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An evaluation of Australian continental shelf sea surface temperature estimates from Bluelink ReANalysis

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TRANSLATING**NATURE**INTO**KNOWLEDGE**

An evaluation of Australian continental shelf sea surface temperature estimates from Bluelink ReANalysis

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1 Introduction

Accurate estimates of near-shore temperatures is of great importance not only for our understanding of marine climate in the near-shore environment but also for the interaction between marine climate and the local marine ecology. For example, certain marine species have temperature thresholds, below which they cannot survive, such as the spiny sea urchin (*Centrostephanus rodgersii*) which requires water temperatures ≥12°C for successful larval development [2]. While observational products exist, these tend to be either gappy in time and space (e.g., remotely-sensed SST) or only representative of a point location (e.g., an in-situ mooring site such as the Maria Island Time Series operated by the Integrated Marine Observing System; http://imos.aodn.org.au).

Bluelink ReANalysis (BRAN) is an ocean reanalysis product which aims to provide high-quality daily estimates of the three-dimensional ocean state around Australia over the last two decades. While BRAN Version 2 largely succeeds in this respect for the deep ocean environment it does not perform well in the near-shore environment [5] (hereafter OH14). This is due in part to an underlying ocean model which does not properly resolve near-shore ocean processes, does not represent well near-shore bathymetry and coastlines, and uses coarse atmospheric forcing fields and in part to a data assimilation system which omits much of the near-shore observational measurements. OH14 developed a method to improve the near-shore SST climate predictions from BRAN Version 2 by taking advantage of near-shore–deep-ocean statistical connection and the relatively high-quality BRAN estimates in the deep ocean.

BRAN has recently been updated to Version 3 and this update includes changes to the ocean model and the data assimilation system. This report will compare BRAN Versions 2 and 3 in terms of their quality, as compared to observations, of near-shore SST estimates.

2 Observed and reanalysed continental shelf ocean temperatures

Daily fields of observed SSTs from the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Version 5.2 data set [1] were obtained for the period 1/1/1993 to 31/12/2008. Each daily field is defined on a 4 km resolution grid. Reanalysed SSTs were obtained from both BRAN Versions 2.1 and 2.2 [3, 6] and Version 3.5 [4]. Daily fields of SST from BRAN 2.1 (14/10/1992 to 30/12/2006) and from BRAN 2.2 (period 29/11/2006 to 13/5/2008) were merged by a linearly weighted average over the 30 days of overlap between them. The combined dataset is referred to as BRAN2. Daily fields of SST from BRAN 3.5 (1/1/1993 to 31/12/2008) were also obtained and referred to as BRAN3. Both BRAN2 and BRAN3 are defined on the same 1/10° resolution horizontal grid. When comparing BRAN against observations, only data from the nearest observation grid point is used.

The primary differences between BRAN2 and BRAN3 in the present context lie in the underlying ocean models and the data assimilation systems [4]. While both BRAN2 and BRAN3 use the Ocean Forecasting Australia Model (OFAM), BRAN2 uses OFAM1 while BRAN3 uses OFAM2. Both OFAM1 and OFAM2 are based on the GFDL Modular Ocean Model (MOM; versions MOM40d and MOM3p1 respectively) and are eddy-resolving (1/10°) in the greater Australian region (90°E to 180°E and south of ∼20°N). OFAM1 (OFAM2) has a vertical resolution of 10 m (5 m) at the surface, is forced by 6-hourly unaltered ERA-40 (3-hourly globally balanced ERA-Interim) fields, and the two models use different vertical mixing schemes and bathymetry [4]. Both BRAN2 and BRAN3 reanalysis systems (BODAS 5.0 and BODAS 8.2 respectively) have assimilated AVHRR observations of SST: BRAN2 assimilated SST every 7 days using a 1 day window around the assimilation time point while BRAN3 assimilated SST every 4 days using a 5 day window around the assimilation time point. Furthermore, and critically for the present study, BRAN2 assimilated AVHRR SST data at a horizontal resolution of 54 km and only in water depths greater than 200 m while BRAN3. assimilated AVHRR SST data at a much higher horizontal resolution of 4 km and in all ocean cells within 100 km of the coast.

For the observations and the reanalyses we have extracted a time series of SST at each grid cell, denoted T_t where t is a time index. This time series was then decomposed into a sum of three components:

$$T_t = \bar{T} + T_t^{\mathrm{S}} + T_t', \tag{1}$$

where $\bar{T}$ is the time-mean, T_t^{S} is the seasonal cycle (calculated by harmonic regression using the annual cycle and the first two harmonics), and T_t' is the residual (non-seasonal) variability, defined as the variability remaining after removing the mean and seasonal cycle (following OH14). The seasonal cycle and residual variability time series of BRAN2 and BRAN3 were compared against the observations by calculating the correlation coefficient and root mean squared errors (RMSEs). The mean SST was compared against the observations using the measure of "quality" Q defined by OH14: $Q = 1 - \left|(\bar{T}_{\mathrm{BRAN}} - \bar{T}_{\mathrm{Obs.}})/\bar{T}_{\mathrm{Obs.}}\right|$. For both the correlation and the quality, values of one indicate perfect correspondence between the reanalysed and the observed SSTs while values less than one indicate a departure between model and observations.

It is recognized that the residual SSTs contain variability on a variety of time scales, from daily[1] and weekly through to intraseasonal, interannual and longer: in other words, all variability that is not captured by the seasonal cycle. Therefore, we further decompose the residual T'_t into three components at time t:

$$T'_t = T^{\mathrm{D}}_t + T^{\mathrm{M}}_t + T^{\mathrm{A}}_t \tag{2}$$

where the terms represent variability on daily to sub-monthly time scales (T^{D}_t, "daily"), monthly to annual time scales (T^{M}_t, "monthly") and interannual and longer time scales (T^{A}_t, "yearly") respectively. Definitions of these three quantities are provided in Appendix A. For each time scale component we compare reanalysed and observed SSTs using correlation coefficients and RMSEs. Hereafter, "residual" variability refers to T'_t while its decomposition into three times scales, T^{D}_t, T^{M}_t, T^{A}_t, are referred to as "daily", "monthly", and "yearly" variability respectively.

3 Quality of reanalysed continental shelf ocean temperatures

Examples of the performance of BRAN products on the Australian continental shelf are shown for the total SST, SST seasonal cycle, and residual SST in Bass Strait ([40°S,147°E]; Figure 1) and in Spencer Gulf ([34.5°S,136.6°E]; Figure 2). In Bass Strait, total SST from BRAN3 clearly tracks the observed SST closer than does BRAN2 (Figure 1, upper panel) and it is particularly notable how poorly BRAN2 performs at capturing the residual SST (Figure 1, lower panel). In Spencer Gulf, the disparity between total SST from BRAN2 and the observations is even more clear. BRAN2 performs poorly at capturing not only the residual SST (Figure 2, lower panel) but also the seasonal cycle (Figure 2, middle panel) and even the mean SST (evident from Figure 2, upper panel).

Maps showing the quality the mean SST $\bar{T}$, SST seasonal cycle T^{S}, and residual SST T' for BRAN2 and BRAN3 can be seen in Figure 3. It is clear that both BRAN2 and BRAN3 provide high quality estimates of SST in the deep ocean region, with the possible exception of residual SST in the eddy-rich Antarctic Circumpolar Current. It is also clear that generally BRAN2 performs poorly in the near-shore region. BRAN3 however, offers a significant improvement over BRAN2 in the near-shore particularly in terms of the mean SST (most notably in the South Australian Gulfs, the Great Australian Bight, and in Bass Strait) and the residual SST (essentially everywhere). In fact, residual SST correlations against observations have increased

[1]Note that the shortest time scale resolved by BRAN and AVHRR is in fact an oscillation period of two days, i.e., the Nyquist frequency for daily-sampled data.

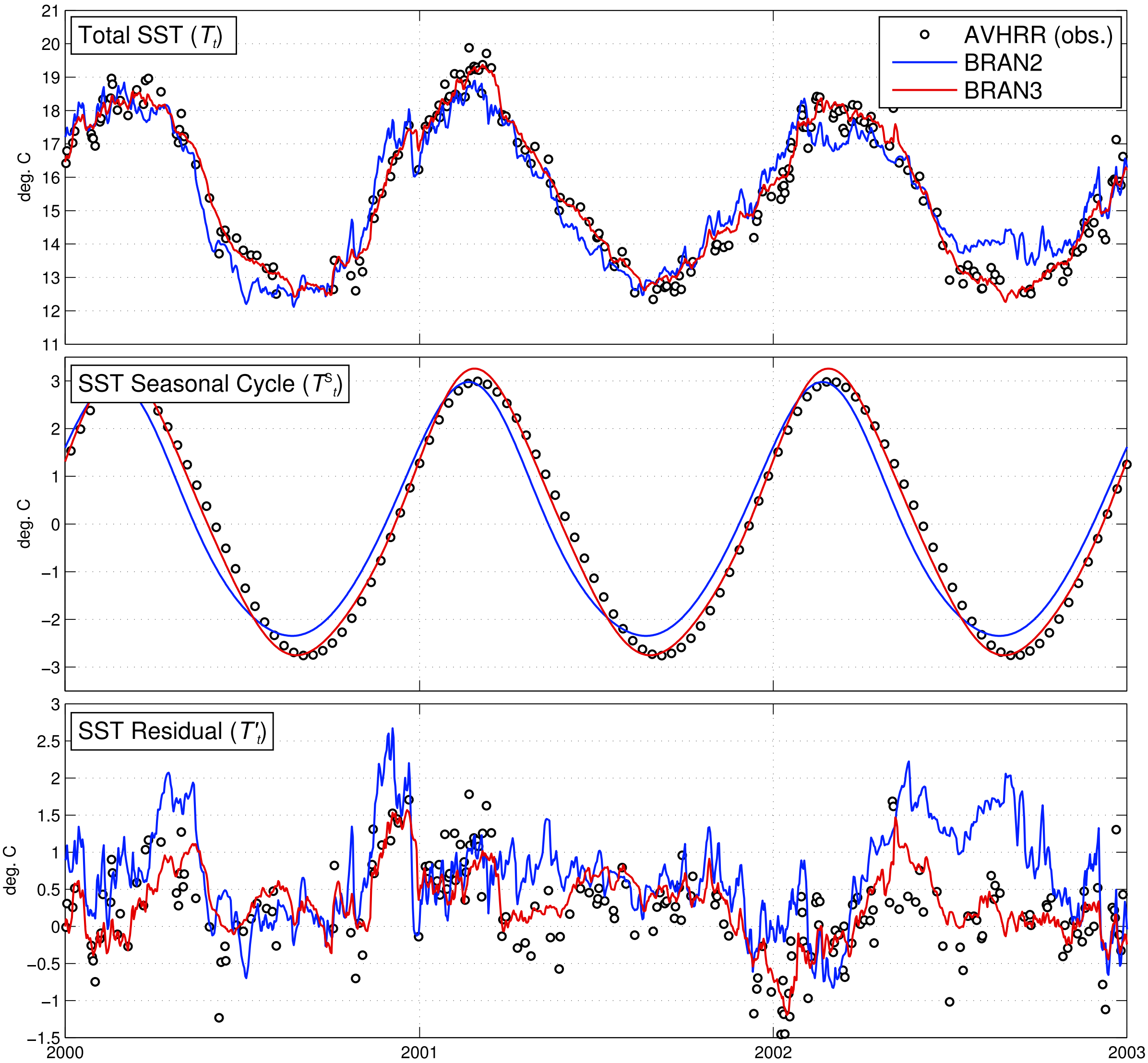

Figure 1: Time series of observed and reanalysed SST in Bass Strait [40°S,147°E]. Total SST is shown in the upper panel, SST seasonal cycle in the middle panel and residual SST in the lower panel for observations (dots), BRAN2 (blue line), and BRAN3 (red line).

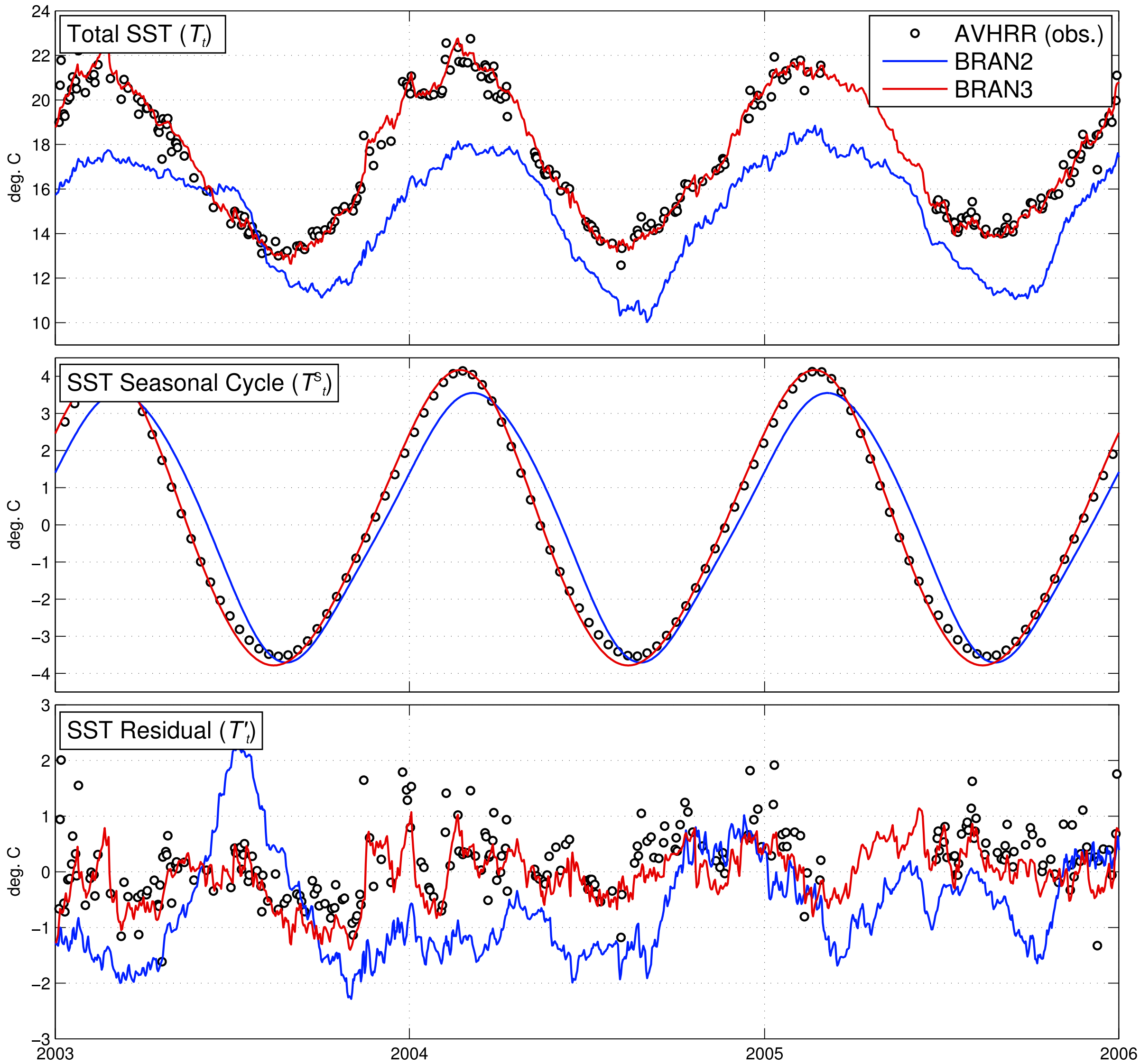

Figure 2: Time series of observed and reanalysed SST in Spencer Gulf [34.5°S,136.6°E]. Total SST is shown in the upper panel, SST seasonal cycle in the middle panel and residual SST in the lower panel for observations (dots), BRAN2 (blue line), and BRAN3 (red line).

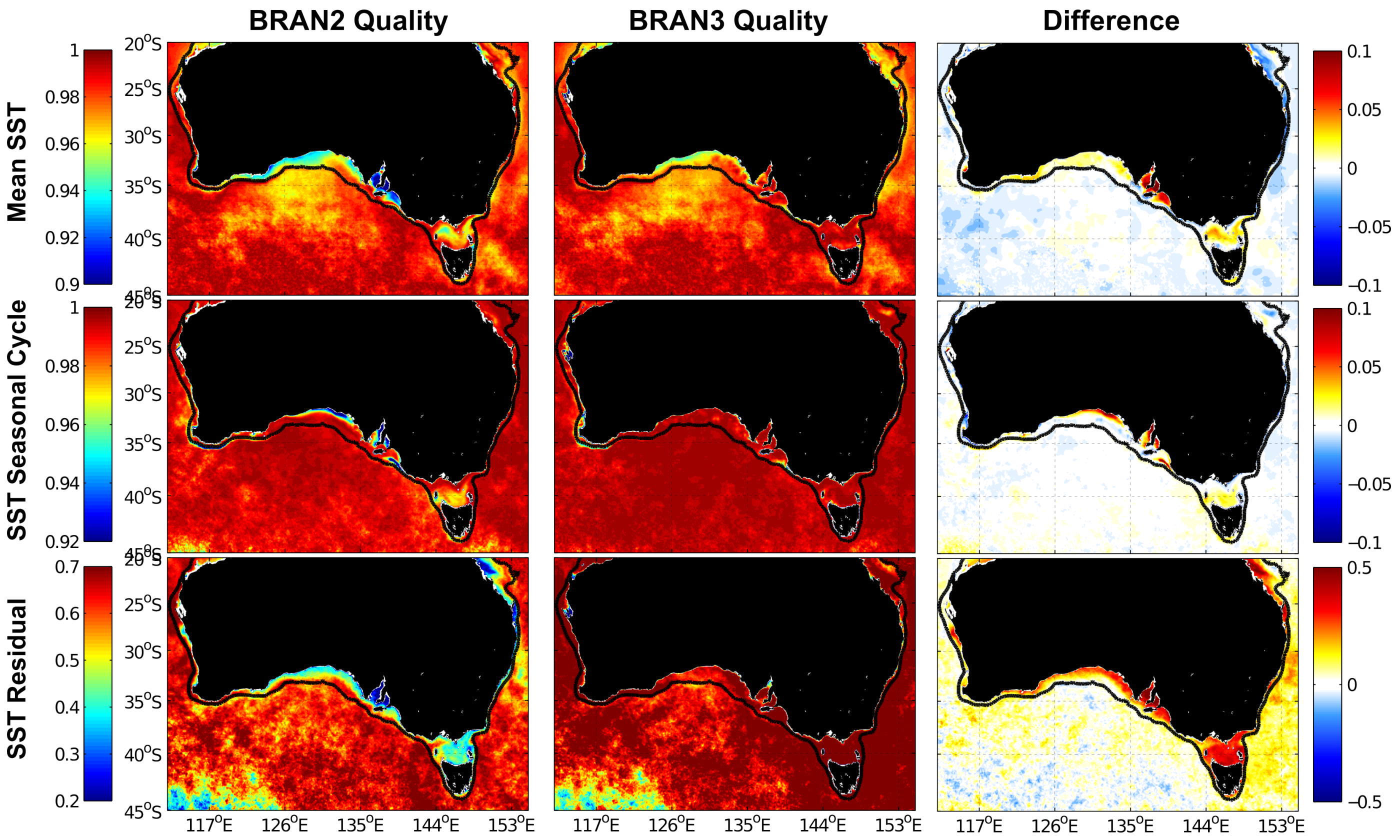

Figure 3: Quality maps of BRAN2 and BRAN3 SST. The quality Q of mean SST (T^{M}, upper row), SST seasonal cycle (T^{S}, middle row) and residual SST (T', bottom row) is shown for BRAN2 (left column) and BRAN3 (right columns). The change in quality (BRAN3 quality minus BRAN2 quality) is shown in the right column. The thick black contour indicates the 200 m isobath, used to represent the continental shelf break.

by up to 0.5 over much of the continental shelf. The improvement of BRAN3 over BRAN2 in the near-shore seasonal cycle is much weaker

Maps showing the quality the daily SST T^{D}, monthly SST T^{M}, and yearly SST T^{A} for BRAN2 and BRAN3 can be seen in Figure 4. Again, it is clear that both BRAN2 and BRAN3 provide high quality estimates of SST in the deep ocean region, although both versions of BRAN have difficulty reproducing SST on daily time scales. It is also clear that BRAN2 performs poorly in the near-shore region. BRAN3 however, offers a significant improvement over BRAN2 in the near-shore for daily, monthly and yearly SSTs. Correlations have increased significantly: by up to 0.3 for daily SST, 0.6 for monthly SST, and 0.5 for yearly SST. Interestingly, BRAN3 provides a reduction in quality, by up to 0.5 correlation, for yearly SSTs in much of the deep ocean region.

A summary of the quality of BRAN2 and BRAN3 SSTs, grouped by region, is shown in Table 1. The regions (Western Australia [WA], The Great Australian Bight [GAB], Bass Strait [BASS],

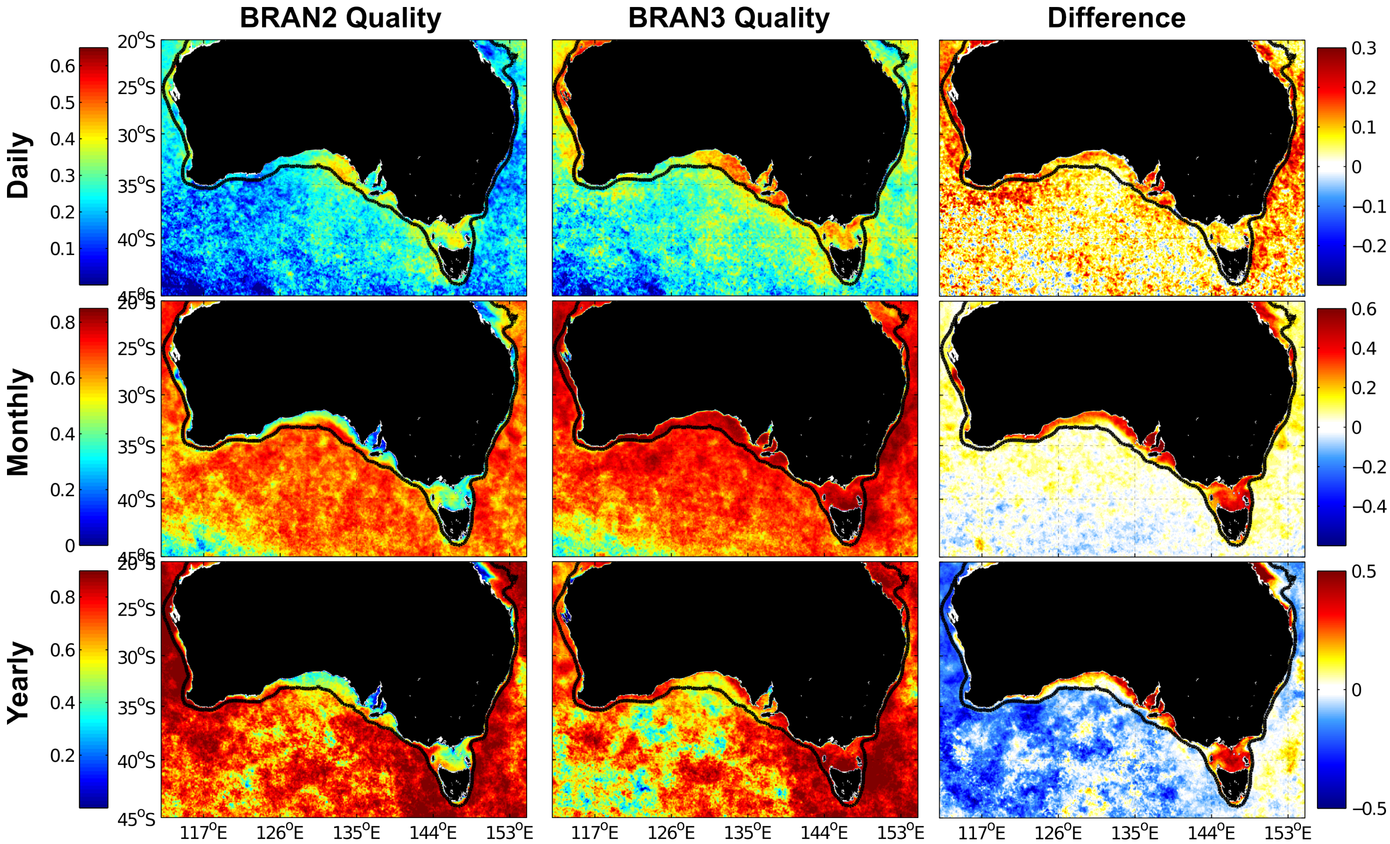

Figure 4: Quality maps of BRAN2 and BRAN3 SST. The quality Q of daily SST (T^{D}, upper row), monthly SST (T^{M}, middle row) and yearly SST (T^{A}, bottom row) is shown for BRAN2 (left column) and BRAN3 (right columns). The change in quality (BRAN3 quality minus BRAN2 quality) is shown in the right column. The thick black contour indicates the 200 m isobath, used to represent the continental shelf break.

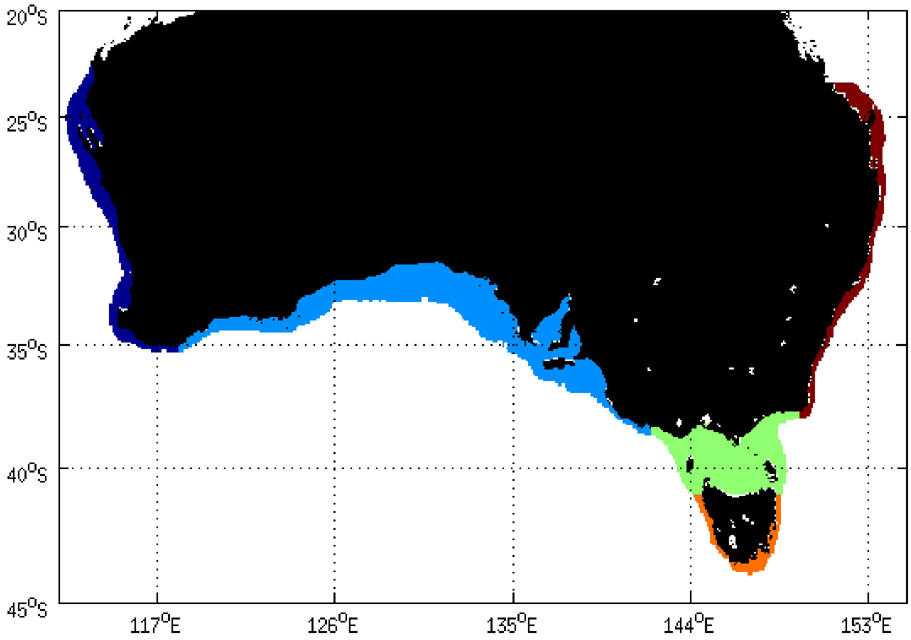

Figure 5: Definition of the regions used in the region-based analysis presented in Tables 1 and 2. The regions are defined by colour: Western Australia [WA] in dark blue, The Great Australian Bight [GAB] in light blue, Bass Strait [BASS] in green, Tasmania [TAS] in orange, and the East Coast [EAST] in red.

Tasmania [TAS], and the East Coast [EAST]) are defined as shown in Figure 5. BRAN3 nearly always provides an improvement in quality over BRAN2. Most notable is the improvement of residual SST on monthly and yearly time scales in the Great Australian Bight, Bass Strait, Tasmania, and along the East Coast. Residual SSTs variability on daily time scales are also improved but much less so than SST variability on longer time scales. Furthermore, Western Australia is a region in which the improvement is least notable, although this may be because SST in this region was better simulated by BRAN2 than was SST in other regions and so there is less of an improvement to be had. However, if we examine the SST errors (Table 2) we see that while the errors between BRAN2 and BRAN3 are reduced over most regions they actually increase in Western Australia for all time scales except daily and monthly variability.

Generally, correlations for BRAN3 are in the 0.6–0.8 range across all time scales compared with 0.4–0.7 for BRAN2. BRAN3 SST Errors are always $<1°C$ and often $<0.5°C$ (excepting Western Australia), and these values are typically half the value of the BRAN2 SST errors.

4 Summary and Discussion

In summary, over the Australian continental shelf, BRAN3 SST provides a vast improvement over BRAN2 SST when compared against observed SSTs. The improvement occurs almost

Region	Product	$\bar{T}$	T^{S}	T'	T^{A}	T^{M}	T^{D}
WA	BRAN2	0.98	0.98	0.64	0.85	0.58	0.30
WA	BRAN3	0.95	0.97	0.70	0.66	0.71	0.46
GAB	BRAN2	0.96	0.98	0.49	0.52	0.50	0.32
GAB	BRAN3	0.98	0.99	0.68	0.65	0.76	0.42
Bass	BRAN2	0.98	0.99	0.47	0.57	0.43	0.35
Bass	BRAN3	0.99	0.99	0.76	0.82	0.76	0.42
Tas	BRAN2	0.98	0.98	0.54	0.65	0.48	0.30
Tas	BRAN3	0.99	0.99	0.73	0.77	0.68	0.34
EAST	BRAN2	0.98	0.99	0.45	0.67	0.46	0.18
EAST	BRAN3	0.98	0.99	0.65	0.75	0.68	0.31

Table 1: Quality of BRAN2 and BRAN3 SSTs, in terms of the correlation coefficient between reanalysed and observed SST, averaged over regions of the continental shelf. Regions are defined as follows: Western Australia [WA], The Great Australian Bight [GAB], Bass Strait [BASS], Tasmania [TAS], and the East Coast [EAST] (see Figure 5).

Region	Product	$\bar{T}$	T^{S}	T'	T^{A}	T^{M}	T^{D}
WA	BRAN2	0.41	0.31	0.90	0.50	0.50	0.54
WA	BRAN3	1.08	0.63	1.44	1.21	0.40	0.44
GAB	BRAN2	0.78	0.42	1.05	0.78	0.50	0.40
GAB	BRAN3	0.42	0.27	0.59	0.38	0.29	0.36
Bass	BRAN2	0.35	0.39	0.94	0.52	0.62	0.42
Bass	BRAN3	0.13	0.26	0.53	0.28	0.31	0.37
Tas	BRAN2	0.34	0.29	0.89	0.53	0.56	0.42
Tas	BRAN3	0.14	0.22	0.58	0.33	0.39	0.36
EAST	BRAN2	0.42	0.32	1.02	0.54	0.60	0.60
EAST	BRAN3	0.53	0.37	0.76	0.39	0.45	0.51

Table 2: Errors of BRAN2 and BRAN3 SSTs averaged over regions of the continental shelf. For mean SST the error is the absolute value of the difference between the reanalysed and observed mean SSTs; for the remainder the error is the root mean square error (RMSE) between the reanalysed and observed SSTs. Units are °C. Regions are defined as follows: Western Australia [WA], The Great Australian Bight [GAB], Bass Strait [BASS], Tasmania [TAS], and the East Coast [EAST] (see Figure 5).

without exception across a range of time scales including the mean, seasonal cycle, and daily, monthly and yearly variability. In fact, BRAN3 SSTs are generally of sufficient quality to be useful in near-shore ecology studies, unlike BRAN2.

The gain in quality by BRAN3 appears to come principally from the inclusion of SST data into BRAN3 (i.e., data assimilation) over the shelf (unlike BRAN2). This is because the minor changes from BRAN2 to BRAN3 in the ocean model configuration are unlikely to provide such an improvement while the inclusion of near-shore SST observations into the BRAN3 data assimilation system clearly would. Therefore, since the underlying ocean model itself still fails to simulate to coastal dynamics, studies focusing on near-shore marine climate must proceed with caution when using parameters which have not been data assimilated over the shelf, including salinity, ocean currents, and even subsurface temperature. This conclusion raises the need for a dedicated pan-Australian continental shelf model, potentially data-assimilative (i.e., a reanalysis), which provides realistic historical estimates of marine climate, not just SSTs, over the entire Australian continental shelf.

Appendix A: Definition of residual variability split over several time scales

Here it is defined how the time series of residual variability T_t' was split into a sum of time series with variability on different, and mutually exclusive, time scales. First, the submonthy, or "daily", variability T_t^{D} was defined as the difference between T_t' and a 30-day moving average of T_t':

$$T_t^{\mathrm{D}} = T_t' - T_t^{\mathrm{M*}} \tag{3}$$

where $T_t^{\mathrm{M*}} = \mathrm{movavg}(T_t',\ 30\ \mathrm{days})$ and $\mathrm{movavg}(x, T)$ defines a moving average of x with a window of length T. $T_t^{\mathrm{M*}}$ now contains all variability on time scales of 30 days or longer, including "low-frequency" (e.g., interannual) variability. To isolate the "low-frequency" component we define T_t^{M} to be the difference between $T_t^{\mathrm{M*}}$ and a 1-year moving average of $T_t^{\mathrm{M*}}$:

$$T_t^{\mathrm{M}} = T_t^{\mathrm{M*}} - T_t^{\mathrm{A}} \tag{4}$$

where $T_t^{\mathrm{A}} = \mathrm{movavg}(T_t^{\mathrm{M*}},\ 1\ \mathrm{year})$. Variability on annual time scales and longer ("yearly") is represented by T_t^{A} while variability on time scales between monthly and annual ("monthly") is represented by T_t^{M}. The definitions of T_t^{D}, T_t^{M}, and T_t^{A} are such that their sum recovers the total residual variability T_t'.

Sample power spectra for residual variability at a location in Bass Strait split across these three time scales is shown in Figure 6. There is a clear division of variance so that most of the variance of T_t^{D} occurs on time scales shorter than $\sim$50 days, most of the variance of T_t^{M} occurs on time scales between 50 and 300 days, and most of the variance of T_t^{A} occurs on time scales longer than 300 days.

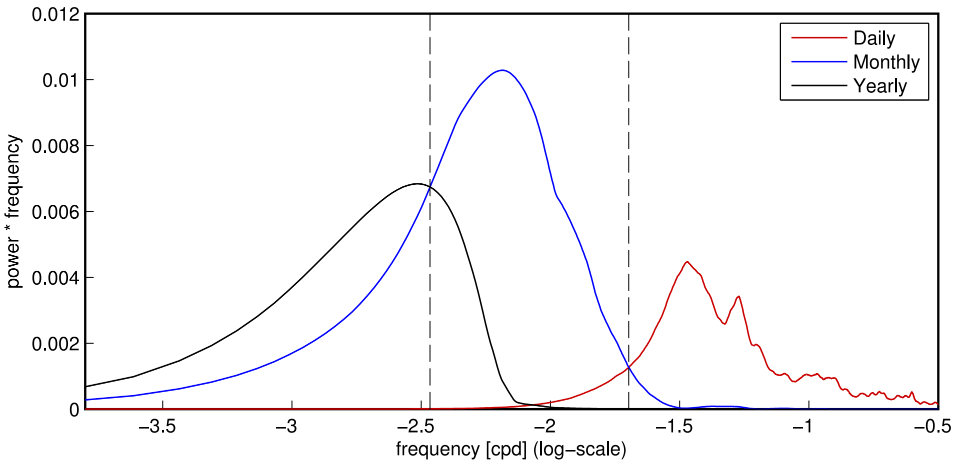

Figure 6: Power spectra of residual SST variability in Bass Strait (see Figure 1) split over several time scales. Shown are power spectra of the "daily" variability (T_t^{D}, red line), "monthly" variability (T_t^{M}, blue line) and "yearly" variability (T_t^{A}, black line). Vertical lines indicate oscillation periods of 300 days and 50 days. Spectra are shown in variance preserving form (the product of the spectra and frequency plotted against the logarithm of frequency).

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