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Forecasting spatial distribution of Southern Bluefin Tuna habitat in the Great Australian Bight – updating and improving habitat and forecast models

An Industry Partnership Agreement

J. Paige Eveson, Jason R. Hartog, Claire M. Spillman, Kirsten Rough

FRDC Project No 2018-194
February 2021

AUSTRALIAN SOUTHERN BLUEFIN TUNA
INDUSTRY ASSOCIATION LTD (ASBTIA)

Australian Government
Bureau of Meteorology

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Executive Summary

What the report is about

This report describes a collaborative project between CSIRO, the Australian Southern Bluefin Tuna Industry Association (ASBTIA) and the Australian Bureau of Meteorology (BoM), co-funded by the Fisheries Research and Development Corporation. The project aim was to update work done as part of FRDC Project 2012/239 “Forecasting spatial distribution of Southern Bluefin Tuna habitat in the Great Australian Bight”. In the original project, habitat preferences models were developed for juvenile Southern Bluefin Tuna (*Thunnus maccoyii*) in the Great Australian Bight and forecasts of expected habitat distribution were delivered via an industry-targeted website to aid industry members in planning their operations. The current project was motivated by two factors: (i) the BoM’s seasonal climate forecasting model on which the habitat forecasts were based was superseded by a new higher resolution, state-of-the-art model; (ii) new Southern Bluefin Tuna biological data from archival tags became available since the original project to inform the habitat preference models. Thus, the key goal of the project was to provide industry with habitat preference forecasts based on the new seasonal climate forecasting model and the updated preference models. The amount of new archival tag data was greater than anticipated, which allowed for age-specific models to be developed, with age classes 3 to 4 of particular interest to industry for their farming operations. The website was revised significantly to deliver the new age-specific habitat forecasts, as well as to accommodate requests for additional material. The revised website is being used in the current (2020-21) fishing season, and should prove even more useful than the original website for planning fishing operations given the age-specific preference models and the much finer spatial resolution of the forecasts. The website has been very well received to date based on feedback provided by the industry co-investigator.

Background

Changes in the distribution of juvenile Southern Bluefin Tuna in the Great Australian Bight have been observed over the past decade, with fish being distributed further east than previously observed and the majority of purse-seine catches no longer occurring from traditional fishing areas. The presence of fish in unusual locations makes fishing operations for stocking ranching pontoons challenging. The pontoon towing speed precludes rapid response to shifts in fish distribution, so vessels need to be positioned prior to Southern Bluefin Tuna arrival. Having forecasts of areas of preferred Southern Bluefin Tuna habitat can help fishers better plan their operations, to guarantee stocking of the ranching sector and potentially increase efficiency, productivity and profitability of the overall operation.

As part of a previous industry-supported FRDC project (2012/239), a habitat forecast system for Southern Bluefin Tuna was established based on a habitat preference model developed using data from electronically tagged fish coupled with a seasonal climate forecasting system developed by the BoM called POAMA (Predictive Ocean Atmosphere Model for Australia). A daily-updating website was created to deliver forecasts of suitable Southern Bluefin Tuna habitat up to two months in future, with the website design based on engagement with stakeholders. This website has been used consistently by industry members in the lead up to and throughout every fishing season since its development to aid in their decision-making and planning of fishing operations.

In 2020, POAMA was decommissioned by the BoM and superseded by a new state-of-the-art seasonal climate forecasting model referred to as the Australian Community Climate Earth-System Simulator – Seasonal (ACCESS-S). One of the key benefits of ACCESS-S is the increased spatial resolution of the ocean model, from approximately 200 km (longitude) x 100 km (latitude) with POAMA, to 25 km x 25 km with ACCESS-S. In order to keep the habitat forecasts on the website operational, a switch from POAMA to ACCESS-S was required.

While the decommissioning of POAMA was the initial motivator for this project, another important motivator was the availability of additional archival tag data with which to inform the habitat models. Regular updates to the habitat models are essential to ensure the habitat forecasts remain relevant, particularly in the face of climate change and possible changes in fish behaviour in response to altered environmental conditions. In addition, industry expressed an interest in having age-specific preference models if the archival tag data proved sufficient, with age-classes 3 and 4 being of particular interest as these are the size/age of fish mainly targeted for farming operations.

Objectives

The primary objectives of the project were:

- to update the Southern Bluefin Tuna habitat preference models for the Great Australian Bight using new archival tag data acquired since the original project, and estimate age-specific models if the data proved sufficient;
- to obtain sea surface temperature (SST) forecasts from the BoM's new seasonal climate forecasting model, ACCESS-S, and assess the skill of these forecasts; and
- to deliver fortnightly to monthly forecasts of Southern Bluefin Tuna habitat distribution in the Great Australian Bight based on the updated habitat preference models and the ACCESS-S SST forecasts via an updated website.

Secondary objectives were to provide "now-casts" (i.e., real-time predictions) of areas of suitable Southern Bluefin Tuna habitat based on updated habitat preference models, to make additions and modifications to the website as requested by industry, addressing ideas for potential improvements identified by using the website over the past six years, and to include more recent case studies on the website.

Methods and Results

An operational feed of ACCESS_S SST anomaly forecasts has been made available to the project team by the BoM. In the original project using POAMA, the BoM was able to provide us directly with SST forecasts, rather than just anomalies. Unfortunately, this was not possible with ACCESS-S; therefore, a greater amount of data processing was required by the project team to produce full-field SST forecasts (as required by the habitat models). Code was written to produce SST forecasts for the first two fortnights and the first two calendar months from the forecast start date. Evaluation of the skill (accuracy) of the forecasts was carried out by the BoM, and the relevant skill plots are provided alongside the forecasts delivered on the website.

All additional archival tag data available since the habitat models were developed for the original project were collated. This included not only new tag returns, but also historical tag returns for which it was discovered in the course of this project did not have their data uploaded to the database. Furthermore, an algorithm was developed such that tags whose temperature sensors drifted over time were not omitted entirely from the models (as was done in the original project), but rather only data after the temperature drift started were omitted. Once all of the tag data were collated, a new geolocation algorithm developed at CSIRO, which was not available at the time of the original project, was run on the entire data set. A combination of all of the above resulted in 136 tags with position estimates that could be used in the updated habitat models, compared to 65 tags in the original project. The significant increase in the number of tags meant sufficient data were available in different age-classes to enable us to estimate age-specific habitat preferences.

As in the original project, habitat preference models were developed based on SST data alone and on SST and chlorophyll data combined. The underlying methods were the same, except that for the age-specific models only position estimates for fish in the age range of interest were included. The age-specific habitat preference models suggest that age 3-4 fish prefer slightly cooler surface temperatures (18.5-21.5^{o}C) than age 2 fish (19-22^{o}C), which can make a noticeable difference to the areas deemed to contain preferred habitat. The age-specific habitat preference models derived using SST plus chlorophyll suggest that age 2 fish tend to be found in waters with higher chlorophyll levels than age 3-4 fish, and that this tendency increases slightly with increased SST, and also that the range of preferred conditions is narrower for age 3-4 fish. In general, the inclusion of chlorophyll tends to slightly reduce the area deemed to be preferred habitat, particularly for age 3-4 fish, often because inshore regions that were deemed to contain preferred habitat based on SST only are no longer deemed preferred when chlorophyll is included.

The website designed as part of the original project was revised significantly in the current project, and can be viewed at http://www.cmar.csiro.au/gab-forecasts/index.html. The most important update to the website was to deliver habitat preference forecasts for the next two fortnights and next two calendar months in future based on (i) the ACCESS-S SST forecasting system, and (ii) the new SST-based habitat preference models (note that the models including chlorophyll cannot be used in the habitat forecasts since chlorophyll is not forecasted by ACCESS-S). Because age-specific preference models proved possible, separate habitat preference forecasts are now provided for age 2 fish and for age 3-4 fish. Numerous other modifications were also made to the website based on feedback from industry, including additional plots of observed and historical environmental conditions, and age-specific habitat preference maps for the most recent week ("nowcasts") based on both the SST-only and SST plus chlorophyll preference models.

Implications for relevant stakeholders

The value of the project outputs for industry members (fishers, spotters, managers) has been demonstrated through the dedicated use of the original website in the lead up to and throughout every fishing season since its development. The habitat forecasts have proven useful in planning fishing operations, such as in the 2017 and 2019 fishing seasons, where habitat forecasts indicated slow and delayed warming of the Great Australian Bight so companies opted to delay fishing operations rather than sending boats, pontoons and crew out to sit idle for weeks until conditions became suitable for Southern Bluefin Tuna. We expect the revised website, which is being used in the current (2020-21) fishing season, to prove even more useful than the original website given the habitat forecasts have much greater spatial resolution and are age specific.

A tangential outcome of this project is that the habitat forecasts are used in the Southern Bluefin Tuna gene-tagging programme to help locate areas of most likely fish distribution during tagging operations that occur in February-March each year. Because gene-tagging requires that age 2 fish are tagged and released, the age-specific habitat forecasts on the revised website should be more informative than the previous all-ages forecasts.

Recommendations

To ensure that the forecasting system developed in this project continues to support the Southern Bluefin Tuna industry in future, we recommend ongoing evaluation of the use of the system by industry participants via feedback from ASBTIA. Furthermore, to ensure that the habitat preference nowcasts and forecasts being delivered remain relevant, it is essential for more recent biological data to be obtained, ideally through another round of substantive archival tag releases on juvenile Southern Bluefin Tuna. The current habitat preference models are estimated using biological data obtained from archival tags deployed on Southern Bluefin Tuna mainly during 1998-2011, with only six tags from 2015-2017. This has not allowed us to evaluate whether preferences have changed between the past two decades, which is particularly important given warming waters and other oceanographic changes occurring in the Great Australian Bight under climate change.

Keywords

Southern Bluefin Tuna, *Thunnus maccoyii*, seasonal forecasting, ACCESS-S, age-specific habitat models, environmental preferences, economic efficiency

Introduction

Changes in the distribution of juvenile Southern Bluefin Tuna (SBT; *Thunnus maccoyii*) in the Great Australian Bight (GAB) have been observed over the past decade. In the 2012 fishing season, SBT movement through the GAB was rapid, resulting in fish being distributed further east than previously observed and less than 15% of purse-seine catches being taken from fishing grounds reliably used for the previous 20 years. Since 2012, SBT have not yet returned to what was historically the core fishing area (along the shelf between ~130-133°E). Instead, fish continue to be found further east in general, but with an inconsistent distribution. Rapid movements of surface schools and the presence of fish in unpredictable locations make fishing operations for stocking ranching pontoons challenging. The pontoon towing speed precludes rapid response to shifts in fish distribution, so vessels need to be positioned prior to SBT arrival.

Having forecasts of environmental conditions and areas of preferred SBT habitat allows operators to better plan fishing operations, to guarantee the stocking of the ranching sector and potentially increase efficiency, productivity and profitability of the overall operation. As part of a previous industry-supported FRDC project (2012/239), a habitat forecast system for SBT was established based on a habitat preference model developed using data from electronically tagged fish coupled with a seasonal climate forecasting system developed by the Bureau of Meteorology (BoM) called POAMA (Predictive Ocean Atmosphere Model for Australia). A daily-updating website was created to deliver forecasts of suitable SBT habitat up to two months in future, with the website design based on engagement with stakeholders. This website has been utilised religiously in the lead up to and throughout every fishing season since its development. Based on feedback from industry members, forecasts delivered through the original project have proven a useful aid in their decision-making and planning of fishing operations (Eveson et al. 2015). Clear examples of this are the 2017 and 2019 fishing seasons, where habitat forecasts indicated slow and delayed warming of the GAB so companies were able to make the decision to delay fishing operations rather than sending boats, pontoons and crew out to sit idle for (4-6) weeks until conditions became suitable for SBT.

In 2020, POAMA was decommissioned by the BoM and superseded by a new seasonal climate forecasting model referred to as the Australian Community Climate Earth-System Simulator – Seasonal (ACCESS-S). Thus, the POAMA-based seasonal climate and habitat forecasts provided on the original website were no longer operational. This project undertook the necessary work for the habitat forecasts to be updated to use ACCESS-S.

Updating to ACCESS-S was not only necessary to keep the forecast delivery website operational, but it also meant that a higher resolution, state-of-the-art forecasting model was being used. One of the key differences between ACCESS-S and POAMA is the spatial resolution of the ocean model. POAMA's horizontal resolution was approximately 200 km (longitude) x 100 km (latitude), whereas the resolution of ACCESS-S is 25 km x 25 km. The vertical resolution is also different, with the top layer of the water column 1 metre deep in ACCESS-S, compared to 15m in POAMA. This higher spatial resolution will make the forecasts more useful for industry. Details of ACCESS-S and a system comparison with POAMA can be found at http://poama.bom.gov.au/general/access-s.html.

While the decommissioning of POAMA was the initial motivator for this project, another important motivator was the availability of more archival tag data with which to inform the habitat models. As was noted in the original project final report (Eveson et al. 2014), regular updates to the habitat models are essential to ensure the habitat forecasts remain relevant, particularly in the face of climate change and possible changes in fish behaviour in response to altered environmental conditions. In addition, the archival tag data will be interrogated to see if there is now sufficient data to estimate size/age-specific preference models. Age-classes 3 and 4 are of particular interest to industry since these are the size/age of fish mainly targeted for farming operations.

Objectives

The objectives of the project, as agreed in the project contract, are:

1. Update SBT habitat preference models for the GAB using additional new archival tag data
2. Investigate potential of age-specific habitat preference models
3. Provide "now-casts" (i.e., real-time predictions) of areas of suitable SBT habitat based on updated habitat preference models (note that the habitat model currently in use is based only on SST)
4. Obtain fortnightly to monthly SST forecasts from the BoM's new seasonal climate forecasting model ACCESS-S, and assess skill of these forecasts
5. Produce updated fortnightly to monthly higher resolution forecasts of SBT habitat distribution in the GAB, and deliver these via the existing website
6. Make additions and modifications to the existing website as requested by industry, addressing ideas for potential improvements identified by using the website over the past 6 years
7. Include more recent case studies on the website.

Methods

The work completed in this project involved a number of different tasks:

1) Updating the habitat forecasting system to use seasonal climate forecasts from ACCESS-S in place of POAMA.
2) Compiling available archival tag data for SBT and estimating daily positions using recent geolocations methods developed at CSIRO.
3) Updating the habitat preference models to use all available archival tag data in the GAB, and if data are sufficient, developing age-specific habitat models.
4) Generating spatial maps showing "now-casts" (i.e., areas of preferred habitat corresponding to the most recent oceanographic conditions) and forecasts of SBT habitat distribution based on the new habitat preference models and the ACCESS-S SST forecasts.
5) Modifying the website to include the updated nowcasts and forecasts, as well as making other modifications and additions to the website based on consultation with industry representatives throughout the project.

Updating seasonal forecasting model

ACCESS-S (Australian Community Climate Earth System Simulator – Seasonal) is a new high-resolution global ocean-atmosphere ensemble seasonal forecast system run operationally at the Australian BoM since late 2018 (Smith & Spillman 2020). It comprises a coupled ocean-atmosphere model and data assimilation systems for the initialisation of the ocean, land and atmosphere (Hudson et al. 2017). The ocean model grid resolution in the GAB domain (30-40°S, 110-145°E) is approximately 25 km x 25 km, with top surface layer 1 m thick and increasing in thickness with water depth. Although ACCESS-S forecasts a number of atmosphere and ocean variables, only surface temperature (SST) forecasts were available for use in this project.

An 11 member ensemble of retrospective multi-week forecasts (hindcasts) was generated by starting the model 11 times on the 1st, 9th, 17th and 25th of each month for the period 1990-2012, initialised only with data available before the start date and running forward in forecast mode for six months. Initial conditions are provided by the UK Met Office. In this study we have focused on only the overall ensemble mean forecast, the average of the 11 ensemble members.

Forecast lead time is defined as the time elapsed between the model start date (date the model forecast is issued) and the forecast date. In this project we have used forecasts for the first fortnight (f1: mean of the first 14 daily forecasts), second fortnight (f2: mean of the second 14 daily forecasts), and the first two calendar months (m1 and m2) from the model start date. For the monthly forecasts, the first calendar month (m1) is always the next month after the forecast start date, with the second month (m2) being the month following m1. For example, for a forecast starting on 11 February, f1 refers to the forecast for the period 11-24 February, f2 to 25 February-10 March, m1 to 1-31 March and m2 to 1-30 April.

ACCESS-S SST anomalies (SSTA) were created for f1, f2, m1 and m2 lead times by removing the appropriate fortnightly or monthly model climatology from forecast SST values. The model climatology is the long-term fortnightly or monthly mean SST for 1990-2012, computed relative to start date and lead time, and is removed from SST values to reduce the effects of any model bias (Stockdale 1997).

To assess the accuracy of the model SSTA forecasts, model skill was calculated by correlating model SSTA ensemble mean values with observed monthly SSTA values in both space and time over the 1990-2012 period using the Pearson correlation coefficient (r) (Smith & Spillman 2019). Skill is assessed for the fortnightly and monthly forecasts started on each of the four start dates (1st, 9th, 17th, and 25th) of each month. For example, to assess the skill of a February forecast issued on the 1st of January (a lead time of one month), the February ensemble mean SSTA hindcasts that were started on the 1st of January 1990-

2012 (n=23) were correlated with the observed monthly SSTA values for February 1990-2012. To assess the skill of a fortnightly forecast for 1-14 February issued on the 17th of January (a lead time of two weeks), the fortnightly 1-14 February ensemble mean SSTA hindcasts that were started on the 17th of January 1990-2012 (n=23) were correlated with the observed fortnightly SSTA values for 1-14 February 1990-2012. The observed dataset used for skill assessment was the Reynolds OISSTv2 satellite SST dataset (Reynolds 2002). When r equals 0, there is no correlation between the forecasted SST anomaly and the observed SST anomaly; when r equals 1, there is a perfect positive correlation. Where r is above 0.4, the forecasted SSTA values are considered to have useful skill. Generally, forecast skill is highest for shorter lead times and decays as forecasts are made further into the future (i.e. increasing lead time); however, other factors such as the time of year and dynamics of the ocean in the region of interest also come into play.

The project team have access to an operational feed of ACCESS_S SSTA forecasts. In the original project using POAMA, the BoM was able to provide us directly with SST forecasts, rather than just the anomalies. Unfortunately, with ACCESS-S it was not possible for the BoM to perform any further processing of the SSTA forecasts, due to the fact that this is an operational output. Therefore, a greater amount of data processing was required by the project team when compared to POAMA in order to provide a forecast of SST (and not just an anomaly), as required for input to the habitat preference models.

The monthly forecasts from the BoM contain forecast anomalies for up to 6 months from the issue date. Processing code was written in Python and CDO tools to:

- add the appropriate monthly observed climatology (derived using the Reynolds OISSTv2 satellite data) to the anomalies;
- subset to the Australian region; and
- re-grid the result to a regular latitude/longitude grid from the native tri-polar grid that the BoM use for ACCESS forecasts.

The weekly forecasts from the BoM contain forecast anomalies for up to 35 days from the issue date. Processing code was written in Python and CDO tools to:

- extract data for the first two fortnights (i.e., the first 28 of the 35 days in the forecast anomaly file);
- add the appropriate fortnightly observed climatology (derived using the Reynolds OISSTv2 satellite data, and provided by the BoM for the 1st, 9th, 17th and 25th of each month);
- subset to the Australian region; and
- re-grid the result to a regular latitude/longitude grid from the native tri-polar grid that the BoM use for ACCESS forecasts.

These processing operations are run regularly on CSIRO compute servers to keep the products up to date.

Compiling archival tag data

All additional archival tag data available since the habitat models were developed for the original project were collated (see Table 1 of Results and Discussion for final sample sizes). This included not only new tag returns, but also historical tag returns for which it was discovered in the course of this project did not have their data uploaded to the database. Furthermore, in the original project, over 20 tags were omitted from the habitat models because of an issue with their temperature sensors drifting over time (which is a problem because surface temperature from the tags is input to the geolocation method). Rather than omitting these tags entirely, we developed an algorithm that only omits data after the temperature drift starts.

Once all of the tag data were collated, a new geolocation algorithm developed at CSIRO (Basson et al. 2016), which was not available at the time of the original project, was run on all tags. This included tags for which the previous geolocation method had either not been run or had failed. This method, referred to as the "twilight likelihood" (TL) method, can be summarized as follows:

- The light data from each twilight event is used to estimate the likelihood of having observed that light data given any location on the globe.
- The estimated likelihood surfaces get input to a grid-based Hidden Markov Model (HMM), where the location of a fish (on a 1° x 1° grid) at each twilight is the hidden state to be estimated and the probability of moving between states (i.e. grid cells) is assumed to be a random walk.
- Observational data which may be informative in determining location can be included in the HMM in the form of a likelihood. The HMMs used here included surface temperature and depth data recorded on the tags compared against global SST and bathymetry data.
- The output of the HMM is the posterior probability of a fish being in each possible grid cell on the globe (excluding any cells that correspond to land masses) during each twilight event.
- A "most probable track" is estimated by taking a weighted average of all the grid latitudes and longitudes using the posterior probabilities at each twilight as the weights.

Updating habitat preference models

The underlying methods used to calculate habitat preferences were the same as used in the previous project (Eveson et al. 2014). For convenience, we repeat the steps involved here, with any updates or changes noted:

1) Choose the area of the ocean and the time period from which data will be used to develop the habitat model.

    - We used the Great Australian Bight between 30-40°S and 125-140°E for months January-March (when the majority of juveniles are in the area) in years 1998-2011, 2015-2017 (all years for which we have archival tag data – note the original models only included 1998-2009).

2) Determine the environmental variables to include in the preference model, and the spatial and temporal resolution to use.

    - Based on findings in Basson et al. (2012), we chose to include SST and chlorophyll *a.*
    - We used a spatial resolution of 0.1° latitude by 0.1° longitude, and a temporal resolution of a month.

3) Get the environmental data for the ocean within the area and time period of interest at the spatial and temporal resolution chosen.

    - We extracted SST (source: CSIRO 3-day composite, plus GHRSST after 2014 since the CSIRO product ends) and chlorophyll *a* (source: SeaWiFS, plus MODIS after 2010 since the SeaWiFS product ends) data for the GAB at the resolution the product was available, then averaged the data over a 0.1°x 0.1° grid in each month and year included in the models.
    - Note that chlorophyll *a* tends to have a highly right-skewed distribution, so we use the logarithm of the data in the model, which we will denote by log(chl *a*).

4) Get the subset of environmental data for only those locations where fish were found within the area and time period of interest.

    - We used SBT archival tag tracks to determine locations where fish were found within the GAB during each month and year included in the models, then extracted the subset of the ocean SST and log(chl *a*) datasets corresponding to these locations and time periods.
    - For age-specific models, only locations from fish in the age range of interest are included.

5) Compare the environmental data at fish locations with the environmental data from the ocean to see which conditions the fish tend to 'prefer'.

a) Define suitable bins for the environmental data sets.

- We used 0.5°C bins for SST and 0.25 log(mg/m^3) bins for log(chl *a*).

b) Divide the proportion of fish observations in a given bin by the proportion of ocean observations in that bin. If the value is greater than 1, the conditions in that bin are "preferred" (i.e., they are found in greater proportion in the fish data than in the ocean data).

c) Over all bins, this is referred to as the preference curve if there is just one environmental variable (e.g. SST; see Figure 6 and Figure 7), or as the preference surface if there are two environmental variables (e.g. SST and log(chl *a*); see Figure 8 and Figure 9).

The amount of archival tag data broken down by age was sufficient for estimating age-specific habitat preferences models (see Table 2 of Results and Discussion). Thus, we estimated habitat preferences models for fish of age 2 and for fish of ages 3-4 combined, the latter being the size/age range mainly targeted for farming operations. In both cases, we ran the models using only SST and using SST plus chlorophyll combined. Age was estimated from fish length using the method currently used by the Commission for the Conservation of Southern Bluefin Tuna (Eveson 2011). This method assumes all fish are born on January 1st, and adjusts the length cut-offs for a given age class by time of the year. On January 1st, fish are estimated to be age 2 if their fork length is within the range 68.9-91.6 cm, age 3 if within the range 91.6-105.5 cm, and age 4 if within the range 105.5-117.3 cm.

Generating habitat preference nowcasts and forecasts

Once a preference curve (or surface) has been estimated, it can be used to determine areas of preferred SBT habitat in the GAB for any given time period simply by extracting the environmental conditions for that time period and looking up the preference value corresponding to the environmental conditions at each location. The time period can be in the past using historic environment conditions (hindcast), current using the most recently observed conditions (nowcast), or in future using forecasted conditions (forecast). We can produce habitat preference hindcasts and nowcasts for SBT using both the SST-only preference model and the SST plus chlorophyll model. However, we can only produce habitat preference forecasts using the SST model, because ACCESS-S does not forecast chlorophyll.

The usefulness of the habitat preference forecasts will depend on the skill of the SST forecasts on which they are based. As noted above, SST forecast skill depends on the lead time, as well as the time period and area being considered. Thus, when we provide habitat forecast maps to industry, we also provide the associated skill plot alongside to allow for easy assessment of the expected accuracy of the forecast.

Updating website to deliver results to industry

A website designed specifically for industry was developed as part of the original project, with the content and layout shaped by discussions with industry representatives over the course of the project. In the current project, this website was modified to include habitat preference nowcasts based on the new age-specific habitat preference models (SST only and SST plus chlorophyll), and habitat preference forecasts based on the new age-specific habitat preference models (SST only) and using SST forecasts from ACCESS-S in place of POAMA. Because chlorophyll is not available as a forecasted product from the BoM seasonal forecasting models (POAMA or ACCESS-S), we had not included any results from models using chlorophyll on the original website. However, in discussions with industry during the current project, they indicated that being able to compare preference maps based on the SST only and SST plus chlorophyll models in the nowcasts and in the historic case studies would be of interest. Numerous other modifications were also made to the website based on feedback from industry, as outlined in the Results and Discussion.

Results and Discussion

Seasonal forecasting model

An example of the ACCESS-S monthly SST forecast in the GAB for May 2020, issued on April 25th, is given in Figure 1, along with a comparison of the POAMA SST forecast for May 2020, issued on April 26th. This illustrates the much higher spatial resolution available with ACCESS-S, which will make the forecasts more useful for industry in planning fishing operations. The correlation skill (r) associated with the ACCESS-S forecast is shown in Figure 2. The areas of white indicate where r is less than 0.4, which means the forecast is not expected to have sufficient skill in these areas to be useful. In this case, forecast skill is high inshore all around the coast ($r > 0.7$) but poor offshore in the central GAB.

Skill varies significantly depending on the forecast lead time, as well as on the time of year and region of interest. For example, Figure 3 shows skill plots for January and February SST forecasts issued at different lead times. As expected, skill tends to improve as lead time declines (e.g., the January forecast issued on the 25th of December is more accurate than the January forecast issued on the 1st of December); however, the variability in skill depending on the month and specific region is apparent.

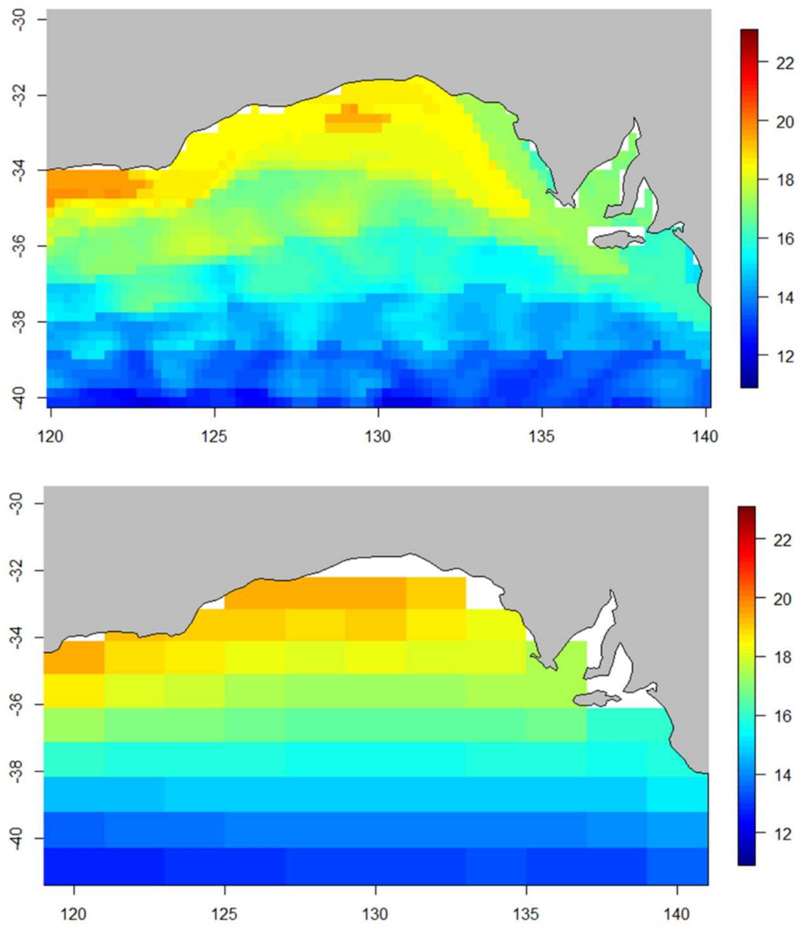

Figure 1. Maps showing the May 2020 SST forecast from ACCESS-S (issued 25 April 2020) (top), and from POAMA (issued 26 April 2020) (bottom). The much finer spatial resolution of ACCESS-S is apparent.

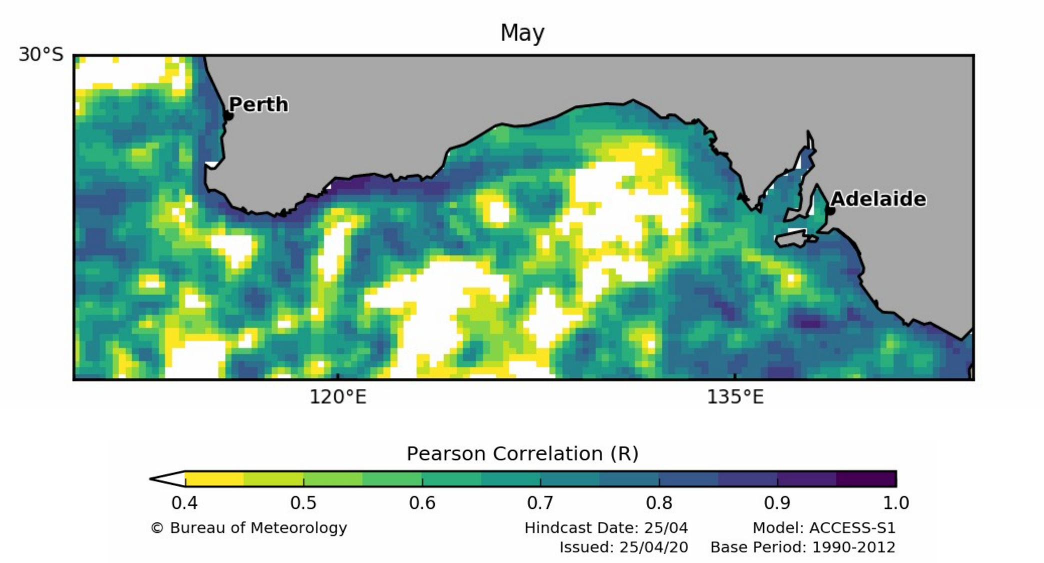

Figure 2. Skill of the May 2020 ACCESS-S SST forecast issued on 25 April, as measured by Pearson's correlation coefficient (R). Areas for which the value of R is greater than 0.4 are considered to have useful skill, with 1 being the highest value possible. (Figure produced by the BoM.)

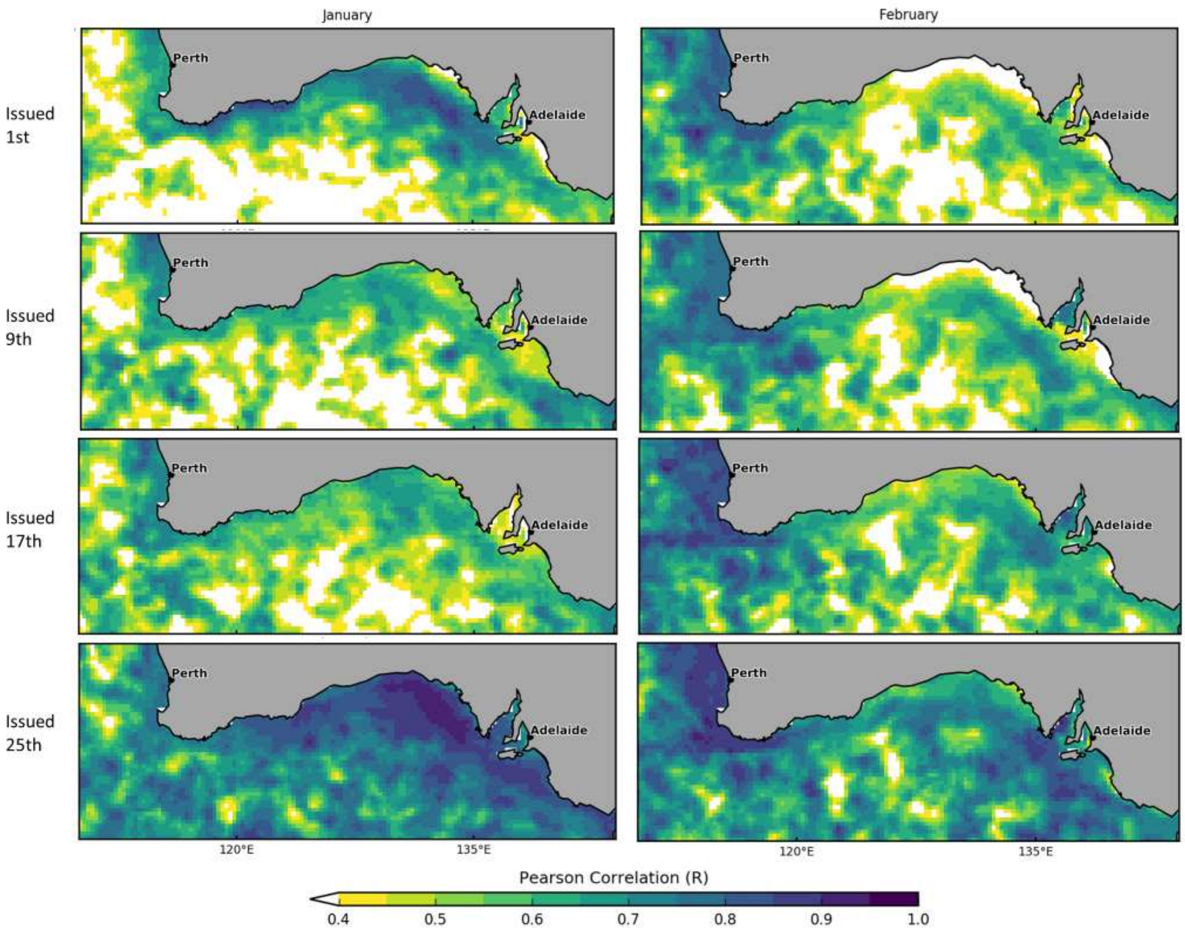

Figure 3. Pearson correlation (r) skill plots for January (left) and February (right) ACCESS-S SST forecasts issued on the 1st, 9th, 17th and 25th of the previous month (i.e., December for the January forecasts, and January for the February forecasts). (Figures produced by the BoM.)

Archival tag data

A combination of (i) new tag returns, (ii) historical tag returns that did not have position estimates when the original habitat models were developed (either because the data were missing from the database, or because the previous geolocation method failed), and (iii) the inclusion of acceptable data from tags exhibiting temperature drift, resulted in 136 tags with position estimates that could be used in the updated habitat models, compared to 65 tags in the original project. Note that to be used in the habitat models, a tag needs to have position estimates within the region we defined as the Great Australian Bight (30-40°S, 125-140°E) and within the months of January-March. Table 1 gives the number of tags released and the number of tags with usable position estimates in each year (noting that a single tag can have position estimates for multiple years). The significant increase in the number of tags meant sufficient data were available in different age-classes (Table 2) to enable us to estimate age-specific habitat preferences.

Table 1. Number of tags released and number of tags with usable position estimates (i.e., in the GAB during January-March), broken down by year. For the latter, the same tag can be counted in more than one year if the fish returned to the GAB in multiple summers.

Year	# Tags released[1]	# Tags with usable positions	Year	# Tags released[1]	# Tags with usable positions
1998	30	30	2007	7	16
1999	10	14	2008	7	13
2000	9	11	2009	-	8
2001	2	3	2010	-	3
2002	5	7	2011	-	2
2003	4	2	2015	6	6
2004	17	6	2016	-	4
2005	19	29	2017	-	2
2006	20	36			

[1] Tags released in December are included in the subsequent calendar year.

Table 2. Number of tags with data for input to the habitat models by age-class. The same tag can be counted in more than one age-class if the fish returned to the Great Australian Bight in multiple summers.

Age-class[1]	# Tags
1	5
2	42
3	102
4	34
5	8
6	1

[1]The age of a fish at release was estimated based on its length (see 'Updating habitat preference models' section of Methods), and its age at subsequent times could be calculated using estimated release age and time at liberty.

Most probable tracks estimated using the twilight likelihood geolocation method for a selection of tags are shown in Figure 4. All position estimates available by age class in the months of January-March (the months included in the habitat models) are shown in Figure 5.

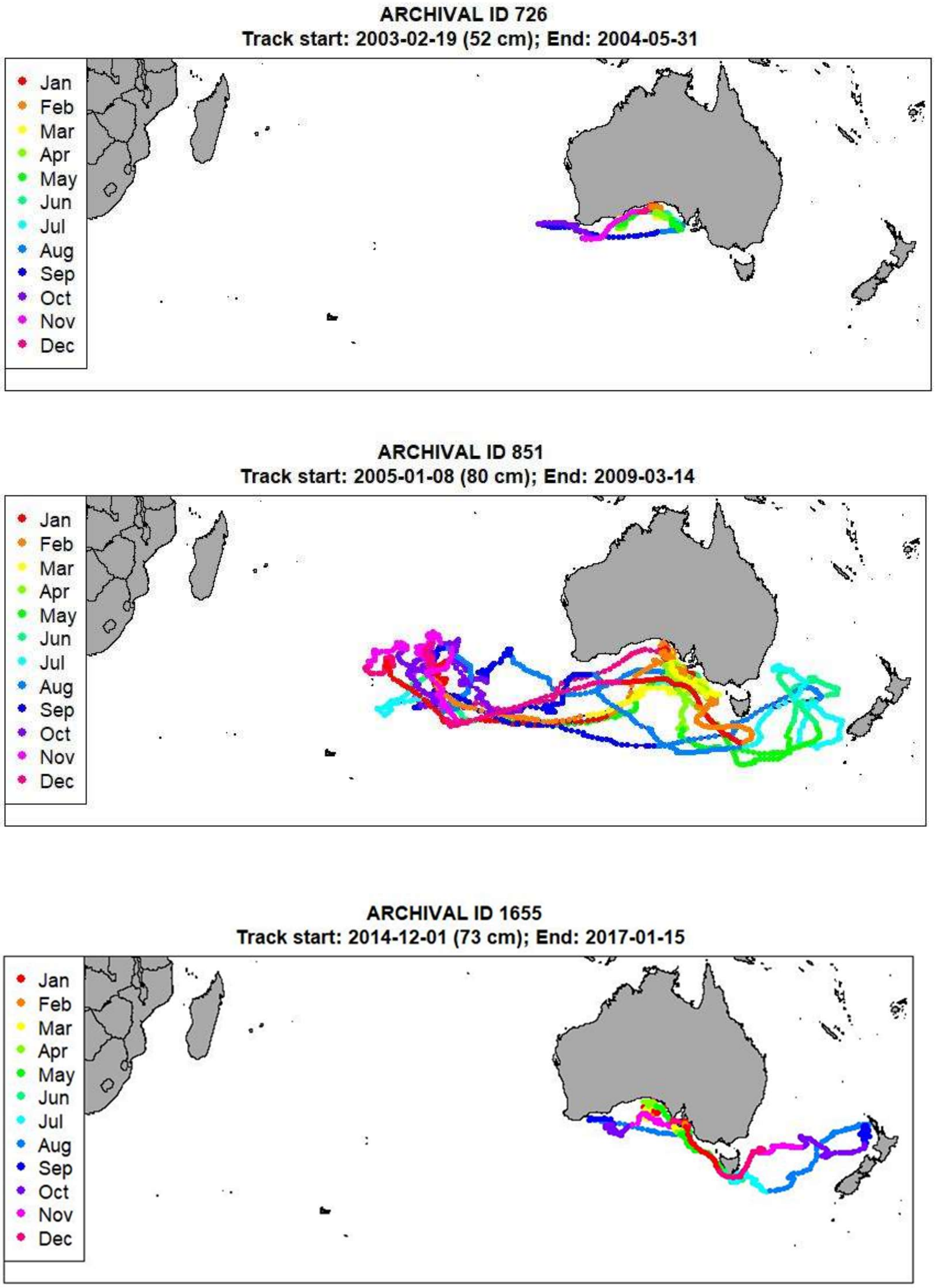

Figure 4. Most probable tracks estimated for three archival tags using the twilight likelihood geolocation method. Release date and end date of the track, and length of fish at release are given in the title. Colour indicates month, as specified in legend.

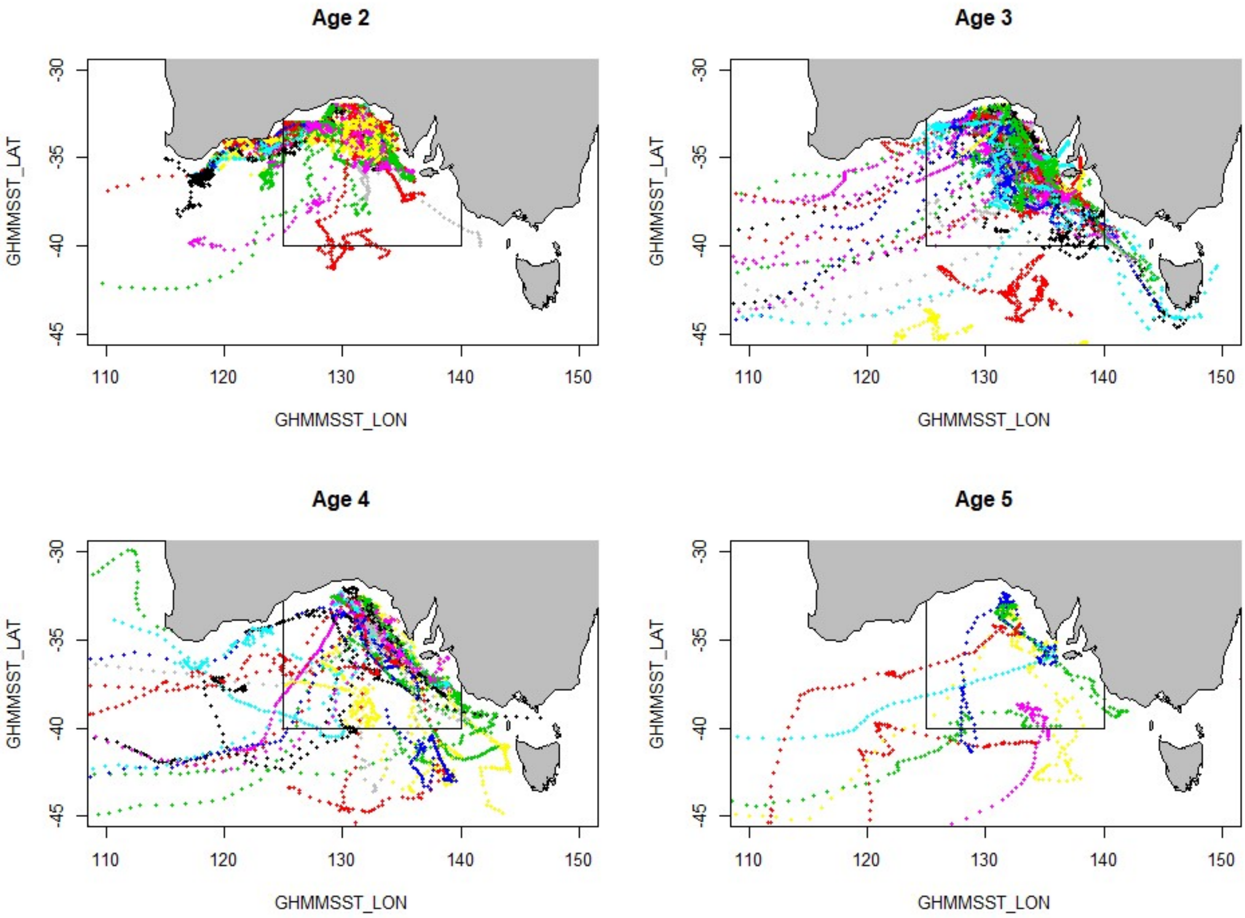

Figure 5. Position estimates within January-March from all available archival tags (years 1998-2011, 2015-2017). Different colours indicate different individuals. Only position estimates that fall within the region defined as the GAB (black box) are included in the habitat models.

Habitat preference models

The age-specific habitat preference models suggest that age 3-4 fish prefer slightly cooler surface temperatures (18.5-21.5^{o}C) than age 2 fish (19-22^{o}C) (see Figure 6 and Figure 7). While this may seem like a small difference, it can make a noticeable difference to the areas deemed to contain preferred habitat, as illustrated in the next section.

The models that included chlorophyll confirmed that chlorophyll influences the distribution of SBT in the GAB (whether directly or indirectly), particularly when combined with SST. Age-specific habitat preference models derived using SST plus chlorophyll suggest that age 2 fish tend to be found in waters with higher chlorophyll levels than age 3-4 fish, and that this tendency increases slightly with increased SST, and also that the range of preferred conditions is narrower for age 3-4 fish (see Figure 8 and Figure 9). The effect that including chlorophyll in the models has on the areas estimated to contain preferred habitat varies depends on the conditions present during the time period of interest. In general, its inclusion tends to slightly reduce the area deemed to be preferred habitat, particularly for age 3-4 fish; often this is because inshore regions that were deemed to contain preferred habitat based on SST only are no longer deemed preferred when chlorophyll is included. This can be seen in the case study example given in the 'Website for delivery of results' section below.

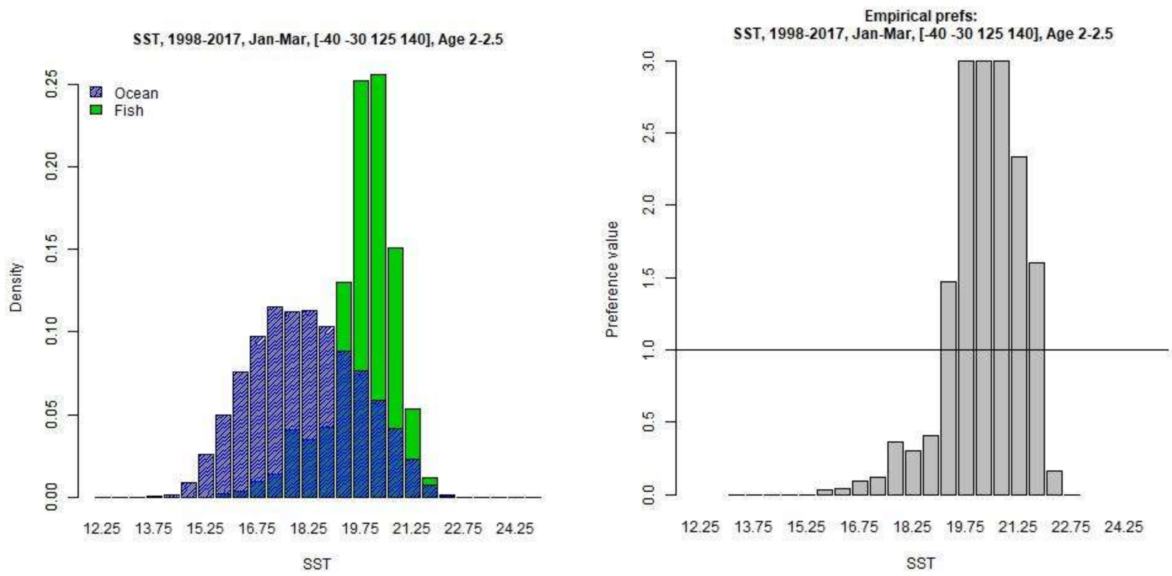

Figure 6. (Left) Distribution of all SST values that occurred in the GAB during Jan-Mar of 1998-2011, 2015-2017 compared with SST values at locations where SBT estimated to be age 2 were found during that same time period. (Right) Preferred SST values, calculated as the proportion of fish observations in a given SST bin divided by the proportion of ocean observations in that bin; preference values greater than 1 indicate SST values where fish density (green bars) is higher than ocean density (blue bars).

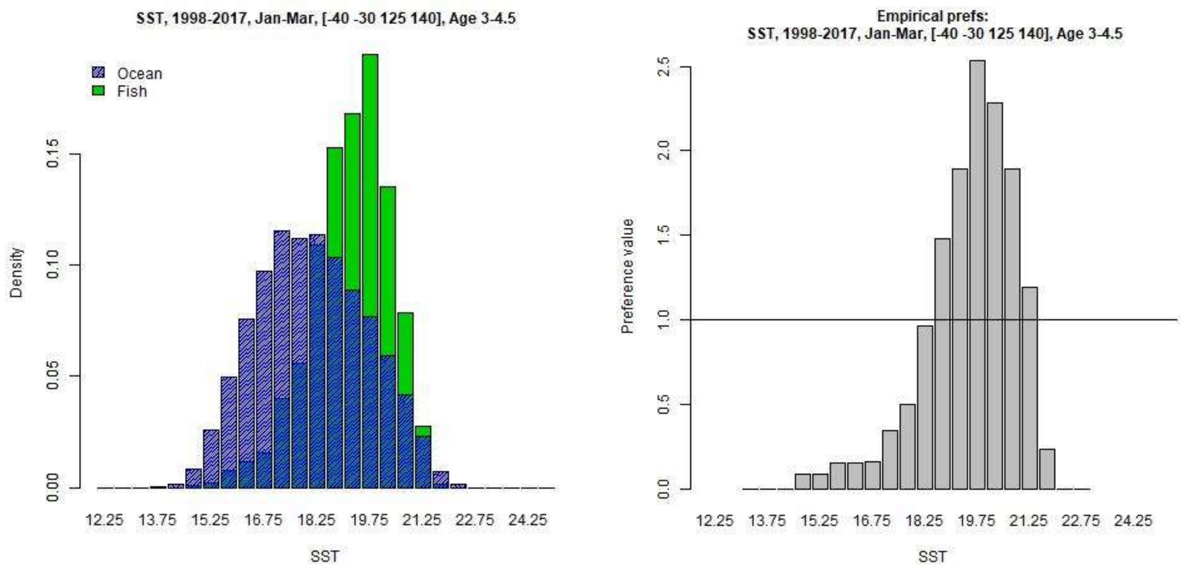

Figure 7. Same as Figure 6 but for SBT estimated to be ages 3-4.

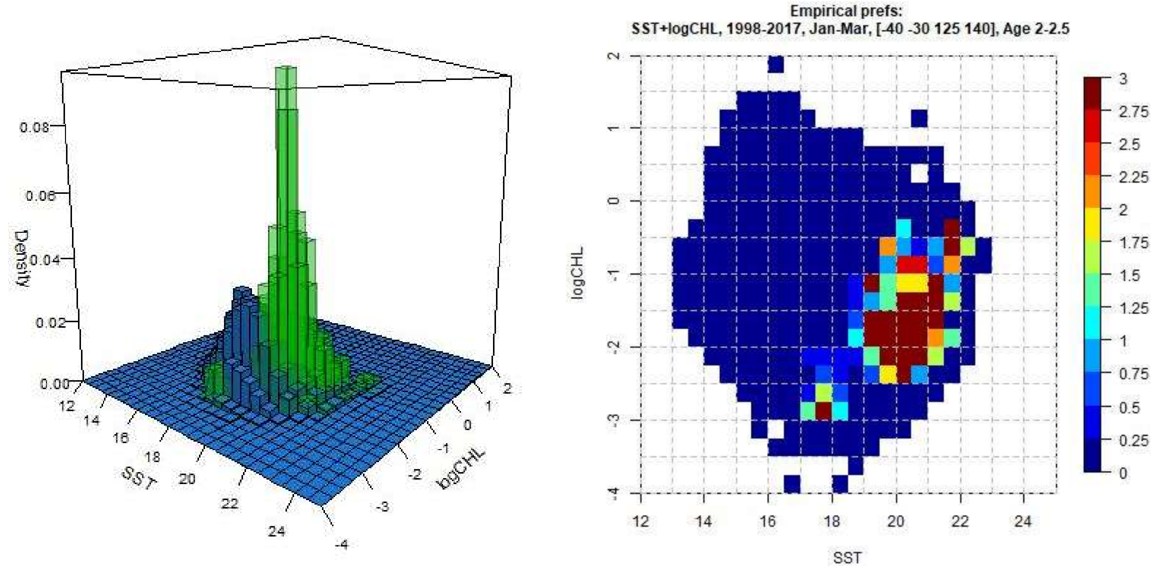

Figure 8. (Left) Joint distribution of all SST and chlorophyll a (log-transformed, denoted logCHL) values that occurred in the GAB during Jan-Mar of 1998-2011, 2015-2017 compared with SST and logCHL values at locations where SBT estimated to be age 2 were found during that same time period. (Right) Preferred combinations of SST and logCHL, calculated as the proportion of fish observations in a given SST-logCHL bin divided by the proportion of ocean observations in that bin; preference values greater than 1 indicate combinations of SST and logCHL where fish density (green bars) is higher than ocean density (blue bars).

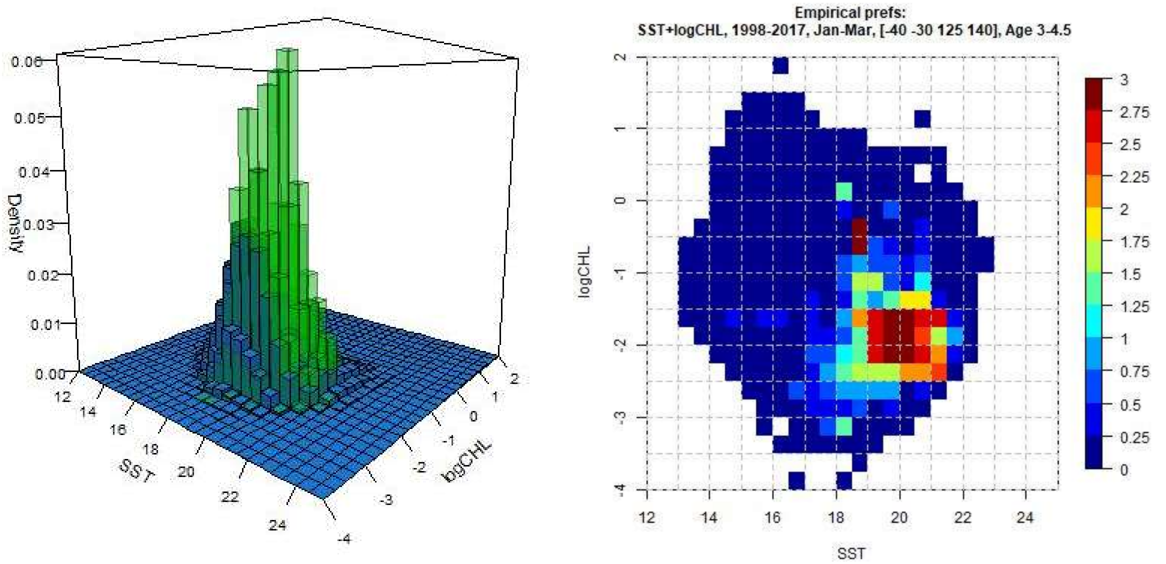

Figure 9. Same as Figure 8 but for SBT estimated to be ages 3-4.

Habitat preference nowcasts and forecasts

The types of habitat preference nowcast and forecast maps that can be produced based on the age-specific preference models are shown in this section, using December 2020 as the example month. Figure 10 shows the age-specific habitat preference nowcast maps produced on the 15th of December 2020 for the previous week (Dec 9-15), using both the SST only and SST plus chlorophyll models. Unfortunately, the chlorophyll data were sparse for that week due to cloud cover obstructing the satellite measurements (note that the degree of cloud cover can vary significantly from week to week). This makes comparison with the SST only forecast more difficult. A better illustration of the type of differences that can be seen between the two models is given in Figure 12 in the next section where the new case studies for the website are discussed.

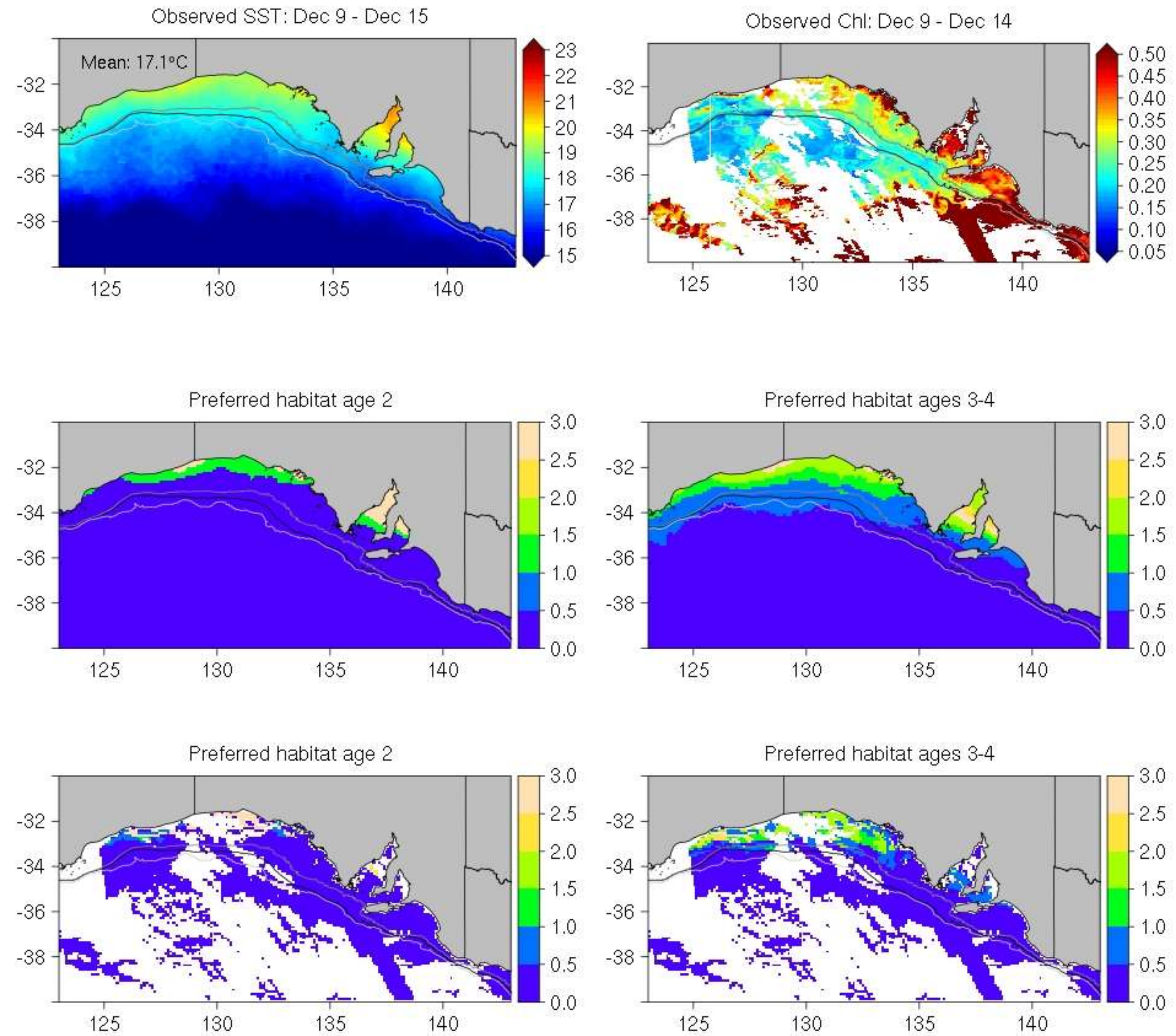

Figure 10. Age-specific habitat preference "nowcast" maps produced on the 15th of December 2020 for the previous week. Top row: SST and chlorophyll conditions observed during the week used in the nowcasts. White regions in the chlorophyll map indicate where data are missing due to cloud cover obstructing the satellite measurements. Middle row: Preference maps based on the SST only model for age 2 fish (left) and age 3-4 fish (right). Bottom row: Preference maps based on the SST plus chlorophyll model for age 2 fish (left) and age 3-4 fish (right).

Age-specific habitat preference forecasts based on ACCESS-S SST forecasts run on the 9th of December 2020 for the next two fortnights and next two calendar months are shown in Figure 11. In the first fortnight (Dec 9-23), the surface temperatures over most of the GAB are forecasted to be too cold to contain preferred habitat for age 2 or age 3-4 fish. As the GAB is forecasted to warm over the next two months, the area predicted to contain preferred habitat increases, particularly for age 3-4 fish because their preference range is slightly cooler than for age 2 fish so more habitat becomes available to them sooner in the season.

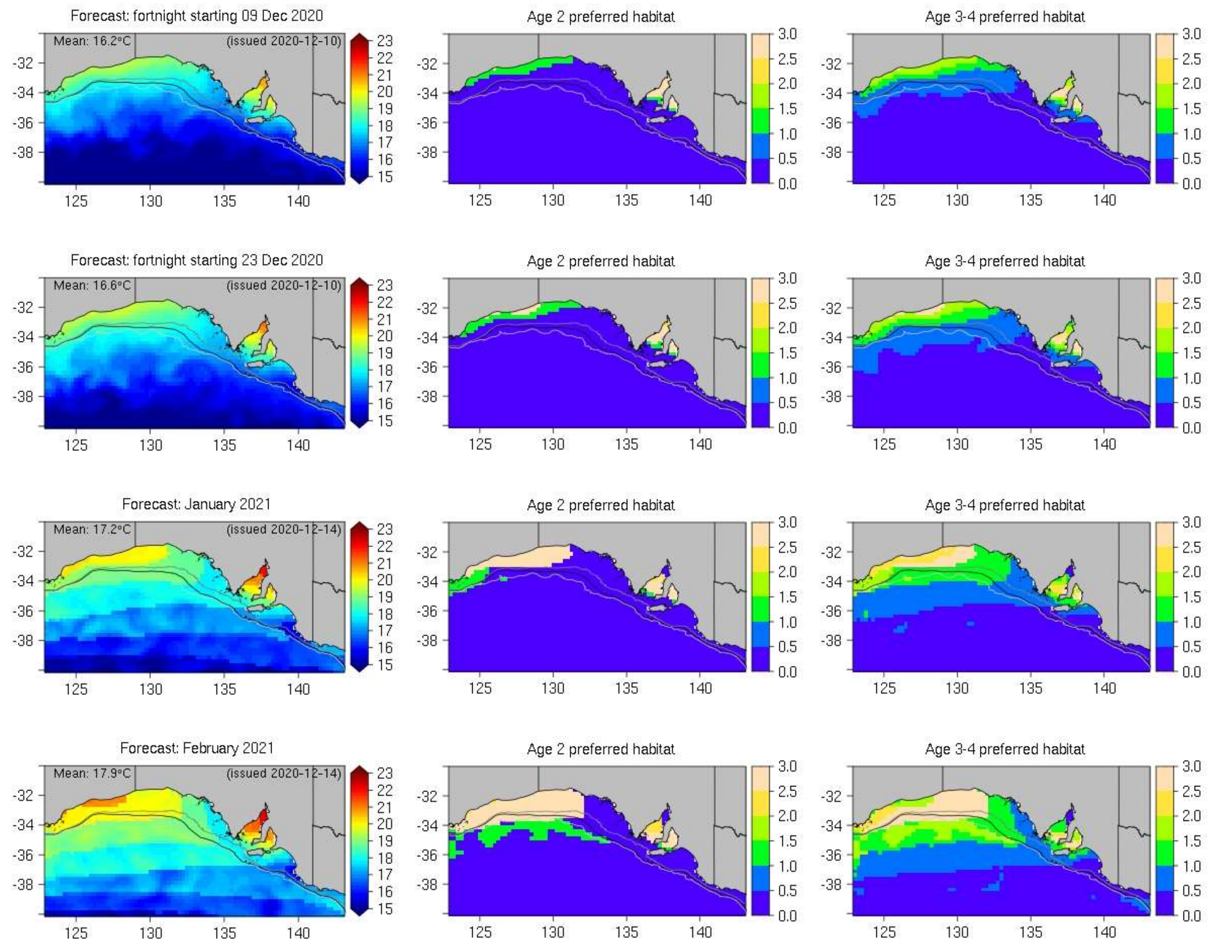

Figure 11. Age-specific habitat preference forecast maps based on ACCESS-S SST forecasts that were started on the 9th of December 2020 for the next two fortnights (rows 1 and 2) and next two calendar months (rows 3 and 4). The left column shows the ACCESS-S SST forecasts, the middle column shows the corresponding age 2 habitat forecasts, and the right column shows the age 3-4 habitat forecasts.

Website for delivery of results

The revised website, which provides a good summary of the work achieved under this project, can be viewed at http://www.cmar.csiro.au/gab-forecasts/index.html.

The most important update to the website was to deliver habitat preference forecasts based on (i) new habitat preference models and (ii) the ACCESS-S SST forecasting system, and this has been achieved. Habitat preference forecasts (and the ACCESS-S SST forecasts on which they are based) are shown for the next two fortnights and next two calendar months in future. Because age-specific preference models proved possible, and were requested by industry, separate habitat preference forecasts are provided for age 2 fish and for age 3-4 fish. See the Habitat preference forecasts page of the new website at http://www.cmar.csiro.au/gab-forecasts/habitat-forecasts.html.

In addition, the following modifications have been made to the website:

- The Observed conditions page has been updated to include temperature at 75 m depth (in addition to SST and chlorophyll), and to show closeups of observed conditions in sub-regions identified to be of interest in the eastern GAB where most fishing operations occur.
- A separate page has been created for habitat preference nowcasts to show areas containing preferred conditions during the most recent week. Separate nowcast maps are provided for age 2 fish and age 3-4 fish based on both the SST-only and the SST plus chlorophyll habitat models (http://www.cmar.csiro.au/gab-forecasts/habitat-nowcasts.html)

- The Case studies pages have been updated and revised to show observed conditions for recent fishing seasons 2015-2019, and to also to show age-specific habitat preference maps for each month of the season using SST only and SST plus chlorophyll models. Sightings from the aerial survey and commercial spotting operations are included on the maps to evaluate whether sightings were made within areas deemed to be preferred habitat (sightings which spotters estimated to be comprised mainly of fish <15 kg are included on the age 2 preference maps, and ≥15 kg on the age 3-4 preference maps). An example of the preference maps for the 2016 case study is given in Figure 12 (to view all case studies, go to the website at: http://www.cmar.csiro.au/gab-forecasts/historical-casestudy.html).
- The Historical SST page has been updated to include time series plots of SST over the past 20 years in small regions of interest.
- The Estimating habitat preferences page has been updated to demonstrate the development of the SST plus chlorophyll model as well as the SST only model. Also, the new geolocation method used to estimate SBT positions for this project is described, and a selection of archival tag tracks estimated using this method are shown.

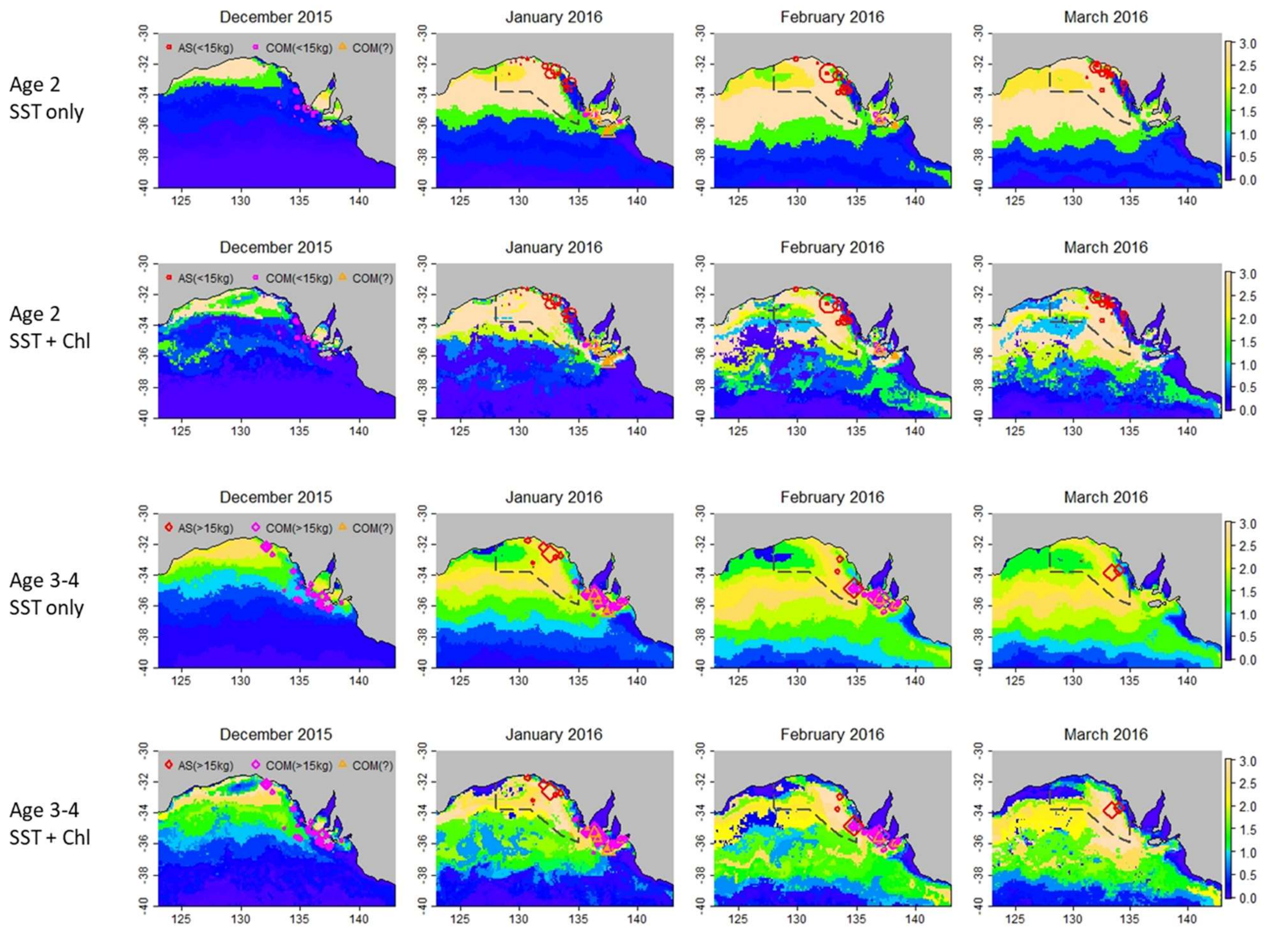

Figure 12. Habitat preference maps shown on the case study page of the website for the 2016 fishing season. The top two rows show areas predicted to contain preferred habitat for age 2 fish in each month of the season based on the SST only (row 1) and SST plus chlorophyll (row 2) models. The bottom two rows show areas predicted to contain preferred habitat for age 3-4 fish in each month of the season based on the SST only (row 3) and SST plus chlorophyll (row 4) models.

Conclusions

This project has met all objectives, including delivering age-specific habitat preference forecasts that were uncertain at the time of the proposal. The overarching goal was to deliver habitat preference forecasts based on (i) the BoM's new seasonal climate forecasting system (ACCESS-S), and (ii) new habitat preference models that use all available archival tag data, and this has been achieved. The amount of available archival tag data was much greater than anticipated for a number of reasons outlined in the report; this allowed for age-specific models to be developed, which showed that age 2 fish tend to prefer warmer waters to older (age 3-4) fish. The much greater spatial resolution of the ACCESS-S-based habitat forecasts, combined with age-specific preference models, should make the revised habitat forecasts even more useful to industry than before for planning fishing operations.

Engagement with industry via regular briefings by the industry co-investigator and a direct presentation of the project at an industry workshop allowed for continual feedback to be received and improvements to be made to the website. As a result, the website now delivers additional environmental information, more comprehensive nowcasts based on both SST-only and SST plus chlorophyll models, more extensive historical SST data, and more recent case studies. Feedback received to date has judged the project to be a success and to have exceeded the expectations of industry.

Overall, the SBT fishing industry in the GAB has a revised seasonal forecasting decision support tool that should prove more informative than the original. The new habitat forecasts and other material delivered on the project website should be a useful aid to industry in decision-making and planning of fishing operations for the current and future fishing seasons. Being able to identify probable distribution of SBT weeks to months ahead of time may also enhance the economic efficiency of this quota-managed fishery.

Implications

The value and impact of the project outputs on industry members (fishers, spotters, managers) has been clearly demonstrated through the fact that the original website has been utilised religiously in the lead up to and throughout every fishing season since its development. The habitat forecasts and other material delivered on the project website have proven a useful aid to industry in decision-making and planning of fishing operations. For example, in the 2017 and 2019 fishing seasons, habitat forecasts indicated slow and delayed warming of the GAB so companies were able to make the decision to delay fishing operations rather than sending boats, pontoons and crew out to sit idle for weeks until conditions became suitable for SBT. As the fishery is quota managed, being able to locate and catch fish more quickly should improve productivity and economic efficiency.

The revised website is being used in the 2020-21 fishing season, and should prove even more useful than the original website for planning fishing operations given the much greater spatial resolution of the forecasts, as well as the age-specific habitat preference models. The website has been very well received so far, with the following feedback provided by Kirsten Rough based on her discussions with industry members: “The website is easy to navigate, images are clear and relevant, the nowcasts of SST and chlorophyll allow individuals to readily translate the forecast to what they are observing on a daily basis, skill plots with each forecast are a great idea - much more user friendly than the previous version.”

A “public good” outcome of this project is that the habitat forecasts are used in the SBT gene-tagging programme (Preece et al. 2019) to help locate areas of most likely fish distribution during tagging operations that occur in February-March each year. Because gene-tagging requires that age 2 fish are tagged and released, the age-specific habitat forecasts on the revised website should be even more informative than the previous all-ages forecasts (particularly since the all-ages habitat model was dominated by data from age 3-4 fish).

Recommendations

Recommendations for other steps that may be taken to further develop and disseminate the results and outcomes from this project include:

- Continue to evaluate the use of the website and forecast system by industry participants via feedback from ASBTIA.
- Publicise the approach to other fishing and aquaculture industries that could use similar systems via presentations at conferences/workshops/meetings. We note that following the original project, similar models have been applied in the Australian Eastern Tuna and Billfish Fishery as part of FRDC Project 2017-004.

Further development

- Further archival tagging of juvenile SBT: The current habitat preference models are estimated using biological data obtained from archival tags deployed on SBT mainly during 1998-2011, with only six tags from 2015-2017. This has not allowed us to evaluate whether preferences have changed between the past two decades, which is particularly important given warming waters and other oceanographic changes in the GAB under climate change. To ensure that the habitat preference nowcasts and forecasts continue to be relevant, it is essential for more recent biological data to be obtained, ideally through another round of substantive archival tag releases on juvenile SBT. This a large undertaking, and funding of such an exercise would need to be determined.
- Investigation of other environmental variables for input to habitat models: Preliminary explorations suggest that environmental variables other than SST and chlorophyll also influence the distribution of SBT in the GAB (e.g. subsurface temperature, salinity). Exploring these variables further was not an objective of the project because they are not available as forecasts; however, given the interest of industry in the habitat nowcasts, and the potential for some of these variables to become available as forecasts in future (see next point), this is an area that could be worthwhile pursuing.
- Keeping abreast of updates to seasonal climate forecasting models: Although ACCESS-S forecasts a number of variables, only SST is available to us from the current version (ACCESS-S1). More variables (such as subsurface temperatures) may become available in the near future as ACCESS-S2 is rolled out, and as CAFE, CSIRO's new decadal prediction system, further develops (https://research.csiro.au/dfp/cafe-csiro-decadal-prediction-system/).

Extension and Adoption

The project results are communicated through a website designed for this purpose, and which has been revised significantly from the website developed as part of the original project. Although the website was specifically designed for industry to aid in planning their fishing operations, it is available for managers and other interested parties to use. The project end date is 1 February 2021; however, the website will continue to update indeterminately, in so far as possible. As was noted in the original project, there are some potential issues with regard to ensuring industry has long-term access to forecasting information via the website after the conclusion of the project. These issues, and possible resolutions, are:

1) There may be situations where small things go wrong, such as changes to the location or format of the files being downloaded for the automatic updates. If the problem is minor, it should be simple to fix (by CSIRO, BoM or ASBTIA staff) without the need for additional funds.
2) Changes to seasonal forecasting model. This was already encountered with the original project, and was the key motivator for the current project, when the BoM replaced POAMA with ACCESS-S. The version of ACCESS-S that is available currently is referred to as ACCESS-S1, but the BoM is in the process of updating to ACCESS-S2. This may require a change to the computer code that generate the forecasts and updates the website, but given it is just a version update, and not an entirely new model, we anticipate the necessary changes to be small.
3) Loss of primary data. More significant problems (such as loss of satellite data coverage, loss of internet services, etc.) could disrupt forecast delivery. Such scenarios are beyond the control of the project team and could lead to cessation of forecast capability.

As a research scientist with ASBTIA and a co-investigator on the project, Kirsten Rough provided continual liaison with industry throughout the project, and will continue to promote the project and website after the conclusion of the project. Results from the website get included in the regular information updates (weekly during the fishing season) that she produces for distribution to all quota holders operating out of Western Australia and South Australia. For South Australia this includes key staff (spotters, fishing skippers, farm managers) as well as owners (distribution list ranges from 48-54 individuals).

Additional contact/communication with beneficiaries occurred through the following:

- October 2019, ASBTIA Workshop: Kirsten Rough (research scientist with ASBTIA and a co-investigator on the project) presented results from the original project website, and noted that the new project and new website were underway.
- February 2020. Kirsten Rough visited Hobart from 17-21 February to meet with the Hobart-based project team. This was a valuable meeting to discuss additions and modification to make to the website based on Kirsten's knowledge of the fishery and on feedback she had received from industry.
- October 2020, ASBTIA Workshop: Presentation by Paige Eveson to give an update on the project, demonstrate the revised website and obtain feedback/suggestions. The workshop was held in Port Lincoln, but due to COVID restrictions the presentation was given virtually from Hobart.
- Milestones were forwarded to ASBTIA and AFMA as per the Extension and Adoption Plan.

Project coverage

There were no media, industry or government articles on this project to report.

Project materials developed

- Website for use by industry showing forecasts of environmental variables and preferred habitat of SBT in the GAB, available at: http://www.cmar.csiro.au/gab-forecasts/index.html
- PowerPoint presentation given by P. Eveson at the October 2020 ASBTIA workshop (provided to K. Rough for distribution afterwards)

Appendix 1: List of researchers and project staff

- Paige Eveson (PI), CSIRO
- Jason Hartog, CSIRO
- Claire Spillman, Bureau of Meteorology (BoM)
- Kirsten Rough, Australian Southern Bluefin Tuna Industry Association (ASBTIA)

Appendix 2: Intellectual Property

The archival tag data used in this project were collected under other projects and the IP remains with those projects. The methods applied in this project relating to geolocation from archival tag data and estimating habitat preferences were also developed under external project funding arrangements. The IP for these methods remains with the original developers and projects. Environmental data from remote-sensed products used in the analyses is publicly available and so should not be considered IP from this project.

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