Subseasonal prediction of the 2020 Great Barrier Reef and Coral Sea marine heatwave

Jessica A Benthuysen, Grant A Smith, Claire M Spillman and Craig R Steinberg

Australian Institute of Marine Science, Crawley, WA 6009, Australia
Bureau of Meteorology, GPO Box 1239, Melbourne, VIC 3001, Australia
Australian Institute of Marine Science, Townsville, QLD 4810, Australia
* Author to whom any correspondence should be addressed.
E-mail: j.benthuysen@aims.gov.au

Keywords: sea surface temperature, marine heatwave, seasonal prediction, coral bleaching, ACCESS-S, Coral Sea, Great Barrier Reef

Abstract
The 2020 marine heatwave (MHW) in the Great Barrier Reef (GBR) and Coral Sea led to mass coral bleaching. Sea surface temperature anomalies reached +1.7 °C for the whole of the GBR and Coral Sea and exceeded +2 °C across broad regions (referenced to 1990–2012). The MHW reached Category 2 (Strong) and warm anomalies peaked between mid-February and mid-March 2020. The MHW’s peak intensity aligned with regions of reduced cloud cover and weak wind speeds. We used a MHW framework to assess the ability of an operational coupled ocean-atmosphere prediction system (Australian Community Climate and Earth System Simulator Seasonal version 1) to capture the MHW’s severity, duration, and spatial extent. For initial week predictions, the predicted MHW severity generally agreed with the magnitude and spatial extent of the observed severity for that week. The model ensemble mean did not capture the MHW’s development phase at lead times beyond the first week. The model underestimated the MHW’s spatial extent, which reached up to 95% of the study area with at least Moderate severity and up to 43% with at least Strong severity. However, most forecast ensemble members correctly predicted the period of Strong severity in the first week of the model forecast. The model correctly predicted MHW conditions to persist from mid-February to mid-March but did not capture the end of the MHW. The inability to predict the end of the event and other periods of less skilful prediction were related to subseasonal variability owing to weather systems, including the passage of tropical cyclones not simulated in the model. On subseasonal time scale, evaluating daily to weekly forecasts of ocean temperature extremes is an important step toward implementing methods for developing operational forecast extremes products for use in early warning systems.

1. Introduction
In austral summer 2020, the Great Barrier Reef (GBR) and Coral Sea experienced prolonged, extremely warm waters coinciding with extensive coral bleaching (Hughes and Pratchett 2020). This marine heatwave (MHW) occurred during the GBR’s third mass coral bleaching event in five years (Great Barrier Reef Marine Park Authority, Australian Institute of Marine Science, and CSIRO 2020) and the fifth event since 1998 (Hughes and Pratchett 2020) and followed the 2016 and 2017 Coral Sea bleaching events (Harrison et al 2019). Coral bleaching occurs when ocean temperatures exceed their thermal limits and corals expel their symbiotic algae (e.g. Weis 2008). Recent mass coral bleaching events on the GBR have led to regional-scale changes in coral reef assemblages (Hughes et al 2018), impacts on other habitat forming species, such as reduced recovery of inshore seagrasses (McKenzie et al 2018), and reports of flow on effects to reef fishes (Richardson et al 2018, Bernal et al 2020, Taylor et al 2020, Brown et al 2021). There is increasing recognition that MHWs threaten GBR ecological, social, and cultural values (e.g. Johnson et al 2018, Curnock et al 2019, Great Barrier Reef Marine Park Authority 2019). Given MHW’s severe consequences, reduced time for coral recovery with recurrent events, and increased risk of MHWs in Australian
climate projections (Grose et al 2020), there is an urgent need to understand how and why MHWs develop, including those events leading to mass coral bleaching.

The time scales over which MHWs are predictable are dependent on atmospheric and oceanic processes that may interact and affect skillful forecasts (Holbrook et al 2020). A region’s MHW likelihood is elevated or reduced depending on climate modes of variability (Holbrook et al 2019), where longer predictability lead times are dependent on low-frequency climate modes (such as the El Niño Southern Oscillation; ENSO), oceanic pre-conditioning, and atmospheric or oceanic teleconnections (Holbrook et al 2020). For northern Australia, the timing of monsoon activity, the Madden-Julian Oscillation (MJO; Madden and Julian 1994), and tropical cyclones affected the 2015/16 MHW variability on intraseasonal time scales (Benthuyisen et al 2018). On seasonal time scales, bleaching outlooks predicted the greatest alert level for thermal stress months in advance of the 2016 GBR coral bleaching event (Liu et al 2018) during the strong 2015/16 El Niño (Santoso et al 2017). The Australian Bureau of Meteorology’s operational seasonal prediction system successfully forecast warm monthly sea surface temperature (SST) anomalies on the GBR during the 1998 El Niño (Spillman and Alves 2009, Smith and Spillman 2019). When major climate modes of variability are neutral, regional weather patterns can challenge forecast models to predict bleaching events (Smith and Spillman 2019).

For coral reef monitoring, seasonal forecast models use weekly to monthly SST data to derive thermal stress metrics, such as Degree Heating Weeks and Degree Heating Months, which measure heat accumulation when SSTs exceed a threshold based on the climatological warmest month (Liu et al 2018, Smith and Spillman 2019, Spillman and Smith 2021). Metrics based on monthly data have utility in identifying elevated monthly SSTs and the increased risk of MHWs occurring or MHW conditions persisting longer than a month. However, monthly analyses are unable to characterise how heat stress evolves on submonthly time scales, which can provide useful information for decision making and evaluating ecological consequences.

For MHWs, periods of thermal stress have been identified by comparing daily SST values against a seasonally varying climatology and extreme threshold based on percentiles (Hobday et al 2016a). The MHW framework is a complementary approach that provides metrics quantifying thermal stress year-round, not only during the warmest months. This approach has yet to be applied to seasonal ensemble prediction models to evaluate their MHW prediction capabilities.

This study aims to (a) characterise the 2020 MHW event in the GBR and Coral Sea using SST observations and (b) test the ability of a seasonal, multi-week prediction system to capture the event on subseasonal time scales. We apply a MHW framework and assess the predicted MHW severity. We consider the factors contributing to the model performance in predicting the MHW’s temporal evolution. This study is the first time a seasonal SST forecast model has been evaluated based on its ability to represent SST for MHW predictions.

2. Data and methods

2.1. Observations and reanalysis products

We used SST data from the National Oceanic and Atmospheric Administration (NOAA) 0.25° daily Optimum Interpolation SST version 2.1 (dOISSTv2.1) dataset (Reynolds et al 2007, Huang et al 2021). We area-averaged the SST data over the Great Barrier Reef Marine Park (GBRMP) and a section of the Coral Sea (figure 1). We used data from 1 January 1990 to 1 July 2020. In all products, we used a 1990–2012 reference period for consistent comparison with the Australian Community Climate and Earth System Simulator Seasonal version 1 (ACCESS-S1) SST anomalies, which are referenced to a daily 1990–2012 climatology.

We used the NOAA daily and monthly mean interpolated outgoing longwave radiation (OLR) product with 2.5° horizontal resolution (Liebmann and Smith 1996). We used monthly OLR data from 1990 to 2012 (the reference period) and daily data from 2019 to 2020, area-averaged over the GBRMP and Coral Sea.

Monthly averaged wind velocity at 10 m and air-sea heat fluxes (0.25° horizontal resolution) were obtained from ERA5, which is the fifth-generation European Centre for Medium-Range Weather Forecasts global atmospheric reanalysis (Hersbach et al 2019, 2020). Monthly anomalies were referenced to a 1990–2012 monthly climatology.

2.2. Operational multi-week forecast model

The Australian Bureau of Meteorology’s operational seasonal prediction system is the ACCESS-S since 2018. ACCESS-S is a coupled dynamical ocean-atmosphere ensemble prediction system, and full model details are described in Hudson et al (2017). The ocean model component is the Nucleus for European Modelling of the Ocean community model (Madec and the NEMO team 2008) and has ∼25 km horizontal resolution and a 1 m surface layer thickness. Ocean initial conditions are provided by the Forecast Ocean Assimilation Model analysis (Blockley et al 2014), which assimilates satellite and in situ observations of SST, sea level anomalies, subsurface temperature and salinity profiles, and sea-ice concentration (Spillman and Smith 2021). The atmospheric initial conditions use the same data assimilation as the Bureau of Meteorology’s ACCESS-G numerical
weather prediction model (Hudson et al 2017). Each ensemble member is initialised using a perturbation of the atmospheric initial conditions, with no perturbations occurring on the land surface, ocean, or sea-ice models. Operational real-time fortnightly and monthly SST anomaly and thermal stress forecast products are produced twice weekly for Australian waters (Smith and Spillman 2019, 2020).

The real-time multi-week forecasts consist of a 99-member forecast ensemble, formed by 33 members per day lagged over three days, predicting 35 days into the future (Hudson et al 2016a). This definition is implemented in the MHW software package in Python (https://github.com/ecjoliver/marineHeatWaves). We applied this package to the observed SST time series at each grid cell and the area-averaged SST in the GBRMP and Coral Sea (figure 1). From 1990 to 2012 data, the seasonally varying SST climatology and 90th percentile SST threshold were calculated daily from an 11 day moving window.

Using dOISSTv2.1, we examined MHW metrics, including the intensity (maximum SST anomaly), duration, cumulative intensity (time-integrated SST anomaly; figure 1 in Hobday et al 2016a), severity, and category (figure 2 in Hobday et al 2018). Within a MHW’s start and end times, a time-varying severity index was defined as the daily SST anomaly divided by the difference between the 90th percentile SST and the climatological mean SST (Sen Gupta et al 2020). A MHW’s category was the maximum severity ranging from Category 1 (Moderate) to 4 (Extreme). We calculated these metrics for MHWs reaching maximum intensity in December through March. For January through March, the SST anomaly (mean and standard deviation) needed to exceed the difference between the 90th percentile SST and climatological mean SST was $0.7 \pm 0.07 \, ^\circ\text{C}$ ($0.7 \pm 0.04 \, ^\circ\text{C}$) for the area-averaged GBRMP (Coral Sea). In addition, we calculated the percent of the study area that was affected by MHWs with at least Moderate or Strong severity to compare with the predictions.

Using real-time ACCESS-S1 daily SST anomaly forecasts, we defined the daily predicted severity as the predicted SST anomaly divided by the difference between the observed 90th percentile SST threshold and observed climatological mean SST, for each ensemble member and the ensemble mean. This method tested whether the daily model SST anomalies exceeded the threshold for extreme SST anomalies defined by the observations. The model was considered to forecast a MHW if more than 50% of 99 daily ensemble members exceeded the observed 90th percentile SST. For each daily prediction, a ‘Hit’ occurred when the model correctly forecast observed MHW conditions, and a ‘Correct negative’ occurred when the model correctly forecast a non-event. A ‘Miss’ occurred if the model did not predict observed MHW conditions, and a ‘False alarm’ occurred if the model predicted MHW conditions that did not occur. Furthermore, for each start date, we calculated the Hit Rate = Hits/(Hits + Misses), which focused on whether the model correctly predicted the MHW occurrence during an event. In addition, for each start date, we calculated the model Accuracy = (Hits + Correct negatives)/Total days, which provided a measure over the entire forecast period (35 days) and was reduced by False alarms. The Hit Rate and Accuracy values ranged from 0 to 1, where 1 was a perfect score.

3. Results and discussion

3.1. Characteristics of the 2020 MHW

The 2020 MHW developed with different timings in the build-up of heat throughout the GBRMP and Coral Sea. In early January 2020, weekly mean SST anomalies of $\sim1 \, ^\circ\text{C}$ to $2 \, ^\circ\text{C}$ were present in the Gulf of Carpentaria, Torres Strait, and GBRMP’s Far Northern sector (figure 1(a)). During January, the SST anomalies gradually increased by $\sim0.5 \, ^\circ\text{C}$ to $1.0 \, ^\circ\text{C}$ across the GBRMP and Coral Sea (figures 1(a)–(d) and 4(a), (b)). While warm anomalies were widespread, only some areas of the GBRMP and western Coral Sea exceeded MHW thresholds by February (figures 2(a), (b) and 3(a)).

During the first two weeks of February, SST anomalies continued to warm and the MHW expanded in area. By mid-February, 86% (52%) of the GBRMP (Coral Sea) had experienced MHW conditions (figures 2(a) and (b)) and SST anomalies ($\sim1.5 \, ^\circ\text{C}$ to $2.5 \, ^\circ\text{C}$) peaked locally within the GBRMP and exceeded $2 \, ^\circ\text{C}$ in the western Coral Sea (figure 1(g)). In the third week, 86% (64%) of the GBRMP (Coral Sea) experienced a MHW, reaching 41% (24%) with Strong severity (figures 2(a) and (b)). The whole of the GBRMP reached its maximum intensity ($+1.7 \, ^\circ\text{C}$) at Category 2 (Strong) on 19 February 2020 (figure 4(a)). In the fourth week, warm anomalies cooled in the central and southern GBRMP (figure 1(h)), with a temporary decrease (up to $-19\%$) in MHW areas (figure 2(a)).
Strong severity reduced in the GBRMP (figure 2(a)), the MHW expanded spatially and covered 96% of the area on 7–8 March. Between 11 and 14 March, the GBRMP rapidly cooled, reducing the areas with MHW conditions from 85% to 24% (figure 2(a)).

In the Coral Sea, the MHW intensified and evolved differently from mid-February. In late-February, the Coral Sea experienced a brief reduction in areas experiencing Strong severity (figure 2(b)). However, the warm anomalies spread and further intensified locally to 2 °C–2.5 °C (weekly mean) through the first two weeks of March (figures 1(i) and (j)). The area affected by the MHW continued to increase, reaching 88%–89% during 2–11 March and up to 39% area experiencing Strong severity (figure 2(b)). The Coral Sea reached its maximum intensity (+1.7 °C) at Category 2 (Strong) on 11 March 2020 (figure 4(b)). This peak was followed by the sudden decay in SST anomalies to less than 1 °C (figures 1(k) and (l)), with MHW areas in the Coral Sea shrinking from 88% to 28% between 11 and 14 March. In both regions, the MHW concluded by the end of March (figures 2(a), (b) and 4(a), (b)).

Overall, the 2020 MHW reached Category 2 (Strong), the highest observed severity for the whole of the GBRMP and Coral Sea (figures 2(c) and 4(a), (b)), with maximum intensities of 1.5 °C–2.5 °C (2 °C–2.5 °C) for large portions of the GBRMP (Coral Sea) (figure 2(d)). In the GBRMP (Coral Sea), half of the locations experienced MHWs between 33 and 46 days (21–40 days), with parts of the Far Northern GBRMP reaching up to 81 days (figure 2(e)). Areas of long MHW duration tended to align with high cumulative intensity (figure 2(f)), with half of the locations in the GBRMP (Coral Sea) varying between 7–10 °C × weeks (4–9 °C × weeks). Notably, the cumulative intensity reached 10–14 °C × weeks in the western Coral Sea adjacent to the Cairns/Cooktown and Townsville/Whitsunday sectors and southeast of the Mackay/Capricorn sector (figure 2(f)).

Compared with recent bleaching events, for the whole of the GBRMP (Coral Sea), there were ten days (sixteen days) at Strong severity in January to March 2020 (figures 4(a) and (b)), exceeding zero days (three days) in 2016 and nine days (two days) in 2017 (tables...
Figure 2. Marine heatwave (MHW) characteristics. Percent area of the (a) Great Barrier Reef Marine Park (GBRMP) and (b) Coral Sea in MHW conditions based on severity (shaded as per (c)); adapted from Benthuysen et al (2021). CC BY 4.0. MHW (b) category, (d) maximum intensity (°C), (e) duration (days), and (f) cumulative intensity (°C × weeks) for events occurring in January to March 2020. In (a)–(c), the colours indicate SST anomalies (SSTA) greater than zero but not in a MHW (grey shading) or MHW severity from Moderate to Extreme. In (d), (e), white shading indicates areas where MHWs did not occur. The SST anomaly and severity are referenced to a seasonally varying 1990–2012 daily climatology. The Great Barrier Reef Marine Park (GBRMP) sectors are enclosed within the solid lines. The GBRMP sectors are (north to south): Far Northern, Cairns/Cooktown, Townsville/Whitsunday, and Mackay/Capricorn. The Coral Sea region considered here is outside the GBRMP and within the dashed lines.

A1.1, A1.2 in Benthuysen et al 2021). Hence, the 2020 MHW was distinct from past summer events as it had the greatest duration at the highest observed severity level (Strong) extending over large regions.

3.2. Evaluation of the multi-week MHW forecasts
We assessed the ability of the ACCESS-S1 multi-week forecasts to capture the MHW’s evolution, severity, duration, and spatial extent. First, we examined if the ensemble mean could predict the observed severity during the MHW’s development, peak, and decay phases. Then we examined the proportion of ensemble members predicting the MHW and its maximum severity in the GBRMP and Coral Sea.

For each week in February and March 2020, the observed maximum MHW severities (figure 3(a)) were compared against ensemble mean predictions for weekly model start dates (figures 3(b)–(g)). The maximum severity patterns distinguished between areas with warm anomalies but not in a MHW (grey) and areas with SSTs exceeding the observed 90th percentile SST (i.e. yellow for Moderate severity and orange for Strong severity). During the MHW’s development phase, the area affected by MHWs expanded, reaching 95% of the study area with at least Moderate severity and 43% with at least Strong severity during 7–13 March (figure 3(a)). The first weekly forecast for each start date (figure 3, far left panels) tended to agree with the observed MHW’s severity and spatial extent for that week and did not overpredict the overall magnitude of MHW severity. In particular, the initial week predictions captured the spatial extent of peak severity in the GBRMP for the 15 February start date (figure 3(d)) and in the Coral Sea for 29 February (figure 3(f)) and 7 March (figure 3(g)) start dates. For the initial week predictions, the model correctly predicted 69% of the study area with at least Moderate severity and 37% with at least Strong severity for the 15 February start date (figure 3(d)). However, the model overpredicted the spatial extent with at least Strong severity (67% area predicted and 43% observed) for the 7 March start date’s initial week (figures 3(a) and (g)).

While initial week predictions tended to agree with observations, the model forecasts did not capture the MHW’s development phase, which reached its maximum severity and spatial extent in the GBRMP during 15–21 February (figures 2(a) and 3(a)) and in the Coral Sea during 7–13 March (figures 2(b) and 3(a)). Instead, the predictions indicated a cooling tendency, where the predicted MHW severity in the first week generally dampened in subsequent weekly forecasts. However, for later start dates, forecasts indicated that MHW severity persisted for up to two to three weeks beyond the start date (i.e. 22 February, figure 3(e)). For the 29 February start date (figure 3(f)), the ensemble mean correctly predicted that Strong severity would continue to affect the Coral Sea into the second week (7–13 March) with 31% area predicted and 43% area.
observed with at least Strong severity. The MHW rapidly decayed after that week, shown by patchy areas with Moderate severity (27% area) during 14–20 March (right panel, figure 3(a)). Model predictions for that week tended to show reduced MHW severity but varied in predicted spatial coverage (18%–73% area; right panels, figures 3(d)–(g)). Those predictions might not reflect a response to predicted changes in atmospheric conditions for that week, as discussed in section 3.3. Nevertheless, these results demonstrated that the predicted MHW severity was well represented by the ensemble mean at least in the first week of predictions during weeks of peak severity.

For the GBRMP and Coral Sea as a whole, model predictions demonstrated that most ensemble members forecast correctly (‘Hit’, red; figures 4(c) and (d)) the start of the observed MHW in January (figures 4(a) and (b)). In the GBRMP, the model correctly predicted the MHW’s commencement (17 January) within a week, from 1 to 15 January start dates (figure 3(c)). In the Coral Sea, the model missed (‘Miss’, black) the MHW’s commencement (20 January) from the 1 January start date but correctly predicted (red) it within a week from the 15 January start date (figure 4(d)). However, selected start dates from 25 January to 3 February were unable to predict (black) the re-emergence

---

**Figure 3.** Marine heatwave (MHW) weekly maximum severity: comparison of ((a), top row) observations (dOISSTv2.1) and ((b)–(g), second to bottom rows) ACCESS-S1 predictions during February to March 2020. ACCESS-S1 ensemble mean predictions are from the model start dates from (b) 1 February 2020 to (g) 7 March 2020. The colours indicate SST anomalies (SSTA) less than zero (blue shading), greater than zero but not in a MHW (grey shading), or MHW severity from Moderate to Extreme. Observed and predicted severities are referenced to seasonally varying 1990–2012 daily climatologies. The percent area of the study region, within the dashed lines, with at least Moderate (Strong) severity is indicated in white text. Adapted from Benthuysen et al (2021). CC BY 4.0.
of the MHW (10 February) in the Coral Sea (figure 4(d)).

For the periods with Strong severity, the model missed the GBRMP’s event (13–22 February; figure 4(a)) for start dates from 25 January to 3 February (figure 4(c)) and in the Coral Sea (26 February–12 March; figure 4(b)) for start dates from 1 to 8 February (figure 4(d)). For start dates from mid-February, the model correctly predicted that MHW conditions were present during those weeks and for much of the MHW period beyond two to three weeks after the start date. For start dates from 12 February to 7 March, the model incorrectly predicted (‘False alarm’, grey) the MHW to persist beyond its end. Misses or false alarms in later weeks were consistent with the ACCESS-S1 multi-week hindcast analyses where skill was reduced in the second fortnight, especially during summer (Smith and Spillman 2019). Notably, the final start date (15 March) provided accurate predictions for the transition between MHW (red) and non-MHW (‘Correct negative’, white) conditions.

Overall, for predicting the MHW’s occurrence, the model Hit Rate was greatest (0.8–1) in the GBRMP for selected start dates 15 January and 18 February–1 March and lowest (<0.5) for selected start dates 15 December and the MHW development phase (1–12 February) (supplementary figure S1(a) available online at stacks.iop.org/ERL/16/124050/mmedia). In the Coral Sea, the model Hit Rate was greatest (0.8–1) on selected start dates from 15 January and 12 February–15 March and lowest (<0.5) for selected start dates 1 January, 25 January–8 February (supplementary figure S1(b)). Similarly, the model Accuracy was lowest (<0.5) for early February start dates in both regions (supplementary figures S1(c) and (d)), indicating that forecasts from those start dates under-predicted the occurrence of the MHW as it developed and reached Strong severity.

Finally, we examined the MHW severity predictions during weeks when Strong severity was observed. The model predicted MHW conditions (>50% probability) two weeks ahead in the GBRMP for 15–21 February (8, 15 February start dates; figure 5(a)) and three weeks ahead in the Coral Sea for 29 February–6 March (15, 22, 29 February start dates; figure 5(b)). However, the model only predicted Strong severity one week ahead in the GBRMP (52% probability; figure 5(a)) and Coral Sea (80%; figure 5(b)). In the Coral Sea, the Strong severity predictions increased from 48% in the previous week’s start date (22 February) and earlier start dates. A small percent of ensemble members (8%) predicted Severe severity one week ahead (29 February;
figure 5(b)). Almost all ensemble members predicted warm SST anomalies up to four weeks ahead, with increasing probability of MHW conditions with decreasing forecast time (exception being 1 February start date in the GBRMP). However, the model only accurately predicted Strong severity one week ahead in both regions.

3.3. Atmospheric influences on MHW predictions

Subseasonal to seasonal variability in weather systems are challenging for accurate MHW prediction. Changes in cloud cover and the atmospheric circulation impact air-sea heat fluxes and the build-up of heat in the ocean. During previous GBR mass coral bleaching events, the timing and spatial extent of weather phenomena and air-sea heat fluxes were important factors influencing MHW evolution (Benthuyen et al. 2018). There were several factors influencing the MHW’s evolution that could have impacted ACCESS-S1’s ability to predict the MHW’s timing and duration.

The 2020 MHW was preceded by a strong positive Indian Ocean Dipole (Abram et al. 2020) and coincided with a delayed monsoon onset (mid-January 2020; Lisonbee and Ribbe 2021) during the decay phase of a central Pacific ENSO event (Freund et al. 2021). The compounding effect of these climate modes likely created favourable atmospheric conditions, including reduced cloud cover, conducive to MHW generation. During the MHW’s development phase, the atmospheric fields showed widespread positive OLR anomalies (figure 6(a)), indicating reduced cloud cover and increased insolation. Over the GBRMP and Coral Sea, OLR anomalies were positive for prolonged periods throughout the summer, with brief periods of elevated cloud cover (figure 6(b)). During January, atmospheric conditions revealed that the GBRMP’s Far Northern sector and the Gulf of Papua had reduced wind speeds and positive shortwave radiation flux anomalies (heat into the ocean), coinciding with the build-up of heat in those areas (figures 7(a) and (c)). Latent heat
flux anomalies were positive over large portions of the GBRMP and western Coral Sea (Figure 7(b)), contributing to the build-up of heat and preconditioning the region for MHW conditions to emerge the following month (Figures 1(a)–(d)).

During February, reduced cloud cover and increased positive shortwave radiation flux anomalies continued over most of the GBRMP and Coral Sea (Figures 6(b) and 7(f)). Wind speeds weakened over the central to southern GBRMP and the western Coral Sea (Figure 7(d)), aligning with elevated positive latent heat flux anomalies (Figure 7(e)). Between 8 and 16 February, positive OLR anomalies decreased (Figure 6(b)), coinciding the tropical low that formed Tropical Cyclone Uesi on 10 February in the Coral Sea (Bureau of Meteorology 2020a) and the passage of a MJO convective episode. Subsequently, the GBRMP experienced brief cooling (−0.6 °C; 19–26 February), reducing the region’s peak severity (Figure 4(a)), while the Coral Sea only cooled by −0.2 °C (20–24 February; Figure 4(b)). For the week of 15–21 February, when the GBRMP MHW reached Strong severity (Figure 4(a)), positive OLR anomalies were observed over the study area but underestimated in the model predictions for start dates 1, 8, 15 February (supplementary figure S2). These results show the influence of air-sea heat flux anomalies and timing of weather events on the MHW evolution. Since the ACCESS-S1 model ensemble mean predictions did not capture the intensification in the GBRMP’s MHW severity in mid-February (Figure 4(c)), understanding how modelled atmospheric components contribute to MHWs is an important aspect for future investigations in predicting a MHW’s development phase.

In March, OLR anomalies were positive during the first week (Figure 6(b)), during which the Coral Sea reached Strong severity (Figure 4(b)). For the week of 29 February–6 March, positive OLR anomalies were observed over the study region and similar magnitude to model predictions in the first week (start date 29 February) but underestimated in model predictions for start dates 15, 22 February (supplementary figure S3). This period was followed by a sudden drop in OLR anomalies, which were negative between 9 and 14 March (Figure 6(b)). A moderate to strong MJO pulse facilitated the development of enhanced rainfall and cloudiness in northern Australian waters (Bureau of Meteorology 2020b). Over the study area, a monsoon trough and a tropical low contributed to increased cloudiness and rainfall over a broad region, with the low-pressure system forming Tropical Cyclone Gretel on 15 March (Bureau of Meteorology 2020c). This weather event cooled the MHW, contributing to its end (Figures 4(a) and (b)). For model start dates from 15 February to 7 March 2020, forecasts incorrectly indicated a MHW persisting beyond 15 March in the GBRMP and 17 March in the Coral Sea (Figures 4(c) and (d)). ACCESS-S1 did not have information on Tropical Cyclone
Gretel’s development and hence overpredicted MHW conditions. Furthermore, several start dates (15, 22 February) incorrectly forecast a suppressed convection phase of the MJO for early March, leading to increased insolation and absent MJO convection in the model. From 15 March 2020, the observed cooling associated with Tropical Cyclone Gretel was present in the model’s initial conditions, and hence model forecasts captured the cooling transition from MHW (Hit) to non-MHW (Correct negative) conditions. These results illustrate how the timing of atmospheric variability and representation of climate modes of variability, weather events, and the ocean’s response are important factors for dynamical prediction of MHWs and their evolution.

4. Conclusion

This study presents a comprehensive description of the 2020 GBR and Coral Sea MHW and the first time a MHW framework has been applied to a dynamical seasonal forecast model for subseasonal MHW prediction. We quantified MHW characteristics, revealing that the Category 2 (Strong) MHW encompassed a vast region. This severity lasted longer than in any other past MHW associated with mass coral bleaching in the GBRMP (figure A1.5 in Benthuysen et al 2021). From January to February 2020, shortwave radiation anomalies, with low cloud cover, and latent heat flux anomalies, including reduced wind speeds, contributed to the timing of warming patterns over the region. In early March, monsoon activity, the passage of a MJO event and Tropical Cyclone Gretel caused rapid cooling to neutral SST conditions. At regional scales, atmospheric variability can challenge MHW prediction, and further work is required to understand how they influence MHW forecast skill.

Using a MHW framework, we tested whether daily forecasts from a dynamical seasonal prediction system could capture the timing, spatial extent, and severity of the 2020 MHW. The MHW approach transformed SST anomaly predictions to MHW severity predictions to categorise temperature extremes based on non-seasonal SST variance. We assessed the MHW severity predictions using the Bureau of Meteorology’s ACCESS-S1 prediction system. Real-time ensemble mean forecasts captured the MHW severity’s broad spatial extent, especially up to one week ahead, but could not forecast the MHW severity during the development phase more than one to two weeks ahead. Most ensemble members could predict the peak MHW severity up to one week ahead in the GBRMP and Coral Sea. The model Hit Rate reached 1 for selected start dates from mid-February to mid-March in both regions, indicating that the model could predict MHW conditions during the peak of the event if MHW conditions were present on the start date. However, the model Accuracy was reduced (0.5–0.8) for those start dates owing to the continued prediction of MHW conditions after the MHW had subsided.

These results contribute to progress in developing approaches for dynamical MHW prediction on subseasonal to seasonal time scales. Early warning systems for MHWs are of increasing importance in planning and conducting monitoring activities for research and management. SST predictions can inform potential early interventions to limit heat stress (e.g. Bay et al 2019, Baird et al 2020) and trigger the mobilisation and deployment of assets to deliver near real time data streams for targeted monitoring. Skilful SST forecasts, at the necessary lead times and temporal and spatial resolution, are an important component to ensure that early warning systems provide guidance for decision making (Hobday et al 2016b). MHW predictions using a seasonally varying threshold, rather than a threshold based on the climatological warmest month, offer opportunities for other ecological applications, such as winter MHWs which can increase risks of coral disease (e.g. Bruno et al 2007) and harmful algal blooms (e.g. Trainer et al 2020).

Globally, MHWs are projected to increase in intensity and duration (Oliver et al 2019, Plecha and Soares 2020), further underscoring the necessity of skilful MHW predictions for marine stakeholders. This study demonstrates that there is scope for the development of operational forecast applications for MHW severity on subseasonal time scales. Further work is needed to implement this approach in seasonal prediction models for decision making in research and management applications. Future directions could include considering bias correction methods using model derived percentile thresholds together with systematic examination of past MHW predictions using a longer hindcast with more ensemble members. Finally, in assessing historical and real-time MHW predictions, mixed-layer heat budget analyses could provide opportunities to identify sources of model skill given compounding atmospheric and oceanographic factors contributing to MHW evolution.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

J A B and C R S were supported through funding from the Australian Government’s National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub (Project 4.2). Figures 1, 2(a), (b), 3, 4(a), (b) were adapted from figures 12, 7(o), (p), 15, 5(o), (p), respectively, in Benthuysen et al (2021). We thank Griffith Young, Morwenna Griffiths and Hailin Yan for preparing ACCESS-S1
forecast data and Andrew Marshall for reviewing an earlier version of the manuscript (all from the Bureau of Meteorology). The OLR data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from https://psl.noaa.gov/data/gridded/data.interp_OLR.html (accessed 22 May 2021). The figures using ERA5 data (accessed 12 September 2020 from https://cds.climate.copernicus.eu/cdsapp#!/home) were generated using Copernicus Climate Change Service information (2019). The NOAA daily OISSTv2.1 was downloaded from: www.nccdc.noaa.gov/oisst/data-access (accessed 31 July 2020). The ACCESS-S1 1990–2012 hindcast and the 2019–2020 data used from the operational ACCESS-S1 predictions are stored on the National Computational Infrastructure (NCI). We thank two anonymous reviewers for their constructive feedback.

**ORCID iDs**

Jessica A Benthuysen  [https://orcid.org/0000-0001-7615-6587](https://orcid.org/0000-0001-7615-6587)

Grant A Smith  [https://orcid.org/0000-0003-4692-6565](https://orcid.org/0000-0003-4692-6565)

Claire M Spillman  [https://orcid.org/0000-0003-0853-8190](https://orcid.org/0000-0003-0853-8190)

Craig R Steinberg  [https://orcid.org/0000-0001-5009-5894](https://orcid.org/0000-0001-5009-5894)

**References**

Abram N J, Hargreaves J A, Wright N M, Thirumalai K, Ummenhofer C C and England M H 2020 Palaeoclimate perspectives on the Indian Ocean Dipole Quat. Sci. Rev. 237 106–302

Baird M E, Green R, Lowe R, Mongin M and Bougeot E 2020 Optimising cool-water injections to reduce thermal stress on coral reefs of the Great Barrier Reef PLoS One 15 e0239978

Bay L, Mead D and Boström-Enarsson L 2019 Reef Restoration and Adaptation Program: Intervention Summary: A report provided to the Australian Government by the Reef Restoration and Adaptation Program p 21 (available at: https://gbrrestoration.org/resources/reports/)

Benthuysen J A, Oliver E C J, Feng M and Marshall A G 2018 Extreme marine warming across tropical Australia during astral summer 2015–2016 J. Geophys. Res. Oceans 123 1301–26

Benthuysen J A, Steinberg C, Spillman C M and Smith G A 2021 Oceanographic drivers of bleaching in the GBR: from observations to prediction. Volume 4: observations and predictions of marine heatwaves Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns p 47 (available at: https://nesptropical.edu.au/index.php/final-reports-round-4/)

Bernal M A, Schunter C, Lehmann R, Lightfoot D J, Allan B J M, Veilleux H D, Rummer J L, Munday P L and Ravasi T 2020 Species-specific molecular responses of wild coral reef fishes during a marine heatwave Sci. Adv. 6 eaay3423

Blockley E W, Martin M J, McLaren A J, Ryan A G, Waters J, Lea D J, Mirouze I, Peterson K A, Sellar A and Storkey D 2014 Recent development of the Met Office operational ocean forecasting system: an overview and assessment of the new Global FOAM forecasts Geosci. Model Dev. 7 2613–38

Brown C J, Mellin C, Edgar G J, Campbell M D and Stuart-Smith R D 2021 Direct and indirect effects of heatwaves on a coral reef fishery Glob. Change Biol. 27 1214–25

Bruno J F, Selig E R, Casey K S, Page C A, Willis B L, Harvell C D, Sweatman H and Melendy A M 2007 Thermal stress and coral cover as drivers of coral disease outbreaks PLoS Biol. 5 e124

Bureau of Meteorology 2020a Monthly Weather Review—Australia February 2020 (available at: http://www.bom.gov.au/climate/mwr/mwr-aus/mwr-aus-202002.pdf)

Bureau of Meteorology 2020b Tropical Climate Update—Archive 10 March 2020 (available at: http://www.bom.gov.au/climate/tropical-note/archive/20200310.archive.shtml)

Bureau of Meteorology 2020c Monthly Weather Review—Australia March 2020 (available at: http://www.bom.gov.au/climate/mwr/aus/mwr-aus-202003.pdf)

Curnock M I, Marshall N A, Thiault L, Heron S F, Hoey J, Williams G, Taylor B, Pert P L and Goldberg J 2019 Shifts in tourists’ sentiments and climate risk perceptions following mass coral bleaching of the Great Barrier Reef Nat. Clim. Change 9 535–41

Freund M B, Marshall A G, Wheeler M C and Brown J N 2021 Central Pacific El Niño as a precursor to summer drought-breaking rainfall over southeastern Australia Geophys. Res. Lett. 48 e2020GL091131

Great Barrier Reef Marine Park Authority, Australian Institute of Marine Science, and CSIRO 2020 Reef snapshot: summer 2019–20, GBRMPA, Townsville (available at: http://hdl.handle.net/11017/3587)

Great Barrier Reef Marine Park Authority 2019 Great Barrier Reef Outlook Report 2019 GBRMPA, Townsville (available at: http://hdl.handle.net/11017/3474)

Grose M R et al 2020 Insights from CMIP6 for Australia’s future climate Earth’s Future 8 e2019EF001469

Harrison H B, Álvarez-Noriega M, Baird A H, Heron S F, MacDonald C and Hughes T P 2019 Back-to-back coral bleaching events on isolated atolls in the Coral Sea Coral Reefs 38 713–9

Hersbach H et al 2019 ERA5 monthly averaged data on single levels from 1979 to present Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Accessed 12 September 2020) (https://doi.org/10.24381/cds.17050d7)

Hersbach H et al 2020 The ERA5 global reanalysis Q. J. R. Meteorol. Soc. 146 1999–2049

Hobday A J et al 2016a A hierarchical approach to defining marine heatwaves Prog. Oceanogr. 141 227–38

Hobday A J, Spillman C M, Eveson J P and Hartog J R 2016b Seasonal forecasting for decision support in marine fisheries and aquaculture Fisheries Oceanogr. 25 45–56

Hobday A J et al 2018 Categorizing and naming marine heatwaves Oceanography 31 162–73

Holbrook N J et al 2019 A global assessment of marine heatwaves and their drivers Nat. Commun. 10 2624

Holbrook N J, Sen Gupta A, Oliver E C J, Hobday A J, Benthuysen J A, Scannell H A and Wernberg T 2020 Keeping pace with marine heatwaves Nat. Rev. Earth Environ. 1 482–93

Huang B, Liu C, Banzon V, Freeman E, Graham G, Hankins B, Smith T and Zhang H-M 2021 Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1 J. Clim. 34 2923–39

Hudson D et al 2017 ACCESS-S1 The new Bureau of Meteorology multi-week to seasonal prediction system J. Southern Hemisphere Earth Syst. Sci. 67 132–59

Hughes T P et al 2018 Global warming transforms coral reef assemblages Nature 556 492–6

Hughes T P and Pratchett M 2020 We just spent two weeks surveying the Great Barrier Reef. What we saw was an utter tragedy The Conversation 7 April 2020 (available at: https://theconversation.com/we-just-spent-two-weeks-surveying-the-great-barrier-reef-what-we-saw-was-an-utter-tragedy-135197)
Johnson J E et al 2018 Characterising the values and connectivity of the northeast Australia seascape: Great Barrier Reef, Torres Strait, Coral Sea and Great Sandy Strait Report to the National Environmental Science Program and Rainforest Research Centre Limited, Cairns p 81 (available at: https://nesptropical.edu.au/index/final-reports-round-3/)

Lieshman B and Smith C A 1996 Description of a complete (interpolated) outgoing longwave radiation dataset Bull. Am. Meteorol. Soc. 77 1275–7

Lisonbee J and Ribbe J 2021 Seasonal climate influences on the timing of the Australian monsoon onset Weather Clim. Dyn. 2 489–506

Liu G et al 2018 Predicting heat stress to inform reef management: NOAA Coral Reef Watch’s 4-month coral bleaching outlook Front. Marine Sci. 5 57

Madden R A and Julian P R 1994 Observations of the 40–50 day tropical oscillation—a review Monthly Weather Rev. 122 814–37

Madec G and the NEMO team 2008 NEMO ocean engine Note du Pôle de modélisation Institut Pierre-Simon Laplace (IPSL), France, No 27, ISSN No 1288–1619

McKenzie L J, Collier C J, Langlois L A, Yoshida R L, Uusitalo J, Smith N and Waycott M 2019 Marine Monitoring Program: Annual Report for Inshore Seagrass Monitoring 2017–18 Report for the Great Barrier Reef Marine Park Authority, Great Barrier Reef Marine Park Authority, Townsville, p 180 (available at: http://hdl.handle.net/11017/3488)

Oliver E C J et al 2019 Projected marine heatwaves in the 21st century and the potential for ecological impact Front. Marine Sci. 6 734

Plecha S M and Soares P M M 2020 Global marine heatwave events using the new CMIP6 multi-model ensemble: from shortcomings in present climate to future projections Environ. Res. Lett. 15 124058

Reynolds R W, Smith T M, Liu C, Chelton D B, Casey K S and Schlax M G 2007 Daily high-resolution-blended analyses for sea surface temperature J. Clim. 20 5473–96

Richardson L E, Graham N A, Pratchett M S, Eurich J G and Hoey A S 2018 Mass coral bleaching causes biotic homogenization of reef fish assemblages Glob. Change Biol. 24 3117–29

Santoso A, McPhaden M J and Cai W 2017 The defining characteristics of ENSO extremes and the strong 2015/2016 El Niño Rev. Geophys. 55 1079–129

Sen Gupta A et al 2020 Drivers and impacts of the most extreme marine heatwave events Sci. Rep. 10 19359

Smith G and Spillman C 2019 New high-resolution sea surface temperature forecasts for coral reef management on the Great Barrier Reef Coral Reefs 38 1039–56

Smith G and Spillman C M 2020 Ocean temperature outlooks—coral bleaching risk: Great Barrier Reef and Australian waters Bureau Research Report BRR043 Bureau of Meteorology May 2020, (Melbourne) (available at: www.bom.gov.au/research/publications/researchreports/BRR-043.pdf)

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

Spillman C M and Smith G A 2021 A new operational seasonal thermal stress prediction tool for coral reefs around Australia Front. Marine Sci. 8 687833

Taylor B M, Benkwitt C E, Choat H, Clements K D, Graham N A J and Meekan M G 2020 Synchronous biological feedbacks in parrotfishes associated with pantropical coral bleaching Glob. Change Biol. 26 1285–94

Trainer V L, Moore S K, Hallegraeff G, Kudela R M, Clement A, Mardones J I and Cochlan W P 2020 Pelagic harmful algal blooms and climate change: lessons from nature’s experiments with extremes Harmful Algae 91 1011591

Weis V M 2008 Cellular mechanisms of Cnidarian bleaching: stress causes the collapse of symbiosis J. Exp. Biol. 211 3059–66