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Understanding the biophysical implications of climate change in southeast Australia: Modelling of physical drivers and future changes

Alistair J. Hobday, Jason Hartog, John F. Middleton, Carlos E. Teixeira, John Luick, Richard Matear, Scott Condie

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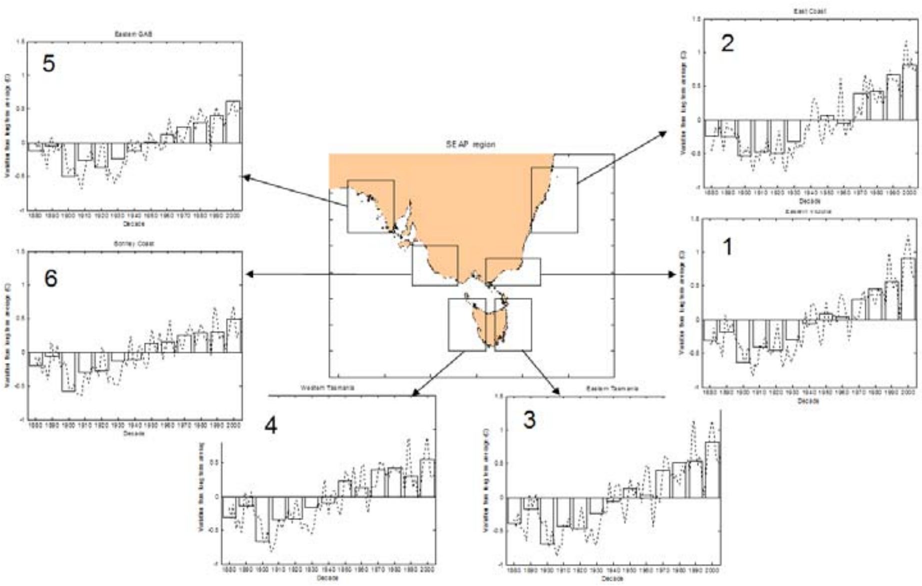

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1 Non-technical Summary

2009/056. Understanding the biophysical implications of climate change in the southeast

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OBJECTIVES:

1. Extract variables from Bluelink and GCM's for fishery regions around the SE
2. Validate variables derived from the Bluelink model against the IMOS and other historical data
3. To complete development of SAROM and validation against the IMOS and historical data for the February 2008 - March 2010 period
4. Compare the predictions of the two models to each other and to GCMs
5. Derive, extract and examine model outputs on derived variables, including acidification levels, in the SE region.
6. Provide these data in written and visual format to the biological and review teams for consideration

Plus

7. Consider historical changes in connectivity in the south-east

OUTCOMES ACHIEVED TO DATE

Fishers, managers, and policy makers in the south-east have a greater appreciation of the physical changes that are occurring in the south-east as a result of the historical analysis as part of this project. The main outcomes to date have been to inform planning of the remaining SEAP investment in the SEAP. On the basis of advice from this project, the SEAP Program Management Committee has decided that investment in oceanographic modeling development is not warranted, and that existing data are sufficient at this stage. The next biological project will use the primary and derived variables developed in this project in the case studies of four key south-east fishery species.

The waters of eastern and south eastern Australian have been identified as being the most vulnerable marine area to both climate change impacts and overall exposure in Australia. This vulnerability particularly relates to changes in the East Australian Current, which has strengthened by 20% in the last 50 years. As a result, water temperatures in the south-eastern region have risen and continue to rise more rapidly than elsewhere in Australia. This warm East Australian Current and other oceanic currents such as the warm Leeuwin Current (which is understood to suppress oceanic upwelling such as the Bonney Upwelling), the cool Flinders Current, and the cool Tasman Outflow converge in this region and together with local ocean processes such as coastal upwelling, are important factors in structuring the composition of marine species, functional groups and communities.

The changing climate in the south-east is already affecting many marine fishes and other organisms. These impacts will have flow-on implications for businesses, communities and economies that are dependent on the marine environment and its resources, such as the fisheries and aquaculture sector. Climate models predict that these physical trends in ocean conditions will continue into the future. Given projected changes, and their possible effect on the fisheries, the south-east Australia program (SEAP) was developed to harness the research capability in a coordinated way, and to link the research to the management needs of the region.

This project set out to improve the understanding of change in the physical environment and determine if further oceanographic model development was required to support biological, social and economic aspects of the SEAP.

The objectives of this project were met. Oceanographic data for the entire south-east region were extracted and archived from the Bluelink ocean model hindcasts for comparison with observations (**Objective 1)** and can be used to examine historical patterns of change. These variables included sea surface temperature, temperature at depth (200 m), surface salinity, and currents. The Bluelink model variables were compared with observations at a range of distances from the coast (i.e. "do they sufficiently represent reality") (**Objective 2)**, which showed that SST was the best performing variable, and the currents were the poorest at the spatial and temporal scales considered. Development of the South Australian Regional Ocean Model (SAROM) model, which covers a smaller region in South Australia, was completed and comparison with in situ IMOS data showed the performance was very good in the regions considered **(Objective 3**)**.** Qualitative comparison of the regional models was completed **(Objective 4**) and we recommend that both models will be useful for a range of biological uses. Projections of future acidification levels were completed (**Objective 5**). There are few studies on the impact of ocean acidification for the south-east region to date. Implications for commercial fishes and invertebrates (e.g. rock lobster and abalone) in the south-east region are unknown, and there is a need for more experiments and field studies before impacts can be more specifically determined. We have provided some future estimates of pH levels, such that critical experiments using realistic values can proceed. Finally, methods to determine marine connectivity in the south-east for the recent past were detailed and patterns of change reported **(Objective 7**). These analyses showed a recent trend towards increasing southward transport off eastern Tasmania, consistent with the documented increase in the strength of the East Australian Current and the associated warming of waters off eastern Tasmania that is predicted to continue over the next half century. We conclude and advise that

1. Data can be extracted from the existing set of physical ocean models that is suitable for retrospective analysis of biological patterns.
2. There is no single best ocean model for all purposes; careful selection and validation should be part of each use of model-based environmental variables. Each model does have strengths and will be appropriate for different uses. We suggest that case studies of fishery species in the south-east discuss their modeling needs with physical oceanographers.
3. Development and improvement of the existing models is not a roadblock to further fishery adaptation planning in the south-east.
4. The suite of available physical data is sufficient to support the next phase of biological case studies as part of SEAP.

KEYWORDS: global climate change, biophysical change, southeast Australia, marine fisheries, acidification.

2 Acknowledgments

This project was undertaken as part of the South-East Australia Program (SEAP). We acknowledge the efforts of Ingrid Holliday and Dallas D'Silva for coordinating and overseeing the direction of the program. Part of the text in this report was developed with Janice Lough, and has been published in Hobday and Lough (2011).

3 Background

The climate of Australia's marine environments has already changed compared with historical baselines (Holbook and Bindoff, 1997; Ridgway 2007; Pearce and Feng 2007; Lough 2008; Poloczanska *et al.,* 2009). On both coasts, water temperatures have warmed and salinity has increased in the poleward-flowing currents on the east and west coasts (Ridgway 2007; Pearce and Feng 2007). The changing climate is predicted to result in changes to oceanic temperatures, stratification, currents and eddies (that transport important nutrients and are important for distributing certain life stages), and chemistry (such as salinity and acidity). These will influence abundance and distribution of species, population dynamics, timing of productivity stages and crustaceans ability to grow their shells. In the ocean surrounding Australia, these physical changes are coincident with biological changes in a range of marine species, including changes in local abundance, geographic range, phenology, and community structure (e.g. Hobday *et al.,* 2007; Poloczanska *et al.,* 2007; Ling 2008; Poloczanska *et al.,* 2009; Figueira and Booth 2010; Pitt *et al.,* 2010; Last *et al.,* 2011). It seems clear that climate is already affecting many marine fishes and other organisms. These impacts will have flow-on implications for businesses, communities and economies that are dependent on the marine environment and its resources, such as the fisheries and aquaculture sector (Hobday and Poloczanska 2008).

Climate models predict that these trends will continue (Hobday and Lough, 2011). The eastern and south eastern Australian marine waters have been identified as being the most vulnerable geographic area to both climate change impacts and overall exposure in Australia (Hobday and Pecl, in review). This vulnerability particularly relates to changes in the East Australian Current, which has strengthened by 20% in the last 50 years (Ridgway 2007). As a result, water temperatures in the south-eastern region have risen and continue to rise more rapidly than elsewhere in Australia. This warm East Australian Current and other oceanic currents such as the warm Leeuwin Current (which is understood to suppress oceanic upwelling such as the Bonney Upwelling), the cool Flinders Current, and the cool Tasman Outflow converge in this region and together with local ocean processes such as coastal upwelling, are important factors in structuring the composition of marine species, functional groups and communities.

Climate change is predicted to further effect the strength of these currents. While the East Australia Current has strengthened (Ridgway 2007), the Leeuwin Current has been weakening in the region since the 1970's (Pearce and Feng 2007) with significant upwelling events recorded along the South Australia/Victoria coastline (Nieblas *et al.,* 2009). These changes are expected to have significant implications in the region. This region is also predicted to experience the greatest increases in sea levels, which will have implications for critical inshore habitats that are important recruitment sites for many species. As sea levels rise, migration opportunities for these habitats will be limited by existing barriers such as coastal infrastructure (Poloczanska *et al.,* 2009). These inshore habitats will also be affected by further increases in salinity levels within embayments and inlets due to increasing evaporation driven by predicted increases in land air temperatures and reduced rainfall (Gillanders *et al.,* 2011).

Given these projected changes, and their possible effect on the fisheries, the south-east Australia program (SEAP was developed to harness the research capability in a coordinated way, and to link the research to the management needs of the region.

3.1 South-East Australia Program (SEAP)

In 2009, Victoria Tasmania, South Australia, New South Wales fisheries management agencies, CSIRO, AFMA and the Fisheries Research and Development Corporation developed a south-eastern Australian program (SEAP) to address adaptation of fisheries and aquaculture to climate change through coordinated action. This program is designed to provide information to help the various fishery and aquaculture sectors and governments manage risk. The program aims to improve understanding of the biophysical, social and economic implications of climate change and to facilitate the preparation and adaptation of the sectors and fisheries management arrangements to these future changes.

SEAP is a key component of a national approach to climate change and fisheries and aquaculture. The program will inform and contribute to the delivery of national and regional planning outcomes, including the National Climate Change and Fisheries Action Plan. To deliver the outcomes of the program, five work themes (strategies) were originally envisaged under a four year program plan (**Figure 1**). This project was under the theme of "Understanding exposure to changes", sub-theme "Understanding the biophysical implications of climate change". Two projects within this sub-theme were funded (this project), and a project to consider the risk from climate change to key fishery species (Pecl *et al*., 2011).

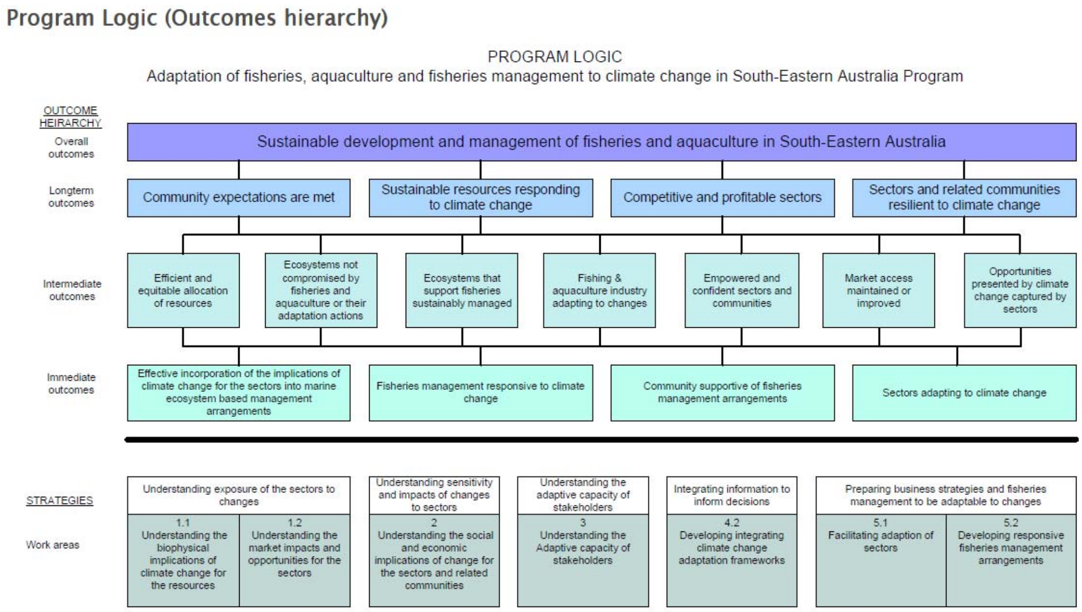


Figure 1. Adaptation of fisheries, aquaculture and fisheries management to climate change in South-Eastern Australia Program. From SEAP project plan – Sept 2009.

As part of initial SEAP planning with regard to understanding change in the physical environment, two projects were initially scoped that would run for three years. The first project was based on modelling of physical drivers in the region (Project 1), while the second was to project future levels of influencing variables (Project 2).

Project 1. Modelling of physical drivers in the region. Three steps were planned over three years to develop model capability for the south-east region

Step 1: Regional Modelling (Year 1 – 2010/11). Two regional models will be further developed and validated against historical and data streams from the national Integrated Marine Observing System.

Step 2: Review (end of Step 1). A review of the "validated" regional models will be made so as to determine what models and extensions are required for climate change scenarios studies. This review will be in consultation with managers and the SEAP PMC.

Step3: Development of more refined models over the next two years (2011/12, 2012/12). Where necessary, as a result of the review (Step 2), more refined models may be developed for areas identified as priorities.

Project 2. Projecting future levels of influencing variables. Three steps were also planned to develop projections of the variables that might influence fish distribution, phenology and abundance, and thus ultimately fishery production.

Step 1. Projecting future acidification levels for the south-east region (Year 1). The rate and level of ocean acidification in the region will be predicted based on available Global Climate, Regional models and information. Seasonal signals are expected to be particularly important for pH, with significant differences between seasons. Through this process, additional ocean variables may be derived, including mixed layer depth, frontal density, and eddy characteristics.

Step 2. Review of needs for other additional variables, such as productivity, zooplankton biomass (end of year 1). The range of variables from the physical models may be insufficient for future understanding and changes in marine resources. The review will consider the extent to which additional variables can be generated.

Step 3. Projections of other key influencing variables (Year 2 and 3). Based on the findings of the review in step 2, other important variables may be extracted or derived to understand the future biophysical changes in the SE region.

In this first SEAP physical project (work area 1.1), we planned to undertake the first steps of both Project 1 and Project 2, although by the conclusion of the project, we can also comment on several other steps, and suggest a revised set of priorities for the SEAP.

4 Need

The eastern and south eastern Australian marine waters have been identified as being the most vulnerable geographic area to both climate change impacts and overall exposure in Australia. These changes are expected to have significant implications in the region.

Information on future physical changes in south-eastern Australia are currently available only through Global Climate Models (GCM) that provide data at coarse spatial scales of 1-2 degrees (latitude & longitude). They currently provide almost no information at the scale of coastal upwelling, eddies and fronts which are important factors driving oceanic productivity (Hobday and Lough 2011). These models currently predict global changes in a range of physical variables both in the atmosphere and in the ocean for the 20th (hindcast mode) and 21st (forecast mode) centuries and a suite of GCMs are currently used in IPCC reporting.

Further refined modelling of physical drivers in this region may be required to understand drivers at scales relevant to fisheries and aquaculture for driving productivity, distribution and abundance of species. While a number of national (Bluelink) and regional finer-resolution ocean models exist for the south-east region (Baird *et al.,* model, NSW; Huon Estuary model, Tas; SAROM, SA), in this project outputs from two (Bluelink and SAROM) will be used to determine the utility of the physical data for supporting fishery studies in the south-east.

5 Objectives

The six objectives of the original project were to:

1. Extract variables from Bluelink and GCM's for fishery regions around the south-east of Australia
2. Validate variables derived from the Bluelink model against the IMOS and other historical data
3. To complete development of SAROM and validation against the IMOS and historical data for the February 2008 - March 2010 period
4. Compare the predictions of the two models to each other and to GCMs
5. Derive, extract and examine of model outputs on derived variables, including acidification levels in the SE region.
6. Provide these data in written and visual format to the biological and review teams for consideration

Partway through the project, a seventh objective was added:

7. Consider historical changes in connectivity in the south-east

6 Models can provide data on physical ocean variables

Observations of the ocean are sometimes sparse in time and space, although satellite platforms over the last few decades have improved surface observations. For sub-surface data, models represent an alternative source of “data”. Models can be used to generate information on historical conditions (hindcasts) or the future (projections, or forecasts).

Regional ocean models are often at a spatial scale of <20 km, and so may produce useful data for fisheries studies. Two “regional” ocean models are used in this project, which will allow issues with the scale of the model in representing important coastal processes (e.g. upwelling) to be determined, comparison between models, and validation against observations. The coarser Bluelink model (~10km resolution) covers the entire south-east region (and Australia[1]), while the SAROM model (~4 km resolution) covers a smaller region in South Australia, as defined below. These models do not currently produce future data on long time scales, but may be partially able to do so in future by nesting within global climate models (GCMs) that will provide boundary conditions to force the models. Both these regional models are evaluated in this project for use in the south-east Australia region.

6.1 Model 1. Bluelink

Bluelink is an Australian partnership between the Commonwealth Scientific and Industrial Research Organisation, the Bureau of Meteorology (BoM) and the Royal Australian Navy. The primary objective of Bluelink is the development of a short-term forecast system for the mesoscale ocean circulation in the Australian region which became operational at the BoM in August 2007 (www.bom.gov.au/oceanography/forecasts/) (Oke *et al.,* 2008).

The key elements of the Bluelink system are the Bluelink ocean data assimilation system (BODAS) and the Ocean Forecasting Australia Model (OFAM), a

[1] Bluelink does cover the whole globe, but the high resolution area covers only the Australasian region. It is eddy-resolving over the region 90E–180E, 60S–10N (0.1 degrees in latitude and longitude).

global ocean general circulation model. OFAM is based on version 4.0d of the Modular Ocean Model (Oke *et al.,* 2008). The horizontal grid has 1191 and 968 points in the zonal and meridional directions, respectively; with 1/10° horizontal resolution around Australia (90–180°E, south of 17°N). Outside of this domain, the horizontal resolution decreases to 0.9° across the Pacific and Indian basins (to 10°E, 60°W and 40°N) and to 2° in the Atlantic Ocean. OFAM has 47 vertical levels, with 10 m resolution down to 200 m depth. Bluelink has been used to provide data for a number of marine applications for historical and near realtime periods (e.g. Hobday *et al.,* 2011).

6.2 Model 2. South Australia Regional Ocean Model (SAROM)

This model adopts the Regional Ocean Modelling System (ROMS; http://www.myroms.org/) which is now recognised as the leading coastal modelling suite in the United States. The domain extends from Thevenard near the head of the Great Australian Bight to Robe in the east and about 800 km offshore. The present grid resolution is approximately 0.05° (5.55 km) although the ROMS allows for high resolution nesting. In the vertical, there are 30 levels, distributed such that the layers near the surface and bottom are more highly resolved than the mid-depths. A split time-stepping scheme is employed which solves the equations containing depth-dependent terms once for each time the non-depth-dependent equations are solved. This is a standard device employed to save computer time.

The model is forced by daily averaged winds, heating and evaporation (less precipitation). The model takes around 12 hrs to run for one calendar year. A version of SAROM has already been developed to provide the circulation forced by a monthly mean atmospheric climatology obtained from the global NCEP/NCAR data repository. The results have been shown to qualitatively describe the known circulation features of the region. These include summertime upwelling and dense salty water formation at the head of the gulfs and restricted exchange between the gulfs and shelf. During winter, the model shows the expected dense water outflow from the gulf and coastal regions, and downwelling to depths of 250 m or so. The atmospheric forcing is being obtained from the Bureau of Meteorology’s Local Area Prediction Scheme (LAPS) which results in an hourly assimilated (model/data) product at 12 km resolution.

Further model development will include boundary forcing that arises from the Leeuwin Current in the west as well as the equator-ward Sverdrup transport (that drives the Flinders Current). Following previous studies (e.g., Middleton and Black 1994; Middleton 2006), a coastal trapped wave (CTW) paddle will be adopted for Thevenard so as to represent incoming wind-forced circulation generated to the west and outside the model domain. A second version of SAROM is currently being adapted to be driven by daily averaged forcing so that a detailed validation against data can be made.

Data from this model have been used in several South Australian studies where short-term coverage is useful, such as for explaining recruitment patterns.

6.3 Projecting future conditions - Global climate models

One way to estimate future environmental conditions is simply to extrapolate based on historical trends. This approach is not widely used as it would only be useful over short time periods (decades at best) and may not allow for dynamical (non-linear) changes in the ocean-atmosphere system. It could in principle be used to examine near-term changes, however, on these timescales natural climate variability tends to obscure climate trends (Hobday and Lough 2011).

Models that can dynamically represent ocean or atmospheric circulation at a global scale over time periods of centuries are most commonly used to project future conditions. Mathematical models of the general circulation of a planetary atmosphere or ocean and based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat) are known as general circulation models. These equations are the basis for complex computer programs commonly used for simulating the atmosphere or ocean of the Earth. Atmospheric and Oceanic general circulation models (AGCM and OGCM) are key components of Global Climate Models (GCMs) along with sea ice and land-surface components. GCMs are widely applied for weather forecasting, understanding the climate, and projecting climate change. Coupled ocean-atmosphere GCMs are used to project future change under various scenarios. These can be idealised scenarios (e.g. CO2 increasing at 1%/yr) or more realistic (usually the IPCC SRES scenarios). As future conditions for the Earth's climate system will depend not only on the planet's system response to changes in greenhouse gas concentrations and radiative forcing, but also on how humans respond through changes in technology, economies, lifestyle and policy, the future is somewhat uncertain at longer time scales (Moss *et al.,* 2010).

To account for the wide range of possible futures, the Intergovernmental Panel on Climate Change (IPCC) developed alternative future emission scenarios to be used for driving global models (see Figure 1 in Moss *et al.,* 2010). A set of scenarios known as SRES scenarios (Special Report on Emissions Scenarios) was used in the Third Assessment Report (TAR) in 2001 and the Fourth Assessment Report (AR4) in 2007 (IPCC 2007). These scenarios represent a range of warming, and have been widely used in biological studies (e.g. Anthony *et al.,* 2008; Hobday 2010). Relatively low (e.g. SRES B1, CO_2 concentration stablisation at 549 ppm by 2100 and global temperatures ~2-4°C higher than 1990 levels), medium (e.g. A1B, 717 ppm of atmospheric CO_2 by 2100 and global temperatures ~3-5°C higher) and high (e.g. A1FI, 970 ppm of atmospheric CO_2 by 2100 and global temperatures ~5-6°C higher) scenarios are often used in projection studies as a way of bracketing the future change, although given present rates of greenhouse gas emission and observed climate change (Rahmstorf *et al.,* 2007; Le Quéré *et al.,* 2009), low scenarios are now seen as less realistic. For the period up to 2030, all the scenarios are similar, and then diverge to the end of the century. Which scenarios should be considered most realistic is uncertain, as the projections of future CO_2 (and other greenhouse gases) emission are themselves uncertain (Moss *et al*., 2010; Hobday and Lough 2011). Most studies use several scenarios to provide a range of future conditions.

Unfortunately, just as biologists and other "user" scientists were becoming familiar with the SRES scenarios and their nomenclature, an updated set of scenarios is being used for IPCC AR5, based on radiative forcing (Moss *et al.,* 2010). Radiative forcing describes a change in the radiation balance, such as may be caused by changes in atmospheric concentrations of greenhouse gases. Positive forcing, for example, drives warming of the Earth system. These new four main scenarios, known as RCP (representative concentration pathways), differ from the SRES set in that they include scenarios that allow for climate change mitigation and adaptation. The four main RCPs: RCP 8.5, RCP 6.0, RCP 4.5, and RCP 2.6, correspond to CO_2 equivalent (CO_2 plus other greenhouse gases) levels of 1370, 850, 650 and 490 in 2100 (Moss *et al.,* 2010). While the currency has changed (gas concentration (ppm) to radiative forcing ($W\ m^{-2}$)), the SRES and RCPs are related, in that increasing concentrations of greenhouse gases affects the balance between incoming solar radiation and outgoing heat radiation which determines the Earth's average temperature. Previously, SRES greenhouse gas concentrations were converted to radiative forcing of the climate system using radiation conversion codes located within each GCM, which represented an unnecessary additional source of variation now removed under the RCP approach (Moss *et al.,* 2010). Biologists will likely continue to use the SRES scenarios for some time, as many climate models and projections are based on these scenarios. A similar lag and transition period occurred when the IS92 scenarios used in the Second Assessment Report of 1995 were superseded by the SRES set (e.g. Orr *et al.,* 2005; Poloczanska *et al.,* 2007).

Alternative emission scenarios presented by the IPCC are global and based on changes in greenhouse gas concentrations (SRES) or radiative forcing (RCP), necessitating complex conversion into a range of relevant climate variables at finer scales using Global Climate Models (GCM) developed by a number of research organisations around the world. These models are based on the general principles of fluid dynamics and thermodynamics and had their origin in weather prediction. GCMs describe the dynamics of the atmosphere and ocean in an explicit way, typically at horizontal spatial scales of 1-3 degrees, and with varying numbers of vertical layers in the ocean and atmosphere, and provide a way to run quantitative experiments on climate conditions during the past, present, and future. Advances in development of GCMs used for climate modeling are typically oriented around the IPCC reporting timelines, with transition periods as for emission scenarios when both old and new models are available to the wider research community.

Uncertainties in future projections based on climate models should not be underestimated, and result from a combination of scenario uncertainty (what will be the future level of greenhouse gas emissions), climate sensitivity to these emissions, difference between climate models (e.g. how each model incorporates ocean-land-atmosphere processes), and model scale (IPCC 2007). While single model-scenario combinations may have considerable uncertainty, there are a number of approaches to improve confidence in future projections such that dependent biological projections can be useful (Hobday and Lough 2011; **Section 8.2)**.

6.4 Model Validation

6.4.1 Bluelink validation

The Bluelink model has been validated against a number of oceanic variables in western, southern and eastern Australia (Oke and Schiller 2007; Oke *et al.,* 2008) and elsewhere (Schiller *et al.,* 2008). Variables such as temperature, salinity, and current velocities at a range of depths, and surface variables such as sea surface height can be extracted from the archived model runs (Project 1, step 1), and additional derived variables such as frontal density, eddy properties created from the primary variables in turn (Project 2, step 1). A number of these primary variables have already been validated at much larger spatial scales in the open ocean (Schiller *et al.,* 2008), lending confidence to the use of this model. In this project we will examine the ability of this model to represent environmental patterns within south-east Australia.

6.4.2 SAROM validation

Validation of the model output as part of this project will be done against the extensive data sets that are being collected under the Southern Australian Integrated Marine Observing System (SAIMOS) which is being led by John Middleton and SARDI. These data streams consist of ocean currents, temperature and salinity from 6 moorings, including a permanently installed reference station. The moorings are located from Kangaroo Is to the Eyre Peninsula. Temperature, salinity and nutrients are also measured for the region as part of the SAIMOS monthly field surveys. In addition, from October, HF Ocean RADAR data will be available for the region that will provide 6 km binned surface ocean currents at 30 minute intervals and for the Kangaroo Is –Eyre Peninsula region. The mooring data have been collected from August 2008 and with complete data returns from February 2009 onwards. These data, and those to be collected, will be compared with the SAROM model predictions for the period up until March 2010 so as to determine the validity in space, time and process. Improvements to the model are expected to result from this extensive model validation exercise.

6.4.3 GCM validation for the south-east region

Global climate model (CGM) data are coarse compared to the two regional climate models described above. Performance of the IPCC suite of GCMs varies considerably for both marine and terrestrial variables, such as rainfall, air and water temperature, and circulation patterns. To select the best set of GCM s for use in south-east Australian marine waters requires evaluation against each variable independently (Hobday and Lough 2011). The techniques for this validation are described in detail in **Section 8.2**. Without prior identification of the particular variable of interest, a set of best GCM's cannot be recommended. Partnership with modellers is suggested for use of these data in biological studies (Hobday and Lough 2011).

7 Methods and results - Project subsections

Reporting of the results to the SEAP program management committee will allow further investment decisions. These result sections as a whole address **Objective 6** and the data are presented here in a variety of visual formats. The raw data behind all these are now available from the original model, or from the lead author. The size of the data precludes "written" data being supplied, and so examples are used to indicate what data are available.

As part of extracting data for comparison with observations (**Objective 1)**, we illustrate the potential for these data to be used to determine historical patterns of change (**Section 7.1)**. The process for validating the model variables (i.e. "do they sufficiently represent reality") is detailed in **Section 7.2**. (**Objective 2)**, development of the SAROM model is detailed in **Section 7.3 (Objective 3).** Comparison of the regional models is qualitative in **Section 7.4 (Objective 4**). Projections of future acidification levels (**Objective 5**) are shown in **Section 7.6**, and methods to determine marine connectivity in the south-east are presented in **Section 7.7 (Objective 7**).

7.1 Data extraction for the south-east (Objective 1)

The first objective of the project was to extract variables from Bluelink and GCM's for fishery regions around the south-east of Australia. This involves developing computer code to access and process the existing data stored as netcdf files. A range of data could be extracted, as detailed below, but some will be more useful for fisheries applications.

There is a long history of using environmental data in fisheries oceanography (e.g. Laurs 1977) – and explaining the distribution and abundance of species remains a key challenge. Most of the environmental data can be described as primary variables – those that can be directly measured *in situ* or directly from satellite data. With regard to the primary variables, satellite remote sensing has been a breakthrough in terms of the spatial and temporal coverage that is now possible, however, satellite variables are limited to the sea surface, or the surface expression of sub-surface features. Examples of primary variables include moon phase, wind speed, sea surface temperature (SST), sea surface color (SSC, also known as chlorophyll, although chlorophyll is technically a derived variable from SSC), and sea surface height (SSH).

A second category of environmental variables is defined here as derived variables: environmental variables that are derived from the primary variables. Examples of derived variables include fronts, upwelling zones, and eddies. Some derived variables have been used in previous studies with a variety of complexities, e.g. fronts- (Heron *et al.,* 1989; Zainuddin *et al.,* 2006).

Finally external variables are those that have little relationship to the life of the fish, but may be a proxy for environmental variables. Examples include latitude, month, year. External variables are not discussed further, but may be added when seeking to explain patterns in fishery catch data. The use of these variables in future projections of fishery patterns is a contentious area, as they often encompass patterns in historical fisher behavior that may not be appropriate or known for the future.

7.1.1 Primary variables

Primary variables could be extracted from the Bluelink model for the period 1994-2010. These variables were available on a daily, weekly or monthly time scale, and included water temperature, salinity, currents (u – east-west component and v – north south component) at a range of depths (**Table 1)**. These are also discussed further in **Section 7.2.**

Table 1. List of primary variables extracted from Bluelink for use in validation (**Section 7.2**) and secondary variables derived from historical observed datasets for consideration in future studies.

Variable	Time period considered	Notes
Primary variables		*Extracted from stored Bluelink output*
Sea surface temperature	1994-2010	Compared with satellite SST
Temperature at depth (200m[1])	1994-2010	Compared with SynTS. Note that SynTS is also a modeled product itself with significant errors. So this is only a

		model-model comparison.
Salinity	1994-2010	Compared with SynTS
Currents – u (east-west)	1994-2010	Compared with satellite SSH
Currents – v (north south)	1994-2010	Compared with satellite SSH
Secondary variables		*Calculated from historical data*
Frontal activity	1994-2010	Derived from satellite SST data – monthly scale
Eddy kinetic energy (EKE)	1994-2010	Derived from satellite SSH data – weekly scale
Eddies	1994-2010	Derived from satellite SSH data – weekly scale
Chlorophyll[2]	1997-2010	Not available from regional or future climate models at this time.

1. Temperature at depth could be obtained for a range of depths as Bluelink has multiple depth layers. In subsequent sections we illustrate the performance of the 200 m temperature.
2. Chlorophyll is considered a derived variable by some authors. It is available from satellite datasets (e.g. SeaWiFS 1997-2010) but was not evaluated further in this project, but as ocean models develop, we expect they will include chlorophyll as a model variable such that it can be used in future fishery projections.
3. This only provides an estimate of the geostrophic component of the surface current. To get "true" currents, the local wind-forced component should be added. There are also methods for computing subsurface geostrophic components from SynTS by assuming a depth of no motion. However, neither the surface nor subsurface methods work on the shelf and they should both really be regarded as providing model estimates (albeit a simpler model than the hydrodynamics) with major uncertainties. Thus, the velocity comparisons presented may be less informative than if these corrections were possible.

Primary variables were also extracted from historical observed datasets for the validation phase, including satellite sea surface temperature datasets (**Section 7.2**) and blended historical datasets that cover an even longer period (e.g. HadlSST, back to 1850). Documenting historical change for the primary variables was not a focus of this project, but the data collated for this subsequent model validation can be used alone to indicate historical patterns. For example, the HadlSST data reveals long term trends in sea surface temperature. Regions in the south-east show different rates of warming, with the east coast warming fastest (as documented elsewhere, Ridgway 2007) and the eastern Great Australia Bight warming slowest (**Figure 2)**. Considering the temperature changes by decade indicates clearly that the whole south-east region is warming rapidly, with each decade since ~1950 warmer than the previous (**Figure 2)**. Such extractions and analyses can also be useful to a range of SEAP stakeholders, and have been used and distributed for a number of presentations.

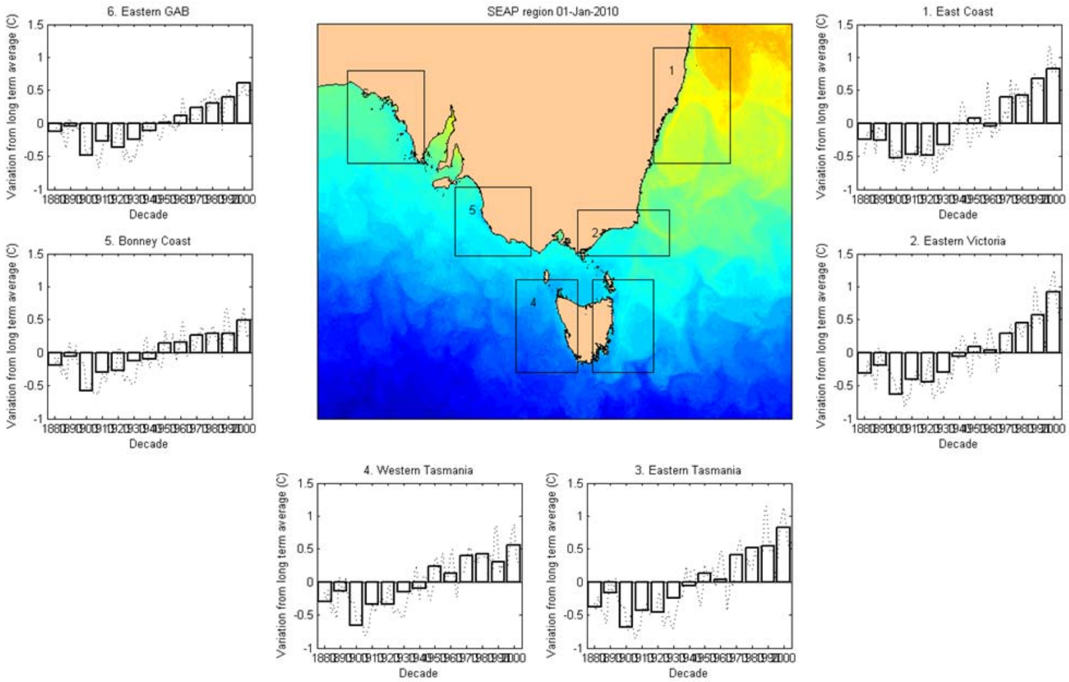


Figure 2. Historical change in surface temperature based on the HadlSST2 dataset for the period 1880-2010 for six regions in the south-east. Bars represent 10 year averages, while the dotted line is the annual time series.

7.1.2 Derived variables

Methods to calculate derived variables were completed in this project, and included measures of eddy kinetic energy (EKE), frontal activity, and eddy presence (**Table 1**, **Figure 3)**. These variables are now available for use in future projects, and can be matched to biological observations as for primary variables. .

Evaluating historical change in the derived variables was not an objective of this project, but such an analysis could also be accomplished quickly using the data generated in this project. That said, the time series may be quite short for some of the variables, and so evidence of a climate signal may be difficult to detect.

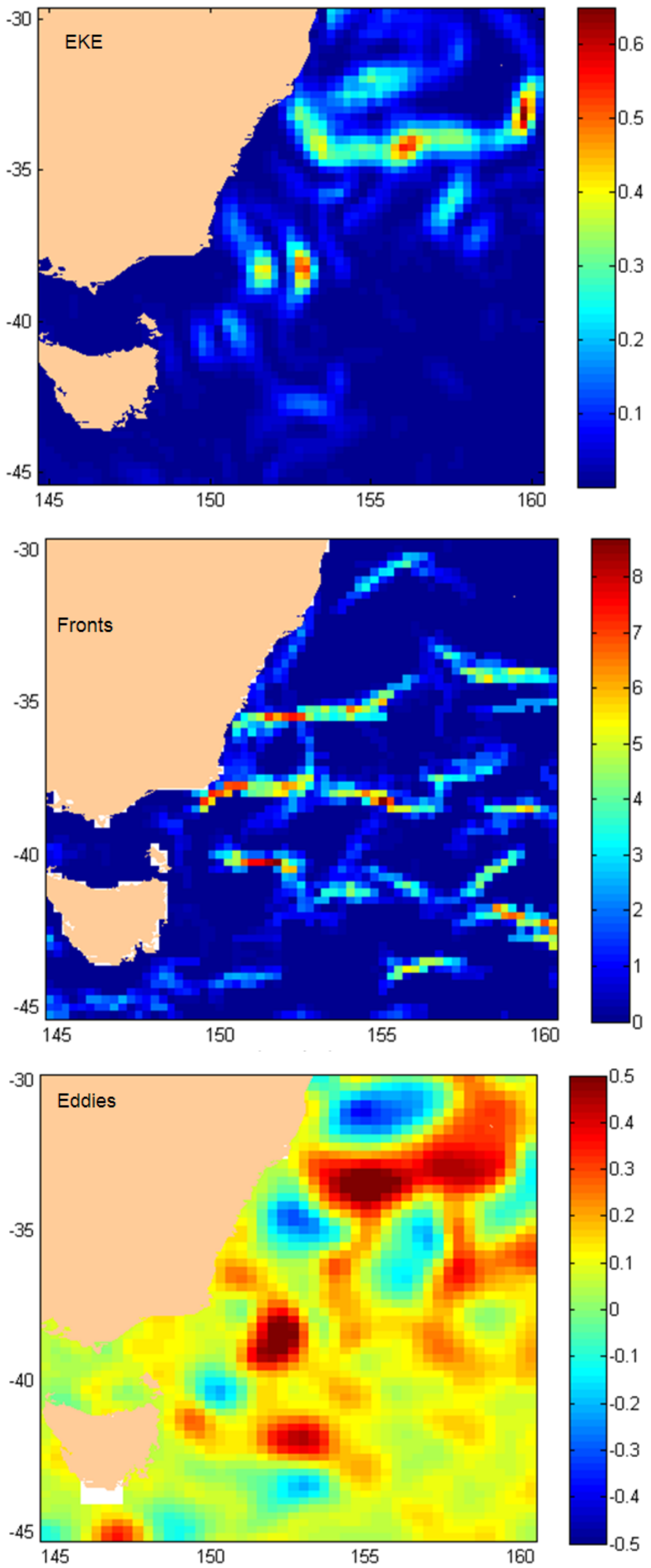


Figure 3. Examples of derived variables generated for the south-east region. Top: Eddy kinetic energy (EKE), center (fronts) and bottom (eddies). Eddies that have positive sea surface height (SSH) are downwelling anticlockwise rotating features, while negative SSH indicates upwelling clockwise rotating features.

7.2 Validation of Bluelink model variables (Objective 2)

If model output (e.g. SST) for the future is to be considered useful, a minimum condition is that the model data is comparable to the observed data. Environmental variables that are comparable could then be extracted from future model output and used, for example, to project change in species distribution and abundance. Thus, comparison between observed and modelled primary variables from the historical period (**Section 7.1, Table 1)** was completed.

Time series of the five primary variables from 1994-2010 at particular locations were extracted (**Figure 4)** and compared to historical data. These variables were SST, Temp at 200 m, surface salinity, u-currents and v-currents. Historical data can be drawn from around the south-east region, and will include surface (e.g. surface signals of upwelling, eddy formation) and vertical ocean properties (e.g. vertical temperature structure). Data from Bluelink was extracted for boxes of side length (0.1, 0.5, 1 and 5 degrees) along the EEZ (200 nm), 200 m contour, and 50 meter contour.

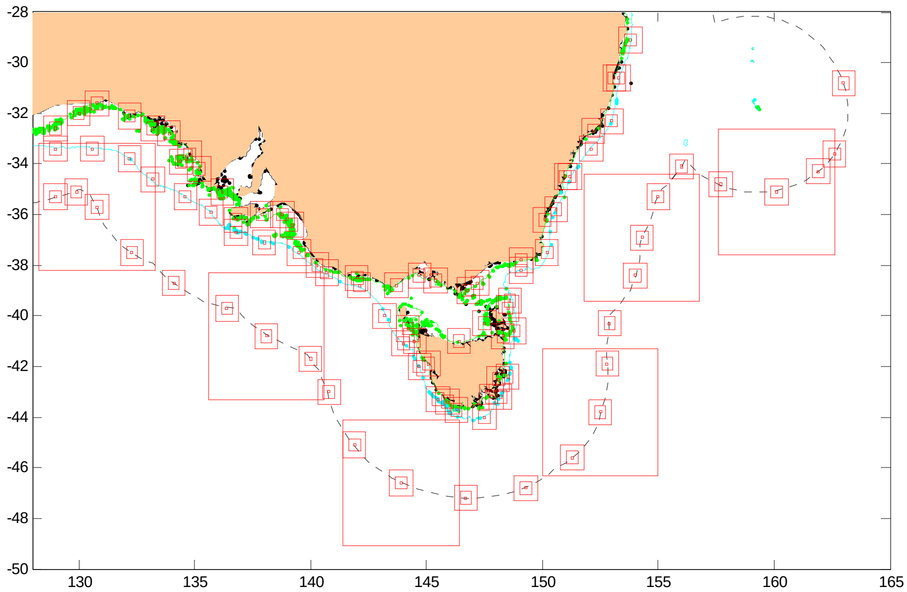


Figure 4. Data from Bluelink was extracted for each box illustrated above (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

These data were extracted at a daily and a monthly scale. The raw time series are illustrated in **Figure 5** which shows daily sea surface temperature from Bluelink and from satellite observations at a spatial scale of 0.5 degrees**. These time series are now available for each box at each temporal scale as a project output.** The match between observations and model output was evaluated with a number of metrics, including correlation coefficient, slope of the regression line, skew, sum of squares (SSQ), sum of squares based on eliminating the 10% of most extreme values (SSQ_{outer}), and the mean difference between the two data sets **(Figure 5 lower)**. In this report we provide examples of evaluation using the correlation coefficient and mean difference. In this example for daily SST on the 50 m contour **(Figure 5**), the correlation coefficient was high ($R^2 = 0.945$), indicating the model is a good measure of the observations as shown in the lower left panel. At a monthly scale, a similar good fit is seen (**Figure 6).**

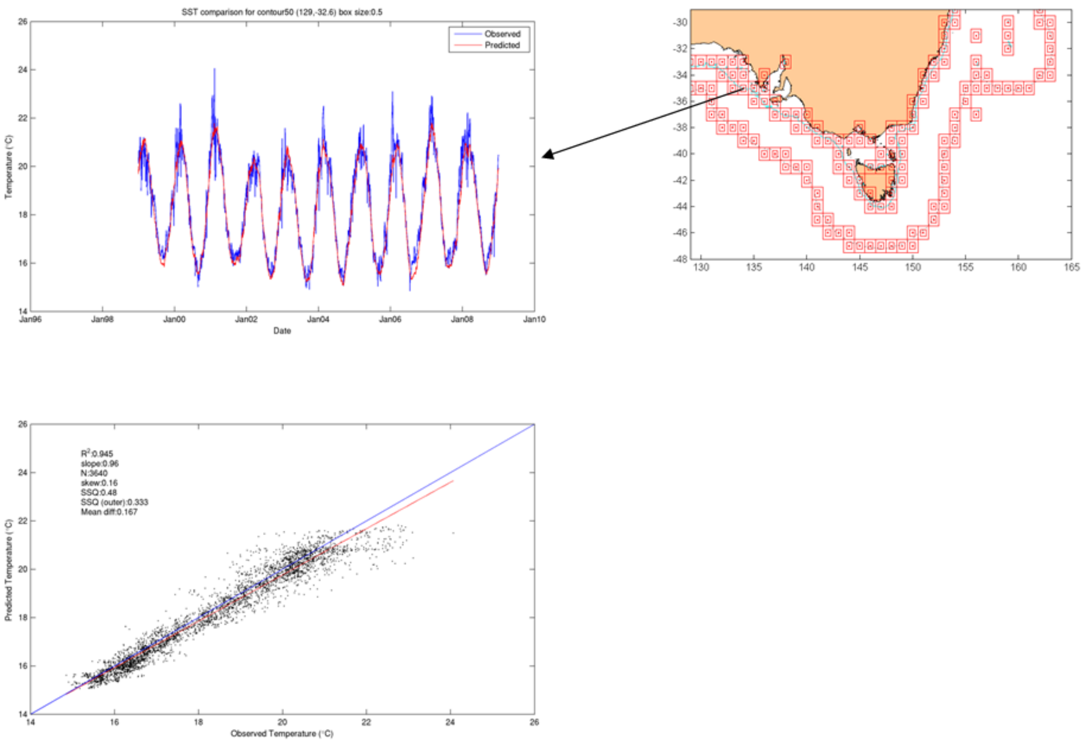


Figure 5. Daily surface water temperature at each time and space scale from Bluelink was compared to observations from the equivalent time and space scale. In this example, a 0.5 degree box from the 50 meter contour near Port Lincoln was chosen (upper right). The agreement between the two time series is good (upper right) as measured by a range of correlation metrics (lower left).

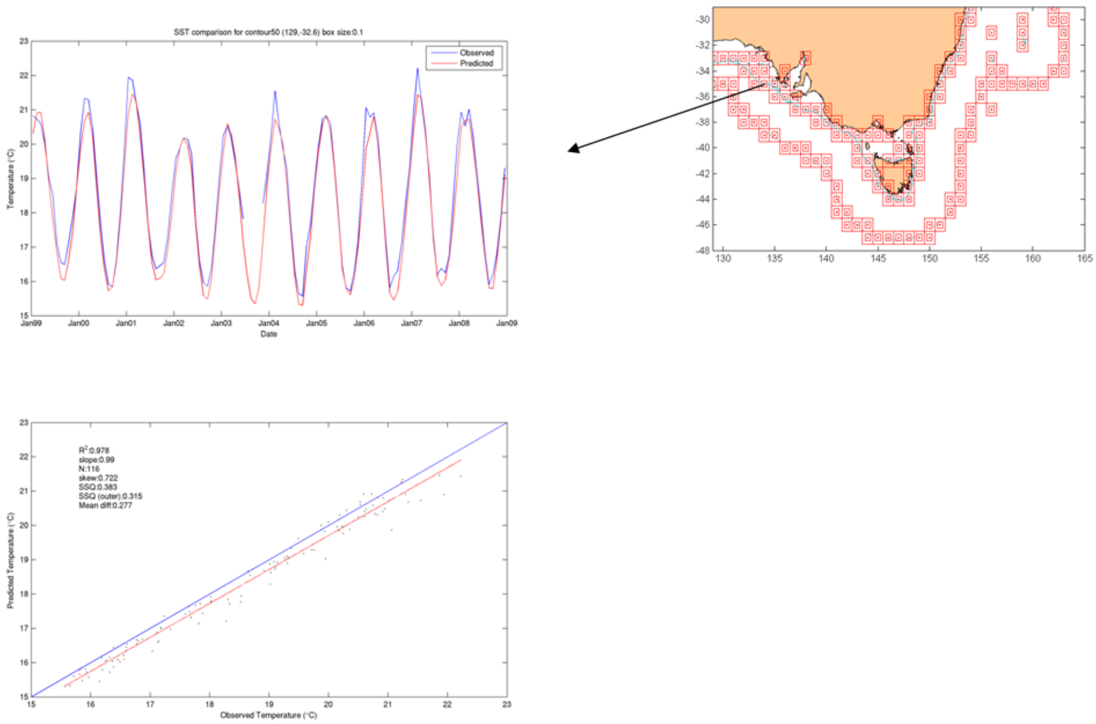


Figure 6. As for **Figure 5,** but for monthly surface water temperature at each time and space scale from Bluelink was compared to observations from the equivalent time and space scale. In this example, a 0.5 degree box from the 200 meter contour near Port Lincoln was chosen (upper right). The agreement between the two time series is good (upper right) as measured by a range of correlation metrics (lower left).

As a further example, temperature at a depth of 200 m (**Figure 7)**, the seasonal signal is obvious and similar between the two time series at a daily scale, but the model data are cooler than indicated by the observations (blue line) and the correlation is poor (R^2 = 0.399). When the temperature at depth of 200 m is compared at a monthly scale, the difference between them is still obvious, but the correlation is improved (**Figure 8,** R^2 = 0.546). This means that a correction factor could be applied, based on the slope of the observed relative to the model data. The same analysis has been completed for every box indicated in **Figure 4**, and archived as part of the project output.

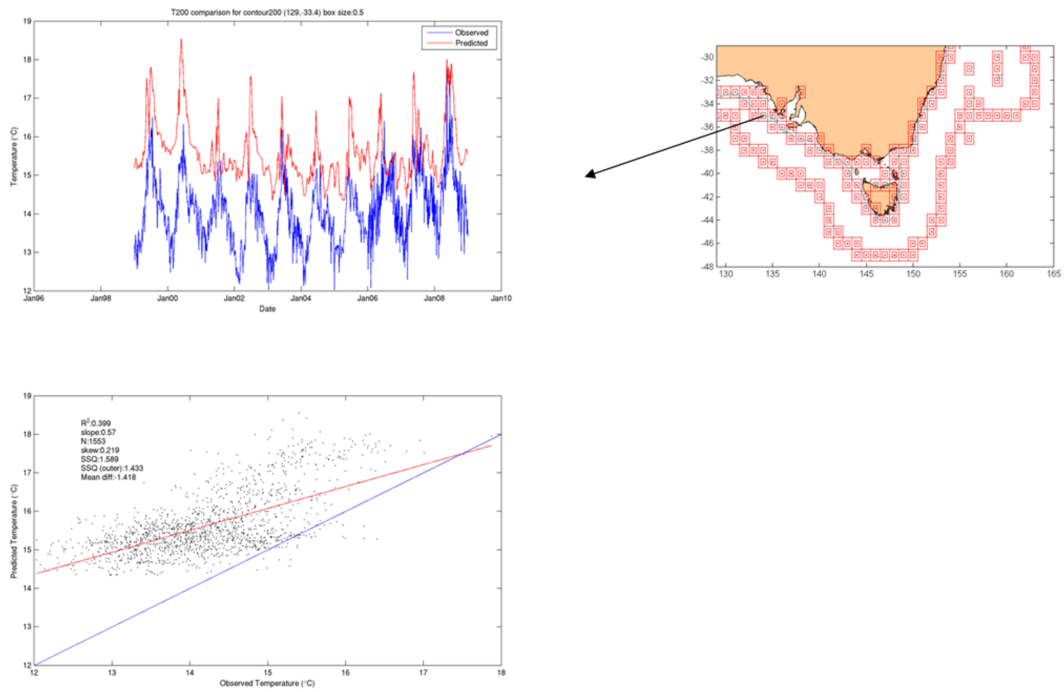


Figure 7. Daily water temperature at a depth of 200 m at each time and space scale from Bluelink was compared to observations from the equivalent time and space scale. In this example, a 0.5 degree box from the 200 meter contour near Port Lincoln was chosen (upper right). The agreement between the two time series is indicated (upper right) by a range of correlation metrics (lower left).

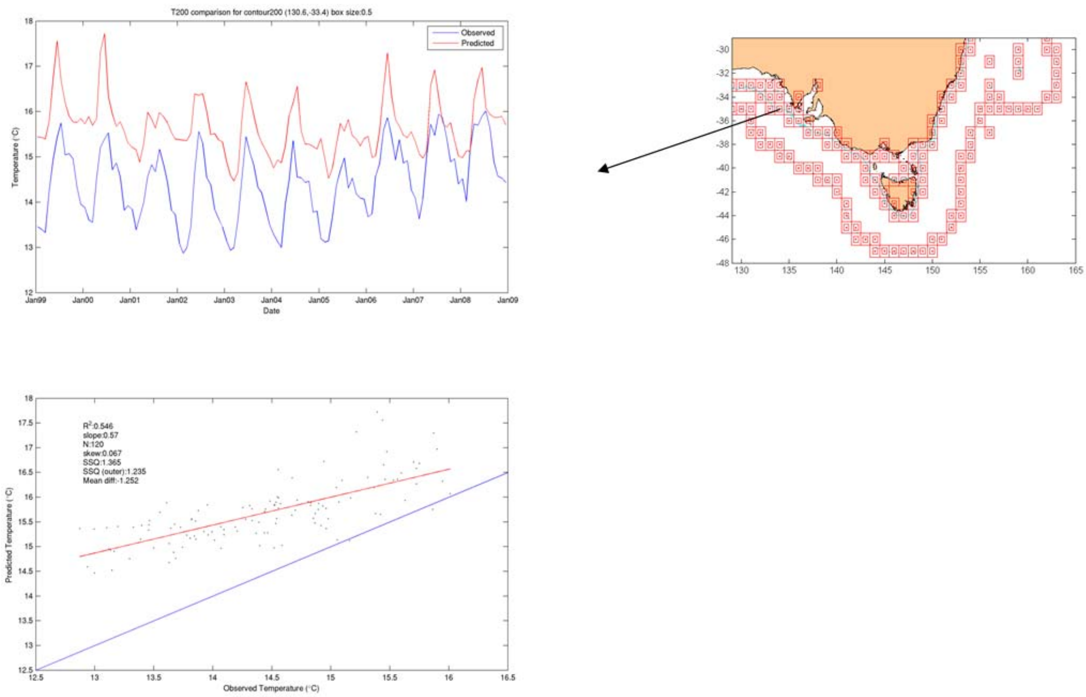


Figure 8. Monthly water temperature at a depth of 200 m at each time and space scale from Bluelink was compared to observations from the equivalent time and space scale. In this example, a 0.5 degree box from the 200 meter contour near Port Lincoln was chosen (upper right). The agreement between the two time series is poor (upper right) as measured by a range of correlation metrics (lower left).

When the summary metrics are calculated for each box, along each contour (50, 200 and EEZ) at each time scale, some clear patterns emerge. For example, **Figure 9** shows the correlation coefficient for each box moving from west to east. At all scales for SST the correlation is high in the GAB ($R^2 > 0.8$), then drops around southern Tasmania ($R^2 < 0.4$), before rising again along the east coast of Australia ($R^2 > 0.6$) (**Figure 9, left column**). The correlations are higher for the larger box sizes, as the area within which the data are averaged increased.

The correlation coefficient for temperatures at a depth of 200 m along the EEZ is generally poor at a scale of 0.1 degree ($R^2 < 0.1$), and improves slightly at a scale of 1 degree ($R^2 \sim 0.25$) (**Figure 9, right column**). There is much less coherent pattern in moving from west to east, indicating that the model does not represent temperature at depth very well at a spatial and temporal scale useful for some biological applications. The same patterns are seen in **Figure 10**, which illustrates SST and T_{200} at a monthly scale along the EEZ. The spatial patterns of correlations in **Figure 9-12** might be related to the locations of fronts and eddies at the end of the East Australia Current. For example, the EEZ predictions south of Tasmania will be sensitive to small errors in the predicted location of the subtropical front, while the 200m predictions will be sensitive to small errors in the predicted location of EAC meanders and eddies.

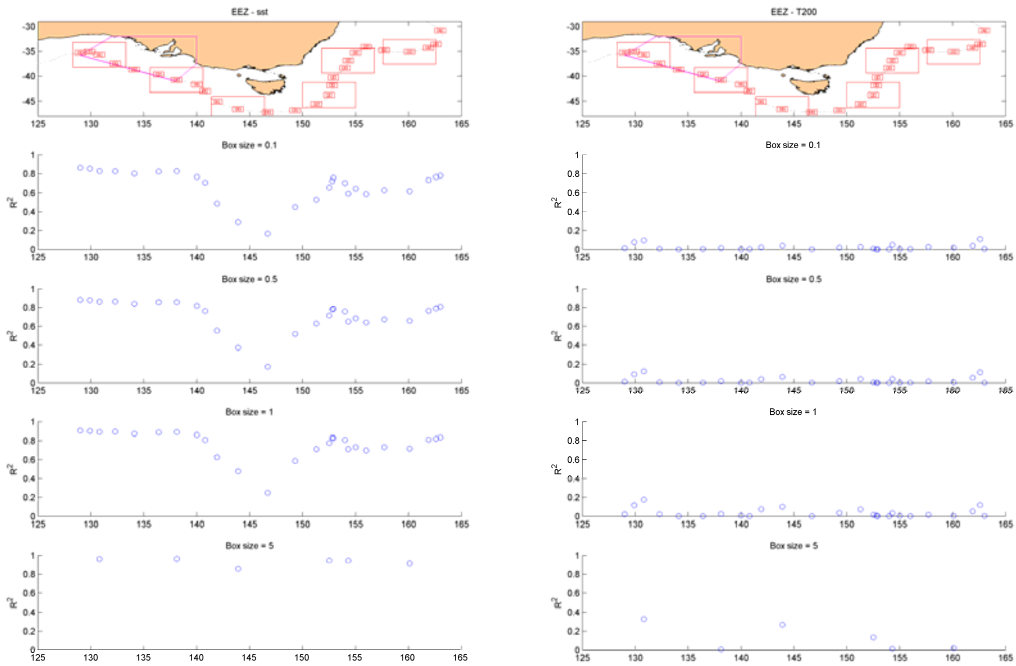


Figure 9. Correlation values between model and observed sea surface temperature (left column) and temperature at 200 m (right column) in each box along the EEZ (row 1) for SST

at a daily time scale for a scale of 0.1 degrees (row 2), 0.5 degree (row 3), 1 degree (row 4), 5 degree (row 5). Generated with BoxLocationAnalysis.m (SEAP Matlab folder)

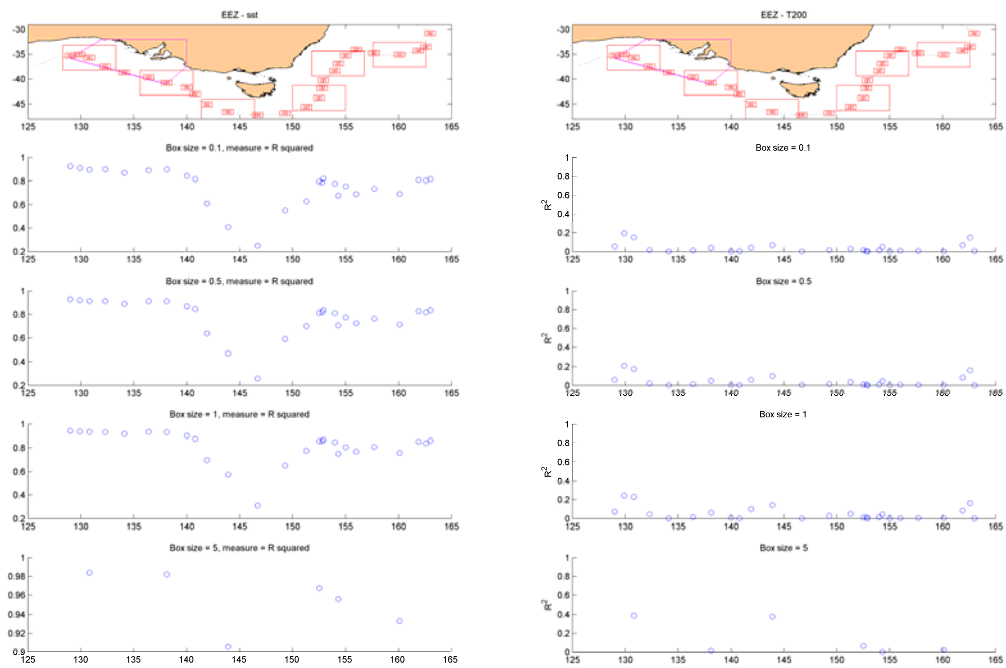


Figure 10. Correlation values between model and observed sea surface temperature (left column) and temperature at 200 m (right column) in each box along the EEZ (row 1) for SST at a monthly time scale for a scale of 0.1 degrees (row 2), 0.5 degree (row 3), 1 degree (row 4), 5 degree (row 5).

Moving closer inshore (200 m contour), the overall correlation is lower for daily SST than further offshore, but not markedly ($R^2 \sim 0.9$) (**Figure 11 left column**). A different spatial pattern was observed compared to the EEZ analysis, with the correlation deteriorating most on the east coast of Australia. At a depth of 200 m, the same spatial pattern is seen for all box sizes at a daily scale, but the correlation coefficients are lower ($R^2 \sim 0.5$) (**Figure 11 right column**). This suggests that the model does not sufficiently capture the dynamics of water movement at the scales analysed here. At a monthly scale the same patterns are seen for SST and T_{200}, with slightly higher correlations (**Figure 12).** For SST along the 50 m contour, the daily and monthly correlations are both high and similar for the 0.1, 0.5 and 1 degree spatial scale (**Figure 12 B**).

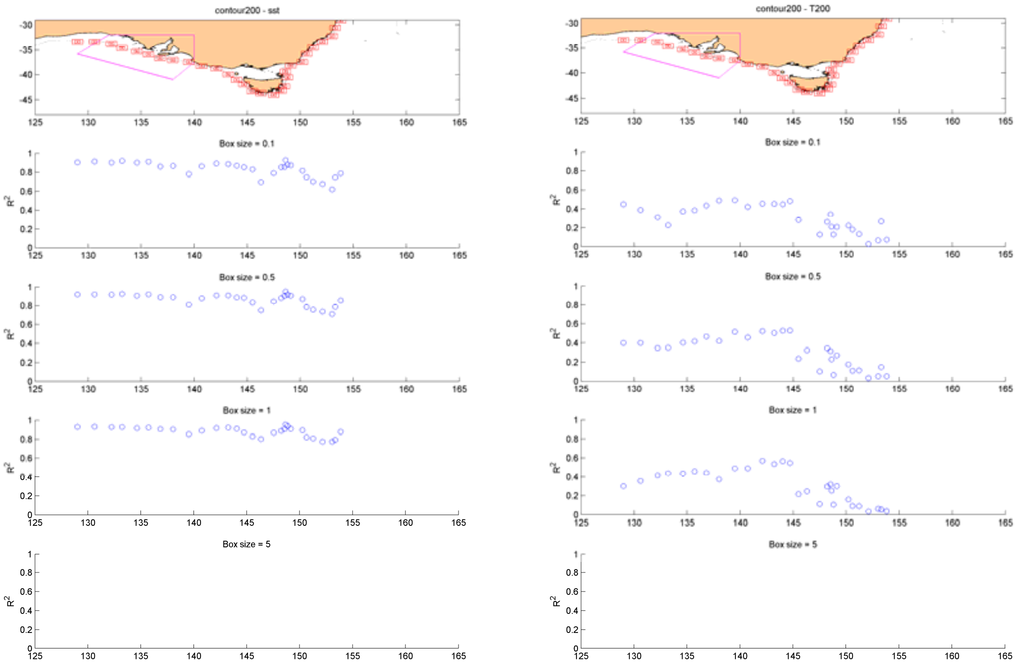


Figure 11. Correlation values between model and observed sea surface temperature (left column) and temperature at 200 m (right column) in each box along the 200 m contour (row 1) for SST at a <u>daily</u> time scale for a scale of 0.1 degrees (row 2), 0.5 degree (row 3) and 1 degree (row 4). The 5 degree scale was not calculated for the 200 m contour.

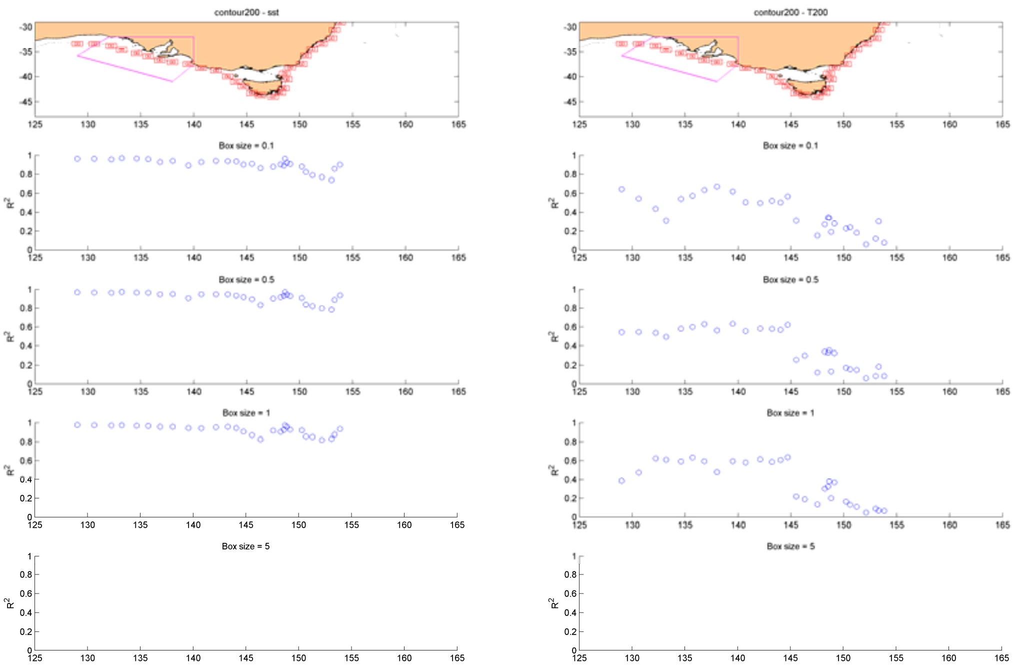


Figure 12. Correlation values between model and observed sea surface temperature (left column) and temperature at 200 m (right column) in each box along the 200 m contour (row 1) for SST at a <u>monthly</u> time scale for a scale of 0.1 degrees (row 2), 0.5 degree (row 3) and 1 degree (row 4). The 5 degree scale was not calculated for the 200 m contour.

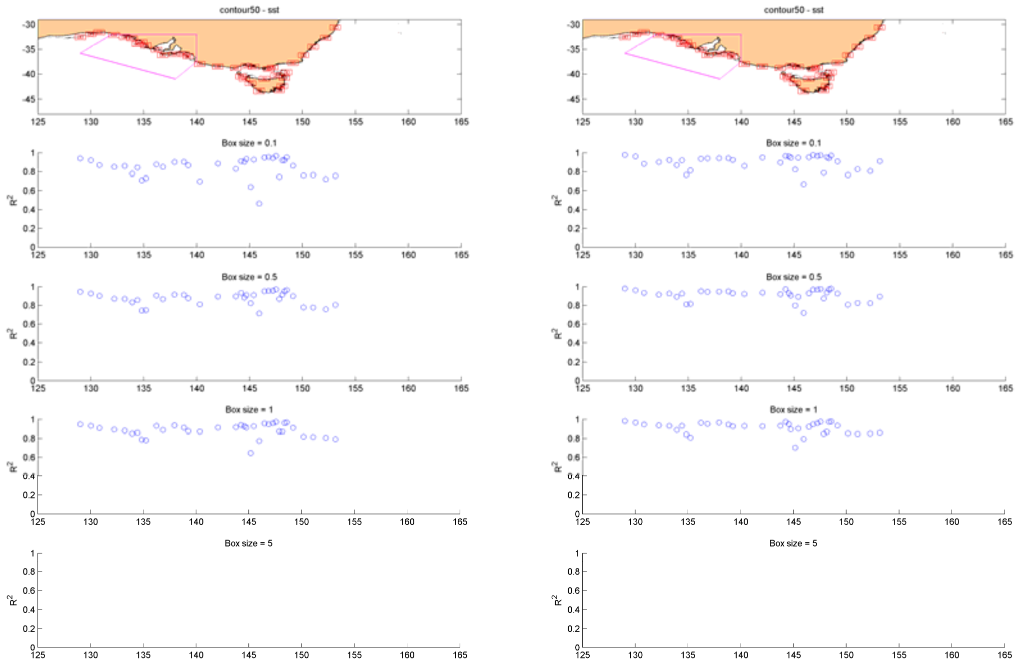


Figure 12B. Correlation values between model and observed daily (left column) and monthly (right column) SST in each box along the 50 m contour (row 1) for a scale of 0.1 degrees (row 2), 0.5 degree (row 3) and 1 degree (row 4). The 5 degree scale was not calculated for the 50 m contour.

The correlation for daily and monthly salinity is lower at all spatial scales throughout the south-east region ($R^2 < 0.2$) (**Figure 13**). The correlation for currents (e.g. east-west, u-current) is even poorer along the EEZ, although it improves slightly for the largest spatial scale (5 degree) (**Figure 14).** Further inshore the correlation improves for u-currents (east-west direction) (data not shown). We reiterate, that given that these currents from the SSH data are not corrected for winds and tides and mean flows, that comparisons presented here must be considered cautiously.

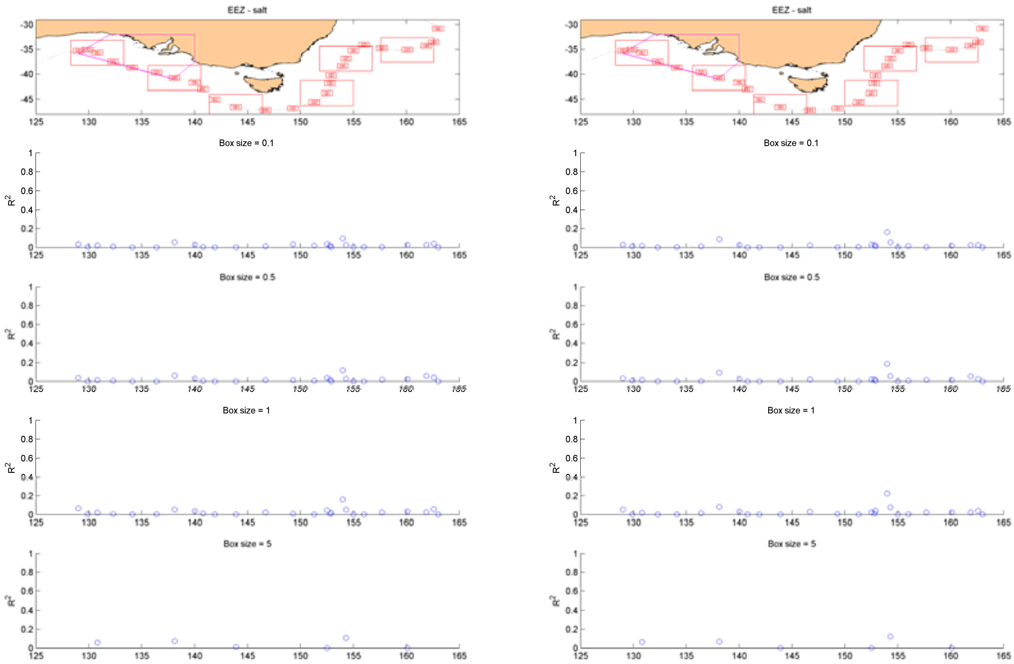


Figure 13. Correlation values between model and observed salinity at a daily (left column) and monthly (right column) scale in each box along the EEZ contour (row 1) at spatial scale of 0.1 degrees (row 2), 0.5 degree (row 3), 1 degree (row 4), and 5 degree (row 5).

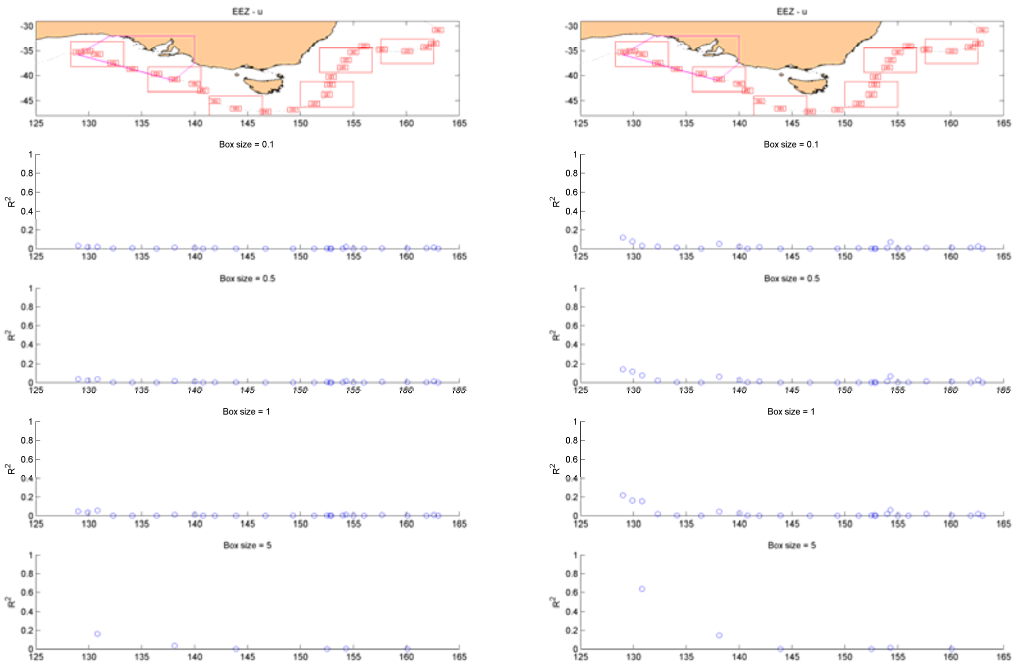


Figure 14. Correlation values between model and observed u-currents at a daily (left column) monthly (right column) in each box along the EEZ contour (row 1) at a

spatial scale of 0.1 degrees (row 2), 0.5 degree (row 3), 1 degree (row 4), and 5 degree (row 5).

The final summary is to compare all time and space scales for all variables along the EEZ, 200 m and 50 m contour for the south-east region based on the correlation coefficient (**Figure 15).** Based on this metric, the best performing variable in the south-east at a daily scale is SST, followed by T_{200}, salinity, and the currents. The correlation is highest for the largest spatial scale (5 degree), and declines as the scale decreases to 0.1 degree. The correlation was also highest at the 200 m and 50 m contour, rather than at the EEZ. This pattern was the same at a monthly scale, with higher correlation scores for all variables (**Figure 16)**.

Using a second metric,"mean difference between the model and observed values", shows that these correlation scores may be poor as the absolute difference is small, particularly for salinity and currents (daily scale: **Figure 17,** monthly scale: **Figure 18)**. The SST differences are very small, while for T_{200}, the model overestimates the temperature (negative differences).

These analyses show that larger spatial and temporal scales will yield more reliable model estimates of the observed conditions. There is also variation around the south-east region, such that the user of these data should make a careful evaluation, such as provided for each box as part of this project. Larger spatial (e.g. > 5 degree) and temporal (e.g. annual) scales were not evaluated, as they are larger than typically desirable for fishery studies, but could be calculated if needed for SEAP projects.

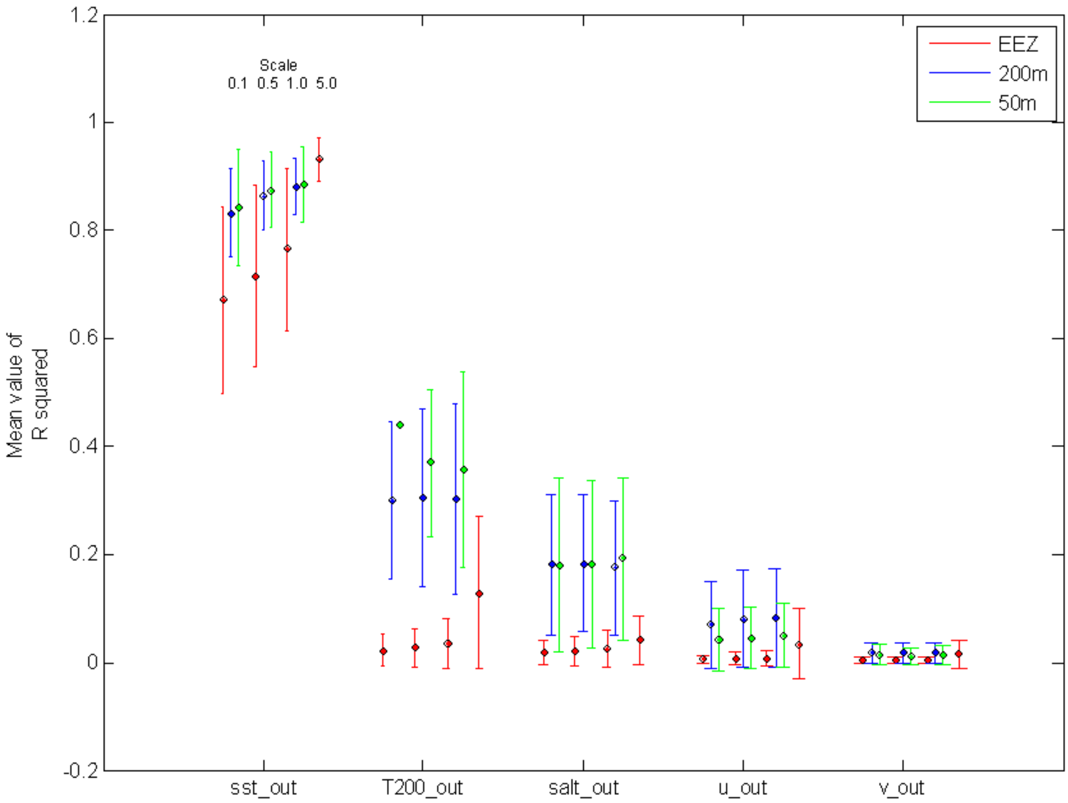


Figure 15. The mean correlation coefficient (R^2) and ± 1 SD for all boxes along the EEZ, 200 m contour and 50 meter contour at a scale of 0.1, 0.5, 1.0 and 5 degree boxes at a daily scale for the five Bluelink variables evaluated.

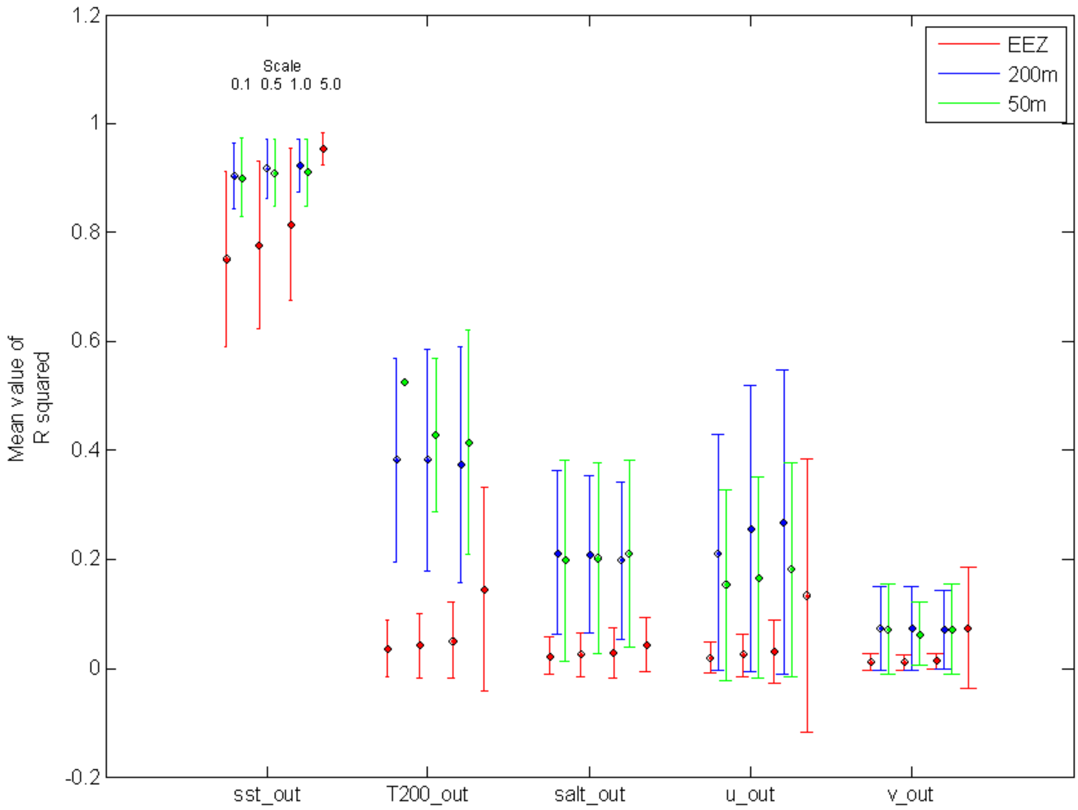


Figure 16. The mean correlation coefficient (R^2) and ± 1 SD for all boxes along the EEZ, 200 m contour and 50 meter contour at a scale of 0.1, 0.5, 1.0 and 5 degree boxes at a monthly scale for the five Bluelink variables evaluated.

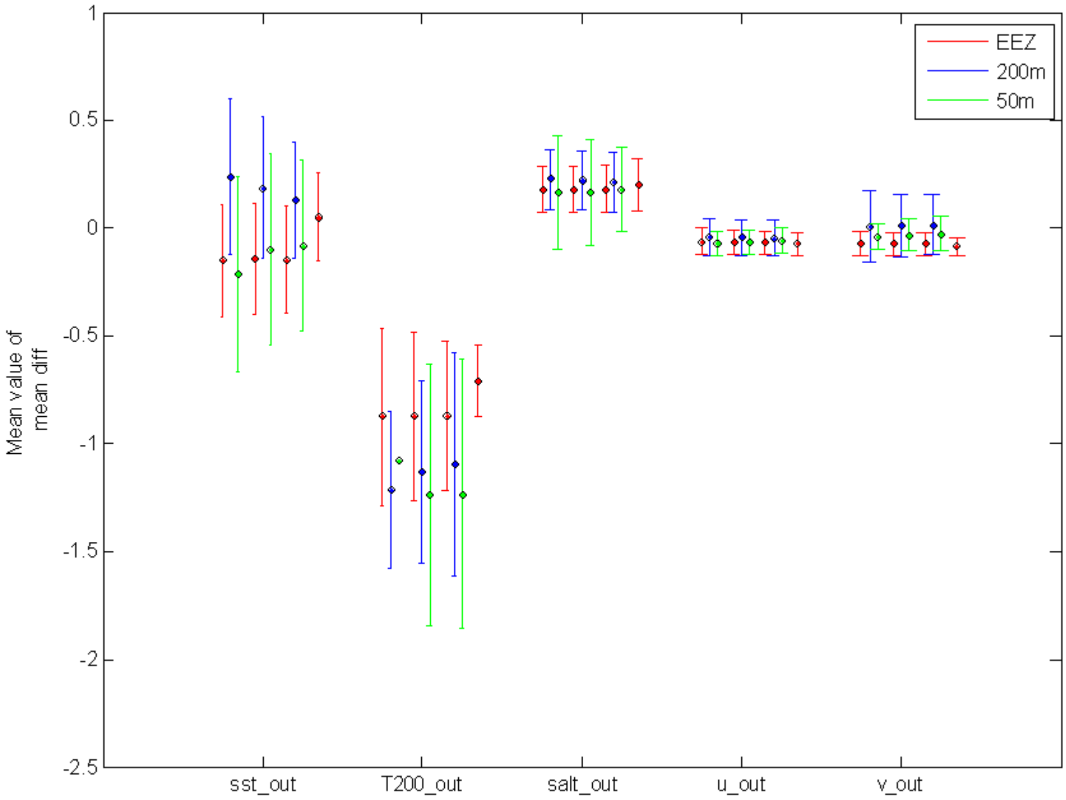


Figure 17. The mean difference in absolute value (± 1 SD) for all boxes along the EEZ, 200 m contour and 50 meter contour at a scale of 0.1, 0.5, 1.0 and 5 degree boxes at a daily scale for the five Bluelink variables evaluated.

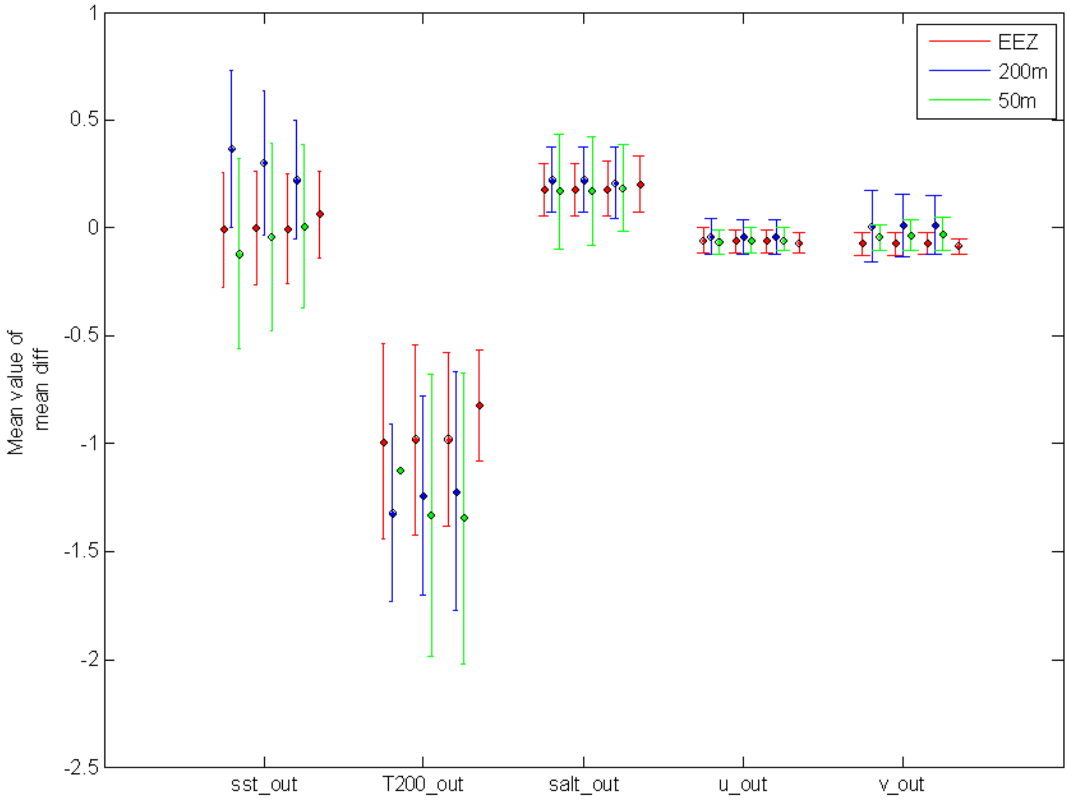


Figure 18. The mean difference in absolute value (± 1 SD) for all boxes along the EEZ, 200 m contour and 50 meter contour at a scale of 0.1, 0.5, 1.0 and 5 degree boxes at a monthly scale for the five Bluelink variables evaluated.

A further summary that combines all the metrics is also useful. As noted above, the metrics used to evaluate the "goodness" of the relationship between observed and modeled ocean data for each scale included three scale independent measures (correlation coefficient, slope of the regression line, and skew) and three metrics that are scale dependent (sum of squares (SSQ), sum of squares eliminating the outer 10% of values (SSQouter) and the mean difference between the two data sets. The three scale-independent metrics allow comparison between each location and spatial scale. Arbitrary cut-off values based on inspection of the range of values for each metric were used to score each relationship as satisfactory/unsatisfactory (1 or 0). The sum of the metric scores could thus range from 0 (all unsatisfactory) to 3 (all 3 metrics were satisfactory). The cutoffs for satisfactory scores were correlation coefficient close to 1 (i.e. R2 >0.8); slope close to 1 (i.e. 0.6 < slope < 1.4); and skew close to zero (i.e. -0.2<skew<0.2).

The results provide a quick visual summary of the quality of the modeled data relative to the observations for the south-east region. For example, for daily SST, the relationships between observed and modeled data were good using all metrics (scores of 2 and 3) for most of the 50 m, 200 m and EEZ contour (**Figure A**). In **Appendix 3**, results for the daily T200 (**Figure B**), salinity (**Figure C**), u-currents (**Figure D**) and v-currents (**Figure E**) at a daily scale, and monthly SST (**Figure F**), T200 (**Figure G**), salinity (**Figure H**), u-currents (**Figure I**) and v-currents (**Figure J**) are provided.

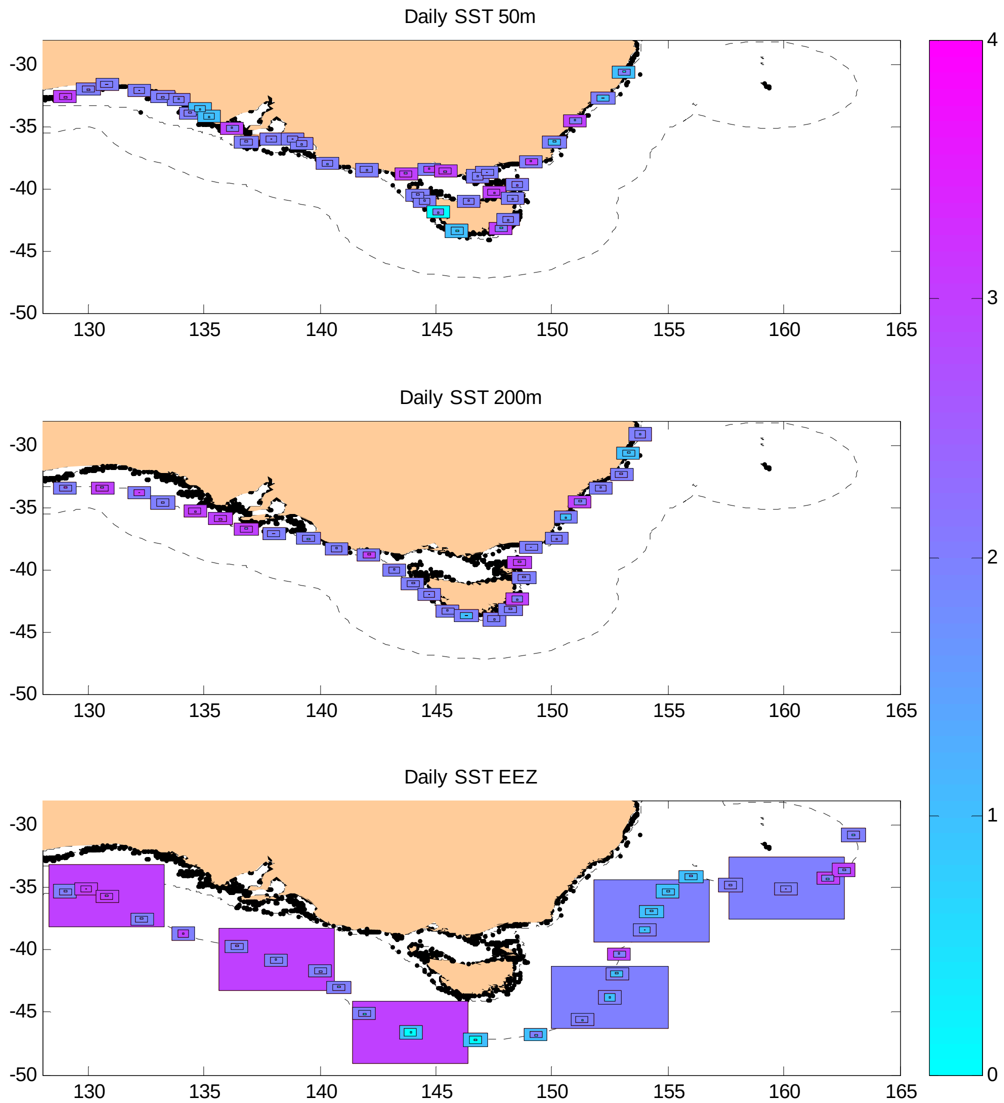


Figure A. Number of metrics that were "satisfactory" for daily SST observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

7.3 Development of SAROM (Objective 3)

In this project, Objective 3 included further development of the South Australian Regional Ocean Model (SAROM) and validation against the *in situ* IMOS data streams for the period of time that observed data are available (2009-2010). An additional performance indicator has also been met: qualitative validation of the SAROM output as forced by monthly atmospheric climatologies. In this section, we discuss the both the additional model development and validation of the model for several environmental variables that are relevant to fisheries studies. Model output and South Australian IMOS data will be averaged monthly and compared. The success of this comparison will then enable us to compare results with those that we have obtained using forcing by the monthly atmospheric climatology. This will then provide confidence (or otherwise) that future scenario studies to be undertaken as part of SEAP in subsequent years using SAROM will be of value (see **Section 3**). We foreshadow here that the future scenario studies will adopt monthly forcing fields modified in line with climate change predictions.

7.3.1 Initial model development

With regard to initial model development, a coastal trapped wave (CTW) paddle has been configured at Thevenard (mid-Bight) and using observed sea level, is able to largely reproduce the local wind-forced shelf circulation that is generated in the western Great Australian Bight. A detailed comparison has been made of the SAROM output with the extensive data streams collected on the shelves as part of the Southern Australian Integrated Marine Observing System (SAIMOS) during the July 2008 - June 2009 period. The SAROM-predicted shelf currents are shown below to explain 60-90% of the variability of current data in the energy containing weather-band (5-20 days). The model is also able to reproduce aspects of the observed temperature and salinity fields in Spencer Gulf and on the shelves. In addition, as part of initial model development, a preliminary analysis of the wind-forced and tidal circulation was completed and is briefly described below.

Wind-forced circulation

A detailed analysis has been made of meteorological forcing data for the South Australian region and showed that the 2005-2006 period was typical of data of the average of the 1990-2007 period. These analyses were then used to determine typical wind stress amplitudes and periods in the baseline studies conducted by Teixeira and Middleton (2010). Detailed scenario studies of the circulation induced by periodic (10 day) winds have demonstrated the fundamental physics that allows southerly winds to drive northward currents on the western and eastern sides of the Spencer Gulf. These currents may act as “conveyor belts” for larval transport to the expected coastal regions of settlement in the upper northwest of the Gulf, and are shown to be enhanced by summertime stratification. Vertical shear in surface to bottom currents were also found to be significant and these will be implicated in larval transport (see below). Wind forced currents generated to the west of the Eyre Peninsula (by the CTW paddle) are shown to be largely unimportant to the circulation and larval transport within Spencer Gulf.

Tidal Circulation

In addition, the SAROM for the tides has been validated against sea level data both from within Spencer Gulf and for the South Australian continental shelves. The model is able to successfully reproduce tidal constituents from data to within 10% or so and reproduce the 15 day periodic dodge tide and resonant amplification of tidal currents within the Gulf (results below). The depth-averaged tidal currents (20-40 cm/s) are large compared to those of the winds (5-15 cm/s). However, the period of the tides is short compared with that of the wind (12 hrs versus 10 days), so their effect on larval transport may be relatively small.

7.3.2 SAROM model runs

The model was initialised using a weekly climatalogical temperature and salinity database known as CARS 2009 (Condie and Dunn 2006). The initialisation date was 4 July 2008. (Starting during well-mixed winter conditions minimises the errors due to inaccuracies in the database.) It is then allowed to evolve under surface forcing from wind, evaporation, precipitation, short- and longwave radiation, and barometric pressure. The meteorological forcing is taken from the “best guess” database from the Bureau, known as the MesoLaps 0.05° daily fields.

The full three-dimensional model runs were preceded by a preliminary run in two dimensions only (no depth dependence). For the 2D run, the sea level and velocity at the across-shelf boundaries were prescribed in accordance with sea level at Thevenard and Portland (at the west and east respectively) under the assumption that the variability at periods longer than 35 hours was due to first mode barotropic coastally trapped waves. For tidal runs, the latest version of the TPXO global tidal model (TPXO 7.0 with ten constituents) was used to prescribe tidal sea level and velocity at the boundaries. These results are required by the radiation boundary conditions in the subsequent 3D model run.

The horizontal viscosity coefficients are equal to 20.0 m^2/s plus a velocity-dependent factor (Smagorinsky-type eddy viscosity). A quadratic bottom drag coefficient of 0.6×10^{-3} (non-dimensional) was used. The vertical mixing/turbulence closure scheme used was the well-known Mellor Yamada 2.5. Other schemes were tested but the outcome (in terms of the evolution of physical fields) was minimal. No horizontal diffusion of momentum was specified.

A plot of the model topography for the Eyre Peninsula-Kangaroo Is region is shown in **Figure 19** along with the mooring sites of data collected by SAIMOS for the 2008-2009 period: not all sites were maintained for the full period. Each mooring typically consisted of a bottom mounted ADCP to provide current data at all depths and a bottom mounted CTD.

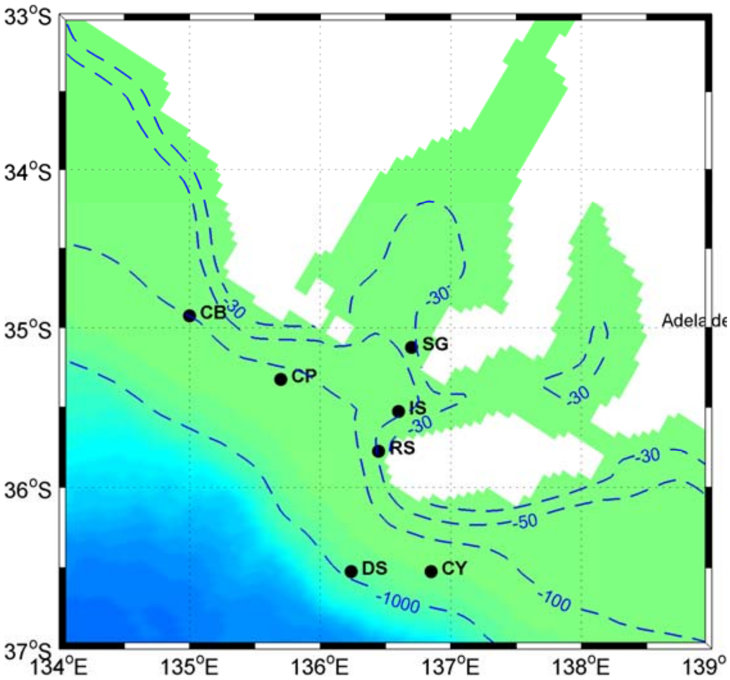


Figure 19 SAROM bathymetric contours and grid mask. Mooring locations: CB: SAM5CB. CP: SAM2CP. RS: NRSKAI. DS: SAM1DS. CY: SAM4CY. IS: SAM6I. No SAM5SG data was collected for 2008-2009.

Output of the model for the 14th February 2009 is shown in **Figure 20**. As can be seen, cold fresh saline water has been upwelled towards the mouth of Spencer Gulf. Within the Spencer Gulf, a warm saline plume is evident and forced by net heating and evaporation. On the shelf, currents of up to 40 cm/s are evident and in the direction of the wind (WD - to the N.W.)

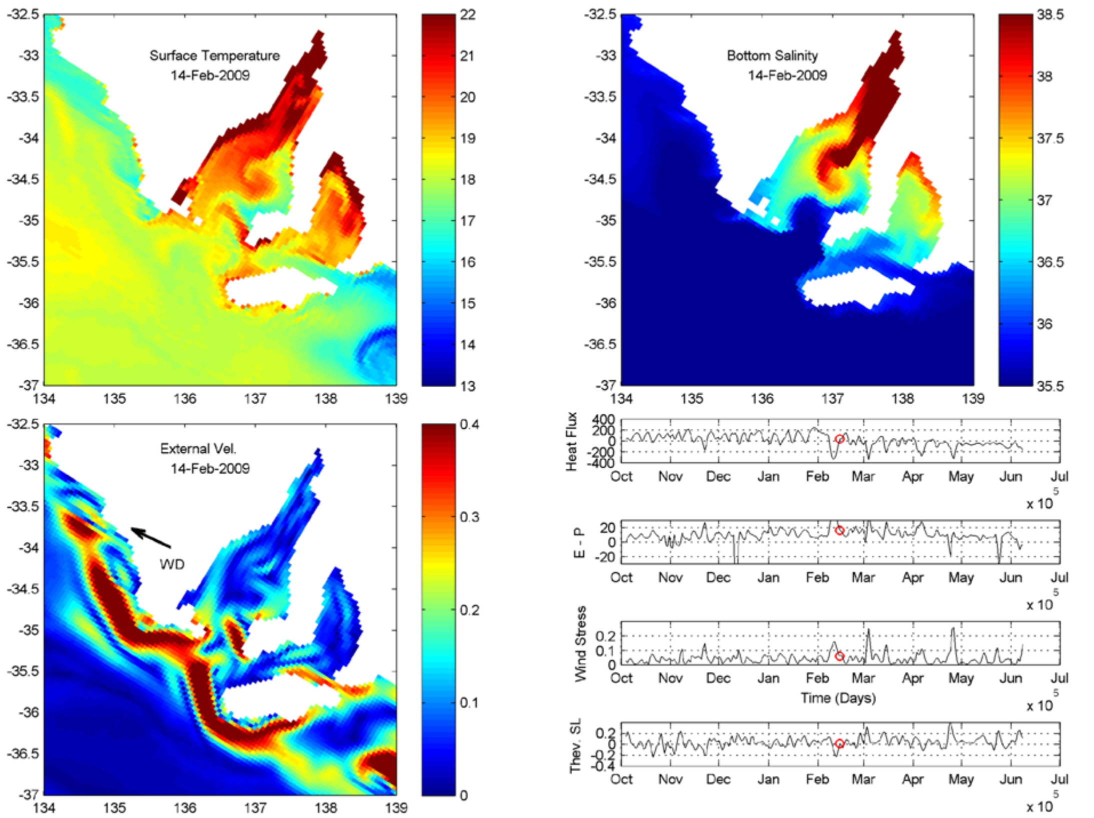


Figure 20: Numerical results for 14th February 2009. Top: Surface temperature and bottom salinity. Bottom Left: the magnitude of depth averaged currents (m/s). Most currents on the shelf are to the N.W. Bottom Right: the net heat flux into the model (positive (W/m^2; the Evaporation-Precipitation (mm/day) and wind stress magnitude (Pa). The wind direction is indicated by the arrow on the left plot labelled WD.

7.3.3 Validation - Ocean Currents

A comparison was with observed and modelled current at 15m from the surface and 15 m from the bottom. The currents were first low-pass filtered (35 hr cut-off) and then resolved along the principal and lesser axes. The reason for comparing principal axis currents is that a) the topography of the model generally differs slightly from that in reality due to the coarse model grid resolution and b) low frequency currents are expected to follow depth contours.

The results for model (blue curves) and near-bottom data (red curves) are shown in **Figure 21** (SAMCB – Coffin Bay) and **Figure 22** (NRSKAI – Kangaroo Is) and are typical of other results for the shelf. Our notation is that positive currents are directed to the south-east (SAMCB) and south (NRSKAI).

The lower model currents show very good agreement with the data (and are similar to upper currents (not shown). An exception here is a 3.5 day variability (indicated by the arrow) that is apparent in the data (notably at the surface) but not in the model. To resolve this inconsistency, a comparison was made of the adopted MESOLAPS wind-stress fields (used to force the model) with data from Neptune Is (not shown) and the 3.5 day signal is apparent in the latter and not the model. Thus incorporation of this signal into the MesoLaps fields will be necessary to improve this aspect of the model.

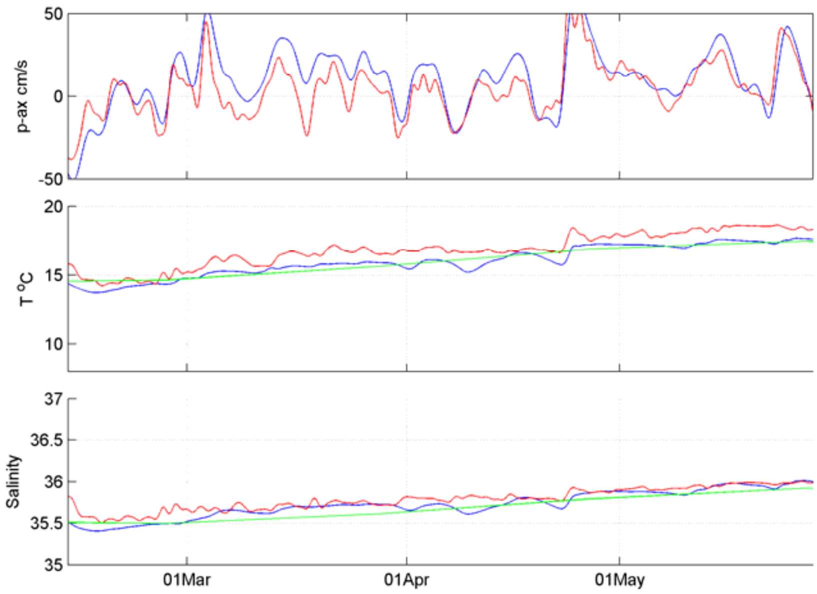


Figure 21 Near-bottom data for mooring SAM5CB). Blue lines: ROMS. Red lines: SAIMOS. Green lines: CARS 2009. Black line: CAT model. Water depth: 95 m. ADCP principle axis angle from east (+CW): 33°. ROMS principle axis angle from east is 47°.

Results for salinity and temperature are also shown. The green curve is climatological data from the CSIRO's Atlas of Regional Seas (CARS). All estimates show a general warming as cold upwelled water on the shelf is mixed with surface mixed layer (SML) water. The eastward winter currents also bring saltier waters from the Bight after April.

Similar results for the mooring NRSKI are presented in **Figure 22**. Note the data and model comparison is for an 8 month period (November 2008 to June 2009).

The agreement between model and data is not as good as at the Coffin Bay site and again there is a 3.5 day signal in the data that is largely absent in the model. Some of the model speeds exceed those of the data which may be due to the coarse topography adopted: as the figure caption shows, the major axes of data and model differ by 148 degrees.

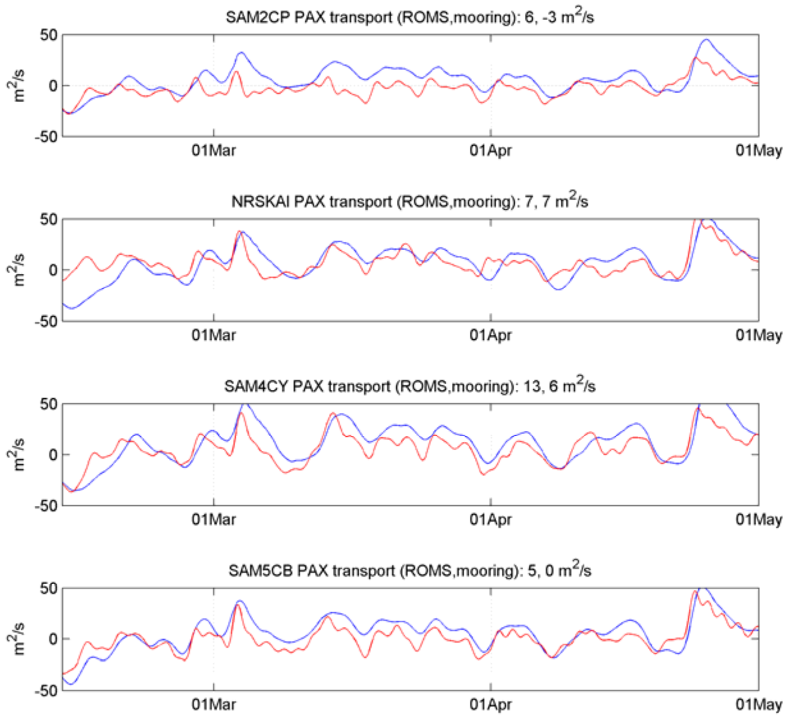
The results for model temperature (T) and salinity (S) are in poor agreement with the data up until March. As we discuss below, this is due to our adoption of the CARS data as an initial fields for the model. By March, ~9 months after model initialisation (July 2008), the heating and cooling in the model has driven it to better agreement with the data. The model still underestimates the T/S data, although there is some similarity with events. Better model resolution, topography and use of the SAIMOS T/S data to improve initial fields should lead to improvements in these results.

2008-2009

Figure 22 NRSKAI mooring-site comparison of near-bottom data. Blue lines: ROMS. Red lines: SAIMOS. Green lines: CARS 2009. Water depth: 110 m. SAIMOS ADCP principle axis angle from east (+CW): 70°. ROMS principle axis angle from east (+CW): -78°.

Returning to the comparison of currents, we note that the effects of errors in model depths at the mooring sites may be removed in part by comparing the top to bottom integrated transport. The results for the shelf moorings are shown in **Figure 23**. The agreement is improved over the comparison of currents. Again the 3.5 day variability is not found in the model and the model currents are generally larger than the data suggesting that the CTW paddle boundary condition may be overestimating shelf transport and/or the smooth model topography leads to an under-estimate of bottom friction.

As a further comparison, we have computed the auto-spectra of the principal axis depth integrated transports (model and data) and these are presented in **Figure 24** in energy preserving form. As is evident, the general shape of the observed transport spectra is approximately re-produced by the model and most energy is contained in the weather band (periods > 5 days; frequencies < 0.2 cpd) although the latter has more energy at these lower frequencies. A more crucial comparison is of the coherence squared (and phase lag) between the model and observed transports. This gives a measure of the fraction of observed transport variance that is explained by the model. For the Kangaroo Is and Coffin Bay sites, these are respectively presented in **Figure 25** and **Figure 26**.



2009

Figure 23. Time series of low-pass filtered transports along principle axes from the SAROM and SAIMOS moorings. Blue lines: ROMS. Red lines: SAIMOS ADCP.

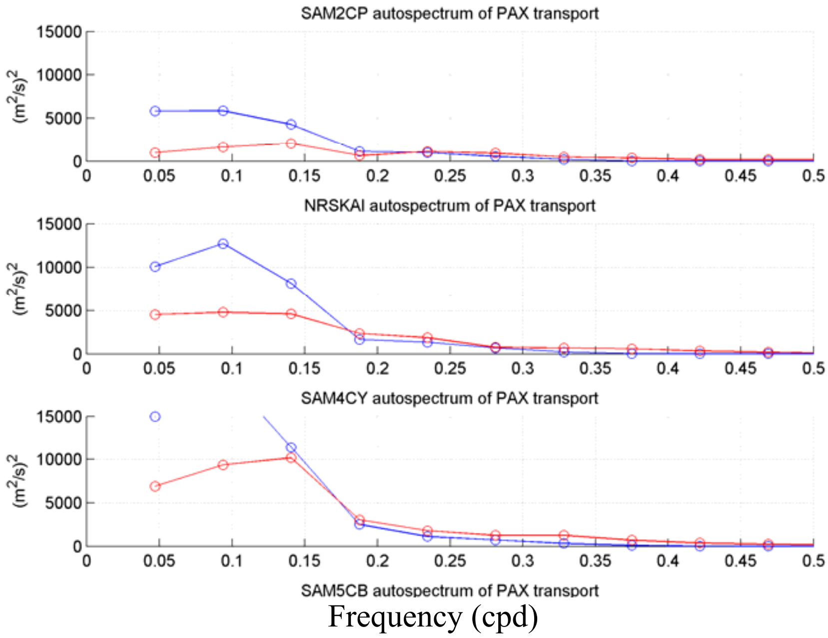


Figure 24. The auto spectra of the depth integrated, filtered transports of along principal axes for each of the shelf mooring sites. SAROM (blue) and SAIMOS mooring data (red).

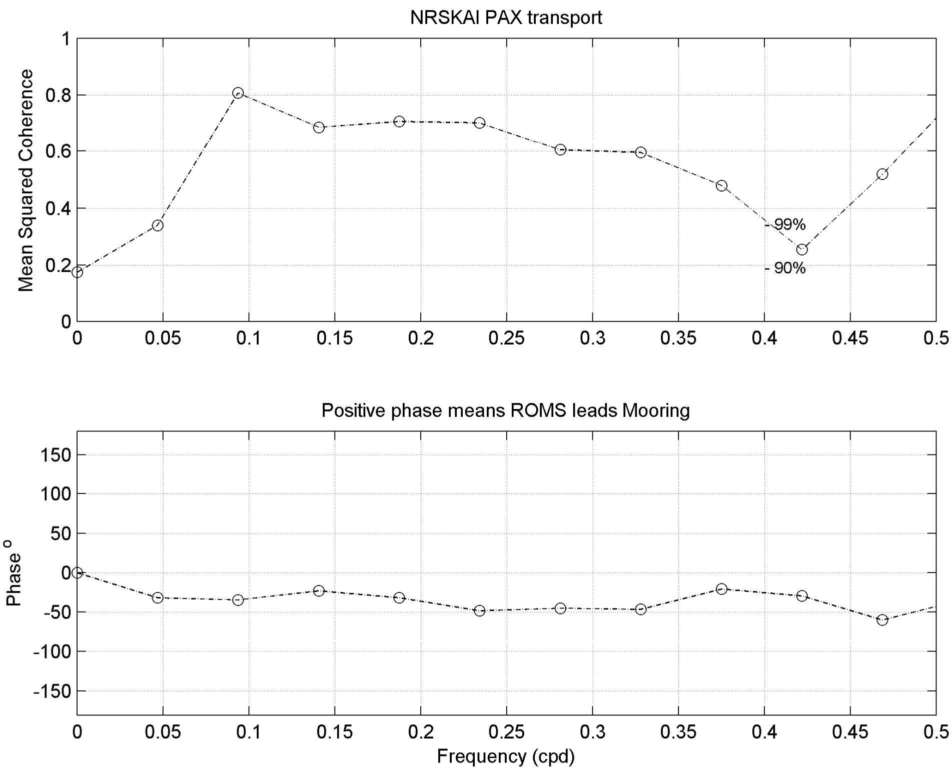


Figure 25. Coherence and phase between the model (MESOLAPS/ROMS) and NRSKAI observed transport along principle axes.

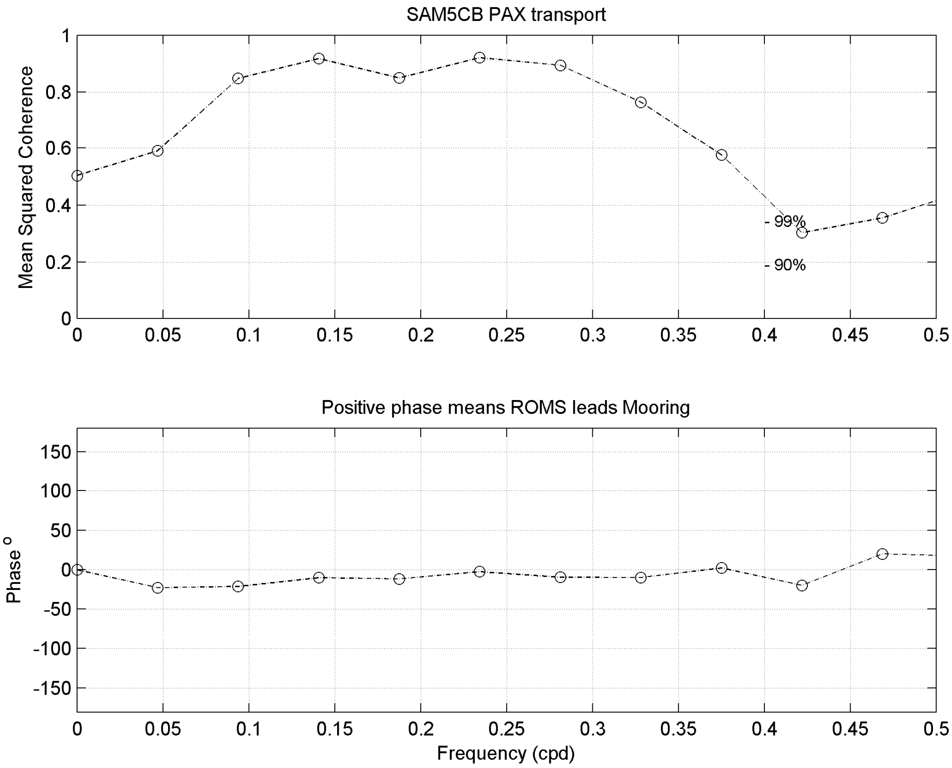


Figure 26. As for **Figure 25**, for mooring SAM5CB.

The estimates of coherence squared were calculated by band averaging resulting in 12 degrees of freedom for each estimate. At the 99% level indicated on each plot, the model results are generally significantly different from zero. Indeed, the results show that the model is able to explain 60-90% of the transport variance or variability for frequencies below 0.3 cpd (period=3 days). The errors in phase are also small being less than 50 degrees for Kangaroo Is and 10 degrees for Coffin Bay: these translate to timing errors of 14% for Kangaroo Is and 3% for Coffin Bay.

7.3.4 Validation - Temperature and Salinity

Eight CTD field surveys are conducted by SAIMOS each year of the shelf region and with an across-shelf section from the mouth of SG to the shelf edge off western Kangaroo Is (lower panel; **Figure 27**). The results for model and observed temperature, salinity and density for November 2008 along this transect are shown in **Figure 27**. As is clear, the model results are too cold and fresh – a result of initialising the model with the CARS weekly climatology for July. By March 17th 2009 (**Figure 28**), the continual forcing by the MESOLAPS fluxes of heat and salt have driven the model solutions away from the unrealistic CARS initial conditions and better agreement is found with the data. Thus, it appears likely that the initial shelf conditions for temperature and salinity could be better determined from a combination of the CARS and SAIMOS data sets.

For Spencer Gulf and near Whyalla, the annual cycle of temperature and salinity was determined for 1984-1986 through monthly sampling by Nunes-Vaz and Lennon (1986). This data is presented in **Figure 29** along with the CARS estimates and the model prediction for the July 2008- June 2009 period. SST satellite data (GHRSST) for this period is also presented. The model is able to reproduce the observed seasonal cycle of temperature data and with an error of less than 2 degrees or so. For salinity, the model predictions indicate substantial variability over the scale of weeks. Agreement is better after March 2010 when the model has been driven for 9 months by the MesoLaps surface fluxes of heat and salt.

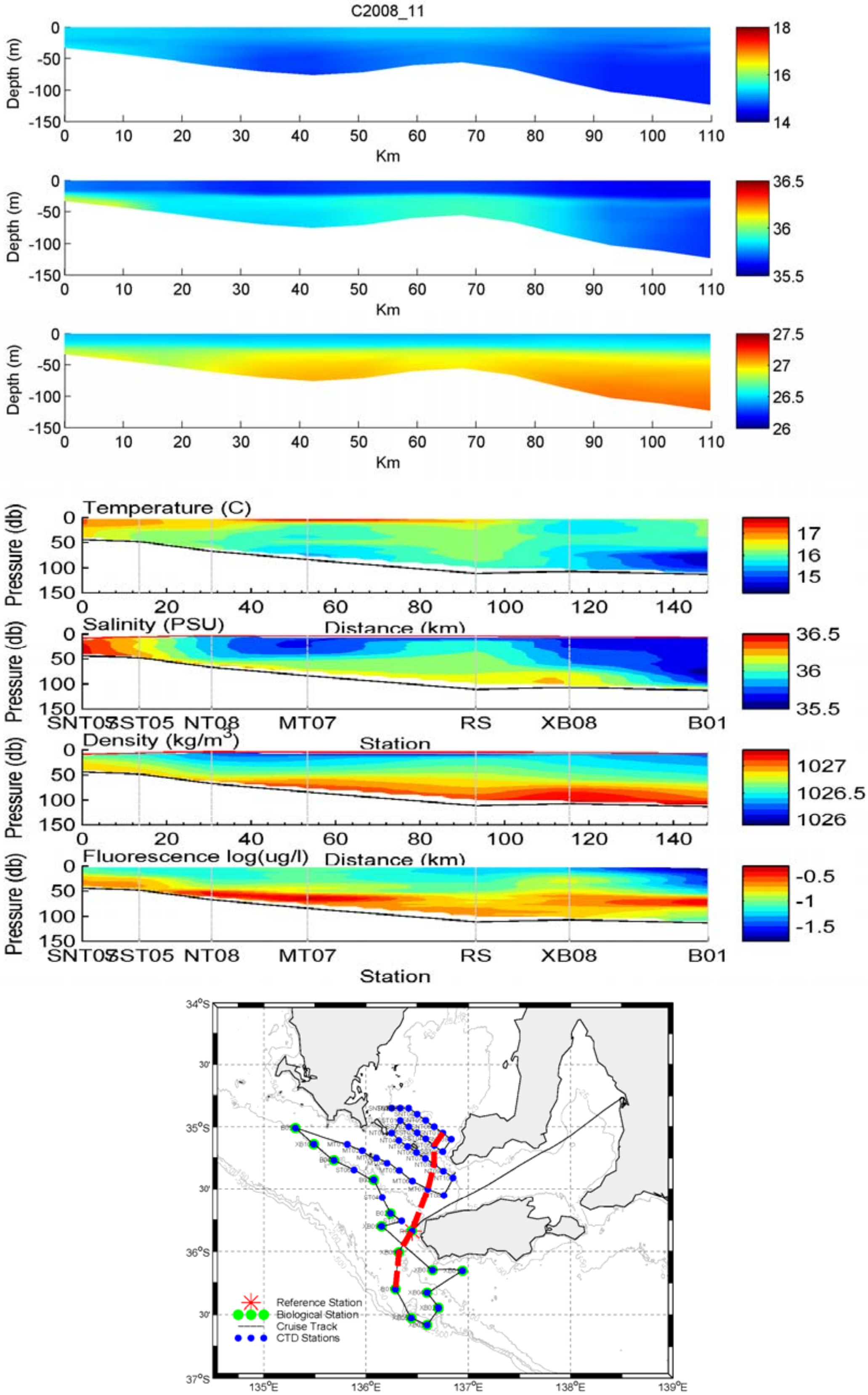


Figure 27. TOP: SAROM/ROMS cross-section at 12 November 2008. MIDDLE: SAIMOS survey cross-section. BOTTOM: survey map.

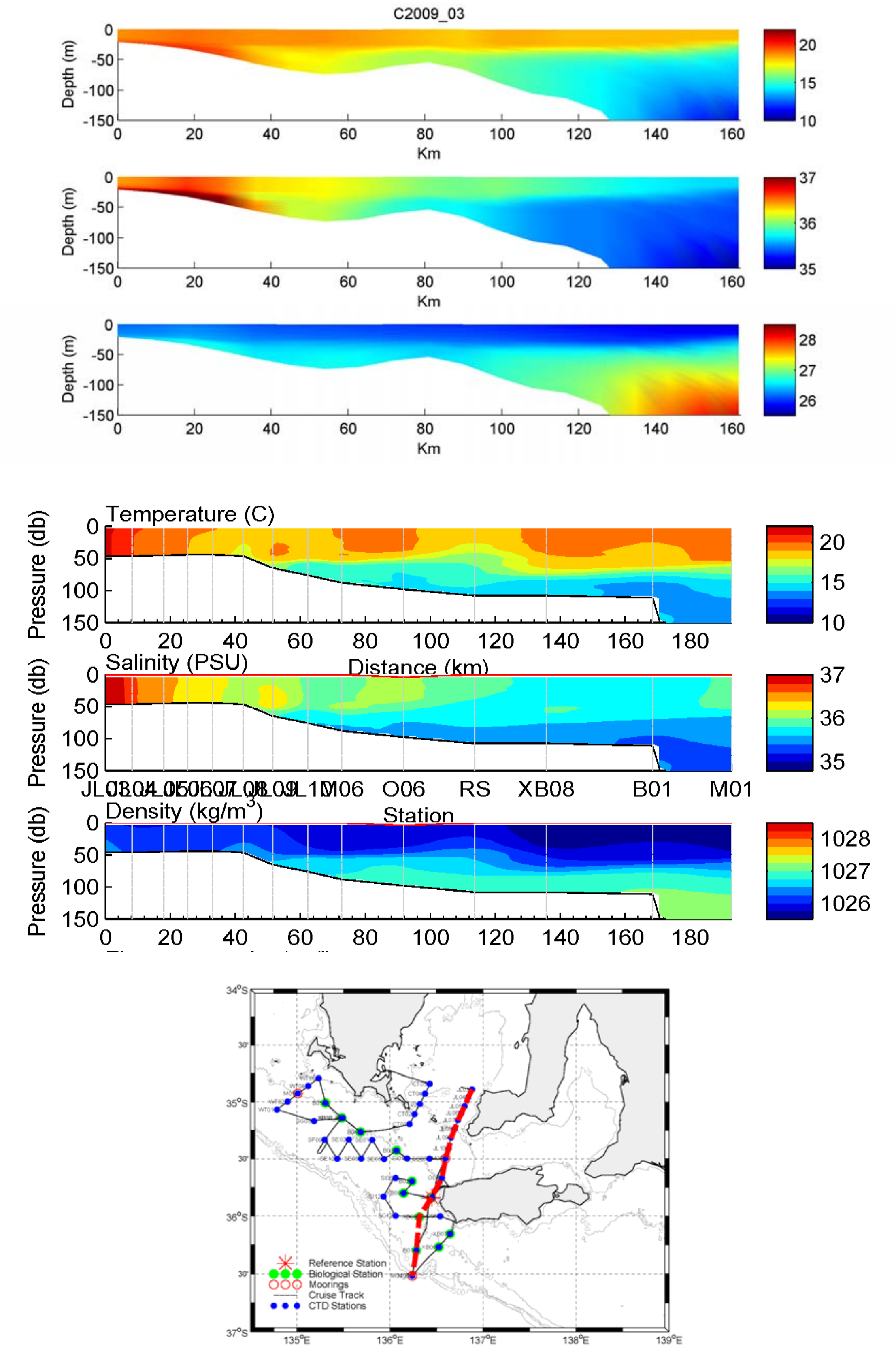


Figure 28. Same as **Figure 27** but for 17 March 2009.

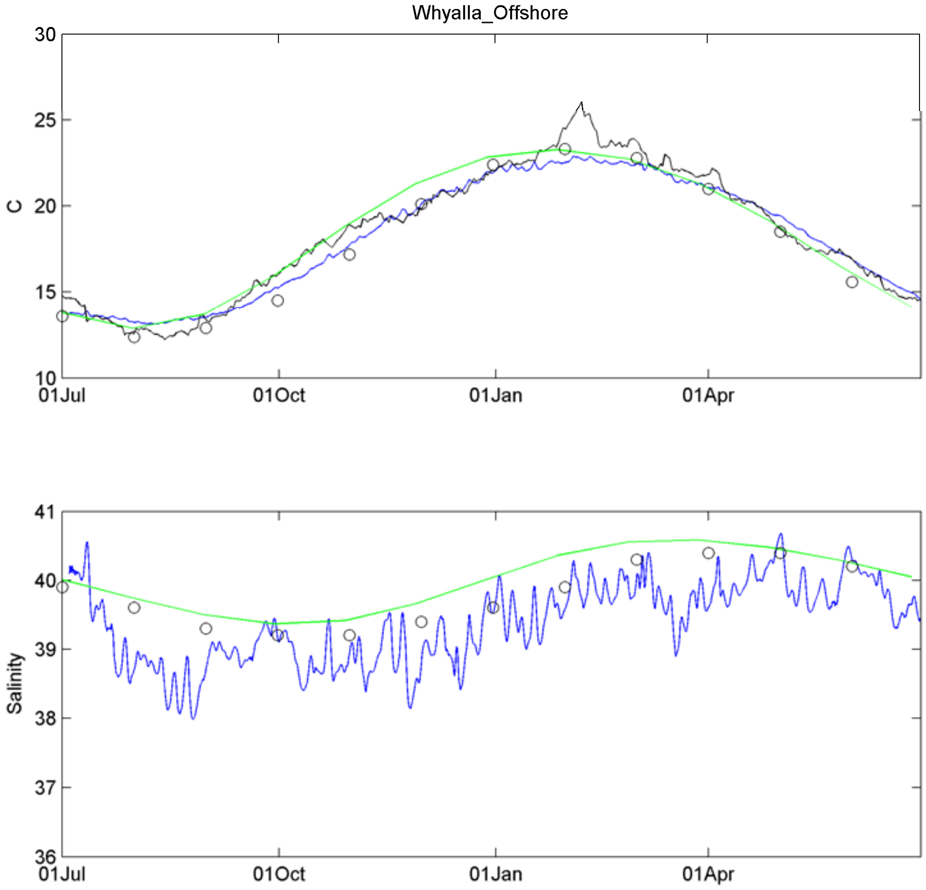


Figure 29. Seasonal temperature and salinity at an offshore site near Whyalla. Blue line: SAROM/ROMS. Black line: satellite SST (GHRSST). Green line: CARS. Circles: Nunes-Vaz and Lennon (1986).

Finally, we note that a similar comparison was made for Port Stanvac in Gulf St Vincent. At this site hourly coastal temperatures are recorded by the NTC. These data were in close agreement with the satellite data (GHRSST) indicating the latter may be used to nudge model SST towards observations and improve predictive skill.

7.3.5 Further Model Development

The idealised circulation driven by winds and tides was determined using the SAROM configuration described above. The results obtained are sufficient to determine a) predictive skill for tides and b) the important physics for the wind forcing and notably, possible paths of larval transport.

Model Development - Tides

The SAROM model described above does not include a tidal component of circulation. Such a model has been developed and the sub-inertial frequency results are very similar to those shown above. Validation of the model has been made through a comparison with observed (barometrically adjusted) sea level for the 2008-2009 period at sites including, Port Lincoln, Port Stanvac, Victor Harbour and Robe. Results for Port Lincoln are presented in **Figure 30** below.

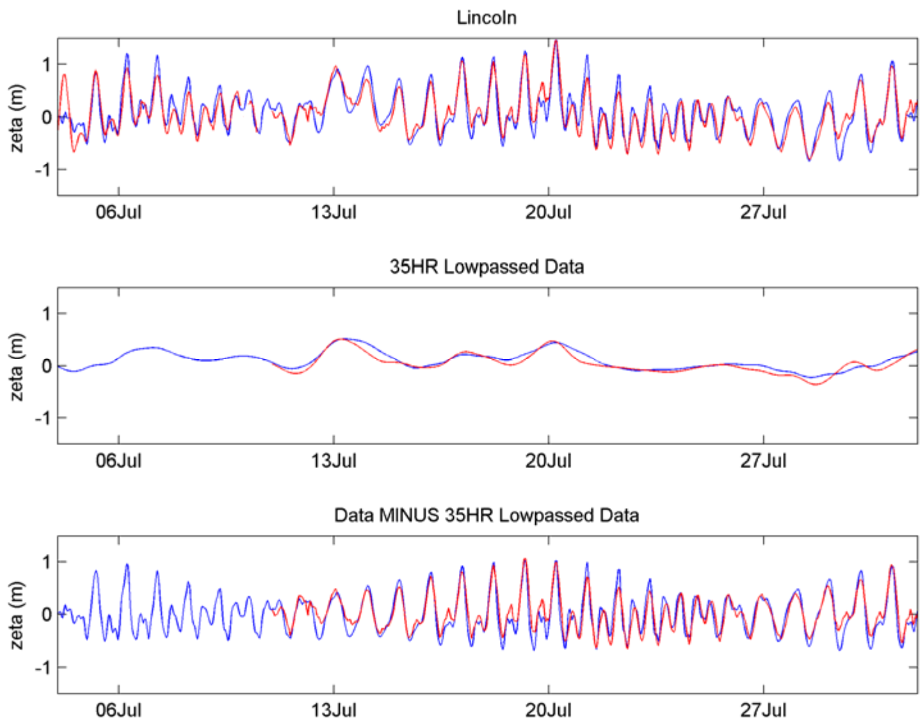


Figure 30. Sea level at Port Lincoln. Blue: SAROM/ROMS; Red: Flinders Ports. Upper panel - raw sea level. Middle panel – low pass filtred sea level. Lower panel – residual sea level (filtered less raw).

At the top panel, the comparison is between Port Lincoln model and observed sea level. The middle panel is a comparison between low-pass filtered (35 hr cut-off) model and observations. The bottom panel is a comparison between model and observations of sea level variability at periods less than the cut-off and is a better indicator of how well the model performs. The model predictions capture both dodge tide and interaction between the four main constituents quite well. This good agreement was found for the other sites mentioned above. The amplitudes and phases were computed for the four main tidal constituents of the model and can be compared (**Table 2**) with the ANTT estimates based on long time series of coastal sea level data. The results are encouraging with amplitudes and phases in agreement to within 5-10% or so. Similar good agreement is found at the other sites.

Table 2: Comparison of model and observed (ANTT) tidal constituents at Port Lincoln.

Constituent	SAROM Amplitude (m)	ANTT amplitude (m)	SAROM phase (deg.)	ANTT phase (deg.)
M2	0.217	0.239	15.6	33.3
S2	0.294	0.257	62.7	85.2
K1	0.285	0.242	19.3	26.9
O1	0.189	0.168	352.8 (-7.2)	1.2

Preliminary particle transport studies were made for the tidal circulation, but without vertical shear. As expected, while the tidal velocities can be large (U=40 cm/s), the displacement X over a tidal period (T=12 hrs) is small: X=UT/(2*PI) = 2.7km. Below we estimate particle displacements for wind-forcing to range from14 km to 123 km for the 10 day and seasonal summer forcing. However, tides may well be important though vertical mixing and current shear that can lead enhanced larval dispersal.

Model Development – Idealised Wind-forced circulation:

Two studies were done for idealised periodic wind forcing. The analysis of the meteorological data was used to determine a typical stress amplitude to be 0.03Pa for period of 10 days. A simple two-layer stratification was adopted from an analysis of all CTD available. This case represents relatively strong stratification with a density difference of 0.5 kg/m^3. However, the analysis also showed that there is no typical stratification for the gulf for any season. Tidal and wind mixing acts to eliminate stratification in the shallow coastal areas while the strong heating and evaporation leads to SMLs in the middle of Spencer Gulf and the formation of dense bottom water. The gulf is not generally well mixed during the November to April period. Preliminary larval results presented below indicate the effects of this stratification and vertical current shear may have a profound effect on larval transport.

Nonetheless, the idealised circulation due to winds can indicate possible paths of larval transport. To this end we present results for the case of a cross-shore (along Gulf) wind stress with period of 10 days. The application of the winds leads to a slow deepening of the SML, but the results are quasi-periodic over the first 30 days. The circulation is largest 1.25 days after the maximum in stress and that driven by the onshore (up-gulf) is shown in **Figure 31**. The results show the depth-averaged circulation with amplitude (the colour bar) in cm/s.

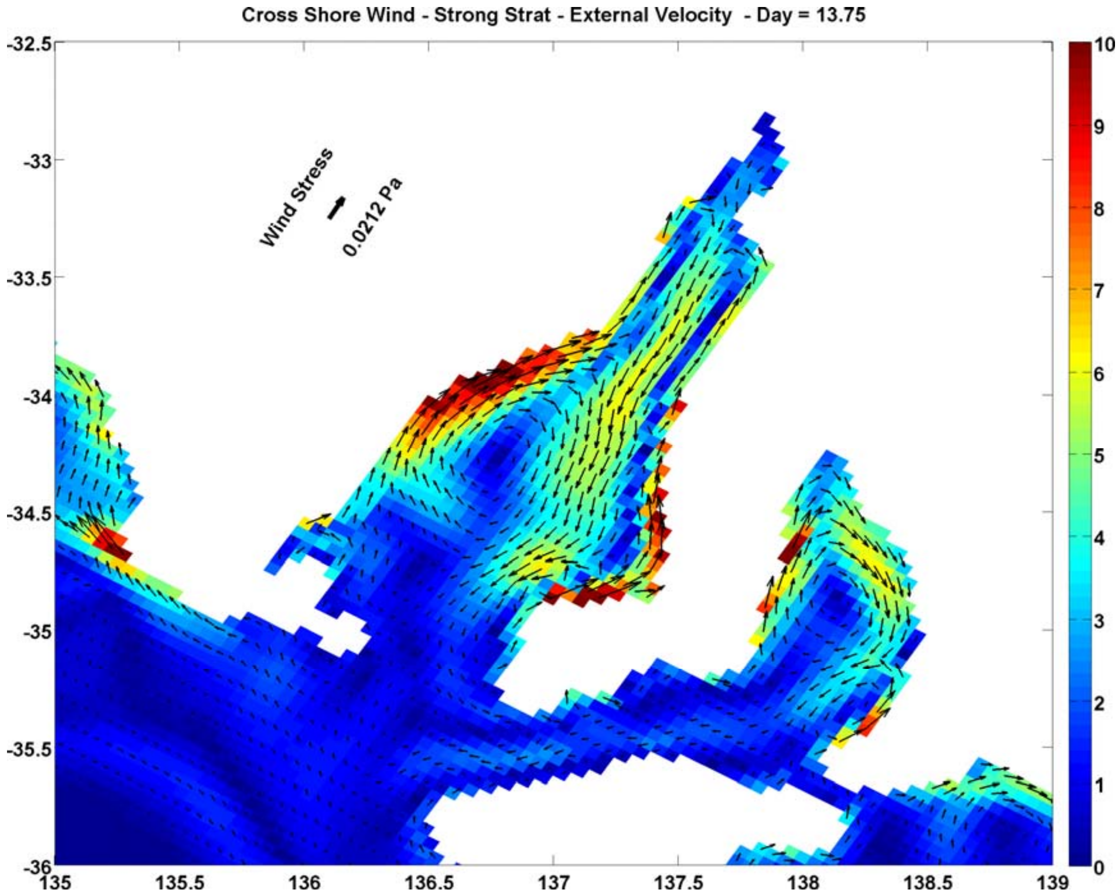


Figure 31. The depth-integrated circulation at day 13.5 that is driven by a cross-shelf (along Gulf) wind stress (amplitude 0.03 Pa, period 10 days). The direction and amplitude of the stress at day 13.5 is indicated on the figure.

The results show cross-shore (up-gulf) velocities of 10 cm/s in the shallow western and eastern edges of the gulf: the corresponding particle displacement is 14 km. This circulation is returned towards the gulf mouth along the central gulf axis. As the winds are periodic, the circulation is reversed 5 days later.

A snapshot of the subsurface circulation is given in **Figure 32** (bottom panel). The SML is illustrated by the results for temperature, salinity and density given in the top three panels. At this time the winds act to upwell deep water on the eastern gulf coast and downwell SML on the western coast. Mixing processes associated with the upwelling and downwelling lead to an enhancement of the up-gulf coastal jets that are colour contoured in the bottom panel (Teixeira and Middleton 2010). The vertical circulation also shows the westward Ekman transport in the 10 m with a corresponding eastward return flow below the SML.

In conjunction with the coastal jets, these circulation features could move larvae both across and along the gulf. We note here that this case may also be indicative of that for the summer period. Over the December to February period, the average wind stress within the gulf is largely directed up the gulf and the coastal jet amplitude of 10 cm/s would imply a particle displacement of 124 km or about half the length of the gulf.

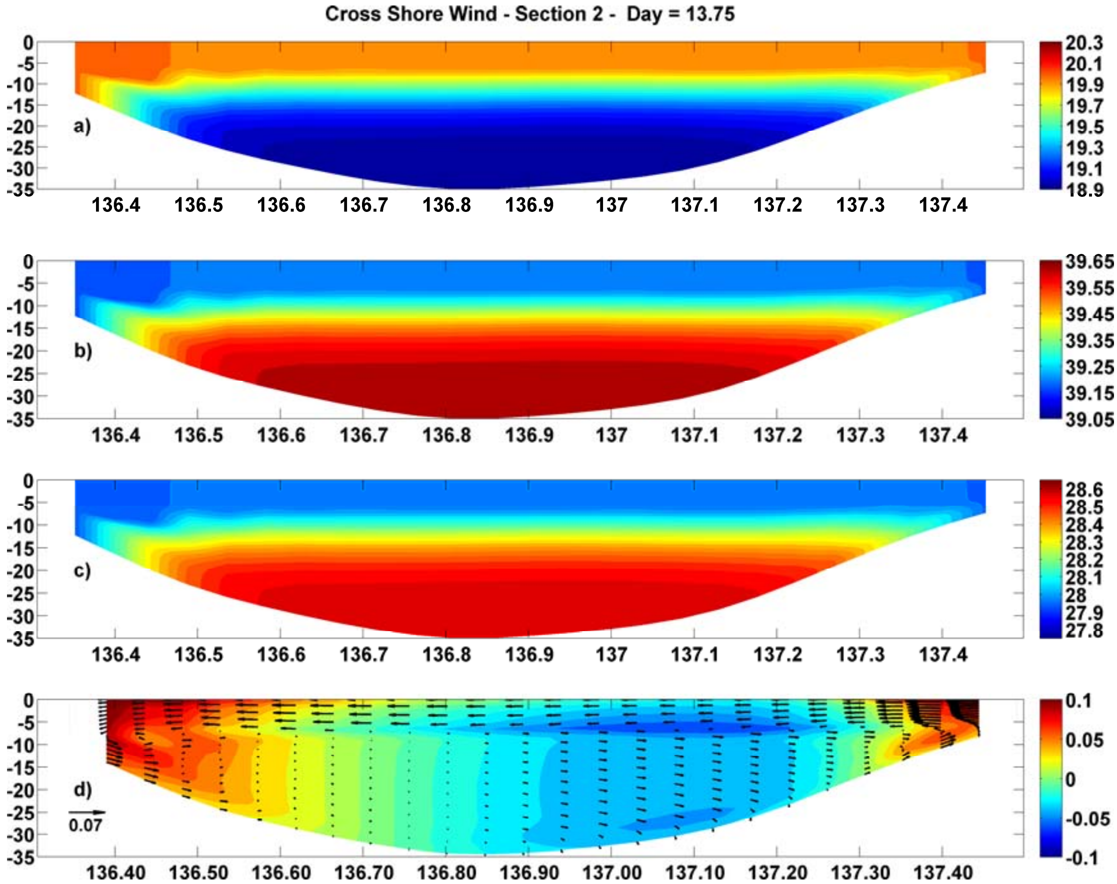


Figure 32. Results at day 13.5 for the cross-shelf (along gulf) wind stress and for a cross section at mid-gulf. The top three panels are temperature, salinity and density with units degrees, psu and kg/m^3. The bottom panel has the along-gulf velocity v colour contoured with units m/s. The up-gulf velocities are positive and red. The cross- gulf (u) and vertical (w) velocity vector is represented by the arrow with w multiplied by 1000 for visualisation purposes.

Results were also obtained for an along-shelf (cross gulf) wind stress and are shown in **Figure 33.**

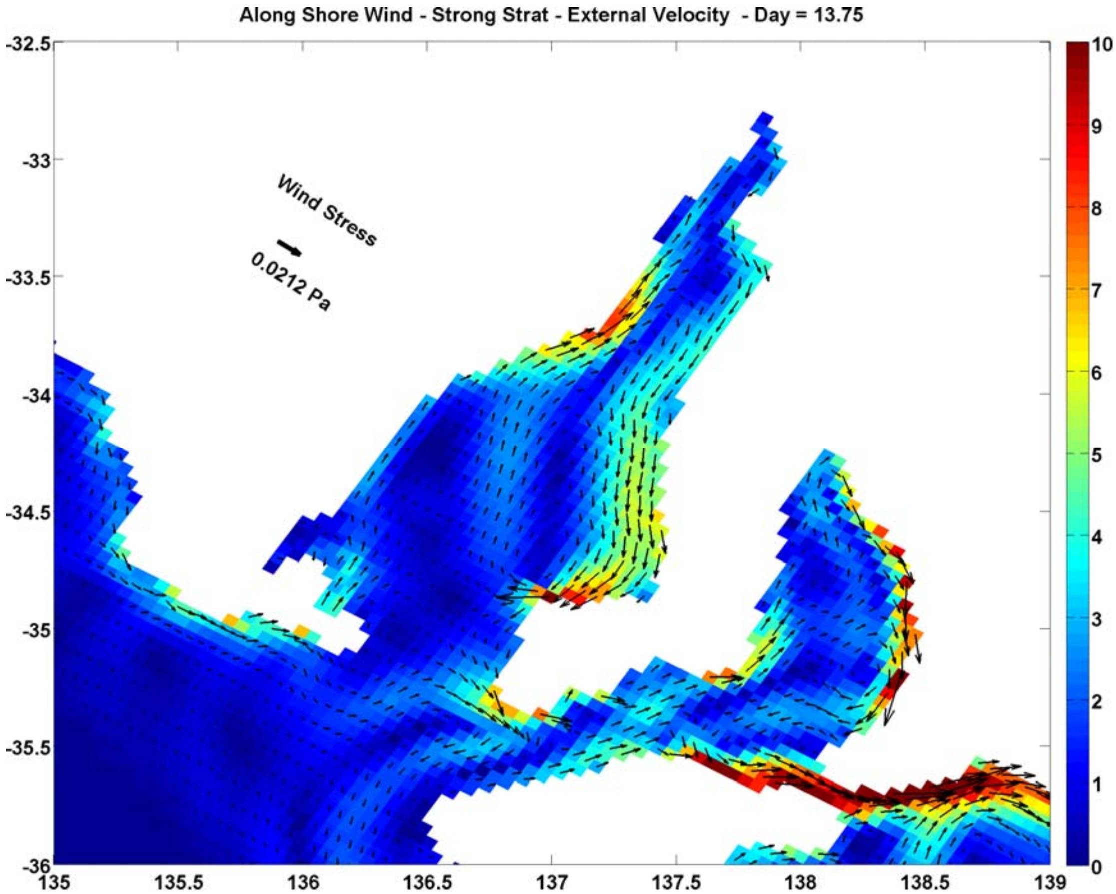


Figure 33. The depth-integrated circulation at day 13.5 that is driven by a along-shelf (cross-gulf) wind stress (amplitude 0.03 Pa, period 10 days). The direction and amplitude of the stress at day 13.5 is indicated on the figure.

The results in **Figure 33** show that this stress direction leads to enhanced coastal jets on either side of the gulf that might also provide paths for larval transport. During summer, the winds within the gulf are typically from the south to south-east so that the coastal jet on the eastern side of the gulf would be enhanced. Finally, we note that the wind-forced component of circulation in the upper two-thirds of the gulf is largely independent of that on the shelf. Thus, the wind-driven component of larval dispersal will be local in character.

Overall, the SAROM model is considered to be suitable for generating variables that are consistent with observations for the South Australian shelf and Spencer Gulf.

7.4 Comparisons of the regional models (Objective 4)

In comparing the dynamic ocean models that can be used to understand the environmental conditions that are important to the fish species of interest, we first compare the model structures, describe the environmental variables that each model can produce (primary variables) or can be derived from the primary variables (derived variables), compare the model output to historical in situ or remotely sensed data, and finally conclude with some general advice about model utility for the different fishery applications.

Model utility can vary based on model features, cost-effectiveness, the level of certainty or confidence in predictions, and flexibility in answering a range of questions. The features of a model that might be relevant include the following:

- Scale of outputs/ predictions in terms of time and area
- Usability for a range of stakeholders (i.e. form of output)
- The range of variables that can be derived (e.g. SST, mixed layer depth, upwelling).

The cost-effectiveness and limitations of using a model include:

- Costs involved in establishing the tool/model
- Costs involved in running and maintaining the tool/model
- Costs and types of input required (data and other)
- Expertise required (ie is the model able to be used by others)
- Model structure, and hence ability to represent the ocean.

7.4.1 Model structure

Each of the regional models evaluated in this project differs slightly in structure, which in turn allows for different strengths and weaknesses with regard to use in fishery studies. The underlying ocean model is different for each (**Table 3)**, which is not critical for the purposes of this study, but the model domain **(Figure 34)** and spatial resolution do have implications as discussed further in subsequent sections**.**

Table 3. Summary of model structure for Bluelink and SAROM.

Aspect	Bluelink	SAROM
Underlying ocean model	OFAM	ROMS
Vertical resolution	47 vertical levels, with 10 m resolution down to 200 m depth	30 sigma levels
Horizontal resolution in the south-east	10 km	5.55km
Model domain (area)	Whole SE region	Subset of SE region (see **Figure 34)**
Boundary conditions – ocean forcing	No tidal forcing	1) CTW paddle at head of Bight to simulate Leeuwin

		Current and wind forced signals. 2) Tidal forcing on all boundaries 3) CARS T/S on all boundaries 4) Model can be nested inside a OGCM
Atmospheric forcing	NCEP	1) Daily LAPS Fluxes of heat, salt and momentum; light 2) NCEP/NCAR monthly climatology
Temporal scale of model output (daily, weekly, monthly)	Daily	Daily
Intended focus of the model – what was it designed for?	Open ocean	1) to model coastal circulation 2) then shelf/slope circulation
Run time	Very long run times, scheduled months ahead of time. Archived data used	24 hours run time per calendar year simulation
Hindcasts	Yes – 1994 to present. Updated with each model version	More limited period of time.

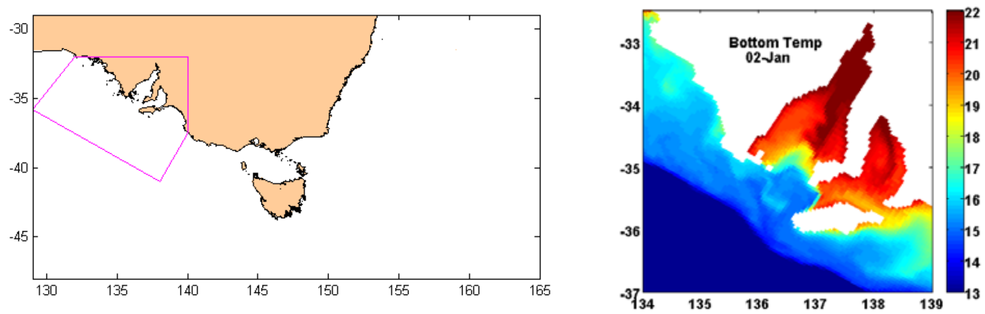


Figure 34. Illustration of the model domain relevant to the SEAP program for **A**. Bluelink with the SAROM insert and **B** SAROM detail showing resolution of circulation in Spencer Gulf. In future SAROM could be extended to cover western Victoria and Tasmania.

7.4.2 Model variables

Each of the models has the standard ocean variables as output, from which secondary variables can be derived (**Table 4).** This aspect does not differentiate the models, rather it is the spatial scale and ability to produce realistic conditions that is relevant. Consideration of these variables should inform the biological studies as part of SEAP.

Table 4. Model variables that can be obtained from each of the models considered. Primary variables are obtained directly from the models, while derived variables are calculated from the primary variables after the model has been run for the region and time period of interest. Some of the primary variables have only limited support linking them to fisheries/fish, but are important for calculating some derived variables which do have a relationship.

Variable	Definition	Fisheries relationship	Bluelink	SAROM	Historical data set that can be used for validation
Primary variables	*Available as direct model output*				
Sea surface temperature	Temperature at the shallowest model layer	Yes	Yes	Yes	Satellite SST
Temperature at depth	At levels in the model (e.g. 200m)	Yes	Yes	Yes	In situ data IMOS CARS
Salinity	Surface and at depth intervals	Less for marine, some in estuaries (flushing)	Yes	Yes, use and focus on inshore	In situ data IMOS ARGOS CARS
Heat content	Surface to 200 m	No	Would need to be calculated	Would need to be calculated	n/a
Sea surface height	Dynamic height relative to a reference level	Limited. Has been used elsewhere as a proxy for ENSO signals	Yes	Yes	Satellite altimetry
u, v, w	Horizontal and vertical velocity	Limited. Current velocity. may influence catchability and longshore cross-shore currents for recruitment signals	Yes	Yes	u, v: Satellite altimetry
T/S structure	Vertical profiles	Limited knowledge	Yes	Yes	Not used in this study, but could

					use ARGOS CARS
Derived variables	*Calculated from primary variables*				*Comments*
Stratification: e.g. Surface mixed layer depth	Derived from T/S output • Delta 0.5C • Monthly average	Limited: e.g. for catchability	Yes	Yes	Not considered here Easier measures are based on T at 0 and T at depth?
Eddies and EKE	Derived from SSH output (EKE over space and time). Frequency distribution	Yes	Yes	Not a focus, scale of model is too small for eddy propagation	Calculated as examples from Bluelink
Thermal fronts	Derived from SST output	Limited	Yes	Yes	Can use easier definitions e.g. SST_{STD}
Transport (current strength)	Average over some depth band for a transect	Yes	Yes	Yes	e.g. EAC strength
Upwelling – coastal	Wind driven • SST-based definition (<2SD from mean) • T_b-T_s	Yes	Yes	Yes	Difficult to determine measures of subsurface upwelling, e.g. King Island and Tasmania, KI and Ayr Peninsula)
Upwelling - offshore	Vertical velocity (w) Average: Week to month	Little evidence Nutrient supply	Yes	Yes, but less interest	Prefer eddies
Productivity –chl (best) - PP - Secondary	Surface Depth integrated	Yes	Not directly, NPZ model is coupled	No, NPZ model to be added	Not used in this project (SSC)

Wind stress curl		Limited	Yes	Yes	Not in this project

7.4.3 Model strengths and limitations

Bluelink has been forced by output from a GCM (e.g. Hartog *et al.*, 2011), indicating that future environmental variables (e.g. SST) can be derived. SAROM could also be nested within a GCM or forced by GCM output and runs rapidly enough to allow a matrix of high-resolution climate change scenario studies for continental shelves. It has already been used to produce a historical monthly climatology of circulation, and future climatology could also be generated when coupled to GCM output. As SAROM is based on the ROMS open source code, the model is continually improved by the international community.

Dispersal pathways can be derived from the models. Bluelink has been used to provide larval trajectory pathways (see **Section 7.7).** Established NPZ and larval transport models could also be linked to SAROM in future. The present primary outputs of both models (u and v-currents) can also be used to simulate simple larval transport but outputs will be most useful when larval "behavior" is included, such as in the dispersal model Connie2 (*www.csiro.au/**connie2**/*).

The SAROM model is not semi-global and so does not automatically incorporate large-scale ENSO signals or forcing by Leeuwin Current or deep-ocean Sverdrup transport, as does Bluelink. The limited SAROM domain (**Figure 34)** does restrict some applications in the south-east, but can be extended to incorporate western Victoria and Tasmania, but not NSW. This limited domain and limited external forcing means that SAROM does not represent mesoscale eddies sufficiently compared to Bluelink.

Each model does have strengths and will be appropriate for different uses. We suggest that case studies of fishery species in the south-east discuss their modeling needs with physical oceanographers before proceeding (Hobday and Lough 2011).

7.5 Projections for the southeast region - GCMs (Objective 4)

As discussed in **Section 6.3** global climate models (GCM) can provide values for environmental ocean variables. Primary variables available from GCMs include the same variables discussed in **Table 1** for the regional models:

- SST
- Temperature at depth (e.g. 200 m)
- Salinity
- Air temperature
- Currents (u and v)

The secondary variables cannot be sensibly calculated from GCM data as GCM data are too coarse and do not resolve fronts and eddies. One exception is pH which is described in **Section 7.6.** Examples of these variables are presented, and can be accessed for any time period, although averages of at least 10 year periods are recommended (Hobday and Lough 2011).

7.5.1 Methods and Results

The primary source of information on future projections comes from the output of GCMs, for example the set of World Climate Research Program CMIP3 models used to support the IPCC AR4. The volume of data from these GCMs can be overwhelming and disparate in file structure and notation. Central repositories were established to facilitate access to consistently formatted model output (www2-pcmdi.llnl.gov/esg_data_portal), however, downloading and accessing complete suites of data requires independent data programming. Recently, data portals have been developed that allow extraction of the desired data without downloading the original files (e.g. http://www.ipcc-data.org/ddc_visualisation.html). This data is coarse in time (e.g. monthly fields) and space and in the case of marine waters, do not resolve mesoscale features such as eddies, coastal upwelling, realistic boundary currents, or fronts (Hobday and Lough 2011).

Data were downloaded from the CMIP3 repository to cover the desired suite of ocean variables for the historical period and the period 2000-2100 for two scenarios (A2 and A1B). These files are in netcdf format, and were accessed with customised Matlab programs. No additional processing was completed at this stage.

Output from six GCMs are used for illustration here, as they covered a wider range of oceanic variables for both a historical period and for the future for the A1B and A2 scenarios, although up to 13 of the CMIP3 archive could be used for SST. Data are at a monthly scale, which also allows seasonal or annual patterns to be derived by compositing data to longer temporal scales.

In the GCM data using a 10 year annual average, only broad latitudinal patterns of warming can be seen, due to the coarse resolution. All models show greatest warming in south-east Australia along the axis of the East Australia Current, as has been reported elsewhere. The six models vary in their estimate of historical temperature values for the period 1999-2000 ranging from 13.29 to 15.85 C – a mean value of 14.7°C (**Figure 35).** As a result, future values must be viewed with caution, as these initial differences between models are preserved into the future. These initial biases could be corrected for individual models by subtraction of individual deviations from the observed value for this period, models judged too far from the observed values could be eliminated, or average values from all models can be used (Hobday and Lough 2011). Unfortunately the best models for one variable and region may not be the best models for a second variable in the same region, or the same variable in a different region. This type of bias correction imposes the "correct" value, but such an empirical offset may not persist at the same level into the future, and so caution is warranted for such an approach.

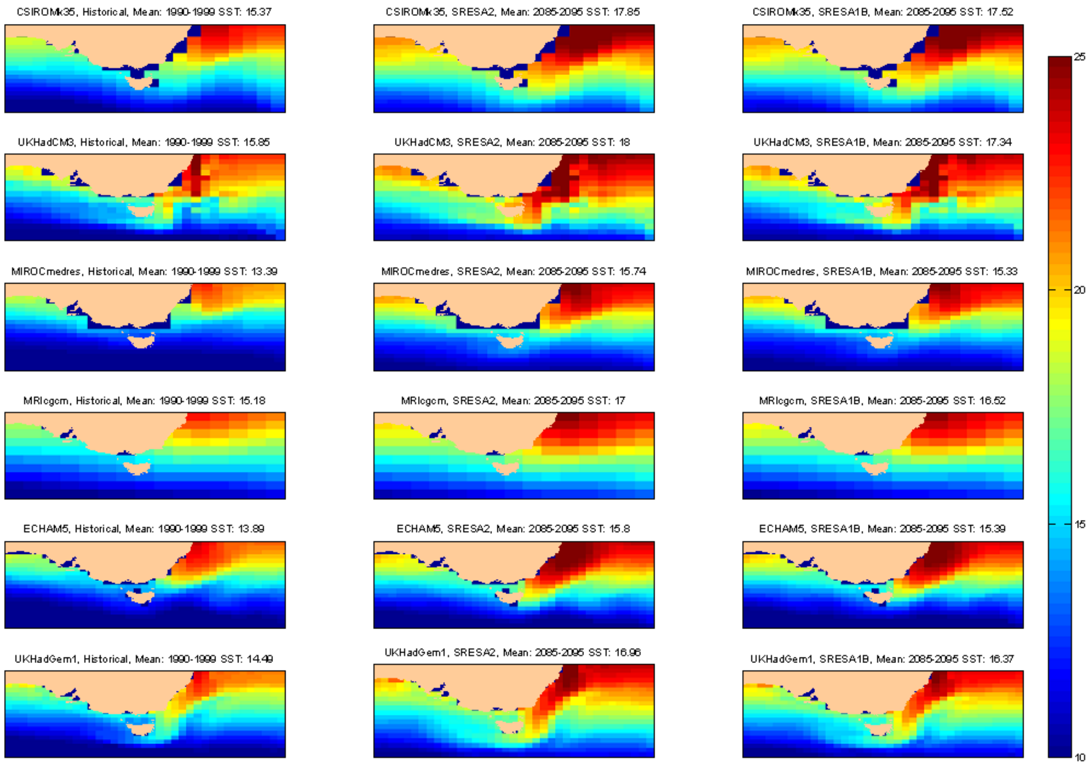


Figure 35. Example of GCM output. Sea surface temperature for the south-east region for the present (1990-99 – left column), and the years 2085-95 for the A2 (middle column) and A1B (right column) scenarios.

Future temperatures in the south-east for the example period (2085-95) range from an overall annual average of 16.9°C (range 15.74 to 18°C) under the A2 scenario to 16.4°C (range 15.38 to 17.5°C) under the A1B scenario, a warming of 2.2°C or 1.73°C respectively. Obviously some regions in the south-east are warming faster or slower, and so an overall average rate of warming for the SEAP region is not particularly useful. Similar plots of salinity, temperature at depth (e.g. 200m), and currents could also be shown. We suggest that all GCM data extraction should be matched to a biological need, time period and desired scenario.

Further processing of GCM output by CSIRO has occurred for a limited number of marine variables (SST, salinity and temperature at 200 m) (see Hobday and Lough 2011) and is included here for comparative purposes. This statistical downscaling approach is based on multiple models for all the SRES scenarios and the global pattern of warming (**Figure 36**).

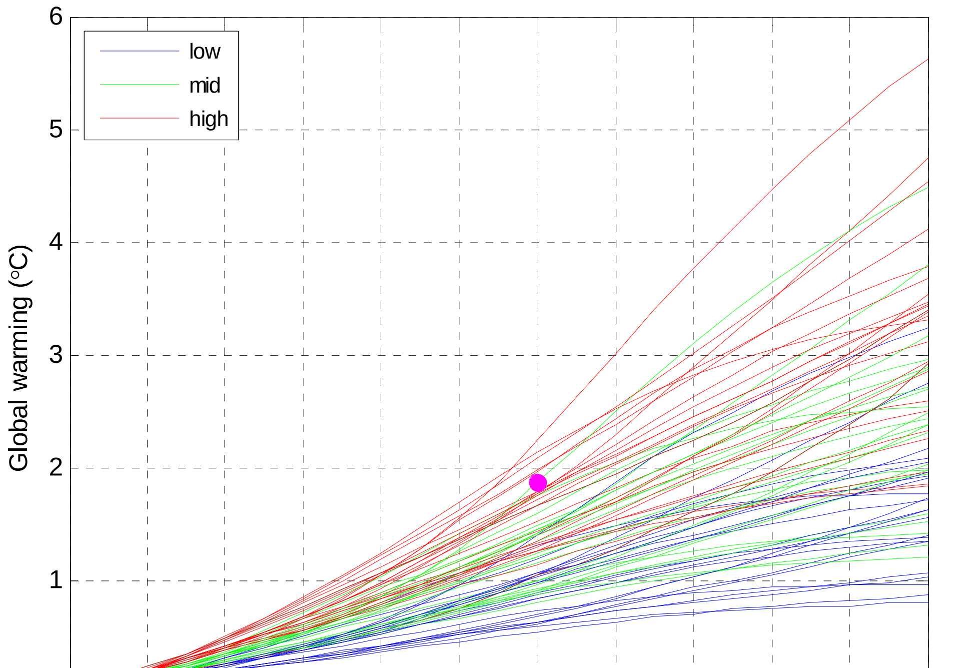


Figure 36. The projected change in global temperature varies depending on the scenario used, and the sensitivity of the climate system to the greenhouse gas levels (low, mid or high). The magenta dot at 2050 indicates the A1FI scenario with mid-range sensitivity.

Ensemble averaging of multiple models for one selected scenario is illustrated in **Figure 37.** This approach shows the difference in sea surface temperature between

1990 and 2050 for each month of the year based on the A1FI scenario using the OzClim approach (**Section 8.3)**. Warming is greatest off eastern Victoria and Tasmania, with least warming in the Bonney Upwelling area of western Victoria. Winter warming is greater than summer warming.

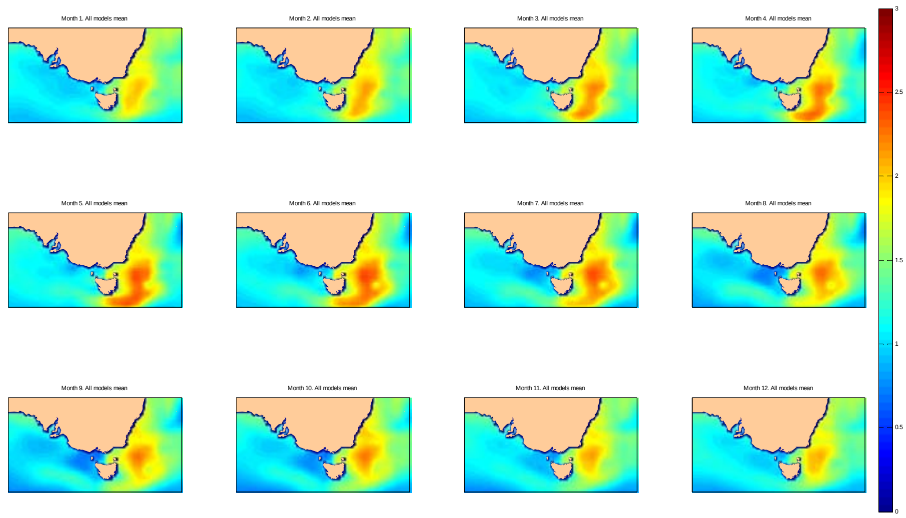


Figure 37. Change in sea surface temperature between 1990 and 2050 for each month of the year based on the A1FI scenario using the OzClim approach.

Overall, original and downscaled GCM data can be used to describe general trends for the south-east region, but caution should be exercised when attempting to use the data at a finer resolution. The range of models, scenarios and time periods, should be sufficient to support subsequent SEAP activities for a limited set of primary variables.

7.6 Acidification levels in the south-east (Objective 5)

Ocean acidification has been increasing with increased greenhouse gas concentration (i.e. pH has been declining), and this trend is expected to continue for the long-term. This change in pH has consequences for calcifying animals and plants, causing reduced calcification rates and higher metabolic costs to biochemically precipitating calcium carbonate from solution.

Specifically, ocean pH at a global scale has fallen 0.1 logarithmic units since the industrial revolution (~1850's). Global projections indicate that a further decline of 0.2-0.3 units can be expected by 2100 (e.g., Orr *et al.*, 2005). Such pH levels in oceanic waters have not been encountered for millions of years, and this rate of change is unprecedented (e.g., Luthi *et al.*, 2008). The effects of changes in ocean pH are evident in the change in saturation state of the two forms of calcium carbonate – aragonite (which is the most soluble form) and calcite (the least soluble form). The aragonite saturation of warmer waters is higher than that of polar oceans because carbon dioxide is more soluble in cold water (Hoegh-Guldberg *et al.*, 2007). As a result, changes in ocean pH will initially occur in polar waters and progressively move with ocean mixing towards lower latitudes and the tropics (McNeil and Matear, 2008).

Different biological taxa use different forms of calcium carbonate in their skeletal structures, and so will have differing responses and vulnerabilities to the change in saturation state (Hoegh-Guldberg *et al.*, 2007). Additionally, evidence of synergies among marine geochemical processes has been found. Seasonal carbon dynamics may potentially hasten ocean acidification and a 450-ppm atmospheric CO_2 has been proposed as a tipping point for calcifying biota in the southern ocean (McNeil and Matear, 2008). Ocean acidification will affect all calcifying algae and animals. The deposition of calcium carbonate ($CaCO_3$) by calcifying biota, such as corals, molluscs, crustaceans, foraminifera and calcareous algae, is essentially a biochemical process, and this process requires more energy exerted by biota as ocean water pH is lowered. The ocean alters the proportions of dissolved carbon dioxide from carbonate and bicarbonate ions of which carbonate is a crucial element for shell-making organisms (Howard *et al.*, 2009). Physiological processes are sensitive to pH itself but the cascade of consequences arising from these ocean water chemistry changes are not well understood. Observations have already detected changes in calcification in Southern Ocean zooplankton (Moy *et al.*, 2009) and in Great Barrier Reef corals (De'ath *et al.*, 2009), indicating that acidification has already having a detectable effect on biological processes (Howard *et al.*, 2009).

Acidification will affect calcification rates of calcareous zooplankton (e.g. foraminifera) which have already declined in abundance by 30-35% since pre-industrial times (Moy *et al.*, 2009). Coralline algae, bryozoans and other benthic calcifiers will similarly exhibit reduced calcification and/or increased dissolution of existing skeletal structures. Acidification will also affect particular life history stages of other fauna and flora. Reduced fertilisation success has been documented in some marine invertebrates such as the Sydney rock oyster (Parker *et al.*, 2009) and impaired olfactory-based navigation has been observed among reef fishes (Munday *et al.*, 2009). Furthermore, squid, annelid worms, and bivalve molluscs have been reported to show metabolic depression as pH of surrounding waters decreases (Pörtner and Farrell 2008). Many of these impacts are little understood or unknown (Howard *et al.*, 2009).

Aragonite saturation state declines with water depth, meaning that benthic calcifiers such as deep-water corals, coralline algae and other benthic calcifiers will also show reduced calcification as ocean acidification causes an the aragonite saturation horizon to become more shallow (Howard *et al.*, 2009). The aragonite saturation state is also correlated with ocean temperature, meaning that southern calcifiers will suffer greater degrees of decalcification than tropical species (Hoegh-Guldberg *et al.*, 2007).

There are few studies on the impact of ocean acidification for the south-east region to date, and these have focused on benthic invertebrates (e.g. Byrne *et al.,* 2009; Sheppard Brennard *et al.,* 2010). Several studies also indicate an interaction between temperature and pH (e.g. Byrne *et al.,* 2009; Connell and Russell 2010). Implications for commercial fishes and invertebrates in the south-east region are unknown, and there is a need for more experiments and field studies before impacts can be more specifically determined. The objective in this component of the report is to illustrate the future pH levels, such that critical experiments using realistic values can be defined.

7.6.1 Methods and Results

Projections of future ocean chemistry were based on a single GCM run, as CO_2 levels drive the pH, and CO_2 levels are the same for all GCM when they are driven by the same scenario. In this project we illustrate the future changes using the A1B scenario.

The average pH value varies slightly across the south-east, with average values around 8.1 to 8.15 (**Figure 38).** Future declines are of the order of 0.08 to 0.1 units by 2030, and 0.26 to 0.33 by 2011, which are in line with global projections (**Figure 38)**.

The two forms of calcium carbonate have different dissolution sensitivities, and are illustrated in **Figure 39.** By way of reference, carbonate accretion on coral reefs approaches zero or becomes negative at aragonite saturation values of 3.3 in today's oceans which occurs when CO_2 approaches 480 ppm and carbonate ion concentrations drop below 200 mmol kg^{-1}. Equivalent thresholds for commercial taxa in the south-east are not known, but are the subject of ongoing research for species such as scallops and abalone.

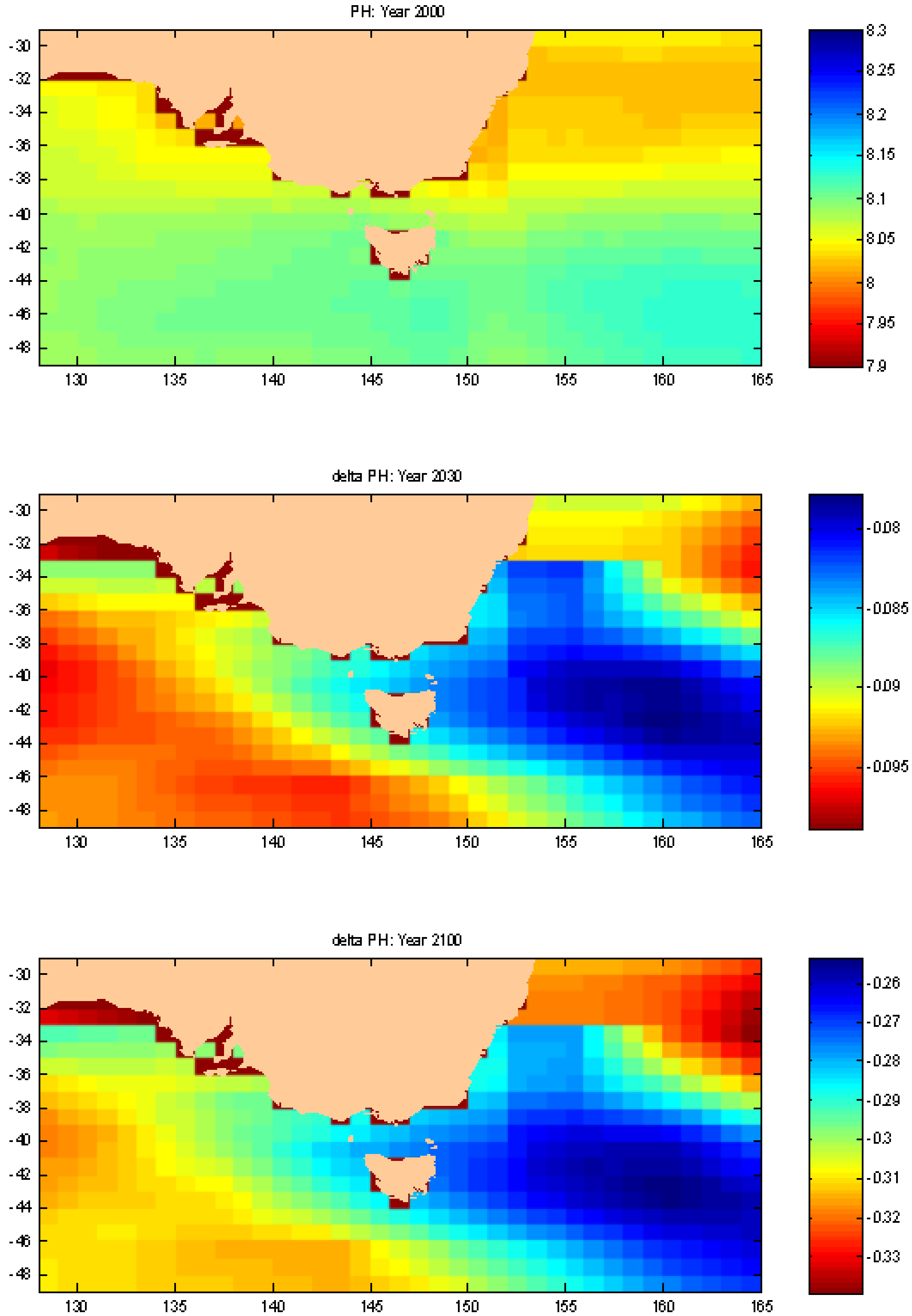


Figure 38. Data from Bluelink was extracted for each box illustrated above (0.1, 0.5, 1 degree) and 5 degree (not shown) along the EEZ (200 nm), 200 m contour, and 50 meter contour.

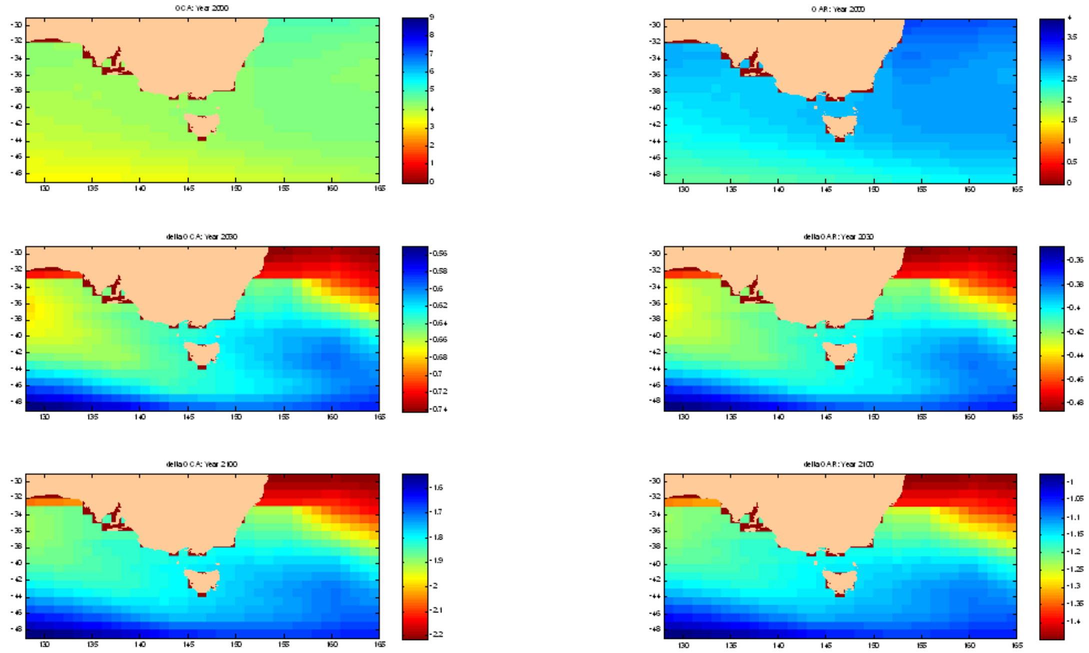


Figure 39. Calcite (left column) and aragonite (right column) are two forms of calcium carbonate. Values for the year 2000 (top row) and the change in each variable for the years 2030 (middle row) and 2100 (bottom row).

7.7 Marine connectivity in the southeast region (Objective 7)

Climate change is likely to be accompanied by significant changes in ocean currents and the associated dispersion of marine larvae and other plankton. Such changes will have a large impact on the life-cycle of many marine species, potentially including important commercial species.

Southeastern Australia is a complex oceanographic environment, encapsulating a wide range of transport and dispersion patterns. This can be illustrated in terms of the local retention rates estimated from particle tracking models (Condie *et al.*, 2005). These approaches suggest low retention in areas directly influenced by the East Australian Current with higher levels (up to 8 times) in the eastern Great Australian Bight and around Tasmania (**Figure 40**). However, within each local area there is also significant seasonal variability (typically a factor of 2) and interannual variability (typically 30- 50%) (**Figure 40**).

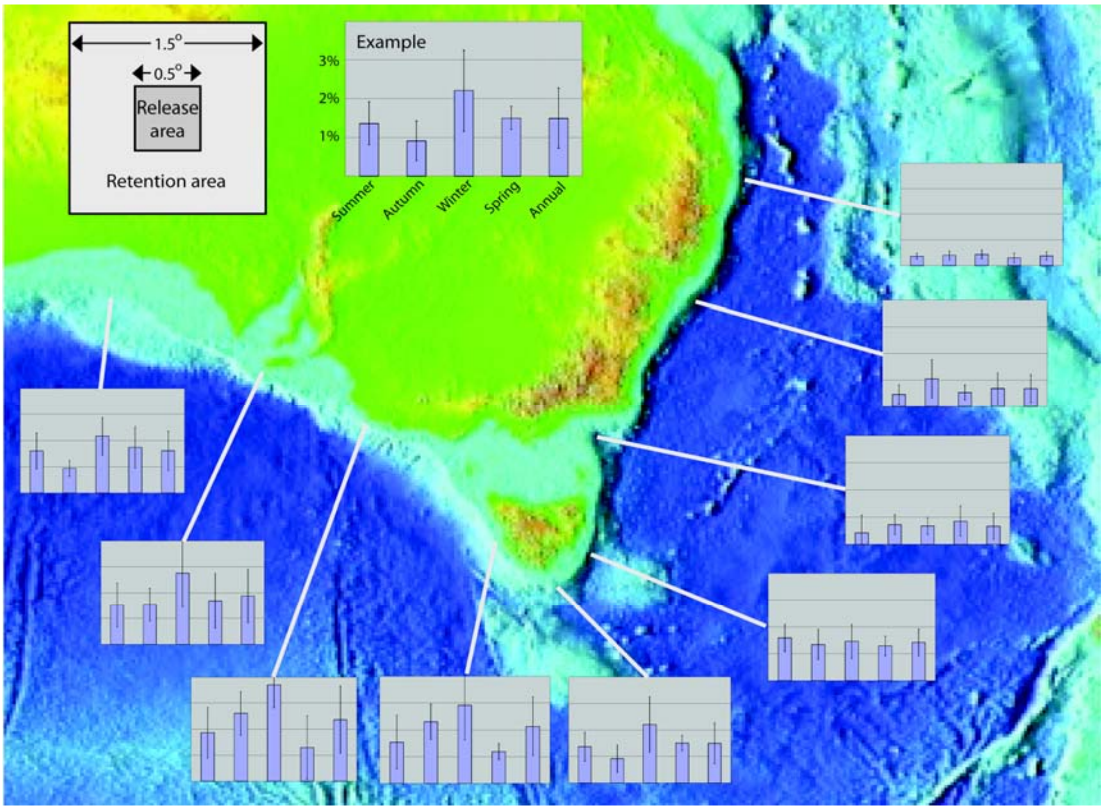


Figure 40. Graphs of quarterly and annually averaged probabilities of modelled larval retention within latitude-longitude boxes (top left) 28 days after release. Results are shown for 9 areas on the outer-shelf and upper-slope around southeastern Australia. Error bars show the standard deviation across years. Adapted from Condie *et al.*, (2011).

7.7.1 Methods and Results

Climate models do not yet resolve ocean currents at the resolution required to examine potential changes in larval transport patterns and are unlikely to provide reliable estimates in the near future (e.g. Hobday and Lough 2011). We have therefore focused here on trends over the past two decades as an indicator of ongoing changes. Modelled ocean currents have been combined with a larval (particle) tracking model to estimate changes over the period 1993 to 2007.

As in the previous sections we used output from a version of the Bluelink model. The oceanographic model known as OFAM (Ocean Forecasting Australia Model) (Oke *et al.*, 2008, Schiller *et al.*, 2008) is a data-assimilating oceanographic model that is used for operational ocean forecasting by the Australian Bureau of Meteorology and for reanalysis by CSIRO. It is a global model that is eddy-resolving over the region 90E–180E, 60S–10N (0.1 degrees in latitude and longitude). The Bluelink Reanalysis (BRAN) archive contains daily outputs of ocean currents from

OFAM over the period 1993–2007. These currents were used to force the particle tracking model.

Individual particles were seeded throughout the study region at a constant rate of 25 particles per 0.1 degree grid cell per day. They were subsequently tracked individually (using a Runge-Kutta ODE solver that linearly interpolates in time and horizontal space to find the horizontal velocity at the required depth and time). Potential long-term changes in larval transport over a 15 year period were identified by mapping changes in mean displacement of particles at various spatial scales and testing for statistically significant trends. Transport patterns in those regions showing statistically significant trends were explored in more detail using the online tool Connie (www.csiro.au/connie2/), which is based on the same oceanographic model and particle-tracking techniques as described above.

A preliminary analysis at the fine spatial resolution of the circulation model (0.1 degree) revealed significant differences between conditions prior to 2000 and those after 2000, particularly of eastern Tasmania (**Figure 41**). However, at this scale trends tended to be confounded by high levels of eddy-scale variability.

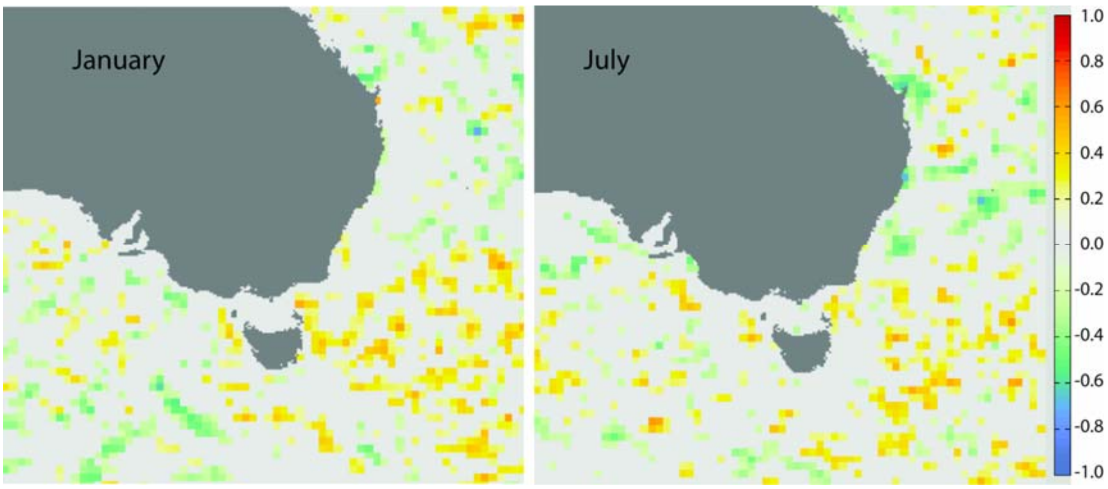


Figure 41: Change in relative dispersion distance from pre-2000 to post-2000 at a depth of 55 m for January (left) and July (right). These were calculated for each month by subtracting the mean displacement of particles dispersing over 14 days for the years 1993-1999 from the mean displacement for the years 2001-2007, then dividing by the mean displacement (1993-2007).

Additional analyses were therefore conducted on a larger scale 9 by 9 degree grid (**Figure 42**). Within each season of each year the displacement of more than 15 million model larvae were computed after dispersing for a fixed number of days (referred to here as the larval duration). Average larval displacement was plotted as a function of year and any temporal trends identified. These trends were considered to be statistically significant if the correlation coefficient exceeded 0.5 and the p-value was less 0.05.

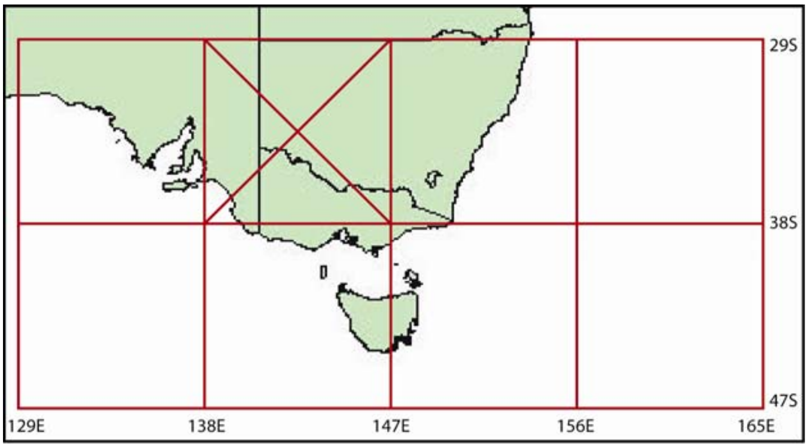


Figure 42. The 9 by 9 degree grid used for the spatially averaged analysis of long-term trends in larval transport.

Results based on a larval duration of 14 days are summarized in **Table 5**. There is a high level of interannual variability (**Figure 43**) and across most of the region no statistically significant trends were detected. The important exceptions were the two boxes off eastern Tasmania, where the minimum correlation coefficient was 0.56 and the maximum p-value was 0.03 (0.66 and 0.008 respectively for a 7 day larval duration). In this region net transports typically increased 1-2% per annum on average (**Table 5**), the largest increase over the 15-year simulation being 26% (autumn). The trend towards increasing transports off eastern Tasmania appears to be largely associated with enhanced southward transport, the most extreme years being 2005 and 2007 (**Figure 40**). This is consistent with the documented increase in the strength of the East Australian Current (Ridgway 2007, Ridgway *et al.,* 2008, Ridgway and Hill 2009) and the associated warming of waters off eastern Tasmania that is predicted to continue over the next half century (Cai *et al.,* 2005).

Table 5: Statistics on long-term trends in larval transport rates expressed in terms of the mean displacement of model particles over 14 days at a depth of 55 m averaged seasonally. Seven values are given for each statistical quantity and season corresponding the seven latitude-longitude boxes shown in **Figure 42**. Trends with both a correlation coefficient greater than 0.5 and a p-value less than 0.05 are shown in bold.

	Spring				Summer				Autumn				Winter			
Mean (km)	76		214	150	69		236	158	80		232	164	98		215	157

	90	94	**117**	**83**	87	88	**121**	**82**	88	96	**125**	**88**	92	101	**122**	**86**
Trend (km/year)	0.5		1.2	-0.1	0.5		1.3	-0.1	1.0		-0.2	-0.5	0.0		-0.7	-0.7
	0.3	0.3	**1.0**	**1.2**	-0.1	0.2	**1.4**	**1.0**	0.2	0.5	**1.6**	**1.5**	0.4	0.3	**1.6**	**1.2**
Correlation coefficient	0.27		0.46	-0.05	0.32		0.46	-0.04	0.58		-0.07	-0.18	0.02		-0.27	-0.31
	0.29	0.27	**0.58**	**0.76**	-0.11	0.22	**0.56**	**0.63**	0.16	0.37	**0.73**	**0.81**	0.38	0.31	**0.70**	**0.70**
P-value	0.334		0.085	0.871	0.240		0.088	0.896	0.024		0.810	0.517	0.939		0.324	0.267
	0.287	0.334	**0.024**	**0.001**	0.697	0.434	**0.030**	**0.011**	0.579	0.180	**0.002**	**0.000**	0.161	0.256	**0.004**	**0.003**

Interannual variability in ocean currents will continue to influence annual recruitment rates of many species. However, the trends identified above in regions such as off eastern Tasmania may determine the long-term viability of species that are sensitive to their pelagic larval phase.

One example is the southern rock lobster (*Jasus edwardsii*), which must return to the continental shelf after an extended larval phase as phyllosoma (9 to 24 months). Phyllosoma larvae tend to concentrate on the southern side of the Tasman Front forming the southern extremity of East Australian Current (Bruce *et al.,* 2000), so that enhanced southward transport beyond Tasmania may prevent recruitment back to the east Tasmanian continental shelf (Bruce *et al.,* 2007, Pecl *et al.,* 2009).

There are a number of small pelagic fish species that spawn off eastern Tasmania (Jordon *et al.,* 1995) and form commercial exploited schools over the continental shelf and slope (e.g. redbait – *Emmelichthys nitidus*, jack mackerel – *Trachurus declivis*). There is evidence of distinct stocks east and west of Tasmania (Bulman *et al.,* 2008) and our analysis suggests that eastern stocks may be susceptible to changing transport patterns. For example, catches of jack mackerel off eastern Tasmania produced Australia's largest fishery in the late 1980s and its subsequent decline has been broadly attributed to environmental changes (Department of Environment and Heritage 2006).

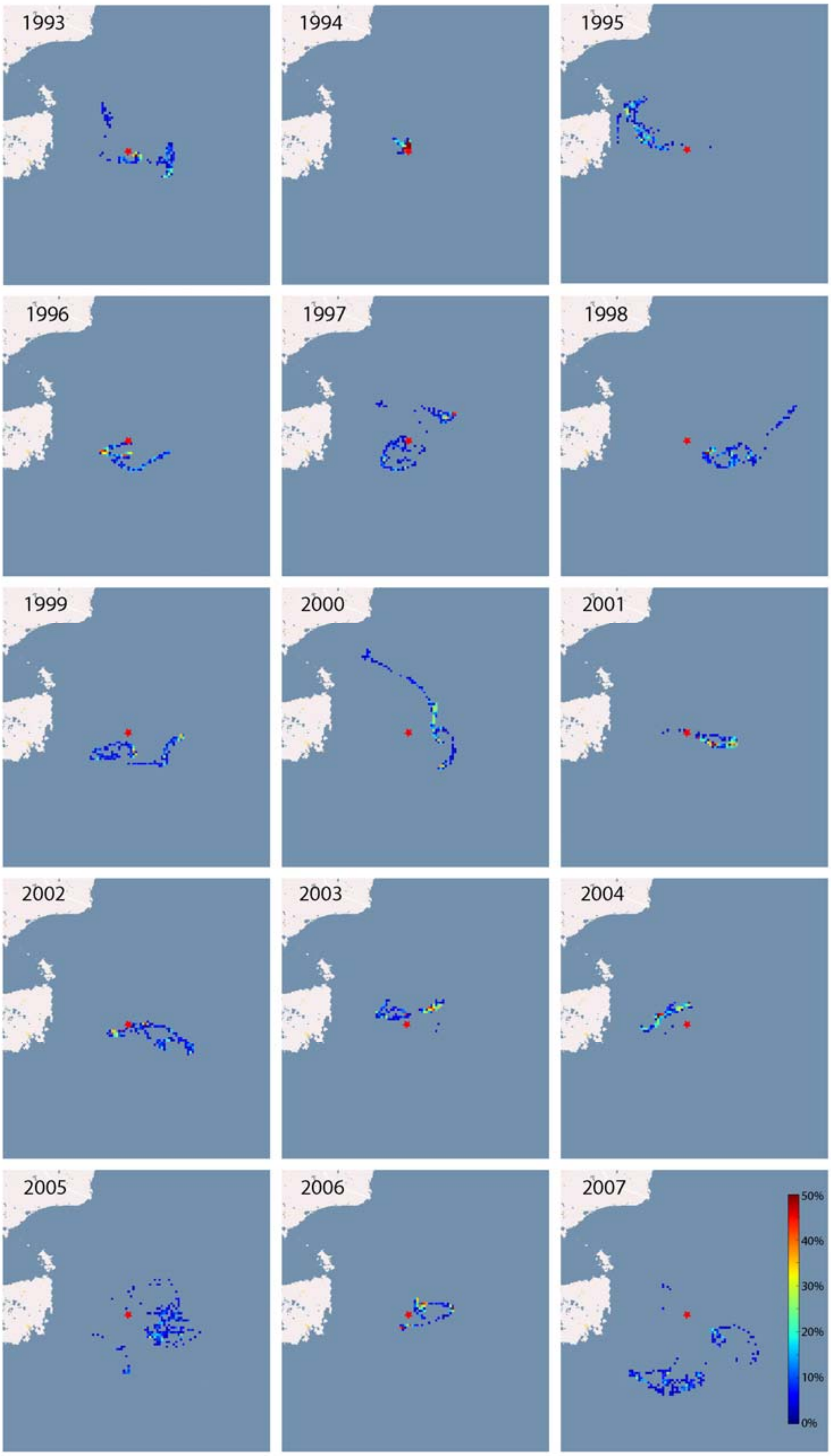


Figure 43. Distribution of larvae (percentage) 14 days after release from the centre of the East Tasmania box (marked by a red star). Larvae were released over the first week of April in each year at a rate of 25 per day. These results were generated using the online connectivity tool CONNIE (www.csiro.au/connie2/).

The key information required now to predict and mitigate for changes in larval transport patterns is an understanding of how climatic and oceanographic variability has influenced recruitment in the recent past. Searches for empirical correlations between recruitment/abundance indices and average environmental conditions (e.g. average water temperature, salinity, or chlorophyll concentration) have achieved only very limited success. However, explicit inclusion of larval transport will provide a direct estimate of larval exposure to local environmental conditions and the potential to identify clear causal relationships for individual species.

We suggest that the species case studies for SEAP consider direct analysis of larval pathways, using the recently upgraded CONNIE tool http://www.csiro.au/connie2/. Passive dispersal, as described in this section can be estimated, and there is a new "behaviours" functionality that allows the specification of:

- dispersal time;
- horizontal propulsion (e.g. swimming) in a constant direction or randomly;
- windage as a percentage of wind speed for surface slicks or floating objects (winds are identical to those used to drive the ocean model);
- vertical depth of particles at day and night (i.e. vertical migration).

Changes in dispersal pathways will be of interest for several of the species to be studied in the SEAP case studies project (Pecl and Ward), and these methods will be useful in providing data.

8 General Discussion

Changes in the environment have already been linked to changes in the distribution of a wide range of invertebrate and fish species in south-east Australia (e.g. Ling *et al.,* 2009; Pitt *et al.,* 2010; Last *et al.,* 2011). The mechanism behind these changes is less clear, although changes in temperature and current strength have been implicated (Ling *et al.,* 2009). To project future changes, (i) the relationship between biology and physical environment must be described, typically based on historical data, (ii) estimates of the future environmental variables made, and then (iii) the two combined for future estimates (e.g. Hartog *et al.,* 2011; Hobday 2010).

With regard to generating estimates of future environmental conditions, we compared model output from Bluelink and SAROM to historical observations. Bluelink model data varied in performance when compared to historical observations. At longer time scales (monthly) and larger space scales (1-5 degrees) the model data were more representative of historical observations. The sea surface temperature variable was the best performing variable.

We also demonstrated that the SAROM has predictive skill for real data sets and at finer spatial and temporal scales than was possible to evaluate with Bluelink. Both models can be forced by GCM data to represent future conditions at finer scales that can be provided from raw GCMs.

The decision to use data from each model cannot be generalized, however, and use without expert input is not recommended.

8.1 Environmental variables needed for SEAP studies

In a companion SEAP project (Pecl *et al.*, 2011) review of 22 key fishery species in the south-east identified the relative important of several primary and secondary variables for each species (**Table 6**).

Species or species group	Temperature	Salinity	Upwelling	Winds & currents	pH	Nutrients/ plankton	Freshwater flows	Biological
Abalone	***				***?			*** sea urchins & pathogens
Australian salmon	*			***	*?			
Black bream	*	*			*?		***	* yellowfin bream, HABs
Blue grenadier	**?			*	*?			
Blue swimmer crab	***	***			*?			
Commercial scallops	**?				***?			
Eastern king prawn	**	*?		**	*?		**	
Flatheads	*	*?		*	*?	*	*	* seagrass
Gummy shark	*?				*?		*?	
King George whiting	**			**	*?	**?		** seagrass
School prawn		*?			*?		***	
Small pelagics	***		***	***	*?	***		** jack mackerel: krill
Snapper	**			**	*?			
Southern bluefin tuna	**		***	*	*?			** small pelagics
Southern calamary	***	*			*?			* seagrass & macroalgae
Southern garfish					*?			*** seagrass
Southern rock lobster	***			**?	*?			*** sea urchins, macroalgae octopus, ERL
Spanner crabs	**			*	*?			
Striped marlin	**			**	*?			
Tunas, other	**			***	*?			
Western king prawns	***	*	***	*	*?			
Yellowtail kingfish	**			**	*?			

Table 6. Summary of key climate change drivers, current and predicted, outlined in descriptive analysis as part of the species risk assessments. Relative level of impact: high (***), medium (**), and low (*). '?' indicates a high level of uncertainty. (Source – reproduced from Pecl *et al.*, 2011, where it was listed as Table 1.7).

The majority of risk assessments identified temperature as a key variable (high 5 species, medium 10 species, and low 4 species), followed by winds and currents. Upwelling was only considered important for three species, but indirectly, upwelling may be important for production upon which a greater number of species depend. In fact nutrients and plankton were considered important in some additional cases. Winds and currents were considered important for 14 of the 22 species. All assessments noted that pH was a potential key variable, but with high uncertainty in all cases (20 low, 2 high). Experimental work on abalone and scallops to determine sensitivity to pH changes is underway, and SEAP should remain aware of these projects.

With the exception of nutrients and freshwater flows, all these variables can be derived from the existing physical models, as this project illustrated in **Section 7**. Freshwater flows were not evaluated, but data from these is available from a range of sources (Lough and Hobday, 2011). Thus, against the original plan for the understanding the exposure of the physical environment to climate change presented in Section 3, we can now evaluate the suitability of continuing the planned steps.

Project 1. Modelling of physical drivers in the region. Three steps were planned over three years to develop model capability for the south-east region

- Step 1: Regional Modelling (Year 1 – 2010/11). Two regional models will be further developed and validated against historical and data streams from the national Integrated Marine Observing System.
    - Completed as part of this project
- Step 2: Review (end of Step 1). A review of the "validated" regional models will be made so as to determine what models and extensions are required for climate change scenarios studies. This review will be in consultation with managers and the SEAP PMC.
    - Completed as part of this project
- Step3: Development of more refined oceanographic models over the next two years (2011/12, 2012/12). Where necessary, as a result of the review (Step 2), more refined models may be developed for areas identified as priorities.
    - Based on the findings in this project, we suggest that no further development of models is needed at this time. (See **Section 10**)

Project 2. Projecting future levels of influencing variables. Three steps were also planned to develop projections of the variables that might influence fish distribution, phenology and abundance, and thus ultimately fishery production.

- Step 1. Projecting future acidification levels for the south-east region (Year 1, this project). The rate and level of ocean acidification in the region will be predicted based on available Global Climate, Regional models and information. Seasonal signals are expected to be particularly important for pH, with significant differences between seasons. Through this process, additional ocean variables may be derived, including mixed layer depth, frontal density, and eddy characteristics.
    - Completed as part of this project.
- Step 2. Review of needs for other additional variables, such as productivity, zooplankton biomass (Year 2). The range of variables from the physical models may be insufficient for future understanding and changes in marine resources. The review will consider the extent to which additional variables can be generated.
    - This step should be informed by the biological studies (Pecl and Ward 2011), and at this time the clear need for additional variables that can be derived in time for use in SEAP has not been demonstrated. In the follow-up biological project, the species selected for detailed case studies are abalone, southern rock lobster, pink snapper and blue grenadier, and appropriate environmental variables have been identified from the suite described as part of this project.
- Step 3. Projections of other key influencing variables (Year 2 and 3). Based on the findings of the review in step 2, other important variables may be extracted or derived to understand the future biophysical changes in the SE region.
    - No need to proceed to this step at this time.

8.2 Downscaling from Global Climate Models

While the resolution of global climate models (GCMs) is improving, model scale is still considered coarse (~100-200 km) with regard to representation of the environmental and biological processes that many aquatic biologists are interested in (< 10 km), such as reef-specific recruitment or growth. In the south-east region, the GCM's are too coarse to be useful in specific species case studies. Thus, downscaling of climate models is considered necessary before projections are meaningful (Hobday and Lough 2011).

In this context, downscaling is the process of transforming information from coarse resolution GCMs to a finer regional spatial resolution. Downscaling is necessary where the mesoscale processes (in the ocean these operate at scales of < 100 km) are very sensitive to local climate, and the drivers of local climate variations, such as topography, are not captured at coarse scales. There are two broad categories of downscaling: dynamic (which simulates physical processes at fine scales) and statistical (which transforms coarse-scale climate projections to a finer scale based on observed relationships between the climate at the two spatial resolutions) (see Hobday and Lough 2011).

Dynamic downscaling uses regional climate models (RCMs) to translate the large-scale weather and ocean evolution from a GCM into a physically consistent evolution at higher resolution. Bluelink and SAROM can both be classified as RCMs. Marine RCMs represent the processes that are sub-grid scale in the GCMs, which makes them computationally expensive, as they solve multiple equations regarding the transfer of heat and energy in multiple depth layers at time steps as short as 30 minutes.

Statistical downscaling is based on empirical relationships between the regional climate (e.g. local sea surface temperature) and large-scale predictor variables (e.g. heat content in the tropical ocean) derived from the GCM. Advantages include computational simplicity and that large-scale predictors can be relatively robust in terms of the relationship with local variables. Different relationships occur in different regions, thus downscaling must be calculated anew for each study region. This approach assumes that the relationship between large scale processes and local variables is stationary over time (Tabor and Williams 2010). This assumption is unlikely to be met over longer time scales, and is a fundamental problem with statistical downscaling. The relationship between variables is projected to change in future, such that present combinations of climate variables cease to occur, and are replaced by novel combinations (Williams *et al.,* 2007).

8.3 Future projections of influencing variables

This project evaluated the ability of current models to produce data that could be useful in understanding the trends in biological production. At present, dynamical downscaling approaches using regional climate models for the Australian region are “experimental” only. For example, in the ocean, the Bluelink model evaluated in this study has been nested in the CSIRO Mk3.5 model and has a limited number of future years of data at a 10-km resolution (2063-2065), that are useful in projecting future habitat distribution of marine species (e.g. Hartog *et al.,* 2011). Mesoscale features are resolved, although there are ongoing challenges with evaluating the reliability of the downscaling. Tabor and Williams (2010) discuss some additional limitations with downscaling GCMs to finer resolution.

Secondary processing of GCM data (e.g. Whetton *et al.*, 2005; Tabor and Williams 2010) offers some options for biologists; however, the flexibility of data selection and limited number of variables available can be problematic (Hobday and Lough 2011). A set of GCM ensembles for the Australian region was released in 2007, and allow web-based access to a limited set of variables for a range of time periods and seasons (www.climatechangeinaustralia.gov.au). For marine users, only a single variable is available (sea surface temperature), although wind speed projections also cover the ocean region, and for freshwater biologists only proxies such as air temperature, solar radiation, potential evapotranspiration and rainfall are available. The spatial resolution in these products is again quite coarse (0.1°), and mesoscale features are not resolved (Hobday and Lough 2011).

Finer scale data are currently available via rescaled GCMs (statistical downscaling based on pattern matching in OzClim and OzClim for Oceans, www.csiro.au/ozclim/home.do; Whetton *et al.*, (2005)) again with a limited number of variables for aquatic users (marine: sea surface temperature, temperature at a depth of 250 m, and salinity; freshwater: rainfall, potential evapotranspiration, air temperature). While the resolution is improved, mesoscale features are still not resolved, although in the ocean, the major boundary currents on the east and west coasts of Australia can be detected (Hobday and Lough 2011). This data source may be the most useful for seeking general patterns of future change, and has been widely used to inform managers and policy makers in a range of terrestrial sectors. More recently, even finer scale downscaling for terrestrial variables (including rainfall, which is an important driver in some marine fish life cycles) has been completed using the OzClim data with a topographical correction at a scale of 1 km^2 (Harwood *et al.*, 2010 – in Hobday and Lough 2011).

The combination of available data described above, including that developed in this project using existing models again suggests that SEAP investment in a targeted model product is not warranted at this time. The development of these products is proceeding such that SEAP can take advantage of these efforts and direct investment to other critical areas (see **Section 10)**.

9 Benefits

The main beneficiaries of this research are the researchers and managers who are partners in the SEAP project. The environmental variables that have been validated and developed are now available for use in other SEAP projects. The results and data derived from this research project will be directly used in the SEAP species case studies project under Gretta Pecl and Tim Ward (commencing Oct 2011).

The companion regional programs (Northern/Tropical Program and Western Program) will also benefit from the data evaluation methods developed here, and we have offered to run extractions of data they may require, as illustrated for the south-east region here. Other marine researchers in the south-east may also be able to use the findings to help select appropriate physical variables for use in climate variability (historical data) and climate change (historical and future data).

The decision for future investment of physical ocean model development was to be based on the outcome of this project and thus guide SEAP strategic decisions. We suggest that this “planned” investment can be better used elsewhere in the SEAP plan. Such a recommendation is a clear benefit to the partners seeking to allocate limited resources.

Finally, fisheries stakeholders more widely have been exposed to the results of this research, in particular, the historical temperature analyses, at a number of meetings and conferences over the course of the project. It is hoped that these presentations have helped to put the seafood industry on the front foot with regard to understanding the climate changes that have been observed in their regions.

10 Further Development

This project has demonstrated the types of data that could be used in future biological and social studies of the south-east region. These data will likely need to be targeted and extracted for each specific use, as the volume of data is such that storing subsets separate to the “full” datasets is not sensible. Examples of the Bluelink data, or the completed extraction at daily or monthly time scale and the range of spatial scales and locations could be stored in repositories such as IMOS datacenter. Extraction of model data from any of the components of this project can now be performed for any other area of interest in the south-east. It may be necessary to consider how to archive these extractions, and discussion with IMOS between the draft and final report may provide some options for easy data access. Data from the SAROM model, while more limited in temporal coverage, can also be extracted and matched to biological project needs.

With regard to further model development, we do not recommend that SEAP directly fund further development of physical oceanographic models. This recommendation means that we should not fully invest in expanding the model domain for existing models where the coverage is for only part of the SEAP region. In the case of SAROM, this model could be important to some regional studies, and co-investment in the model extension to say, the Bonney Upwelling region, might be argued. This recommendation is from a SEAP perspective only, and does not foreclose other investors choosing to expand regional model coverage for other reasons. The reasons for this recommendation are

1. Availability of data from the range of existing models and the areas they cover seems suitable for now to cover the species we are considering, given biological uncertainty in response to most climate variables.
2. This investment in regional model development would lead to better historical data, but in the next 2-3 years would not lead to better future data - regional models must be nested in GCM's to realise future data at a scale that will be useful for most biological modeling at the level of detail we have advanced to under the SEAP umbrella. This nesting is possible and is ongoing as part of other research programs, and SEAP can take advantage of this if time permits. For example, there is a SE Tasmania model, which is already nested within the BlueLink model and includes tides and realistic forcing (and so is in a more advanced state than SAROM for climate studies, but covers a more limited area). While the area is fairly limited, it covers climate sensitive zone where the EAC and Leeuwin/Zeehan meet, and may be useful for some case studies.
3. The SEAP biology projects are yet to use the available data described in this project, so not convinced that "more/better" data is warranted until biology projects use the existing.
4. The cost and time of model development relative to SEAP program timelines and budget is high

This project has also helped to develop some of the computer codes for calculation of derived variables such as fronts, eddies and upwelling. Extraction of these variables for use in other SEAP studies is required, and is planned as part of the SEAP case study project to be led by Pecl and Ward. Extraction and testing of model output for the other two regional fisheries and climate change programs (northern and western) has been suggested by this project team, and should be considered if consistency is desirable.

11 Planned outcomes

Physical data that can be used in SEAP projects to determine the impact of climate change on selected fishery species has been extracted, processed, and validated where historical observations were available. This project has evaluated two "regional[2]" oceanographic models that could be used to support a greater understanding of the physical changes in the south-east region, and support biological studies evaluating the impact of climate change on fishery species. The data available from these models can now be more judiciously used in biological studies by subsequent SEAP projects. Decisions by the SEAP Program Management Committee (PMC) regarding investment in oceanographic modeling development can now be made, which will guide the future portfolio development. Estimates of future pH were provided, which will aid selection of appropriate experimental conditions for studies on taxa of interest. Similarly, changes in dispersal pathways were described, and will also be useful in future projects.

12 Conclusion

The focus of this project was largely on determining if modelled data could represent the past, as to determine the future impacts of climate change on marine fishes, historical environmental data is needed to determine the biological relationships. A range of environmental data is available from observation platforms, including satellites, ships and moorings. These data are not available for the future; instead models must be used to make projections of future conditions. In order to "trust" a model, a minimum condition is that the model output is representative of real

[2] BlueLink has global coverage with varying spatial resolution, but the Australian area is covered at 10 km resolution.

observations. This project evaluated two models that can produce "environmental data" at a scale considered useful for determining mechanistic biological patterns. In addition to assessing "primary" variables that are obtained from these models (e.g. temperature and salinity), we also completed development of a number of "derived" variables that may be useful as measures of fish habitat (e.g. frontal zones).

The objectives of this project were met and several additional elements delivered. Data for the south-east region were extracted from the Bluelink ocean model hindcasts for comparison with observations (**Objective 1)** and can be used to examine historical patterns of change. The Bluelink model variables were compared with observations (i.e. "do they sufficiently represent reality") (**Objective 2)**, which showed that SST was the best performing variable, and the currents were the poorest at the spatial and temporal scales considered. Development of the SAROM model was completed and comparison with in situ IMOS data showed the performance was very good in the regions considered **(Objective 3**)**.** Qualitative comparison of the regional models was completed **(Objective 4**) and we recommend that both models will be useful for a range of biological uses. Projections of future acidification levels were completed (**Objective 5**). We note that there are few studies on the impact of ocean acidification for the south-east region to date, and these have focused on benthic invertebrates. Implications for commercial fishes and invertebrates (e.g. rock lobster and abalone) in the south-east region are unknown, and there is a need for more experiments and field studies before impacts can be more specifically determined. We have provided some future estimates of pH levels, such that critical experiments using realistic values can proceed. Finally, methods to determine marine connectivity in the south-east for the recent past were detailed and patterns of change reported **(Objective 7**). These analyses showed a recent trend towards increasing southward transport off eastern Tasmania, consistent with the documented increase in the strength of the East Australian Current and the associated warming of waters off eastern Tasmania that is predicted to continue over the next half century.

12.1 Recommendations for SEAP

5. Data can be extracted from the existing set of physical ocean models that is suitable for retrospective analysis of biological patterns.
6. There is no single best model for all purposes; careful selection and validation should be part of each use of model-based environmental variables. Each model

does have strengths and will be appropriate for different uses. We suggest that case studies of fishery species in the south-east discuss their modeling needs with physical oceanographers.

7. Development and improvement of the existing models is not a roadblock to further fishery adaptation planning.
8. The suite of available physical data is sufficient to support the next phase of biological case studies.

13 References

Anthony KRN, Kline DI, Diaz-Pulido G, Dove S, Hoegh-Guldberg O (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences* **105**, 17442-17446.

Bruce B., Bradford R., Griffin D., Gardner C., Young J. (2000) A synthesis of existing data on larval rock lobster distribution in southern Australia. Fisheries Research and Development Corporation. CSIRO Marine Research, Hobart.

Bruce B., Griffin D., Bradford R. (2007) Larval transport and recruitment processes of southern rock lobster. Fisheries Research and Development Corporation. CSIRO Marine Research, Hobart.

Bulman C., Condie S., Findlay J., Ward B., Young J. (2008) Management zones from small pelagic fish species stock structure in southern Australian waters. Fisheries Research and Development Corporation and Australian Fisheries Management Authority. FRDC 2006/076. CSIRO Marine Research, Hobart.

Byrne M, Ho M, Selvakumaraswamy P, Ngyuen HD, Dworjanyn SA, Davis AR (2009) Temperature, but not pH, compromises sea urchin fertilization and early development under near-future climate change scenarios. *Proceedings of the Royal Society of London, Series B: Biological Sciences* **276**, 1883–1888.

Cai W., Shi G., Cowan T., Bi D., Ribbe, J. (2005) The response of the Southern Annular Mode, the East Australian Current and the southern mid-latitude circulation to global warming, Geophysical Research Letters 32: L23706, doi:10.1029/2005GL024701.

Condie S.A., Waring J., Mansbridge J.V., Cahill M.L. (2005). Marine connectivity patterns around the Australian continent. Environmental Modelling and Software 20, 1149-1157.

Condie SA, Dunn JR (2006) Seasonal characteristics of the surface mixed layer in the Australasian region: implications for primary production regimes and biogeography. *Marine and Freshwater Research* **57**, 569-590.

Condie SA, Mansbridge JV, Cahill ML (2011) Contrasting local retention and cross-shore transports of the East Australian Current and the Leeuwin Current and their relative influences on the life histories of small pelagic fishes. *Deep-Sea Research II* **58**, 606-616.

Connell SD, Russell BD (2010) The direct effects of increasing CO2 and temperature on non-calcifying organisms: increasing the potential for phase shifts in kelp forests. *Proceedings of the Royal Society of London, Series B: Biological Sciences* **277**, 1409-1415.

De'ath G, Lough JM, Fabricius KE (2009) Declining Coral Calcification on the Great Barrier Reef. *Science* **323**, 116-119.

Department of Environment and Heritage (2006) Assessment of the ecological sustainability of management arrangements for the Small Pelagic Fishery. Commonwealth of Australia, Canberra. http://www.environment.gov.au/coasts/fisheries/commonwealth/pelagics/pubs/small-pelagics-report.pdf

Figueira WF, Booth DJ (2010) Increasing ocean temperatures allow tropical fishes to survive overwinter in temperate waters. *Global Change Biology* **16**, 506-516 doi: 10.1111/j.1365-2486.2009.01934.x.

Gillanders, B. M., Elsson, T. S., Halliday, I. A., Jenkins, G. P., Robins, J. B. and Valesini, F. J. (2011). *Marine and Freshwater Research*.

Hartog J, Hobday AJ, Matear R, Feng M (2011) Habitat overlap of southern bluefin tuna and yellowfin tuna in the east coast longline fishery - implications for present and future spatial management. *Deep Sea Research Part II* **58**, 746-752.

Herron RC, Leming TD, Li J (1989) Satellite-detected fronts and butterfly fish aggregations in the northeastern Gulf of Mexico. *Continental Shelf Research* **9**, 569-589.

Hobday AJ (2010) Ensemble analysis of the future distribution of large pelagic fishes in Australia. *Progress in Oceanography* **86**, 291-301.

Hobday AJ, Lough J (2011) Projected climate change in Australian aquatic environments. *Marine and Freshwater Research*.

Hobday AJ, Poloczanska ES (2008) '12. Marine Fisheries and Aquaculture. In Stokes, C (ed). An overview of climate change adaptation in the Australian agricultural sector - impacts, options and priorities. February 2008. http://www.csiro.au/resources/AgricultureAdaptationReport2008.html.'

Hobday, A. J. and K. Hartmann (2006). Near real-time spatial management based on habitat predictions for a longline bycatch species. Fisheries Management & Ecology 13(6): 365-380.

Hobday, A. J., N. Flint, T. Stone and J. S. Gunn (2009). Electronic tagging data supporting flexible spatial management in an Australian longline fishery. Tagging and Tracking of Marine Animals with Electronic Devices II. Reviews: Methods and Technologies in Fish Biology and Fisheries. J. Nielsen, J. R. Sibert, A. J. Hobday*et al.,* Netherlands, Springer. 9: 381-403.

Hobday, A. J., T. A. Okey, E. S. Poloczanska, T. J. Kunz and A. J. Richardson (2007). Impacts of climate change on Australian marine life, CSIRO Marine and Atmospheric Research. Report to the Australian Greenhouse Office, Canberra, Australia. Available at http://www.greenhouse.gov.au/impacts/publications/marinelife.html.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A. & Hatziolos, M.E. (2007) Coral reefs under rapid climate change and ocean acidification. *Science*, **318**, 1737-1742.

Holbrook, N. L. and N. L. Bindoff (1997). Interannual and Decadal Temperature Variability in the Southwest Pacific Ocean between 1955 and 1988. *Journal of Climate* **10**: 1035-1049.

Howard, W.R., Havenhand, J., Parker, L., Raftos, D., Ross, P., Williamson, J. & Matear, R. (2009) Ocean acidification. A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009 (http://www.oceanclimatechange.org.au). NCCARF Publication 05/09 (ed. by E.S. Poloczanska, A.J. Hobday & A.J. Richardson). National Climate Change Adaptation Research Facility and CSIRO Climate Adaptation Flagship, Brisbane.

IPCC (2007) 'Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.'

Jordan, A., Pullen G., Marshall J., Williams H. (1995) Temporal and spatial patterns of spawning in jack mackerel, Trachurus declivis (Pisces: Carangidae), during

1988-91 in east Tasmanian waters. Marine and Freshwater Research 46, 831-842.

Last PR, White WT, Gledhill DC, Hobday AJ, Brown R, Edgar GJ, Pecl GT (2011) Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global Ecology and Biogeography* **20**, 58-72 DOI: 10.1111/j.1466-8238.2010.00575.x.

Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely RA, Foster P, Friedlingstein P, Gurney K, Houghton RA, House JI, Huntingford C, Levy PE, Lomas MR, Majkut J, Metzl N, Ometto JP, Peters GP, Prentice IC, Randerson JT, Running SW, Sarmiento JL, Schuster U, Sitch S, Takahashi T, Viovy N, van der Werf GR, Woodward FI (2009) Trends in the sources and sinks of carbon dioxide. *Nature geoscience* **2**, 831-836.

Ling SD (2008) Range expansion of a habitat-modifying species leads to loss of taxonomic diversity: a new and impoverished reef state. *Oecologia* **156**, 883-894 DOI 10.1007/s00442-008-1043-9.

Ling SD, Johnson CR, Ridgway K, Hobday AJ, Haddon M (2009) Climate driven range extension of a sea urchin: inferring future trends by analysis of recent population dynamics. *Global Change Biology* **15**, 719 - 731.

Lough JM (2008) Shifting climate zones for Australia's tropical marine ecosystems. *Geophysical Research Letters* **35**, L14708.

Lough JM, Hobday AJ (2011) Observed climate change in Australian marine and freshwater environments. *Marine and Freshwater Research*.

Luthi D, Floch ML, Bereiter B, Blunier T, Barnola J-M, Siegenthaler U, Raynaud D, Jouzel J, Fischer H, Kawamura K, Stocker TF (2008) High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* **435**, 379-382 doi:10.1038/nature06949.

McNeil BI, Matear RJ (2008) Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO_2. *Proceedings of the National Academy of Sciences* **105**, 18860-18864.

Middleton, J. F., 2006: The Coastal trapped Wave paddle as an open boundary condition. Ocean Modelling, 12: 224-236.

Middleton, J.F., and K. P. Black, 1994: The Low Frequency Circulation in and around Bass Strait: a numerical study. Cont. Shelf Res., 14: 1495-1521.

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747-756 doi:10.1038/nature08823.

Moy AD, Howard WR, Bray SG, Trull TW (2009) Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature geoscience*, DOI: 10.1038/NGEO460.

Munday PL, Dixson DL, Donelson JM, Jones GP, Pratchett MS, Devitsina GV, Doving KB (2009) Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences* **www.pnas.org_cgi_doi_10.1073_pnas.0809996106**, 1-8.

Nieblas AE, Sloyan BM, Hobday AJ, Coleman R, Richardson AJ (2009) Variability of biological production in low wind-forced regional upwelling systems: a case study off southeastern Australia. *Limnology and Oceanography* **54**, 1548–1558.

Nunes, R.A., Lennon, G.W. (1986). Physical property distributions and seasonal trends in Spencer Gulf, South Australia: an inverse estuary. Australian Journal of Marine and Freshwater Research 37, 39–53.

Oke P.R., Brassington G.B., Griffin D.A., Schiller A., (2008) The Bluelink Ocean Data Assimilation System (BODAS). Ocean Modelling 20, 46-70, doi:10.1016/j.ocemod.2007.11.002.

Oke, P. R. and A. Schiller (2007). Impact of Argo, SST, and altimeter data on an eddy-resolving ocean reanalysis. Geophysical Research Letters 34: L19601, doi:10.1029/2007GL031549.

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.F., Yamanaka, Y. & Yool, A. (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437**, 681-686.

Parker, L.M., Ross, P.M. & O'Connor, W.A. (2009) The effect of ocean acidification and temperature on the fertilization and embryonic development of the Sydney rock oyster Saccostrea glomerata (Gould 1850). *Global Change Biology*, **15**, 2123-2136.

Pearce A, Feng M (2007) Observations of warming on the Western Australian continental shelf. *Marine and Freshwater Research* **58**, 914-920.

Pecl G., Frusher S., Gardner C., Haward M., Hobday A., Jennings S., Nursey-Bray M., Punt A., Revill H., van Putten I. (2009) The east coast Tasmanian rock lobster fishery – vulnerability to climate change impacts and adaptation response options. Report to the Department of Climate Change, Australia.

Pecl GT, Ward T, Doubleday Z, Clarke S, Day J, Dixon C, Frusher S, Gibbs P, Hobday A, Hutchinson N, Jennings S, Jones K, Li X, Spooner D, and Stoklosa R (2011). Risk Assessment of Impacts of Climate Change for Key Marine Species in South Eastern Australia. Part 1: Fisheries and Aquaculture Risk Assessment. Fisheries Research and Development Corporation, Project 2009/070.

Pitt NR, Poloczanska ES, Hobday AJ (2010) Climate-driven range changes in Tasmanian intertidal fauna. *Marine and Freshwater Research* **61**, 963–970.

Poloczanska ES, Babcock RC, Butler A, Hobday AJ, Hoegh-Guldberg O, Kunz TJ, Matear R, Milton D, Okey TA, Richardson AJ (2007) Climate Change And Australian Marine Life. *Oceanography and Marine Biology Annual Review* **45**, 409-480.

Poloczanska, E.S., A.J. Hobday and A.J. Richardson (Eds.) (2009*). A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009*, NCCARF Publication 05/09, ISBN 978-1-921609-03-9. Available at www.oceanclimatechange.org.au

Pörtner HO, Farrell AP (2008) Physiology and Climate Change. *Science* **322**, 690-692.

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE, Somerville RCJ (2007) Recent Climate Observations Compared to Projections. *Science* **316**, 709. [DOI: 10.1126/science.1136843].

Ridgway K., Hill K. (2009) The East Australian Current. In A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009 (Eds. E.S. Poloczanska, A.J. Hobday and A.J. Richardson), NCCARF Publication 05/09, ISBN 978-1-921609-03-9.

Ridgway K.R. (2007) Long-term trend and decadal variability of the southward penetration of the East Australian current. Geophysical Research Letters 34: L13612, doi:10.1029/2007GL030393, 2007.GRL.

Ridgway K.R., Coleman R.C., Bailey R.J. Sutton P. (2008) Decadal variability of East Australian Current transport inferred from repeated high-density XBT transects, a CTD survey and satellite altimetry. Journal of Geophysical Research 113: C08039,doi:10.1029/2007JC004664.

Schiller, A., P. R. Oke, G. B. Brassington, M. Entel, R. Fiedler, D. A. Griffin and J. V. Mansbridge (2008). Eddy-resolving ocean circulation in the Asian–Australian region inferred from an ocean reanalysis effort. Progress in Oceanography 76: 334-365.

Sheppard Brennand H, Soars N, Dworjanyn SA, Davis AR, Byrne M (2010) Impact of Ocean Warming and Ocean Acidification on Larval Development and Calcification in the Sea Urchin Tripneustes gratilla. *PLoS ONE* **5**, e11372. doi:10.1371/journal.pone.0011372.

Tabor K, Williams JW (2010) Globally downscaled climate projections for assessing the conservation impacts of climate change. *Ecological Applications* **20**, 554-565.

Teixeira, C and J F Middleton, 2010. The wind-forced circulation in Spencer Gulf: process studies. (in preparation).

Whetton PH, McInnes KL, Jones RN, Hennessy KJ, Suppiah R, Page CM, Bathols J, Durack PJ (2005) 'Australian climate change projections for impact assessment and policy application: A review. CSIRO Marine and Atmospheric Research Paper 001. December 2005.'

Williams JW, Jackson ST, Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences* **104**, 5738-5742.

Zainuddin M, Kiyofujia H, Saitohb K, Saitoh S-I (2006) Using multi-sensor satellite remote sensing and catch data to detect ocean hot spots for albacore (Thunnus alalunga) in the northwestern North Pacific. *Deep-Sea Research II* **53**, 419-431.

14 Appendices

14.1 Appendix 1: Intellectual property

Not relevant to this project. No intellectual property separate to the funding agreement is claimed.

14.2 Appendix 2: Staff engaged on the project

CSIRO staff

- Alistair Hobday
- Jason Hartog
- Richard Matear
- Scott Condie
- James Mansbridge
- Ming Feng

SARDI staff

- John Middleton
- John Luick
- Carlos Teixeira

14.3 Appendix 3: Spatial summary of all metrics for comparing model and observation time series.

The metrics used to evaluate the "goodness" of the relationship between observed and modeled ocean data for each scale included three scale independent measures (correlation coefficient, slope of the regression line, and skew) and three metrics that are scale dependent (sum of squares (SSQ), sum of squares eliminating the outer 10% of values (SSQ_{outer}) and the mean difference between the two data sets. The three scale-independent metrics allow comparison between each location and spatial scale. Arbitrary cut-off values based on inspection of the range of values for each metric were used to score each relationship as satisfactory/unsatisfactory (1 or 0). The sum of the metric scores could thus range from 0 (all unsatisfactory) to 3 (all 3 metrics were satisfactory). The cutoffs for satisfactory scores were correlation coefficient close to 1 (i.e. $R^2 > 0.8$); slope close to 1 (i.e. $0.6 < slope < 1.4$); and skew close to zero (i.e. $-0.2 < skew < 0.2$).

The results provide a quick visual summary of the quality of the modeled data relative to the observations for the south-east region. For example, for daily SST, the relationships between observed and modeled data were good using all metrics (scores of 2 and 3) for most of the 50 m, 200 m and EEZ contour (**Figure A**). Results for the daily T_{200} (**Figure B)**, salinity (**Figure C)**, u-currents (**Figure D)** and v-currents (**Figure E)** at a daily scale follow. The monthly SST (**Figure F),** T_{200} (**Figure G)**, salinity (**Figure H)**, u-currents (**Figure I)** and v-currents (**Figure J)** are also provided.

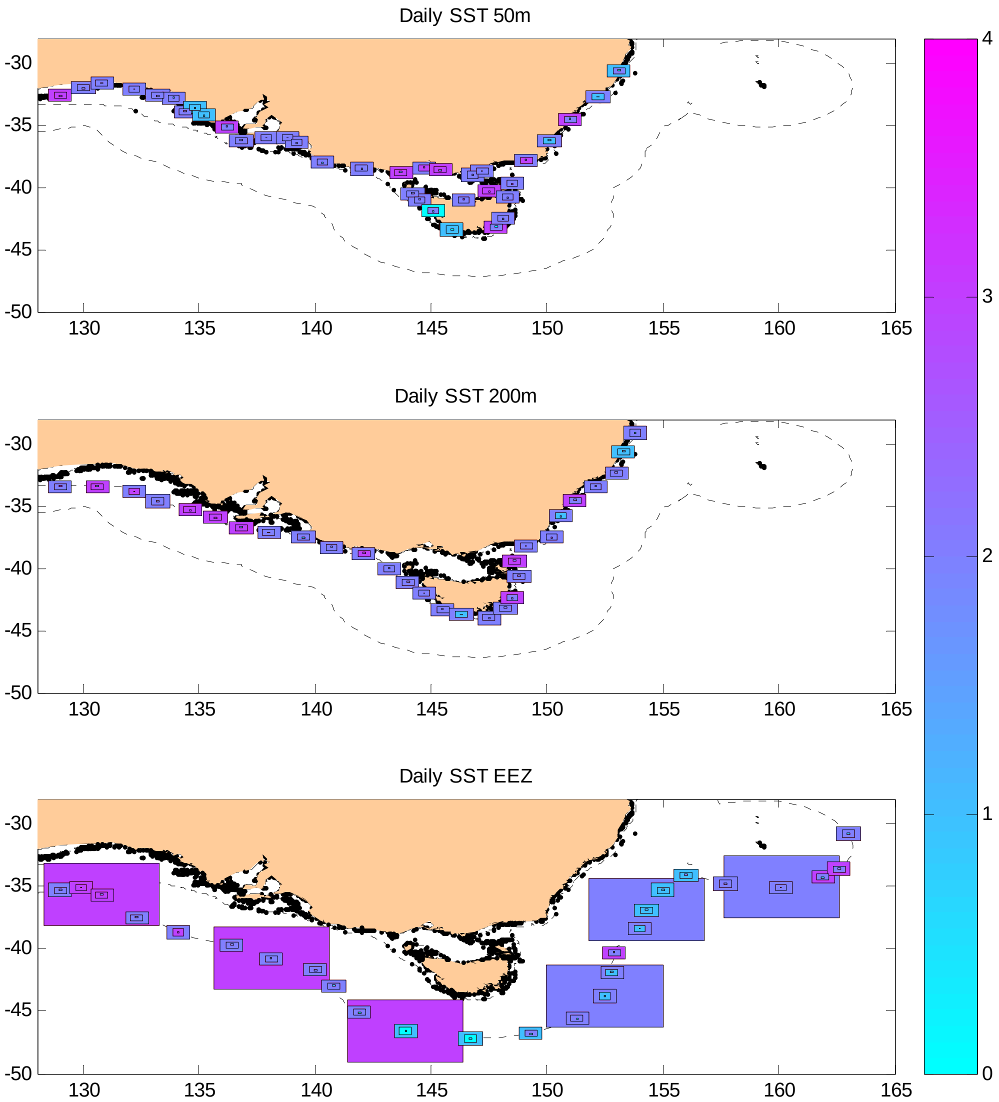


Figure A. Number of metrics that were "satisfactory" for daily SST observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

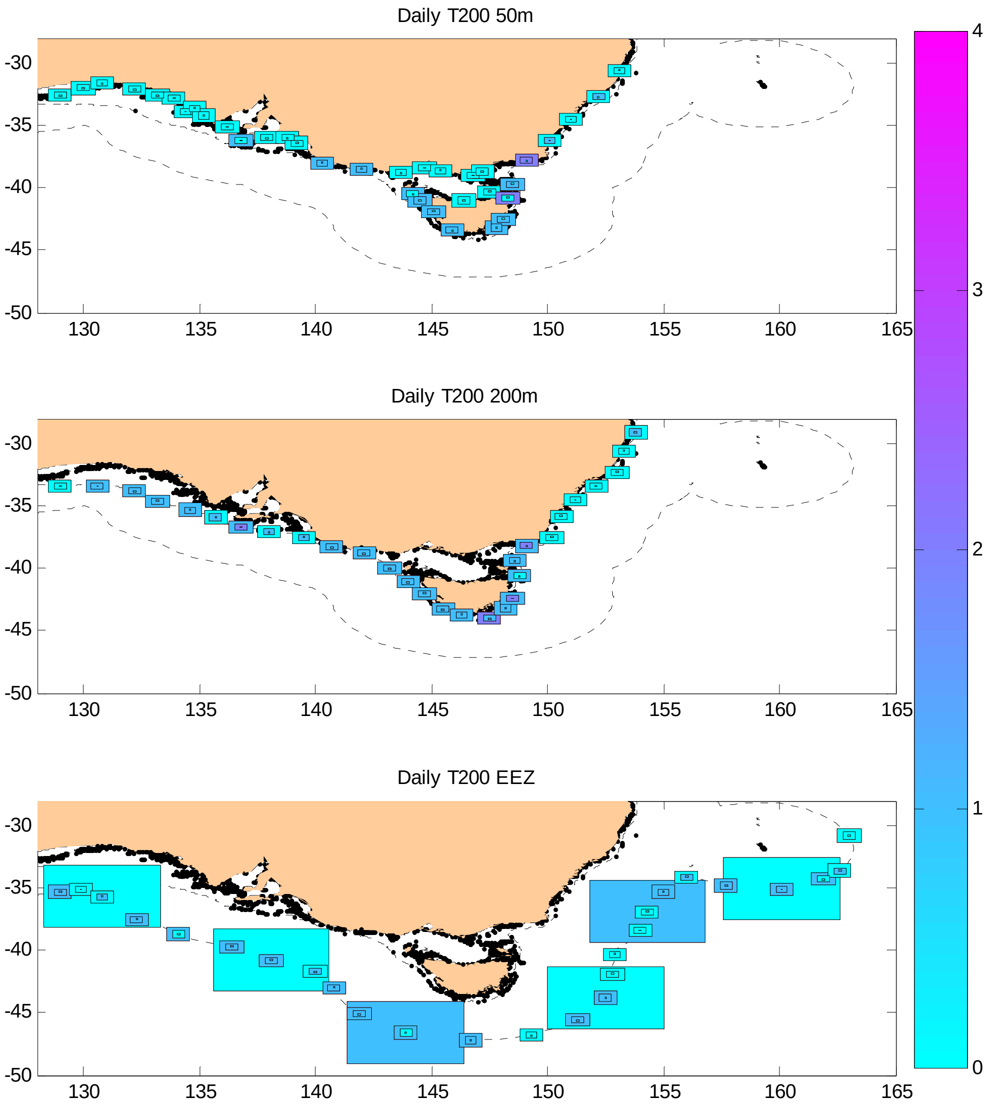


Figure B. Number of metrics that were “satisfactory” for daily T_{200} observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

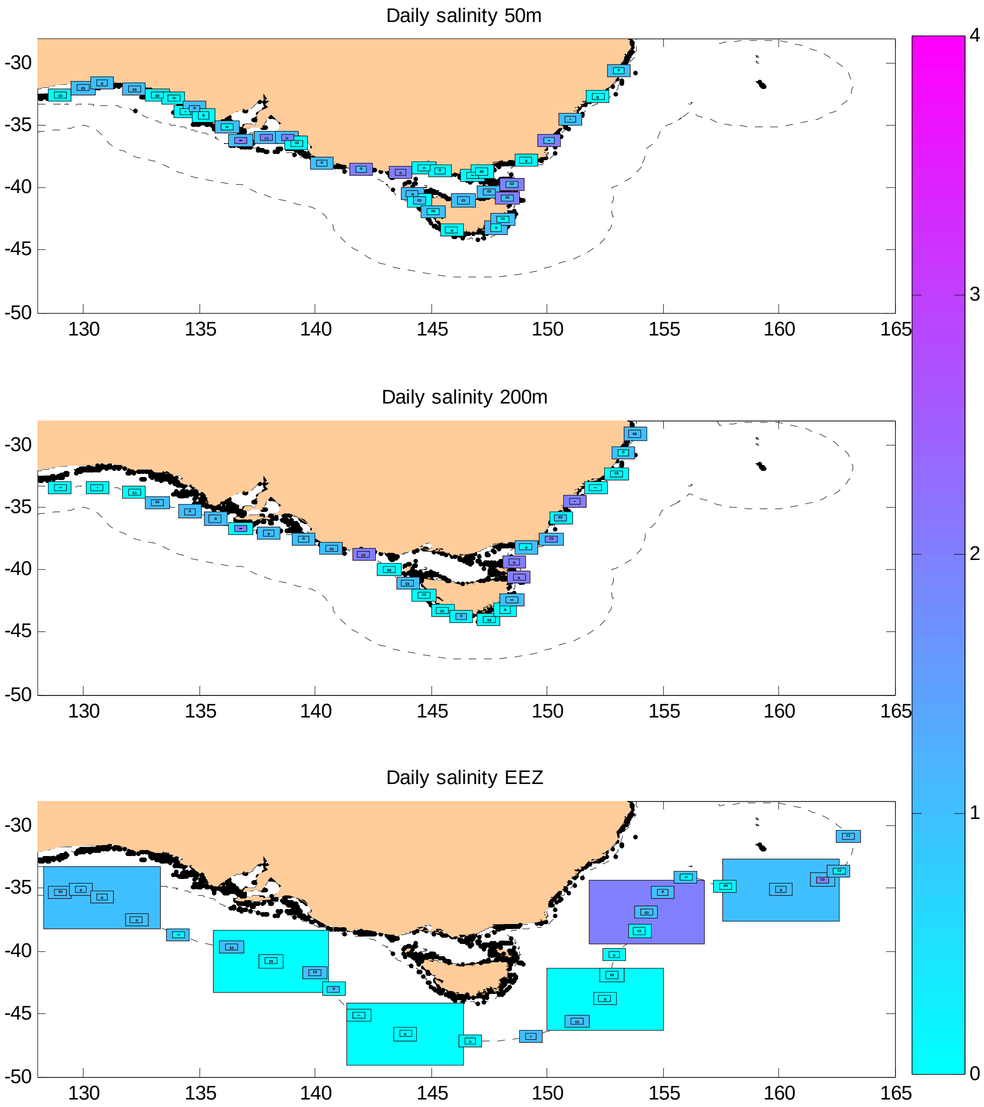


Figure C. Number of metrics that were "satisfactory" for daily salinity observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

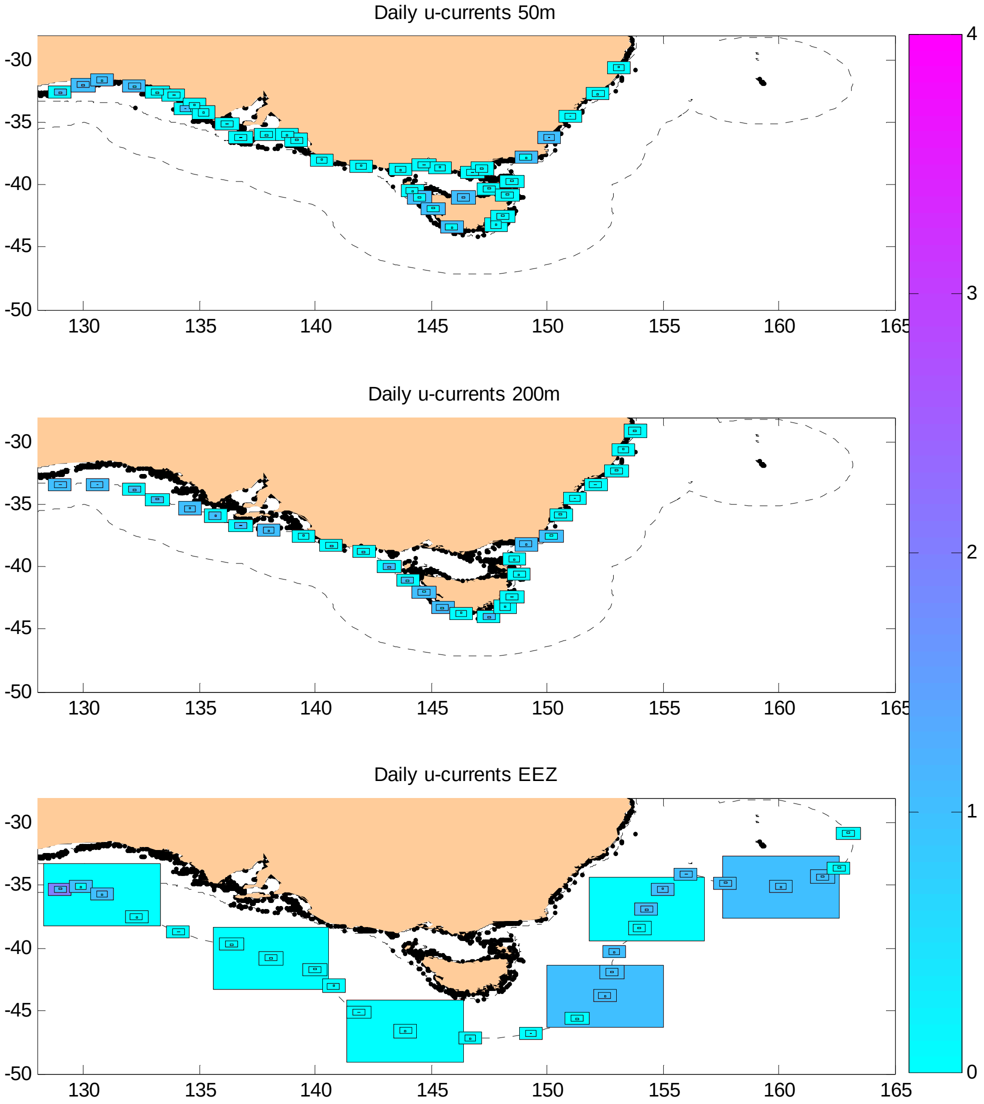


Figure D. Number of metrics that were “satisfactory” for daily u-current observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

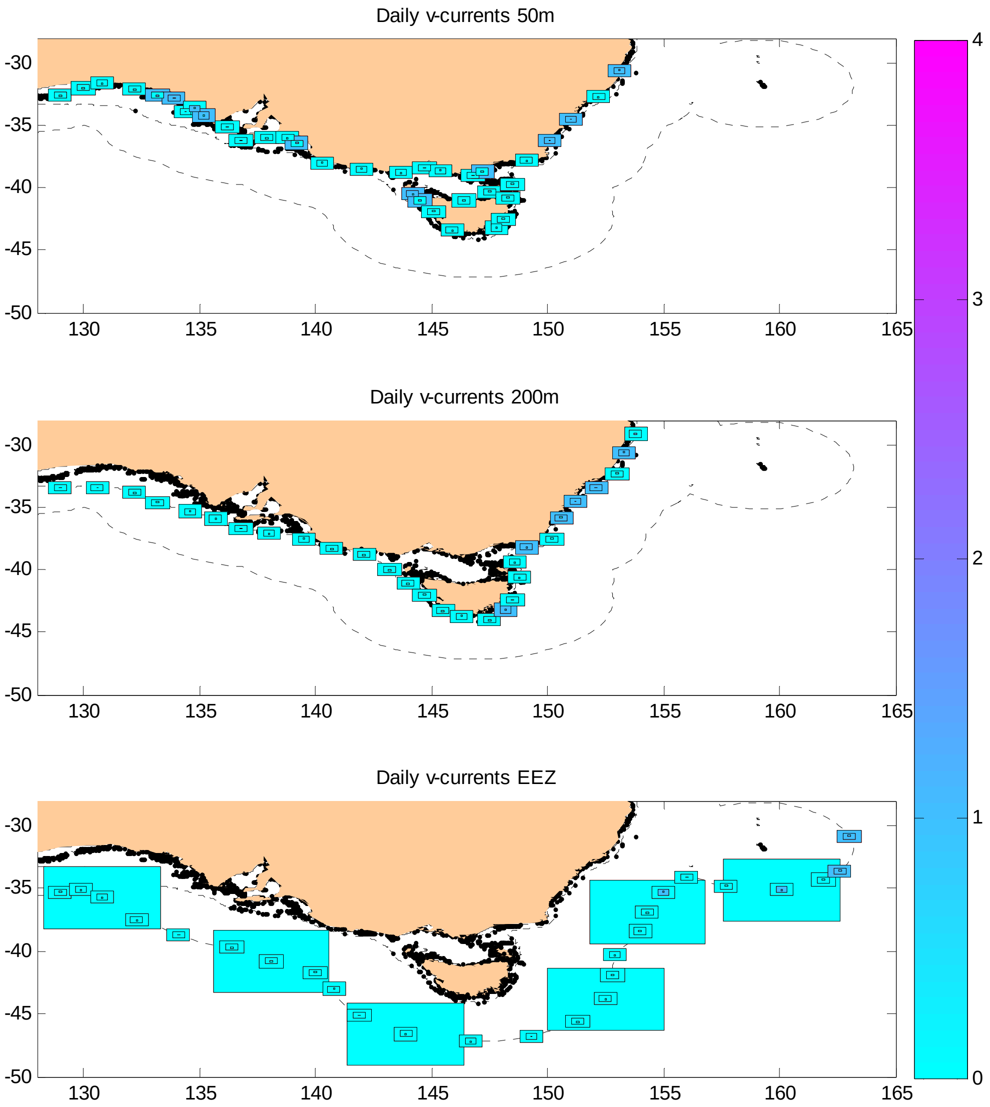


Figure E. Number of metrics that were "satisfactory" for daily v-current observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

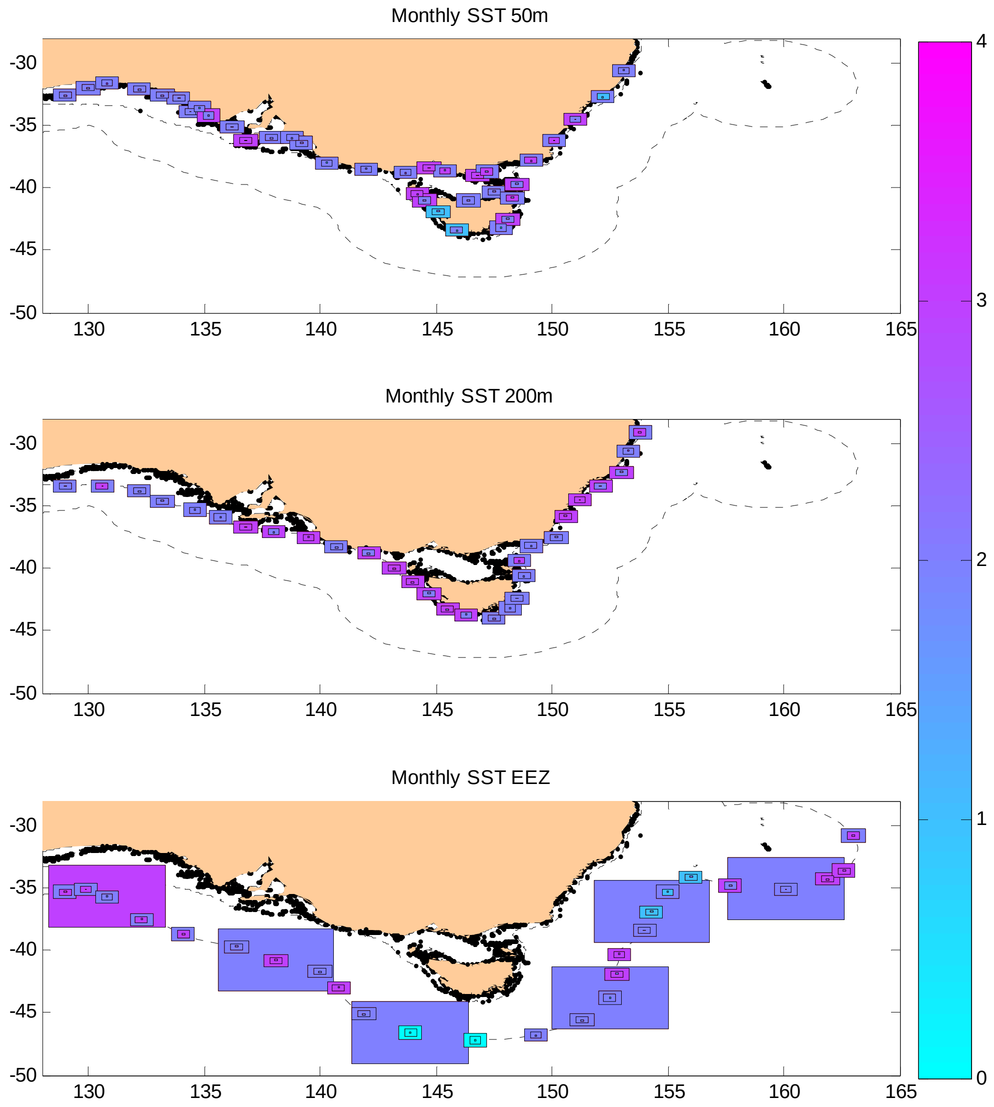


Figure F. Number of metrics that were “satisfactory” for monthly SST observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

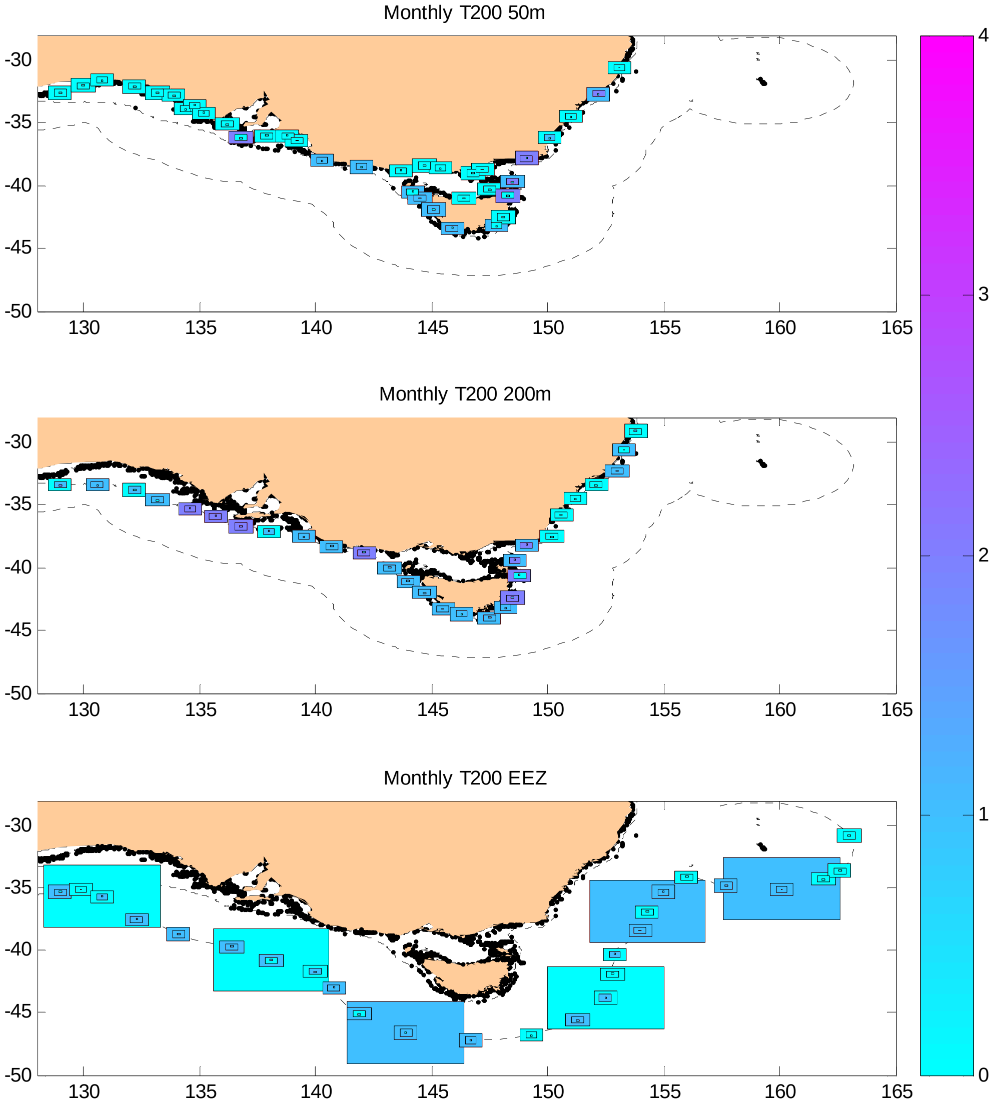


Figure G. Number of metrics that were "satisfactory" for monthly T_{200} observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

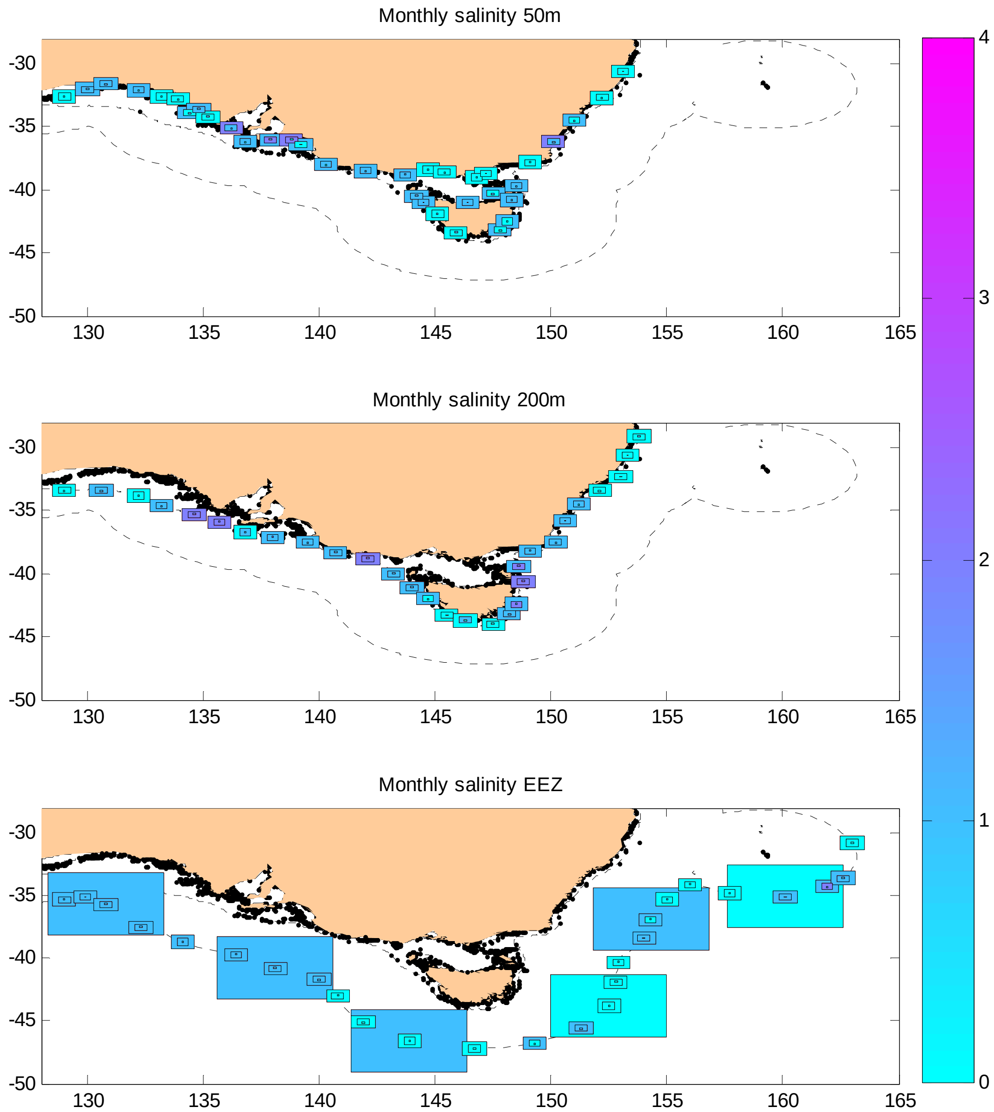


Figure I. Number of metrics that were "satisfactory" for monthly salinity observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

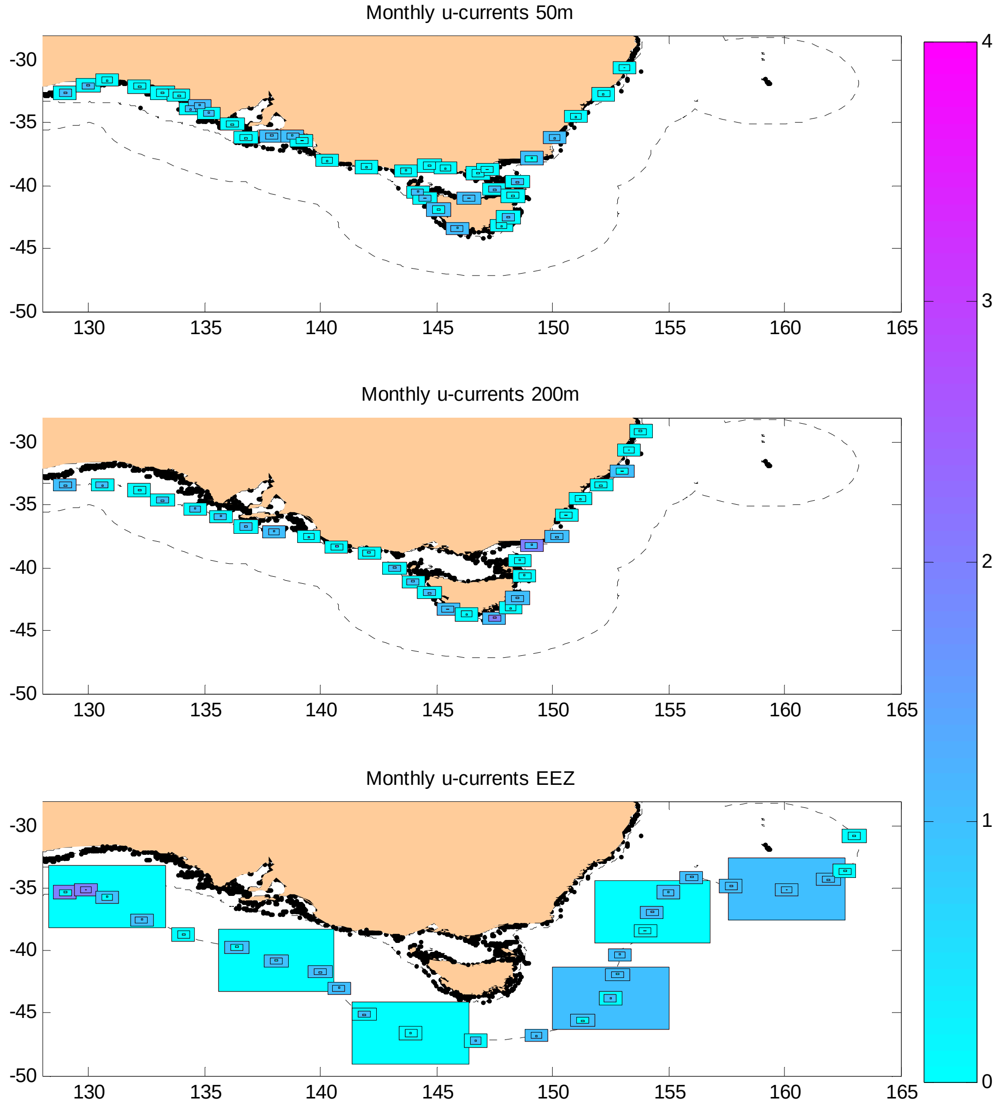


Figure J. Number of metrics that were "satisfactory" for monthly u-currents observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

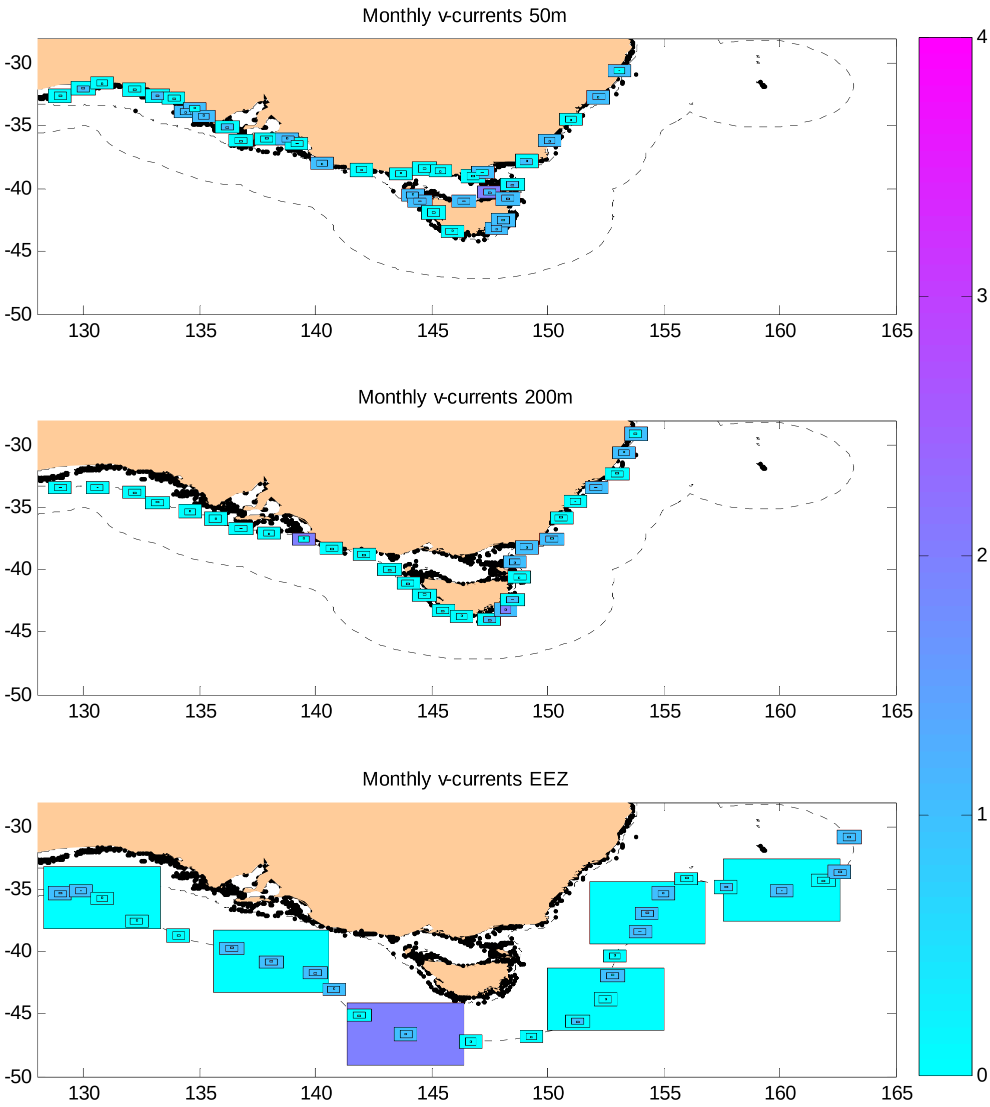


Figure K. Number of metrics that were "satisfactory" for monthly v-currents observation-model relationships in each box (at a scale of 0.1, 0.5, and 1) along the EEZ (200 nm), 200 m contour, and 50 meter contour. The largest scale, 5 degrees, was considered for the EEZ only.

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