Nature Climate Change, 2*(9), 1–6. doi:10.1038/nclimate1674

Gentemann, C.L., Donlon, C.J., Stuart-Menteth, A. and Wentz, F.J. 2003: Diurnal signals in satellite sea surface temperature measurements, *Geophs. Res. Lett.,* **30**, 1140, doi:10.1029/2002GL016291

Glynn, P.W. 1993: Coral reef bleaching: ecological perspectives. *Coral Reefs*, **12**, 1-17

Griffin, D.A., Rathbone, C.E., Smith, G.P., Suber, K.D. and Turner, P.J. 2004: *A Decade of SST Satellite Data*. Final Report for the National Oceans Office, Contract NOOC2003/020, 1-8

Hennessy, K., Fitzharris, B., Bates, B.C., Harvey, N., Howden, S.M., Hughes, L., Salinger J. and Warrick, R. 2007: Australia and New Zealand. Climate Change 2007: *Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 507-40

Heron, S. et al. 2012: Developments in understanding relationships between environmental conditions and coral disease. *Proceedings of the 12th International Coral Reef Symposium*, Cairns, Australia, 9-13 July 2012 (pp. 9–13)

Hoegh-Guldberg, O. 1999: Climate change, coral bleaching and the future of the world's coral reefs. *CSIRO: Marine and Freshwater Research*, **50**, 839-66

Hoegh-Guldberg, O., Mumby P.J., Hooten A.J., Steneck R.S., Greenfield P., Gomez E., Hardvell C.D., Sale P.F., Edwards A.J., Caldeira K., Knowlton N., Eakin C.M.,Iglesias-Prieto R., Muthiga N., Bradbury R.H., Dubi A. and Hatziolos M.E. 2007: Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science*. **318**, 1737-1742, doi: 10.1126/science.1152509

Jones, R.J, Hoegh-Guldberg, O., Larkum, A.W.D. and Schreiber, U. 1998: Temperature-induced bleaching of corals begins with impairment of the CO_2 fixation mechanism in zooxanthellae. *Plant, Cell and Environment*. **21**, 1219-30

Lesser, M. P. 2004: Experimental biology of coral reef ecosystems. *Journal of Experimental Marine Biology and Ecology.* **300**, 217-52

Liu, G., Strong, A.E., Skirving W. and Arzayus. L.F. 2006: Overview of NOAA Coral Reef Watch Program's near-real time global satellite coral bleaching monitoring activities. *Proc. 10th Int. Coral Reef Symp.,* Okinawa, Japan, 1783-93

Lough, J.M. 2008: Shifting climate zones for Australia's tropical marine ecosystems, *Geophysical Research Letters*, **35**, L14708, doi: 10.1029/2008GL034634

Maynard, J.A., Turner, P.J., Anthony, K.R.N., Baird, A.H., Berkelmans, R., Eakin, C.M., Johnson, J., Marshall, P.A., Packer, G.R., Rea A. and Willis, B.L. 2008: *ReefTemp:* An interactive monitoring system for coral bleaching using high-resolution SST and improved stress predictors. *Geophysical Research Letters*, **35**, L05603, doi:10.1029/2007GL032175

Maynard, J.A., Johnson, J.E., Marshall, P.A., Eakin, C.M., Goby, G., Schuttenberg, H. and Spillman, C.M. 2009: A strategic framework for responding to coral bleaching events in a changing climate. *Environmental Management*, **44**, 1-11, doi:10.1007/s00267-009-9295-7

Minnett, P.J. 2003: Radiometric measurements of the sea–surface skin temperature—the competing roles of the diurnal thermocline and the cool skin. *International Journal of Remote Sensing*, **24** (24), 5033–47

Montgomery, R.S. and Strong, A. 1995: Coral bleaching threatens ocean, life, *EOS*, **75**, 145-7

Paltoglou, G., Beggs H. and Majewski, L. 2010: New Australian High Resolution AVHRR SST Products from the Integrated Marine Observing System, *In: Extended Abstracts of the 15th Australasian Remote Sensing and Photogrammetry Conference, Alice Springs, 13-17 September, 2010.* http://imos.org.au/srsdoc.html

Rea, A. 2004: Recent Improvements to the NOAA AVHRR SST Product at the Australian Bureau of Meteorology**,** *Presented to the Fifth GODAE High Resolution SST Pilot Project*

Science Team Workshop, Townsville, Australia, 25-30th July, 2004, http://imos.org.au/srsdoc.html

Saunders, R.W. and Kriebel, K.T. 1998: An improved method for detecting clear sky and cloudy radiances from AVHRR data. *International Journal of Remote Sensing*, **9**, 123-50

Spillman, C.M. 2011a: Advances in forecasting coral bleaching conditions for reef management. *Bulletin of the American Meteorological Society*, **94**, 1426-31

Spillman, C.M. 2011b: Operational real-time seasonal forecasts for coral reef management. *Journal of Operational Oceanography*, **4**, 13-22

Spillman C.M. and Alves, O. 2009: Dynamical seasonal prediction of summer sea surface temperatures in the Great Barrier Reef. *Coral Reefs*, **28**, 197-206

Ward, B. 2006. Near-surface ocean temperature. *Journal of Geophysical Research*, **111**, C02005

Weeks, S. J., Anthony, K.R.N., Bakun, A., Feldman, G.C. and Hoegh-Guldberg, O. 2008: Improved predictions of coral bleaching using seasonal baselines and higher spatial resolution. *Limnology and Oceanography*, **53**, 1369–75. doi:10.4319/lo.2008.53.4.1369

Wilkinson, C. 2008: *Status of coral reefs of the world*: 2008. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia, 296 p

The Centre for Australian Weather and Climate Research is a partnership between CSIRO and the Bureau of Meteorology.