IMAS INSTITUTE FOR MARINE AND ANTARCTIC STUDIES

UTAS

From ocean to coast: Past and future marine climate changes off southeast Australia

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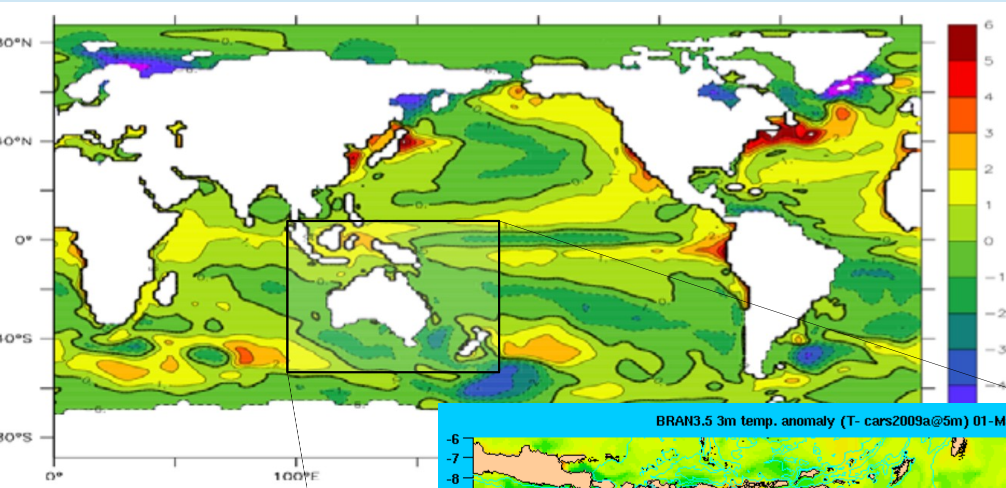
translating**nature**into**knowledge**

From Ocean to Coast

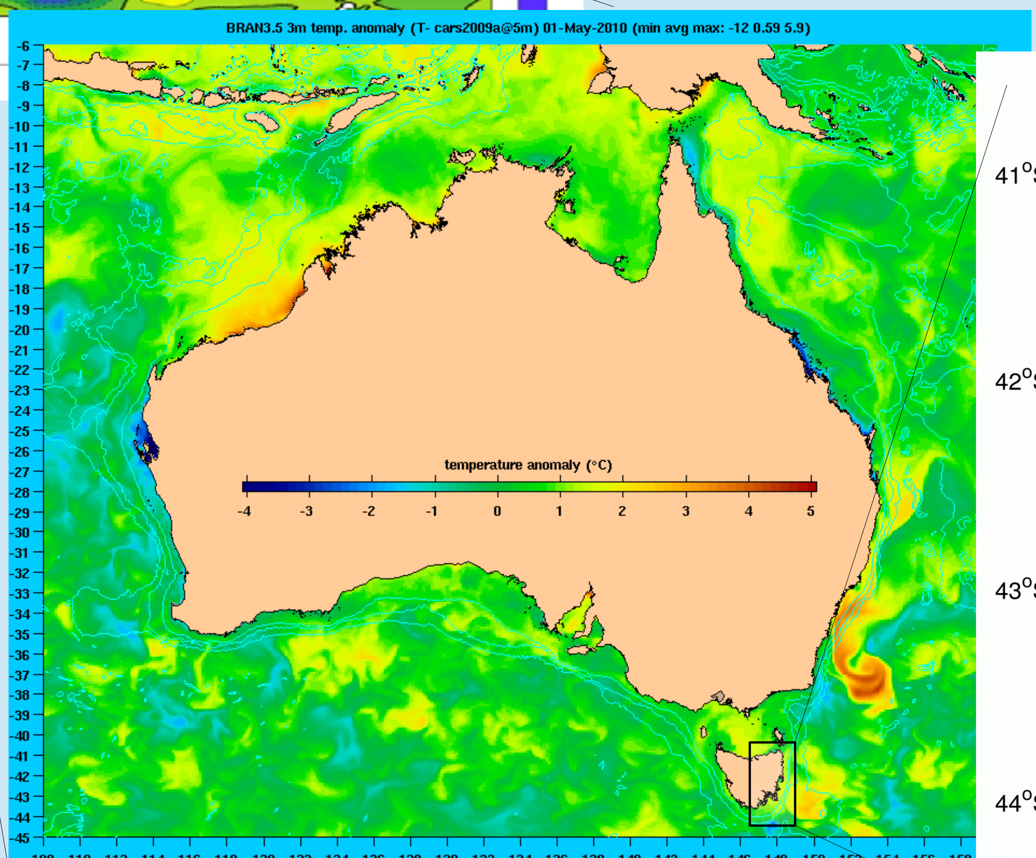
"From ocean to coast": Modeling the ocean across a range of scales from **global** through to **regional** and **shelf / coastal**

Global



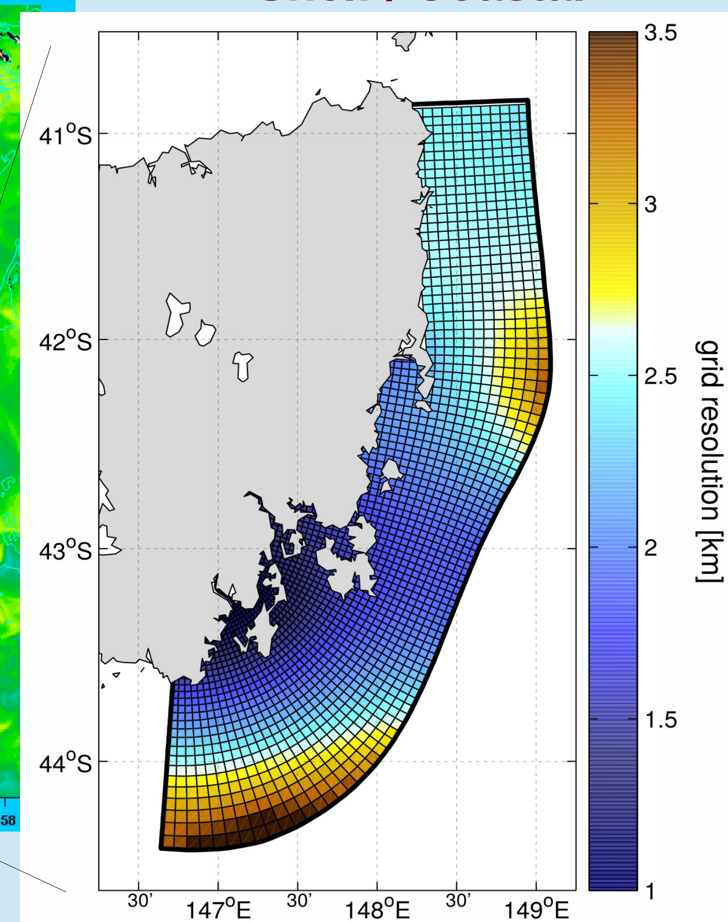
[CAWCR]

Regional



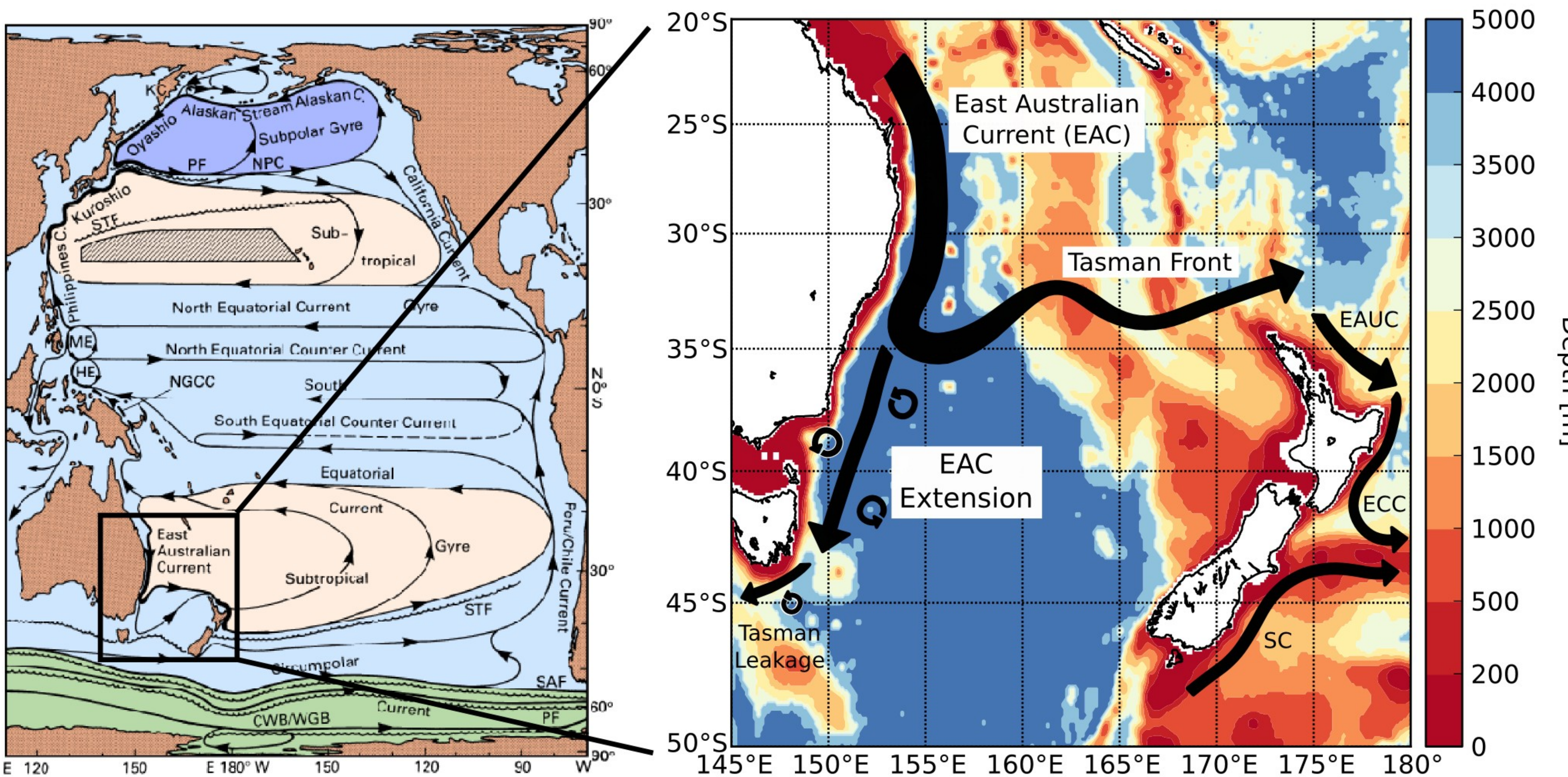
[CSIRO (Peter Oke)]

Shelf / Coastal



Southeastern Australia

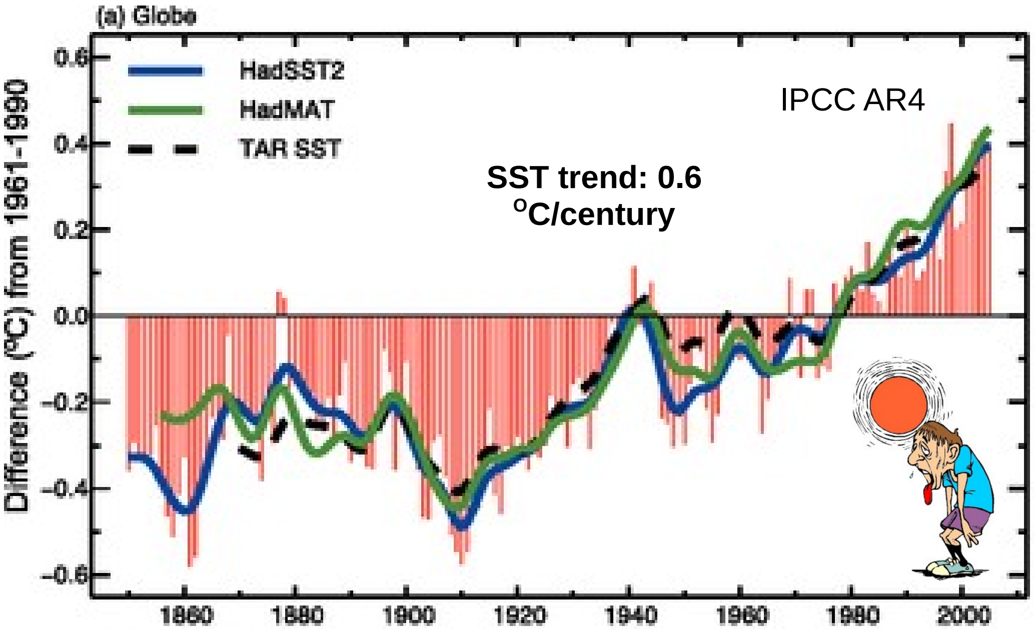
- **Regional oceanography of the Tasman Sea**
- western boundary current, eddy-rich region, complex bathymetry



[Tomczak and Godfrey, 1994]

Overview

- Global marine climate is **warming**
- The SW Pacific (Tasman Sea) is a **hotspot of change**
- Impacts on **marine ecology** are already being felt
- **Historical marine climate** in Eastern Tasmania is poorly understood
- Large-scale models and reanalysis are not designed for near-shore studies
- Alternatives
  - Statistical downscaling
  - Dynamical downscaling



Chavez et al., 2011

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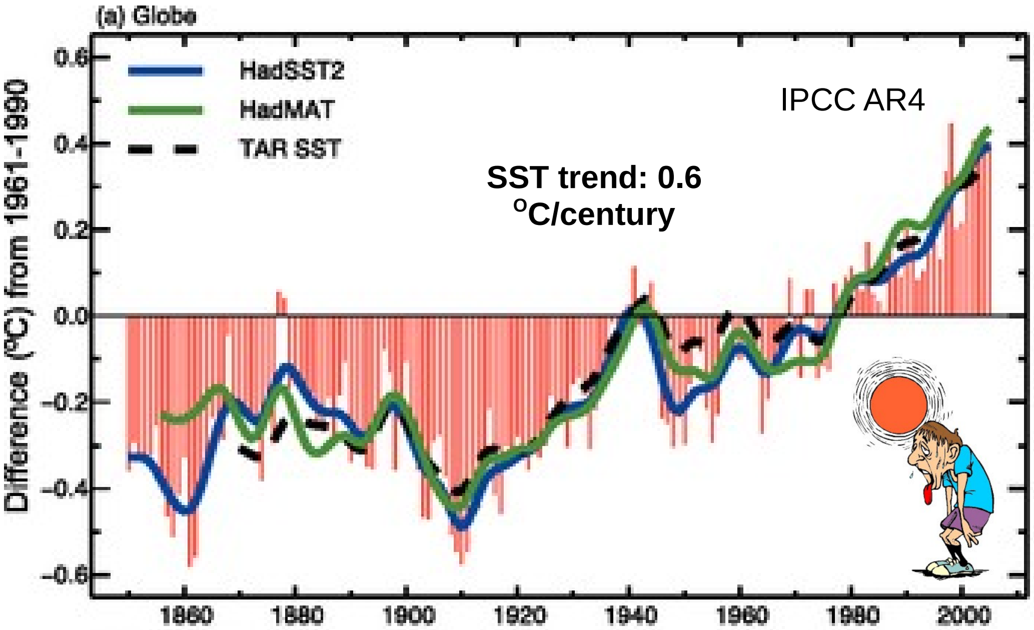

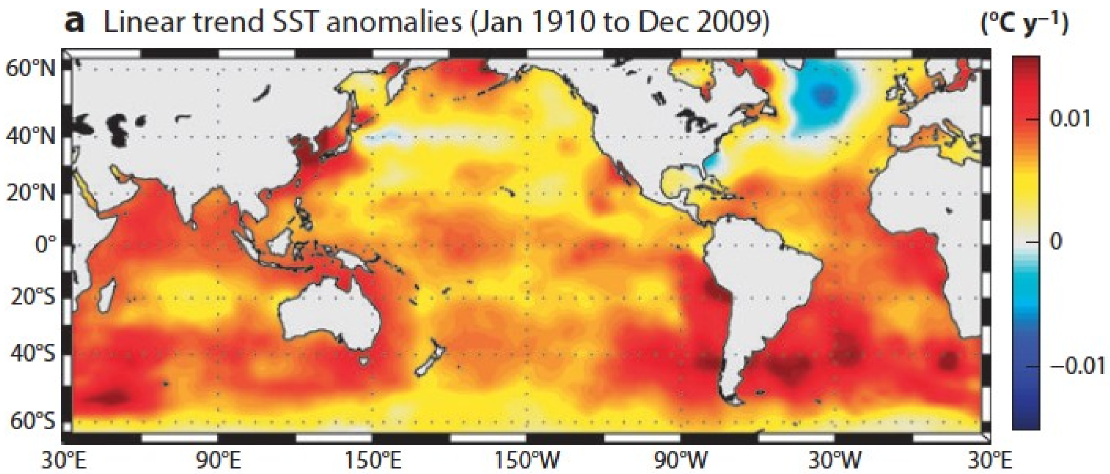

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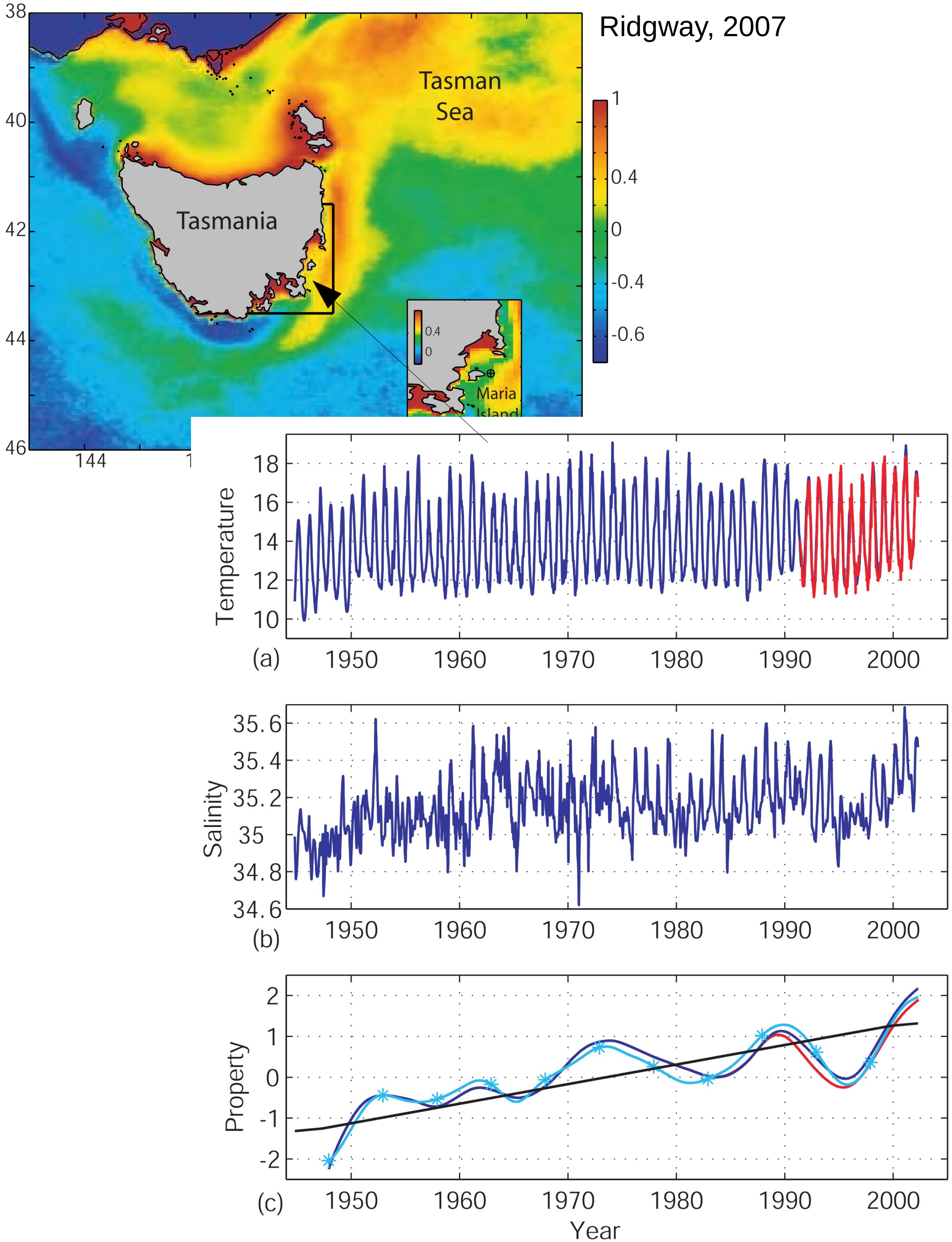

Ridgway, 2007

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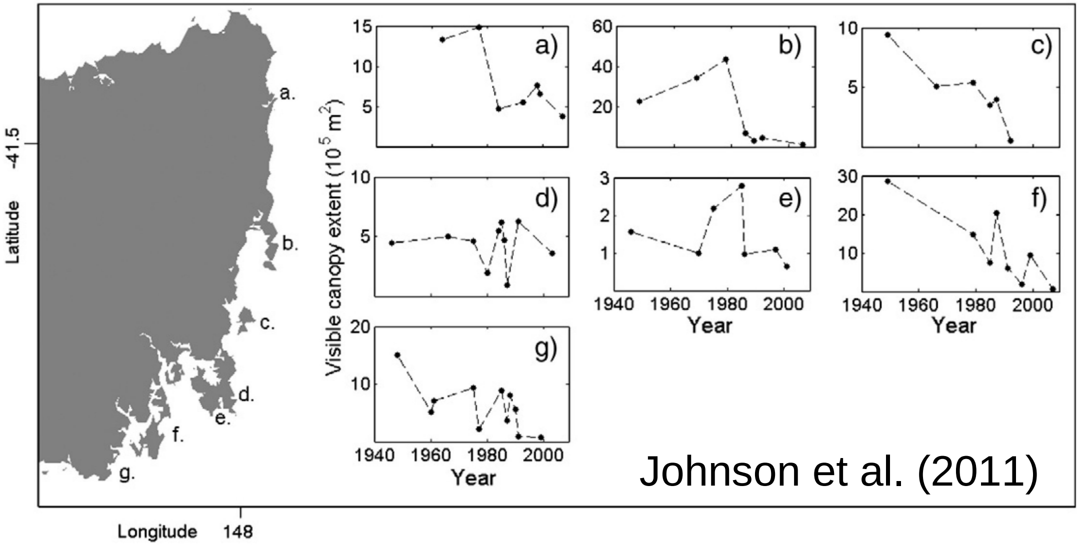
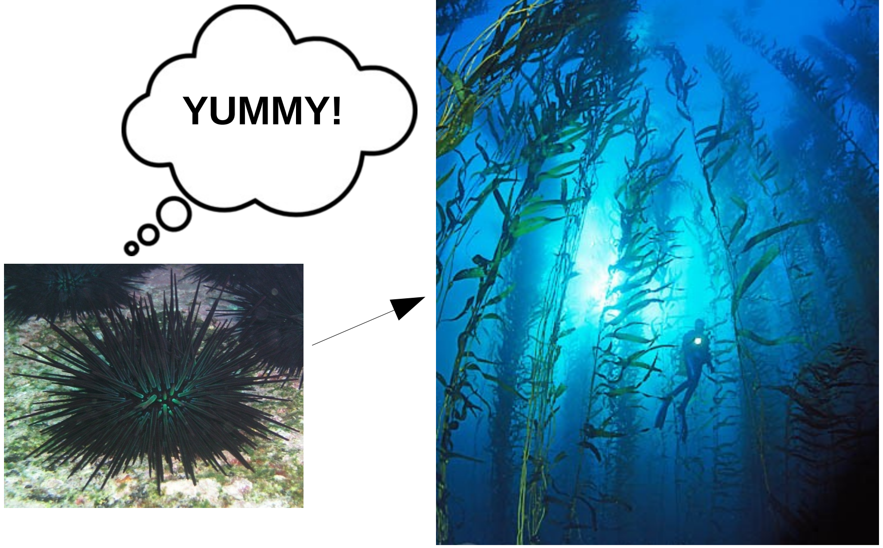
Change in visible surface kelp canopy (Macrocystis pyrifera)

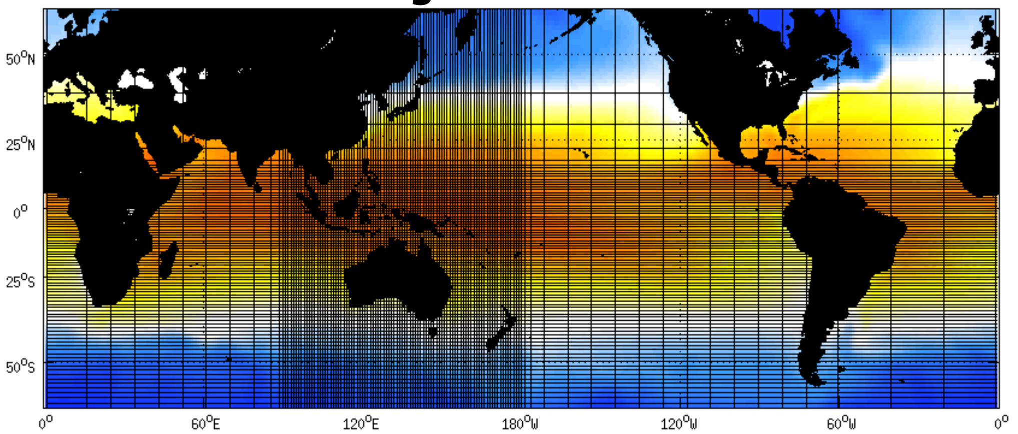




Ocean Modeling

- **Eddy-resolving dynamical downscaling in Australia region performed by Chamberlain et al. (2010)**:
- Two ocean model runs using Ocean Forecasting Australia Model (**OFAM**; 70^{O}S–70^{O}N domain, 1/10^{O} resolution around Australasia)

OFAM grid with mean SST



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- **Climate change scenario** provided by CSIRO Mk3.5 GCM with an A1B emissions scenario

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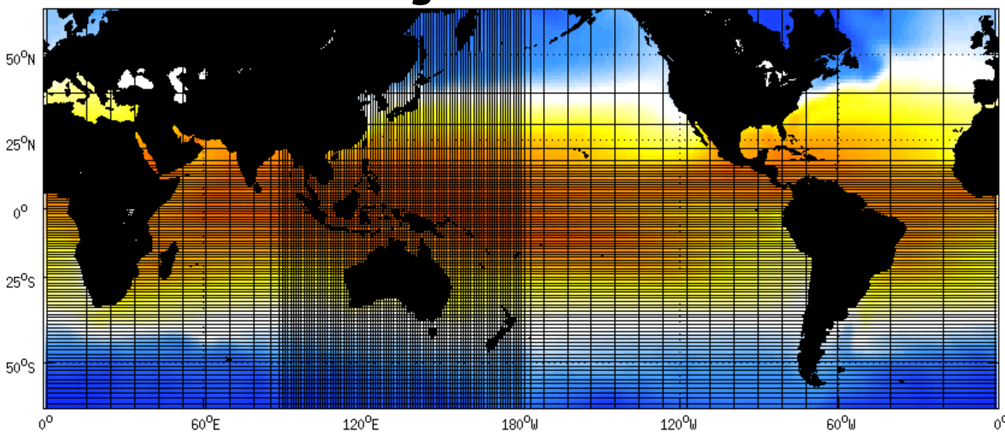
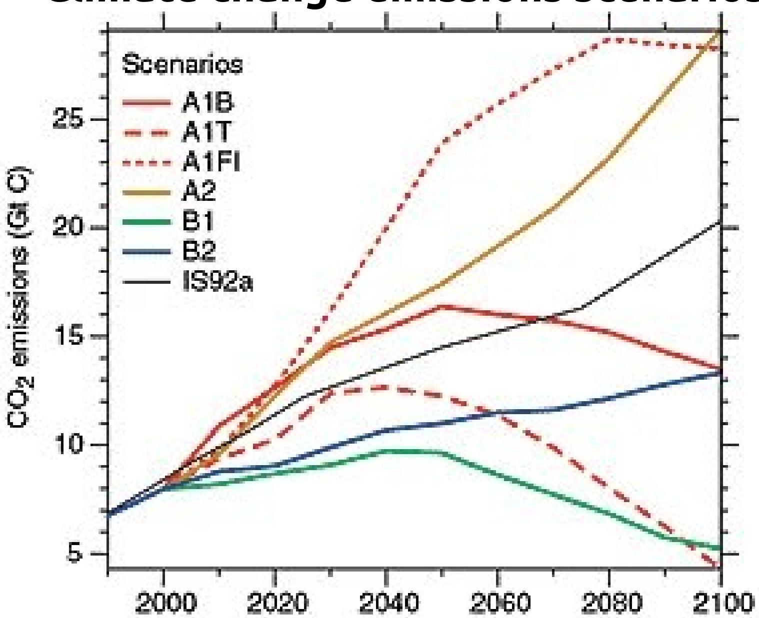


Climate change emissions scenarios



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- Models represent well general circulation and temperature distribution around Australia, including seasonality [Sun et al, 2012; Matear et al., 2013]

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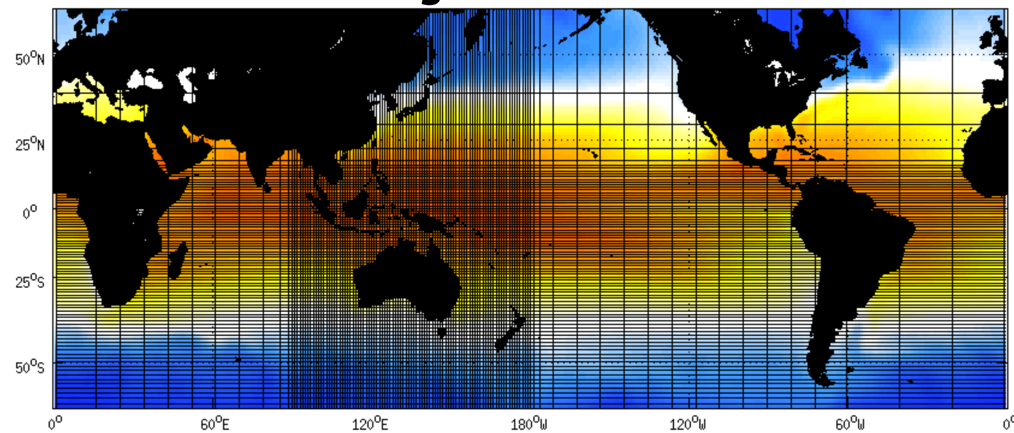

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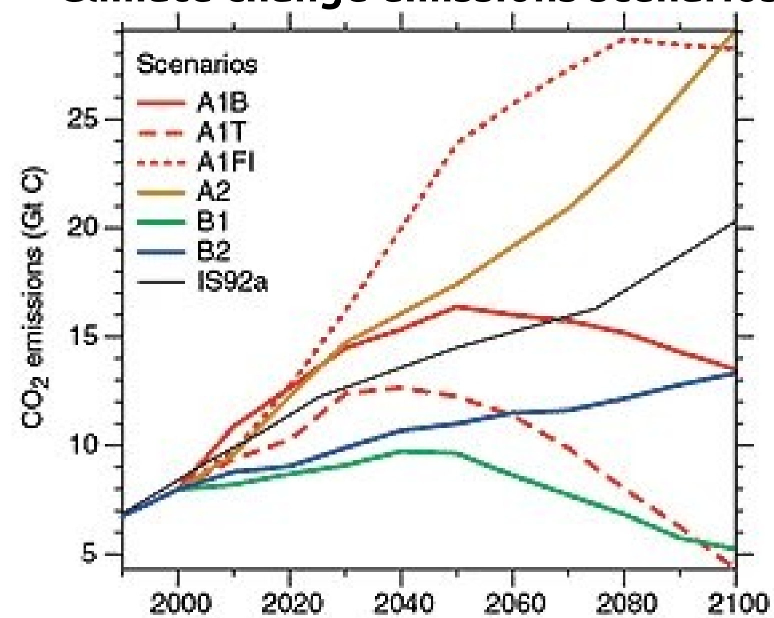
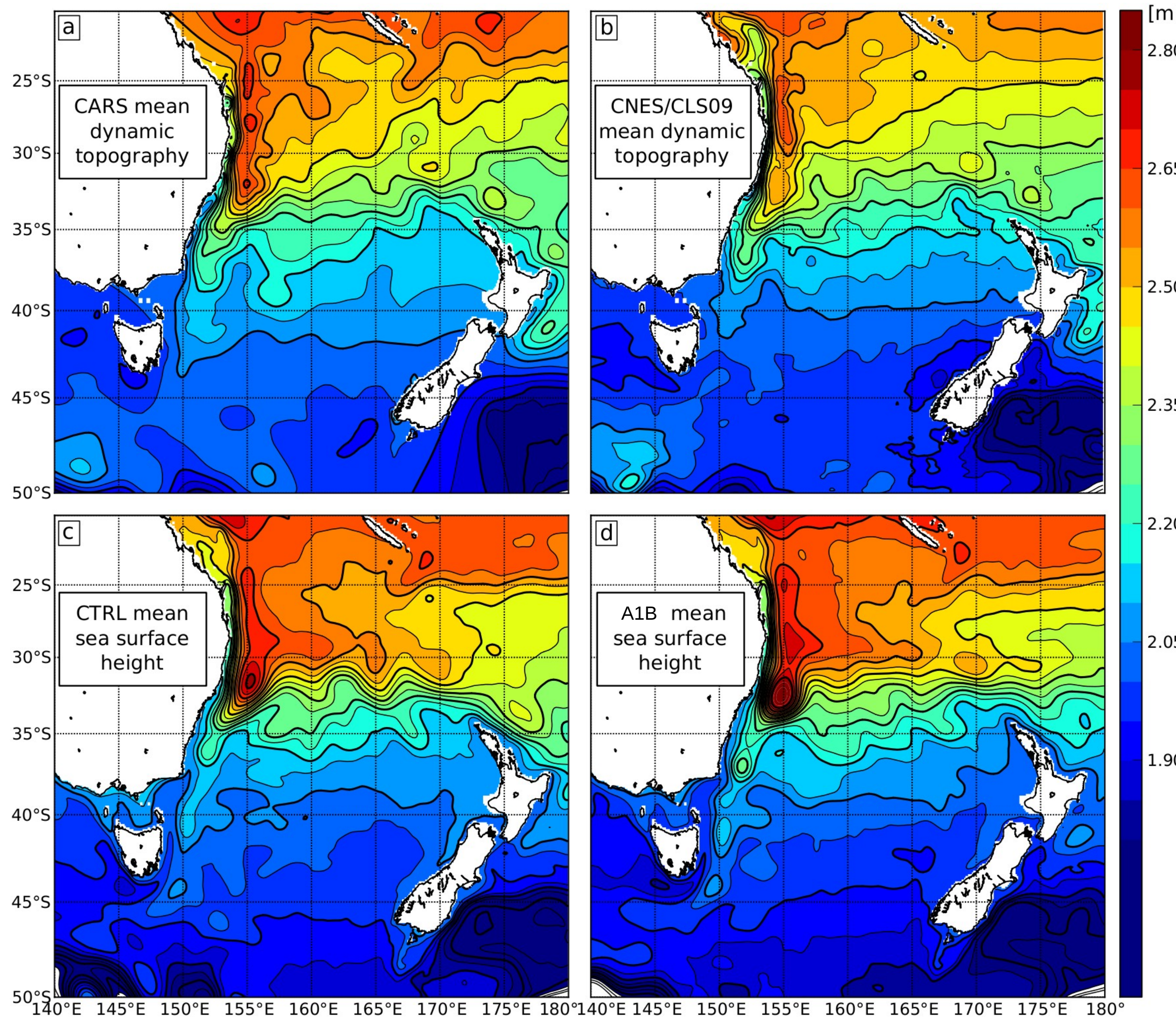


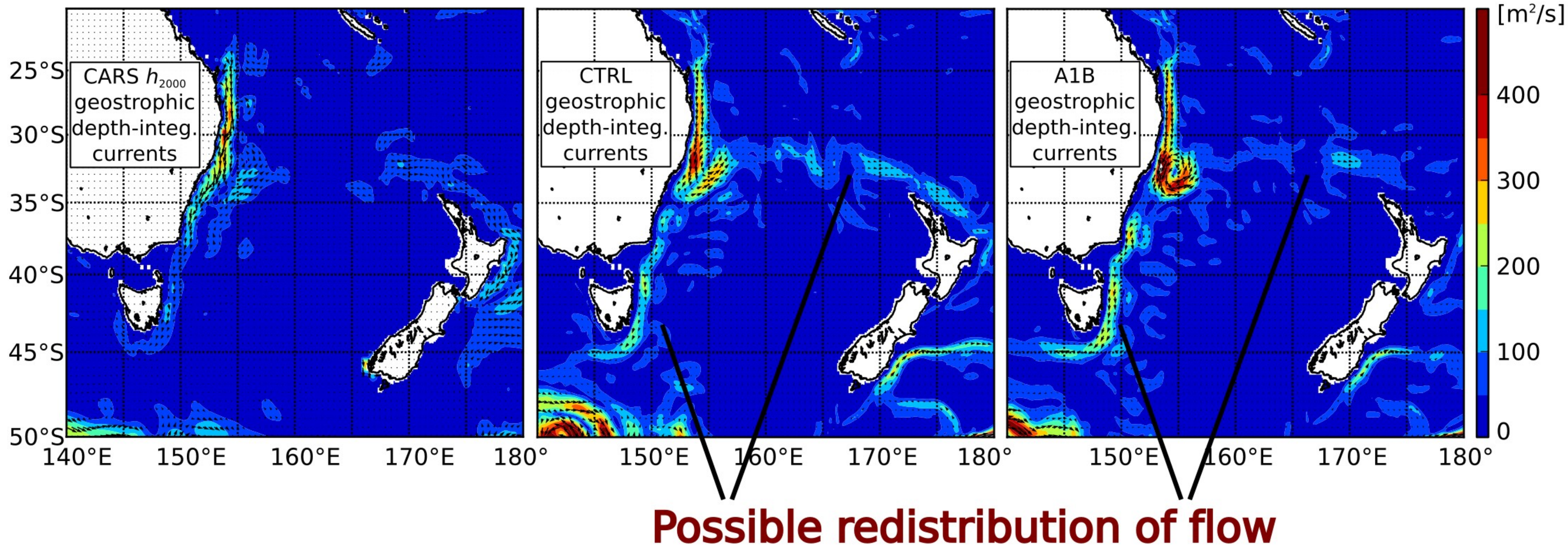
Mean Circulation

Model simulated **surface mean dynamic topography** (indicative of surface geostrophic flow) consistent with observations



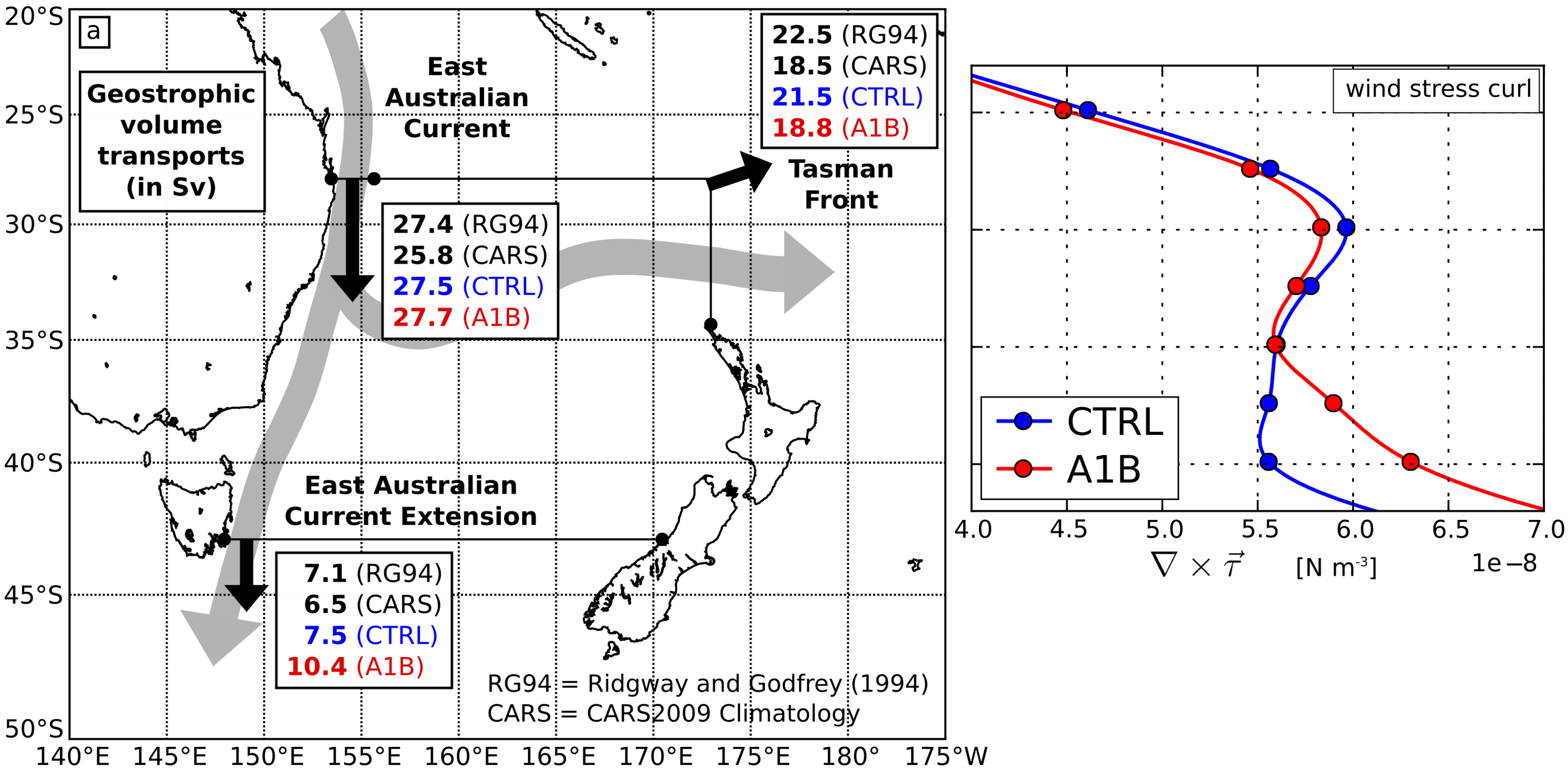
Mean Circulation

- Model simulated **mean volume transport**



Mean Circulation

- **Redistribution of flow** through the Tasman Sea



- Enhanced EAC extension and reduced flow along Tasman Front, consistent with basin-wide changes in wind stress curl

Wind-driven circulation

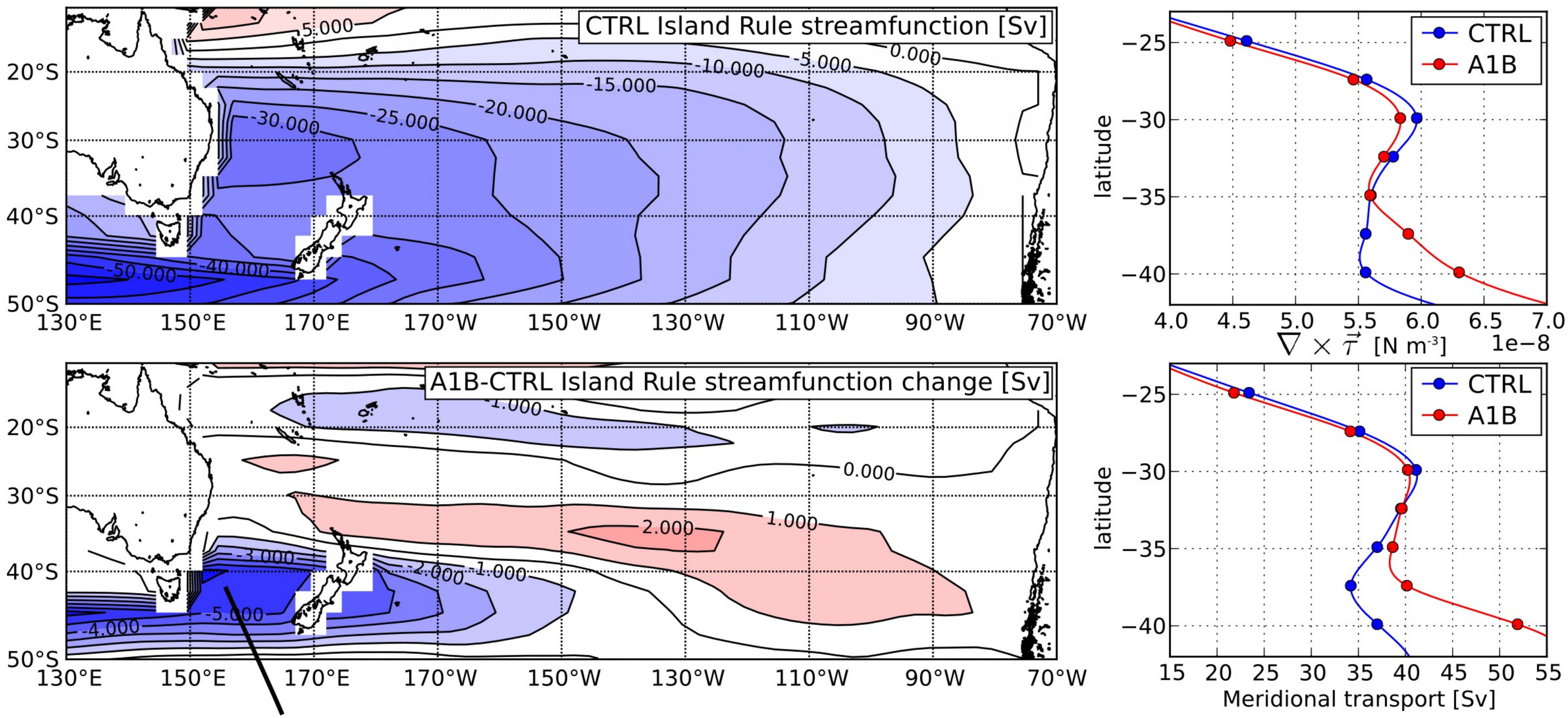
- **Simple linear, wind-driven, barotropic circulation model**
  - If the changes in mean circulation are simply due to changes in wind-stress, then we may be able to capture them with such a model
  - Sverdrup stream function $\psi(x,y)$ given by zonally integrating meridional flow according to $d\psi/dx=V$
  - Wind-driven V in the interior of the ocean given by the Sverdrup balance:

$$\beta V = \frac{1}{\rho H} \nabla \times \vec{\tau}$$

- Value of ψ along island boundaries (i.e., Aus., NZ) handled by Godfrey (1989) Island Rule

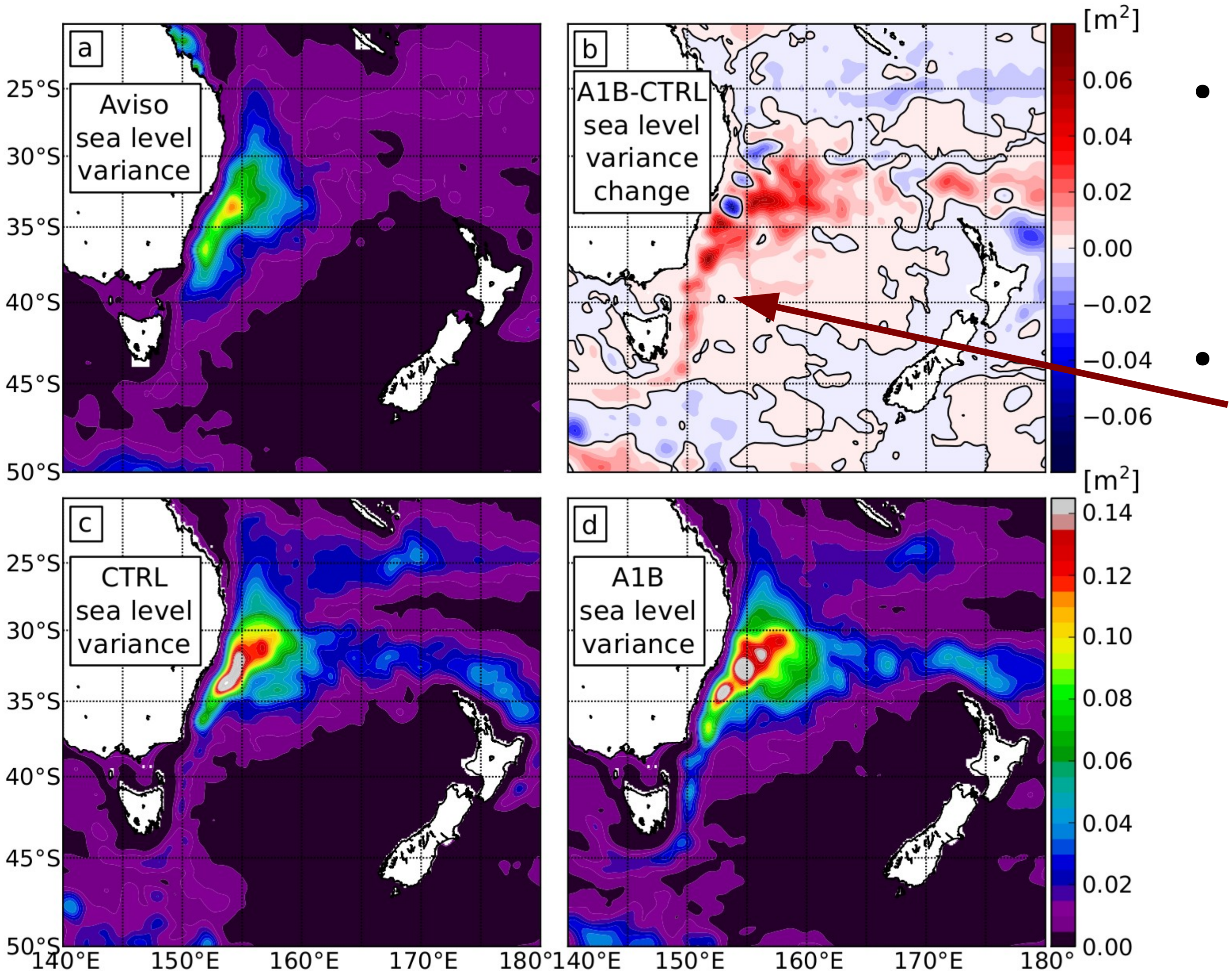
Wind-driven circulation

- Island Rule stream function for CTRL (1990s) winds, and change for A1B (2060s) wind



circulation changes at high latitudes in the Tasman Sea (EAC extension)

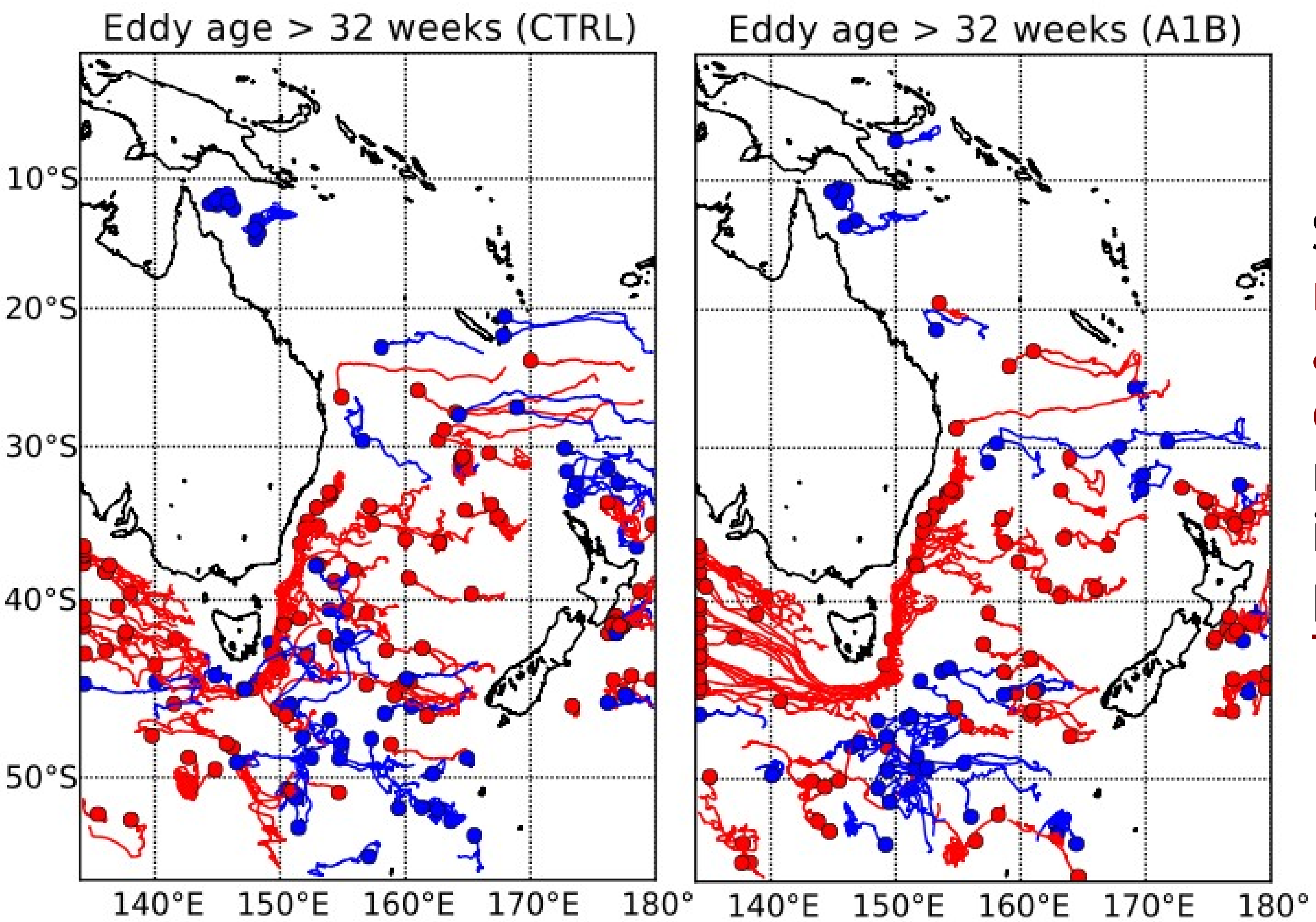
Eddy Kinetic Energy



- Sea level variance (~eddy kinetic energy) consistent between model and observations
- Significant increase in eddy kinetic energy in EAC Extension region, where flow is not steady but in fact consists of a train of mesoscale eddies…

Eddy Statistics

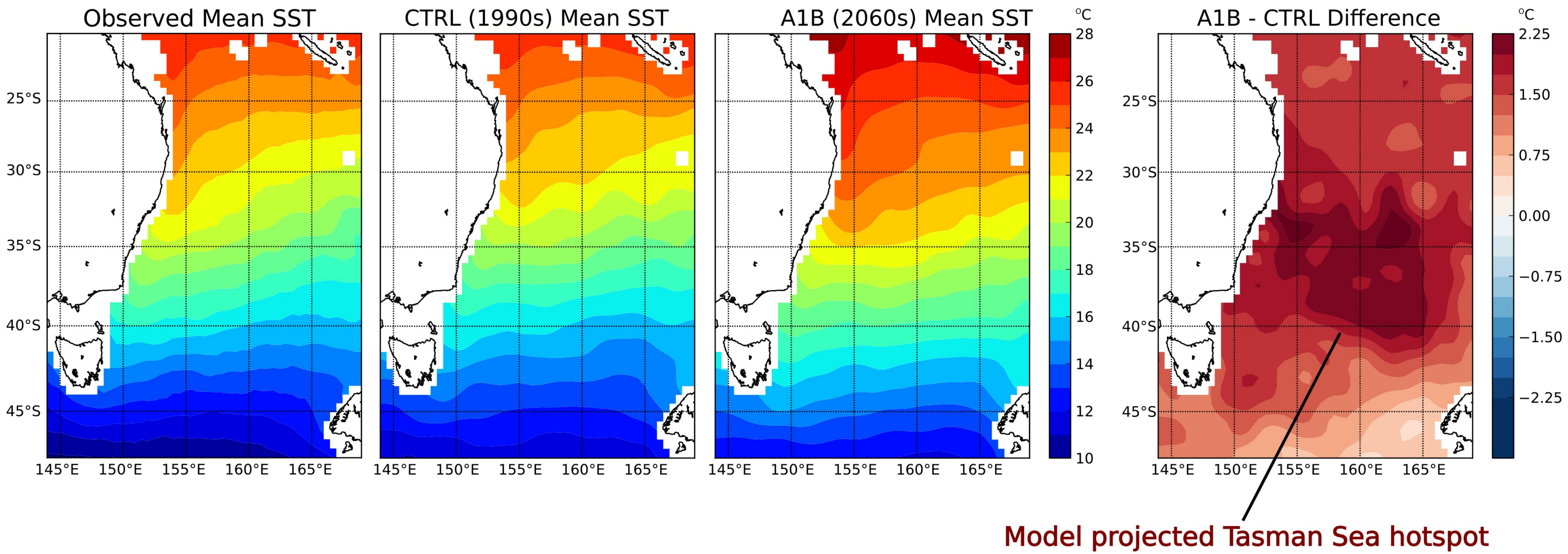
Cyclonic (blue) and **anticyclonic (red)** eddies tracked using Chelton et al. (2011) sea level algorithm:



Significant increase in number of long-lived anticyclonic (warm core) eddies in EAC Extension region, and possibly an increase in eddies passing through the Tasman Leakage

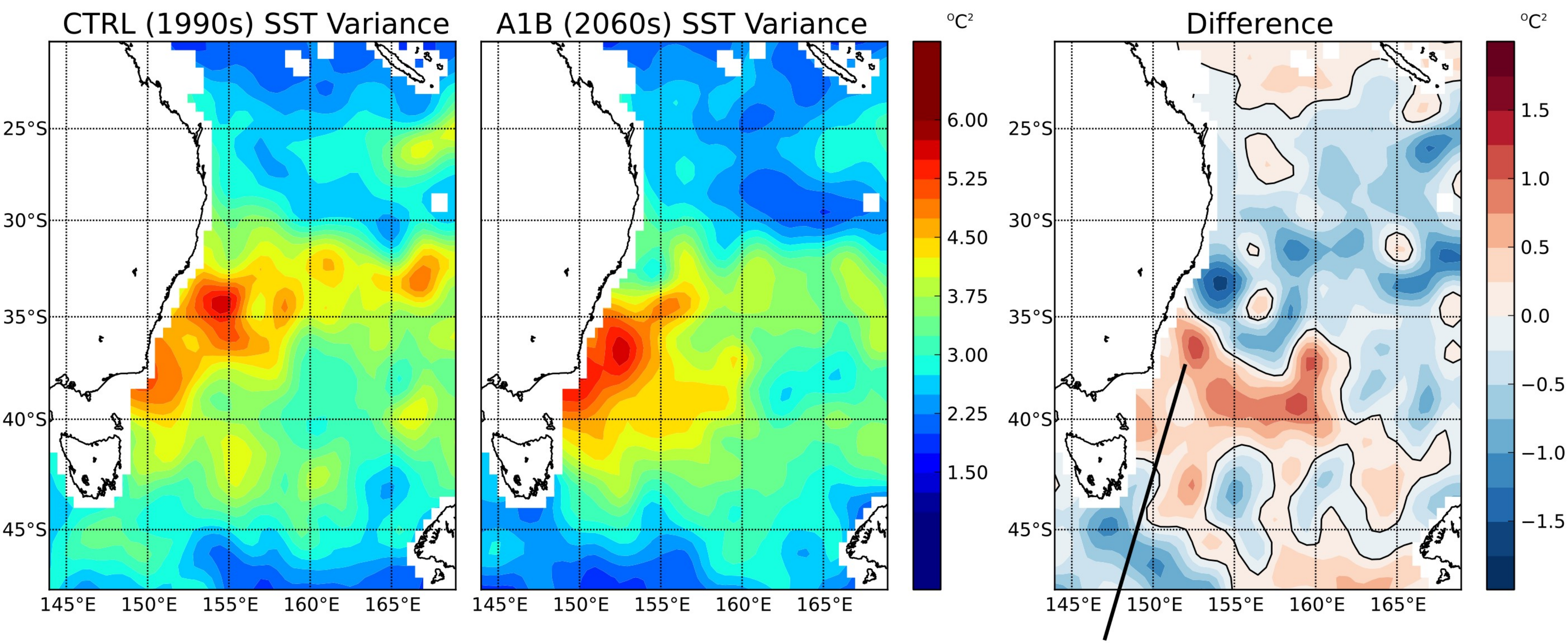
The Mean SST

- Model projected change to **mean SST**



SST Variability

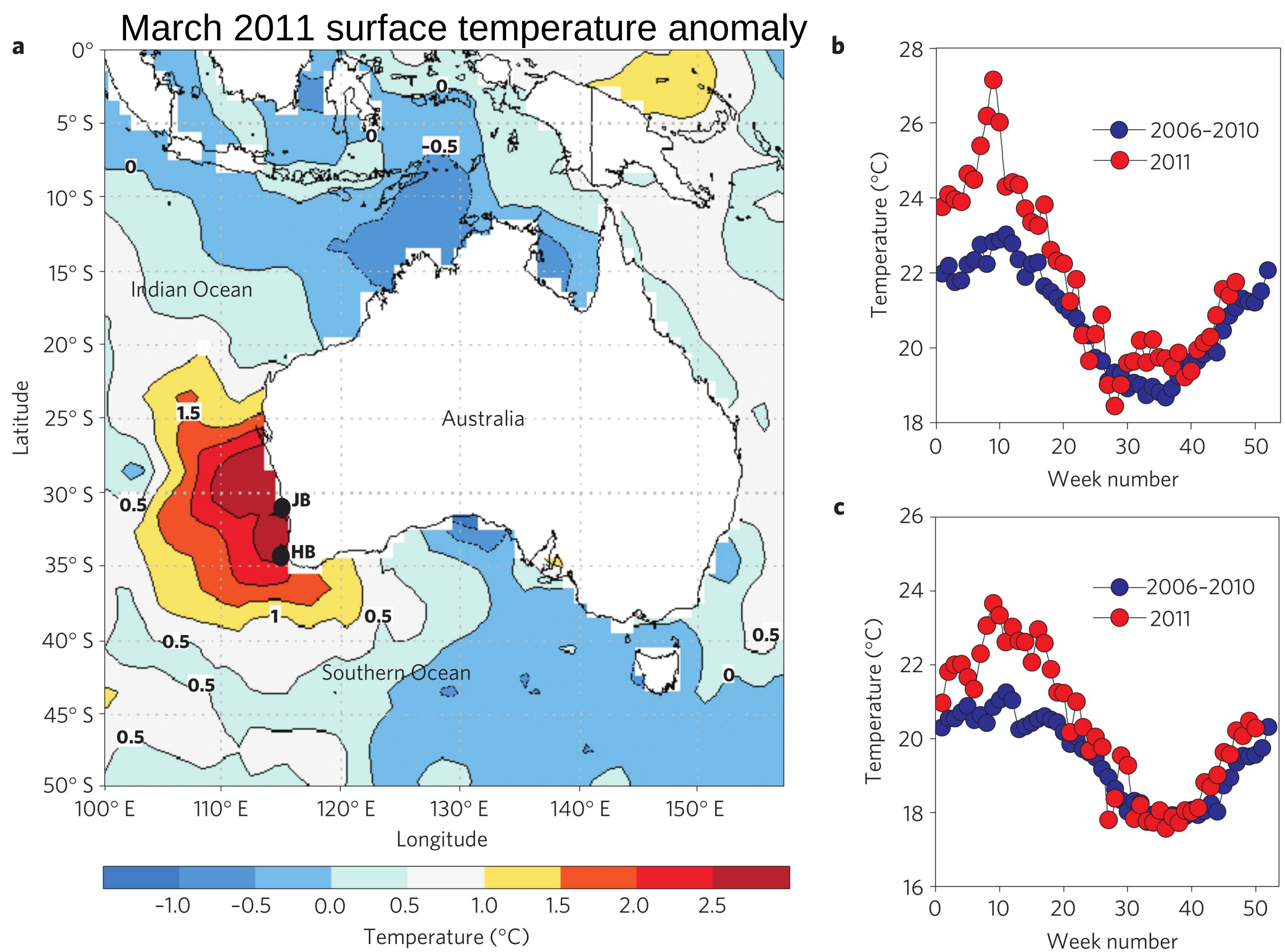
- ...and an associated increase in **SST variance** in same region



Increase of SST variability
in EAC extension region

Marine Heat Waves

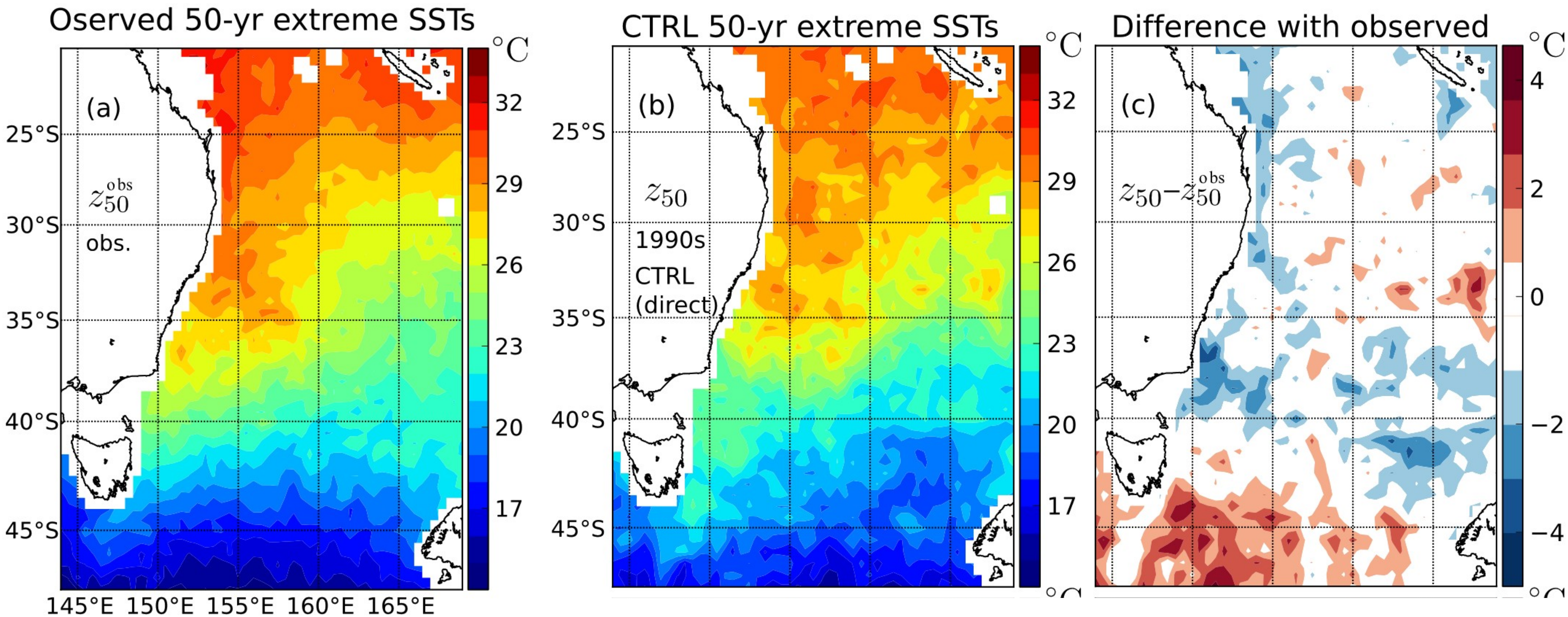
- In **2011**, a "**marine heat wave**" off of **Western Australia** was documented (Pearce and Feng, 2013; Feng et al., 2013)



Wernberg et al (2013)

- Some species experienced range extensions during the marine heat wave which persisted after the heat wave dissipated (Wernberg et al. 2013)

Extreme SSTs



- The ocean model runs **do not** fully represent the extremes
- The ocean model runs **do represent** well the overall climate
- Extremes can be represented using the "climate" alone, e.g.:
  - Griffiths et al. (2005), Ballester et al. (2010), Simolo et al. (2011), de Vries at al. (2012)

Extremes Model

- SST Extremes modeled using a **Bayesian hierarchical model**

- **For the 1990s climate:**
  - The CTRL run yields good estimates of the large-scale marine climate, e.g., the mean circulation and eddy variability and overall marine climate (mean SST, variance, etc)
  - Model observed historical extremes using climate statistics as predictors: *"extremes" = f("climate")*

- **For the 2060s climate:**
  - Use fitted model, *f("climate")*, and the projected future climate statistics to estimate future extremes
  - Assumes the model is stationary in time

Extremes Model

- **Bayesian hierarchical model**
- **Data Layer**
  - Assume that at each location *j* the annual maxima $\boldsymbol{y}_j$ are distributed according to an extreme value distribution:

$$\boldsymbol{y}_j \sim EVD\,(\, a_j \,,\, \phi_j)$$

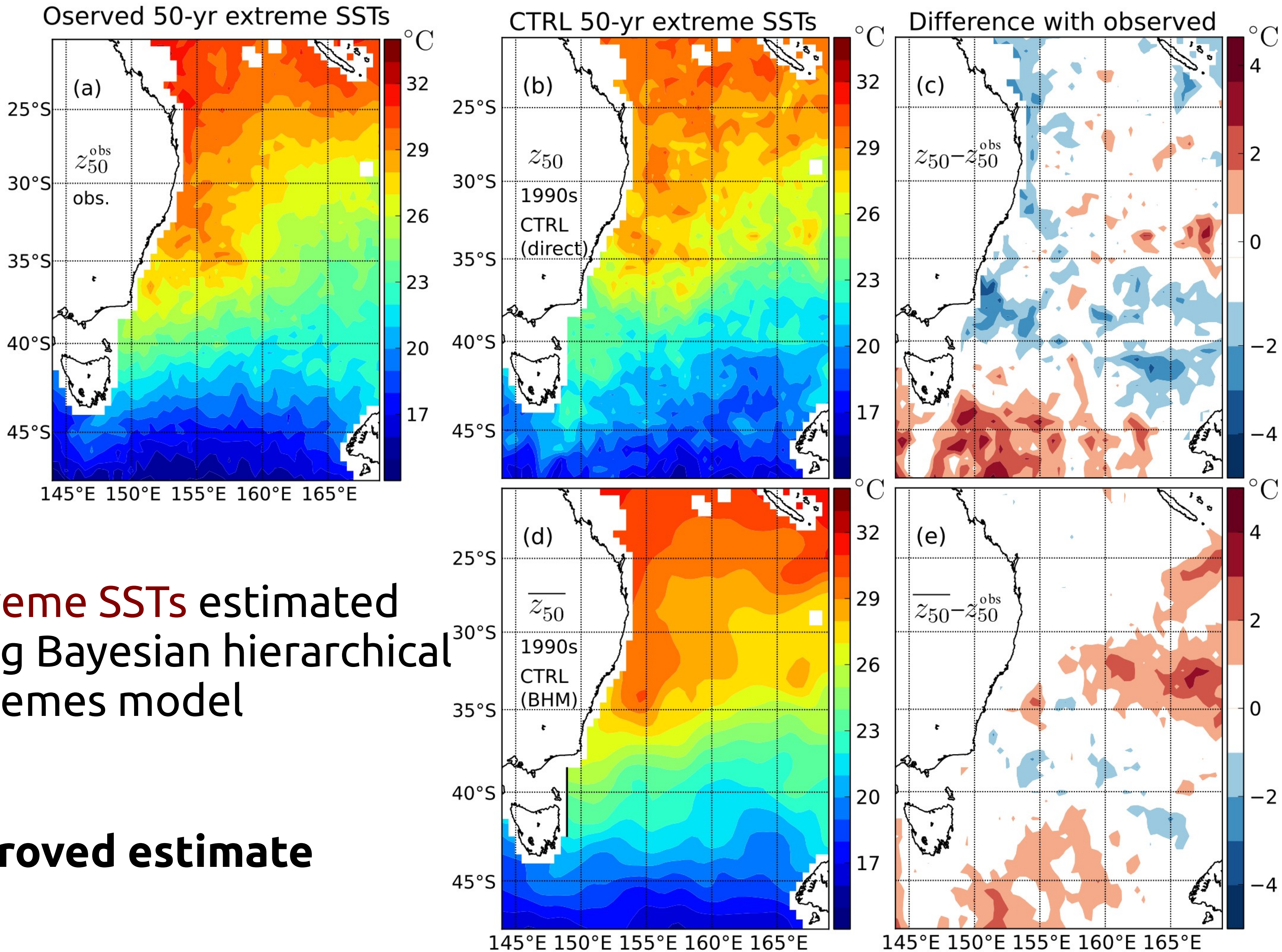
- **Climate process layer**
  - Assume the model parameters over all space ($\boldsymbol{a}$, $\boldsymbol{\phi}$) can be estimated by a linear regression onto a set of predictors $\boldsymbol{X}$, consisting of the mean SST, SST variance, skewness, etc:

$$\boldsymbol{a} = \boldsymbol{X\beta}_{\boldsymbol{a}} + \boldsymbol{\varepsilon}$$

$$\boldsymbol{\phi} = \boldsymbol{X\beta}_{\boldsymbol{\phi}} + \boldsymbol{\varepsilon}$$

  - The errors ($\boldsymbol{\varepsilon}$) are assumed to be normally distributed
- **Priors** are diffuse, non-informative
- Parameters are **sampled** using MCMC, Metropolis rule, Gibbs sampler

Extreme SSTs

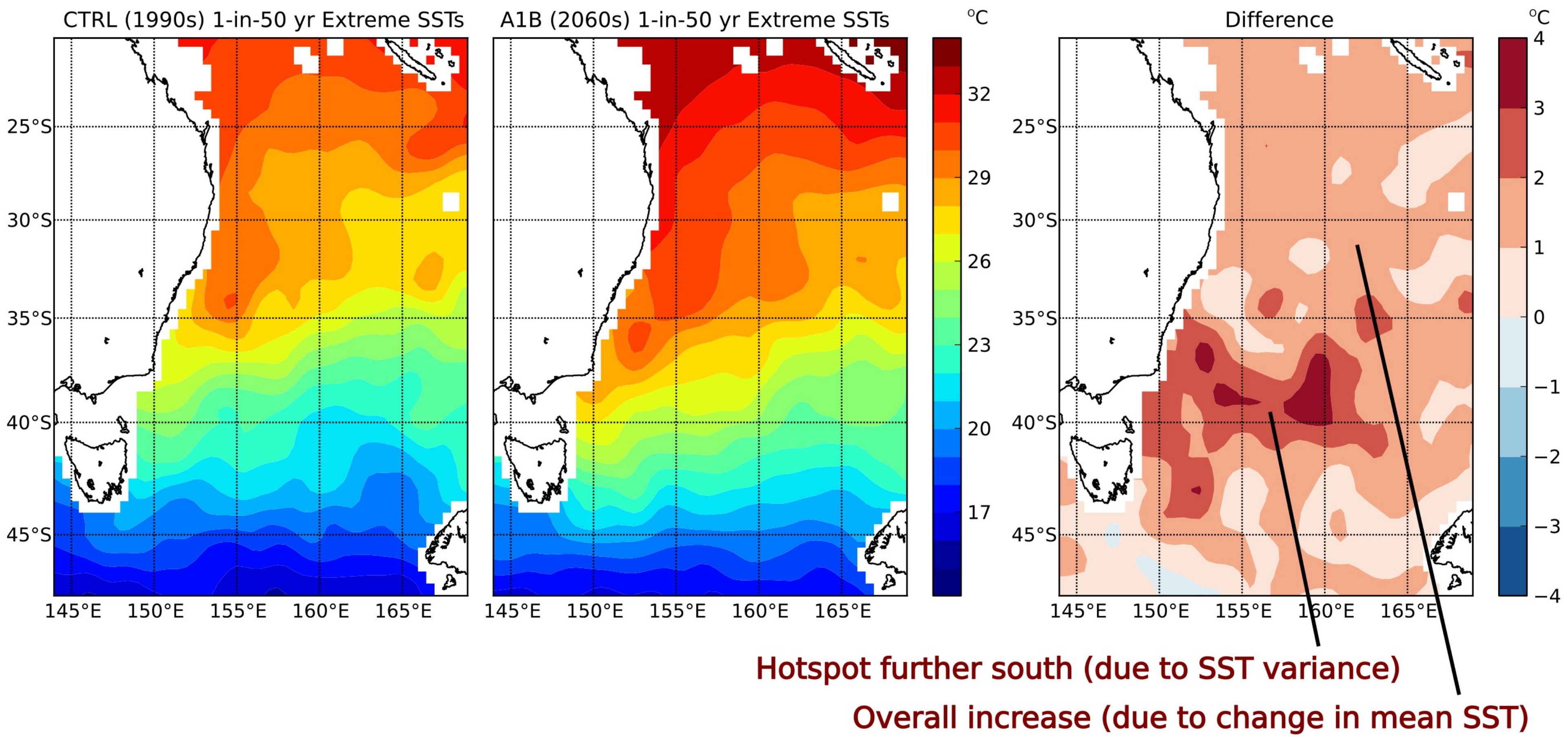


Extreme SSTs estimated using Bayesian hierarchical extremes model

Improved estimate

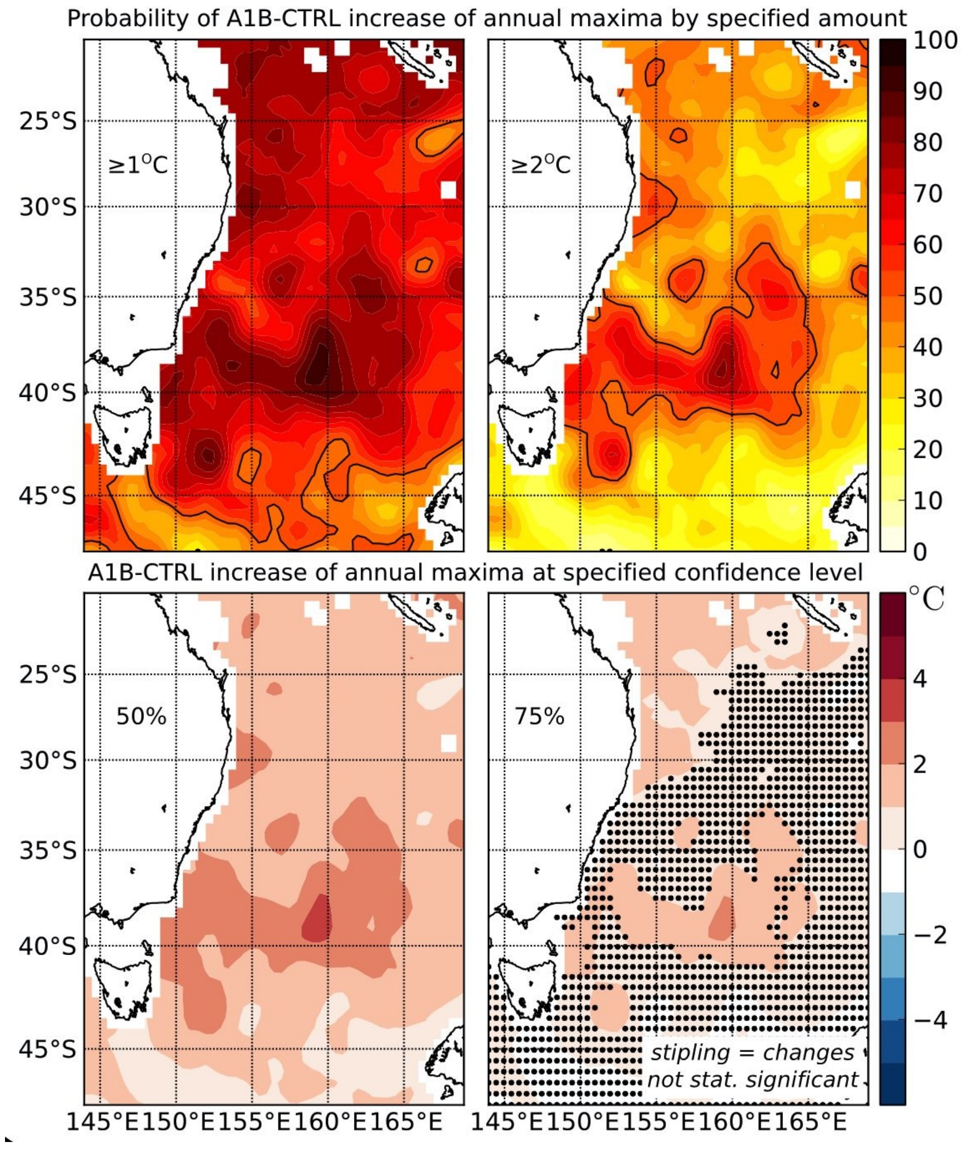
Extreme SSTs

- Projected change in extreme SSTs (50-year return levels) is due to a combination of the changes in mean and variance



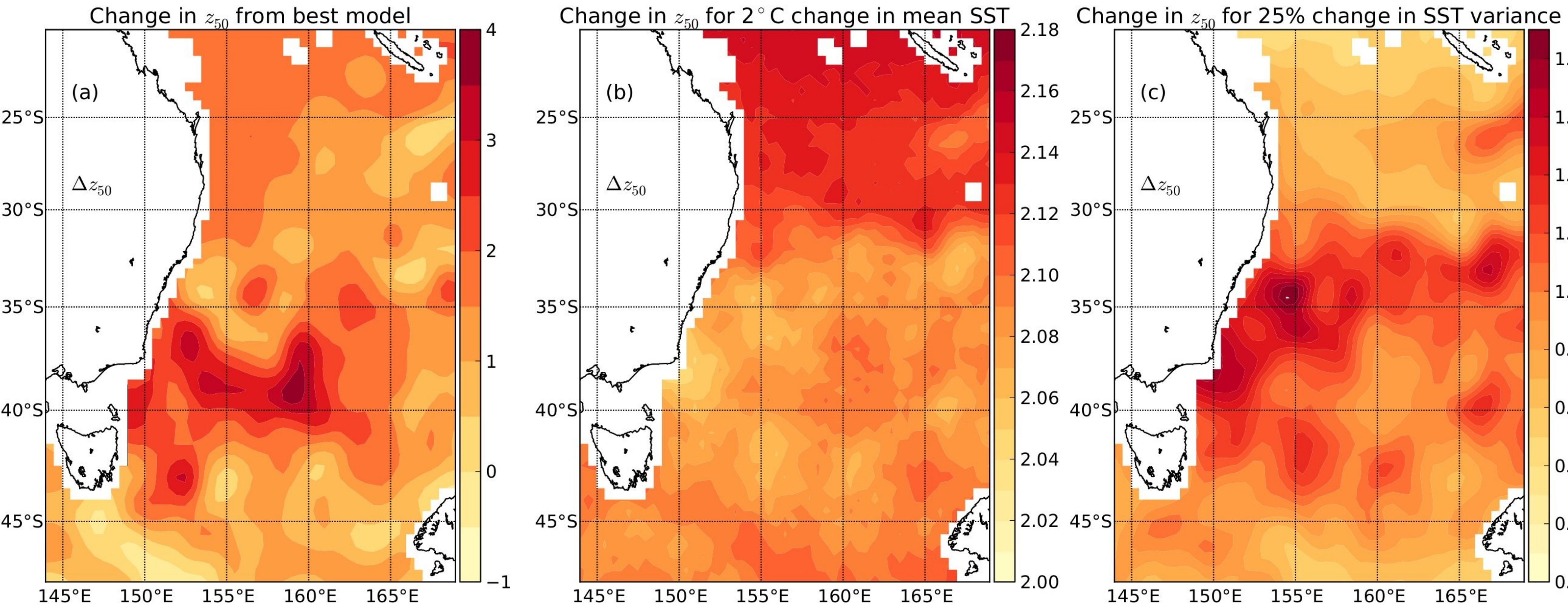
Extreme SSTs

- The extremes model is probabilistic in nature (Bayesian) and so we can put confidence limits on our predictions
- This type of information is very helpful when making statements about climate change



Extreme SSTs

- Can use the extremes model as a "toy model"
- Test the response of the extremes to specified changes in climate



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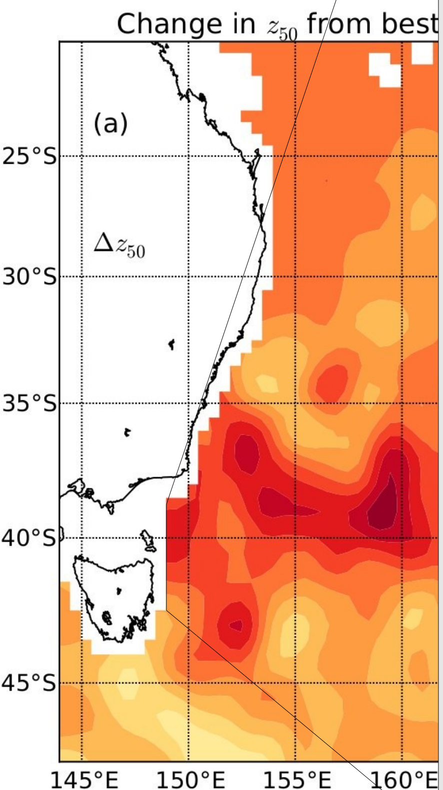
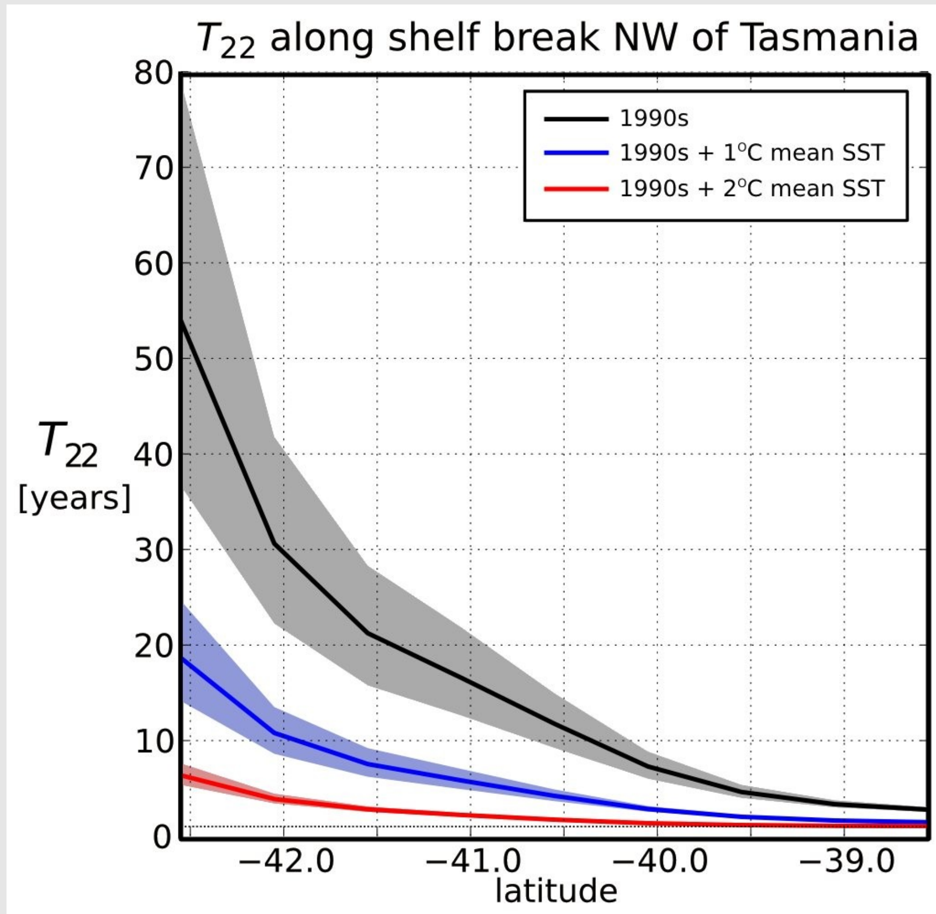
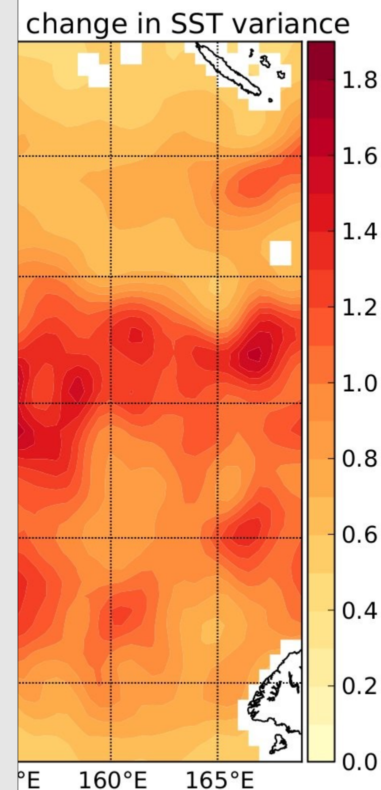
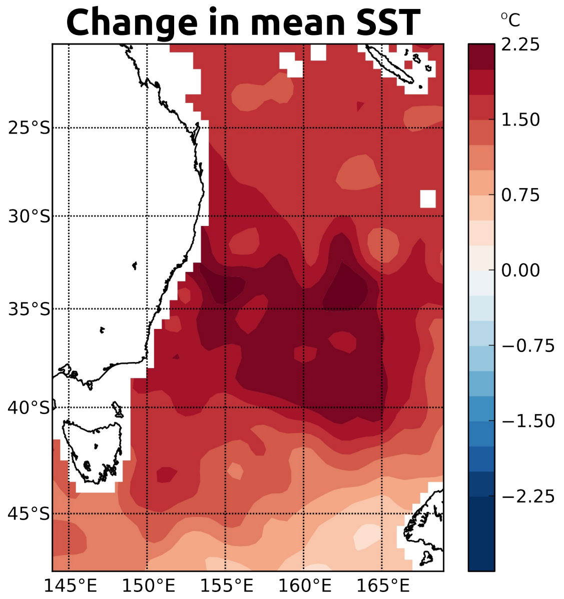






Conclusions – Part I

- Projected changes in the mean state:
  - **Tasman Sea SST hotspot**



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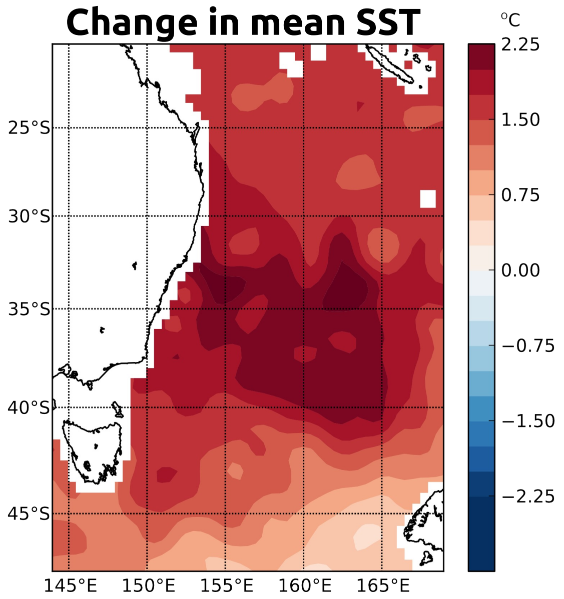

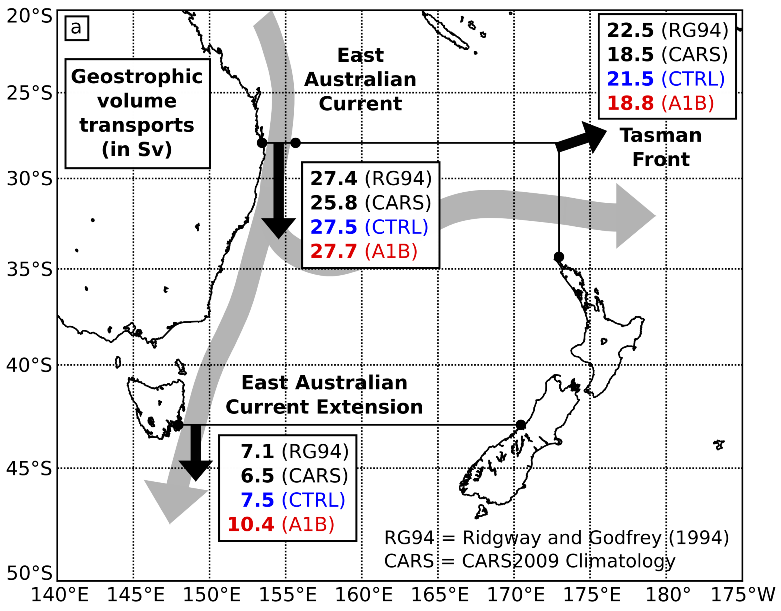

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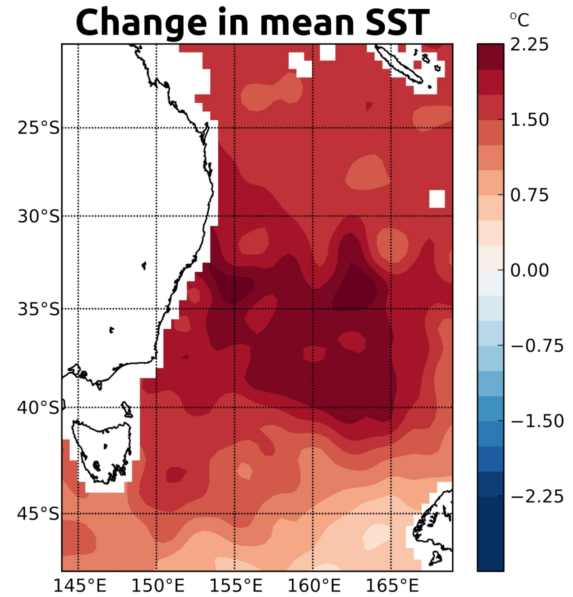

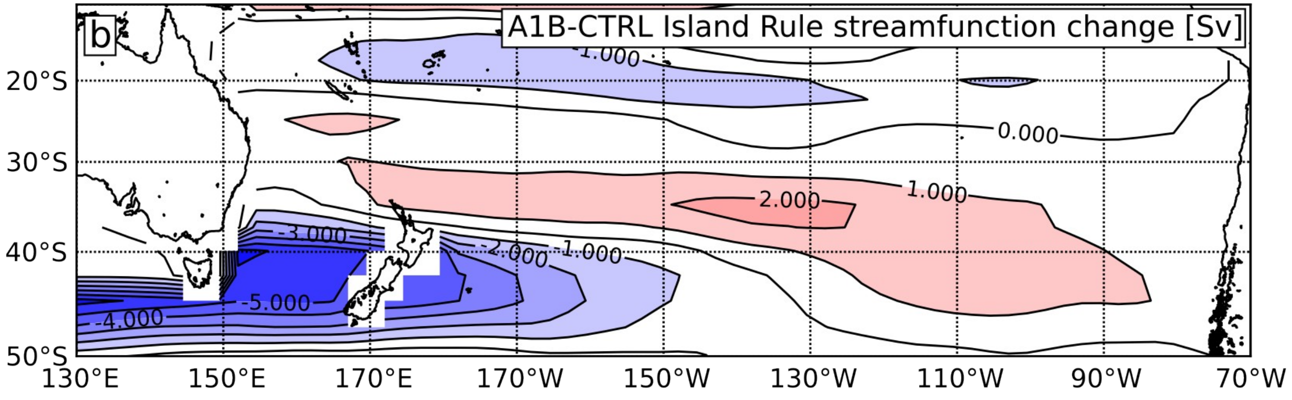

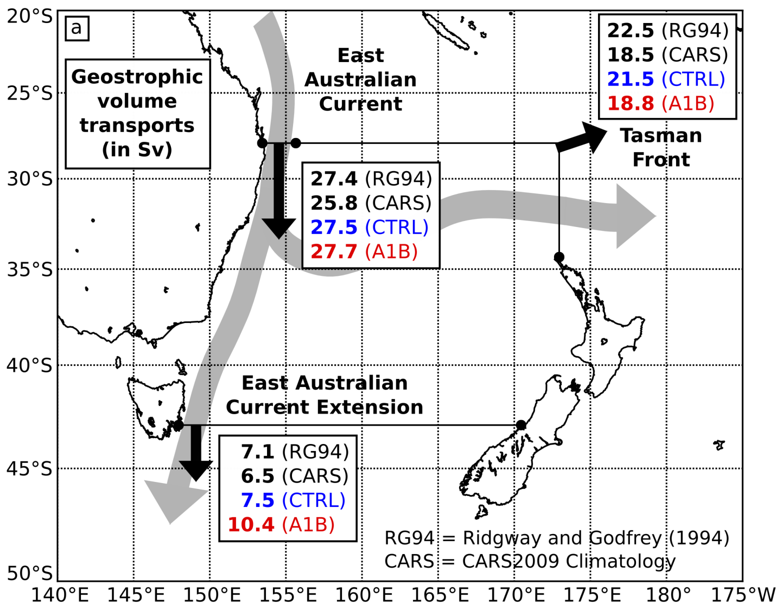

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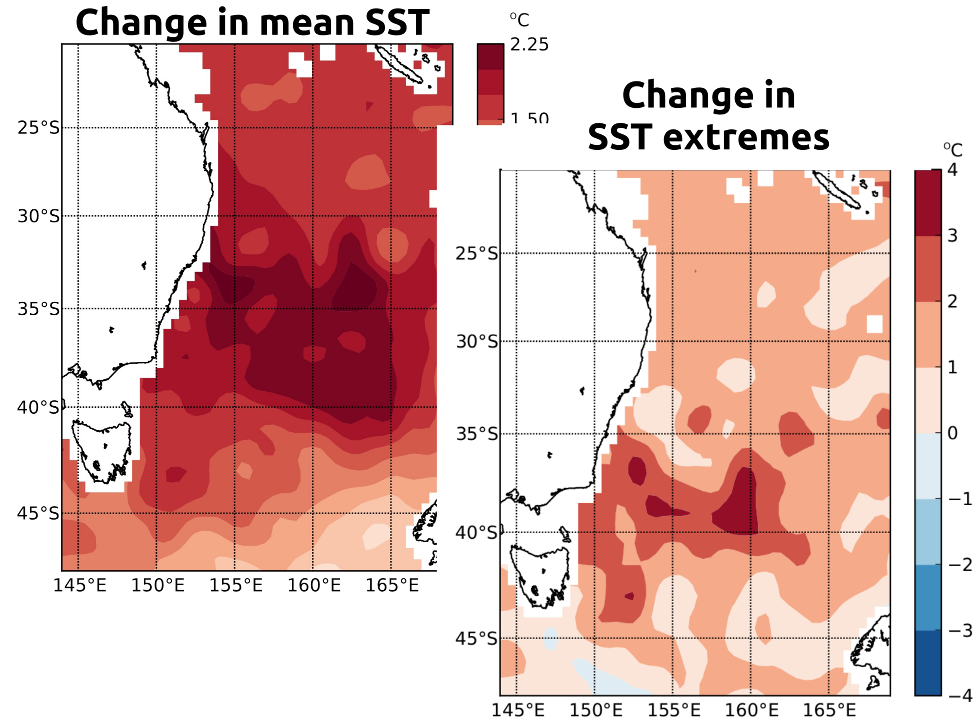

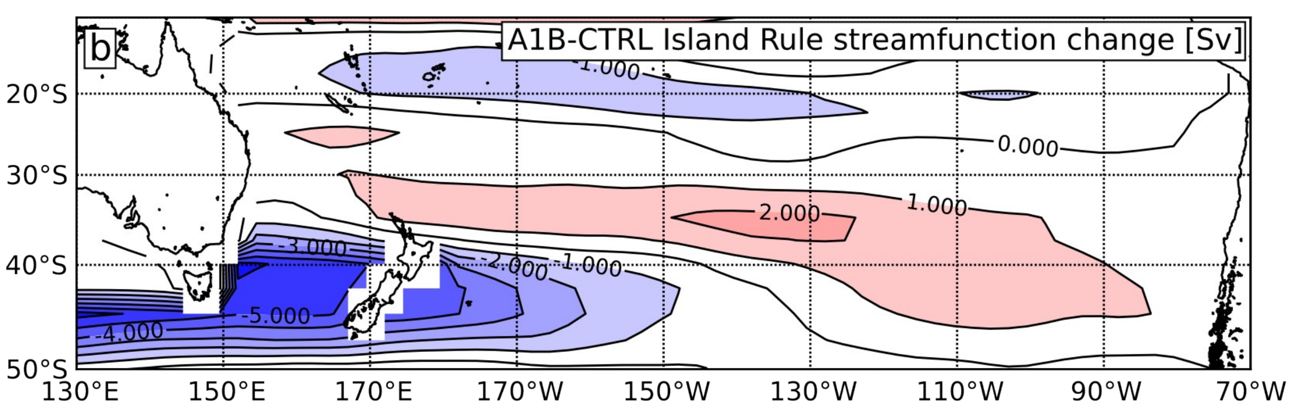

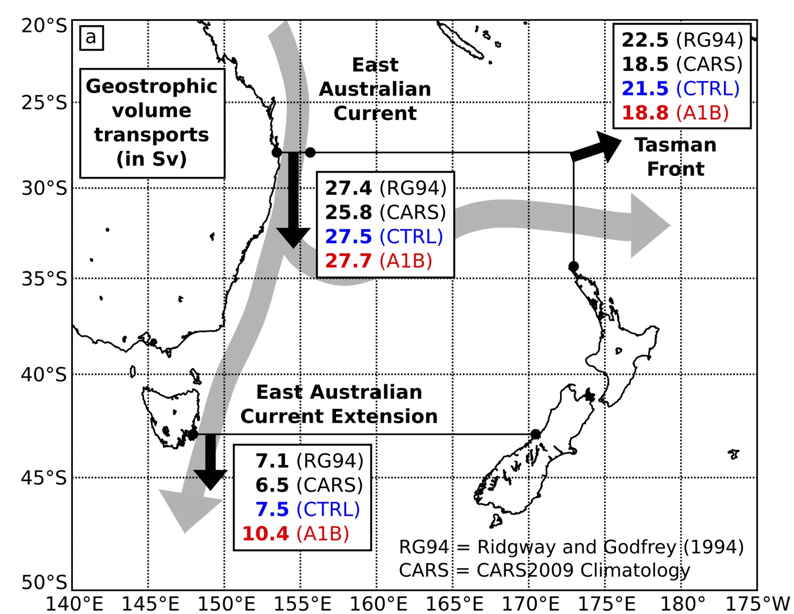

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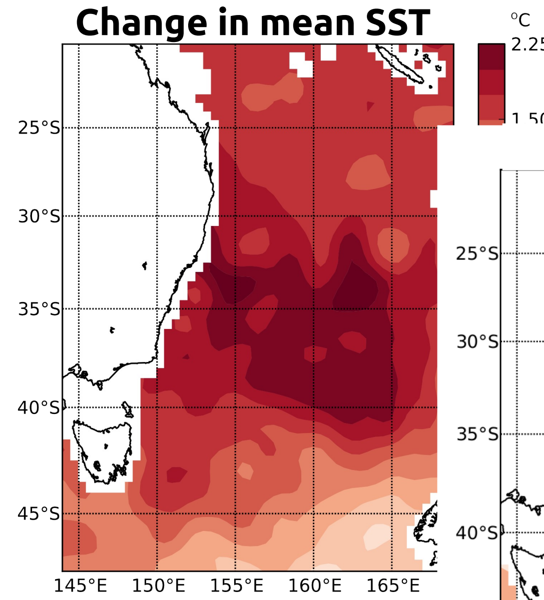
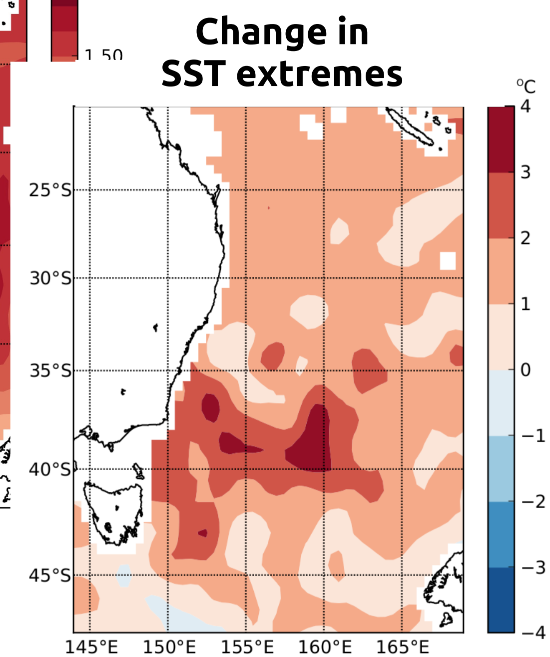
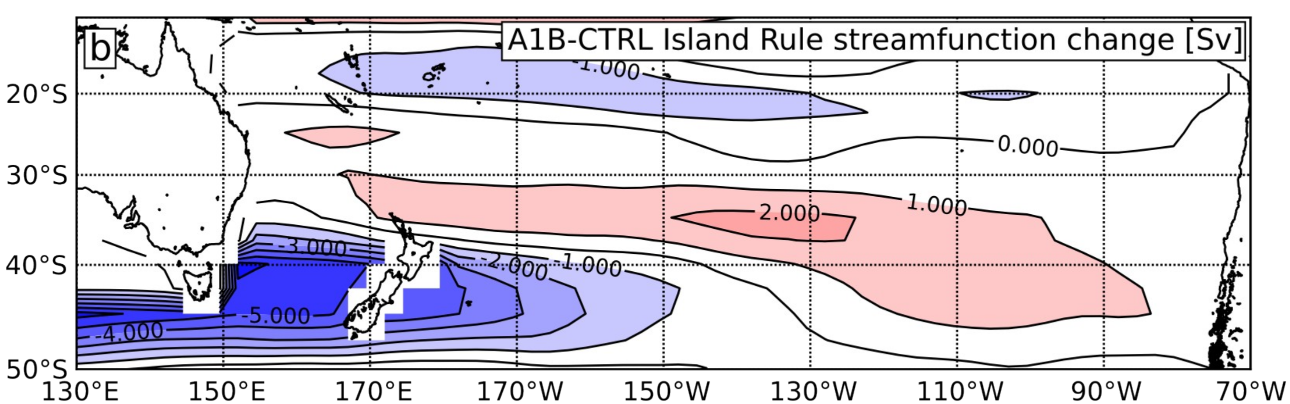
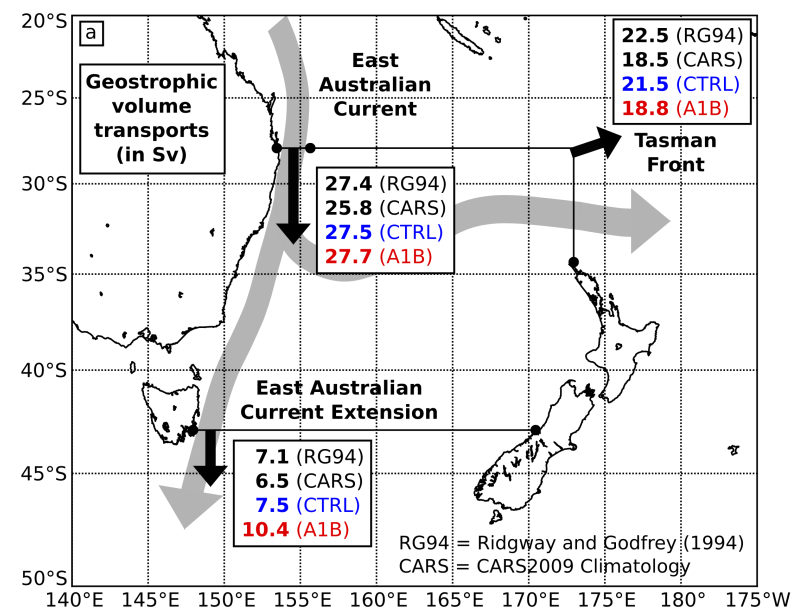
- The **Bayesian hierarchical extremes model** a general framework for estimating extremes from climate/ocean models (bias correction)









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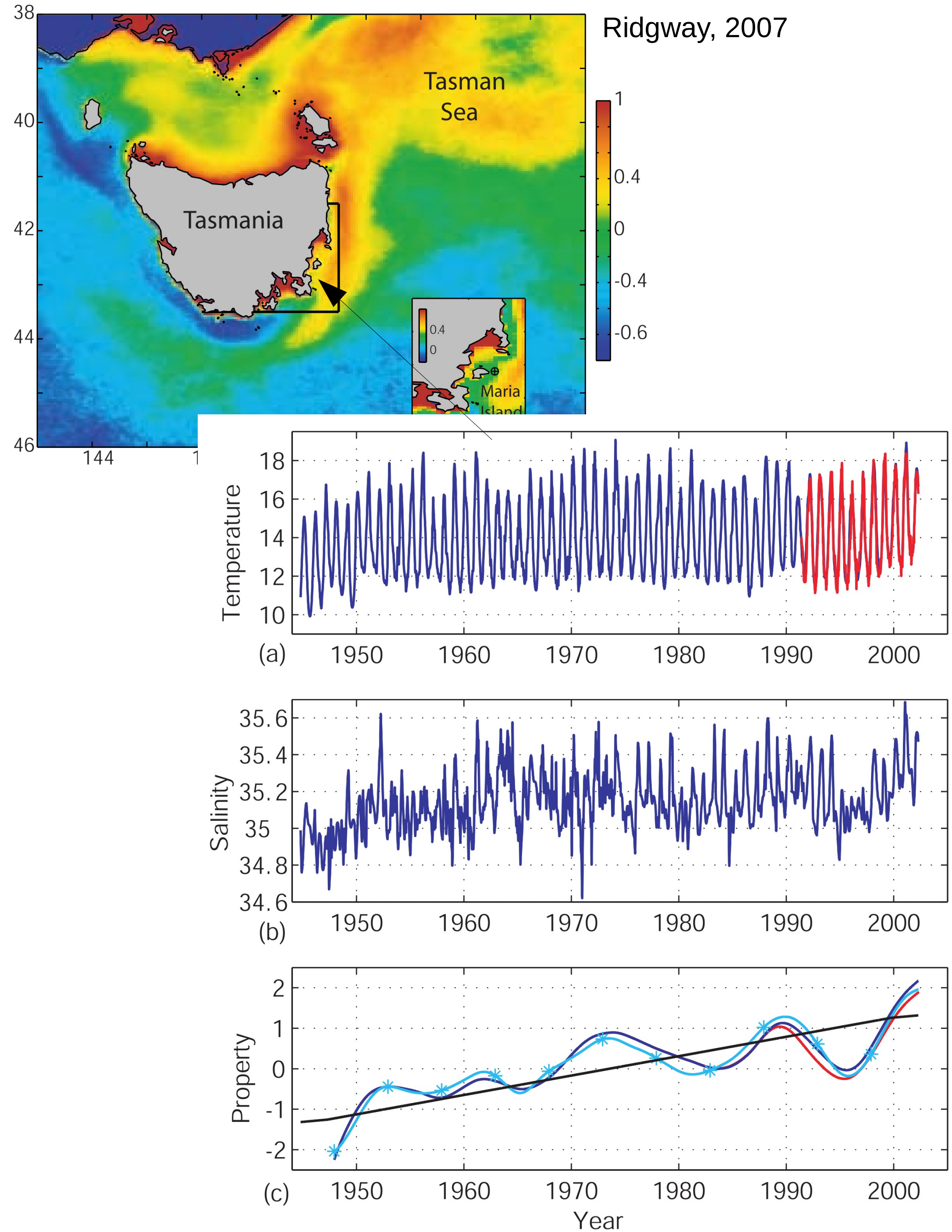

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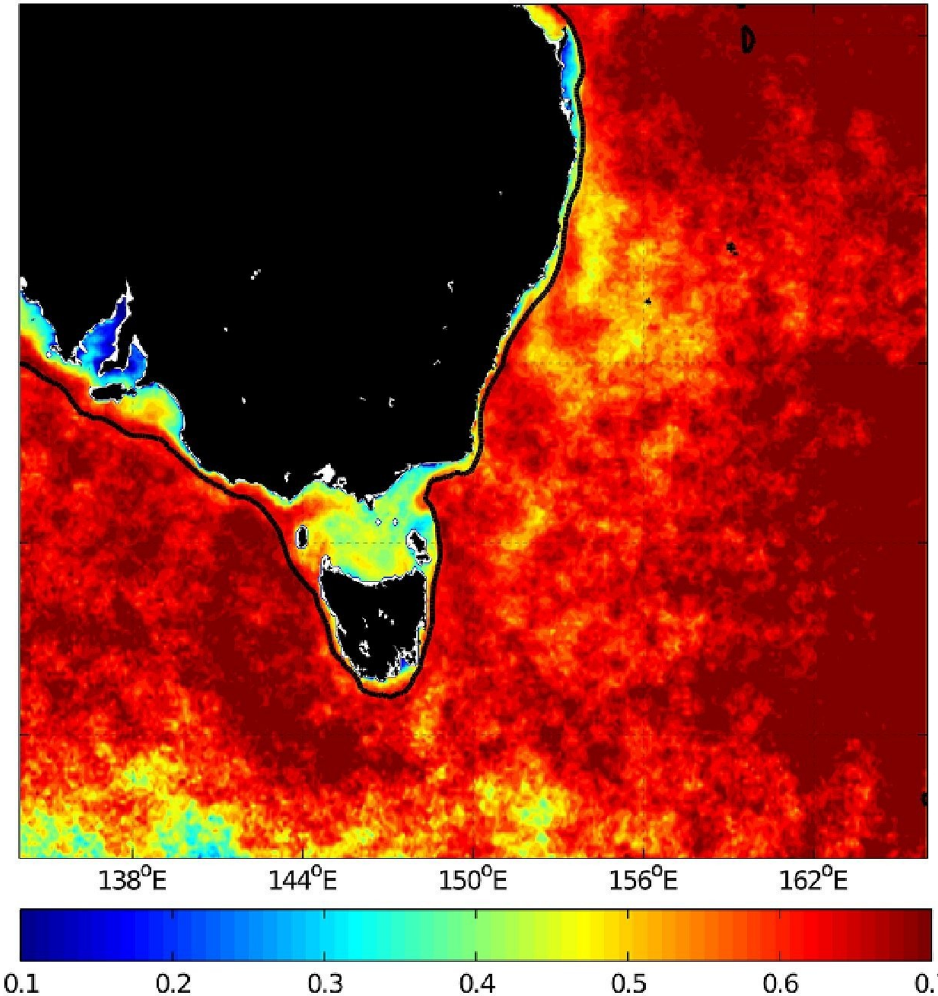

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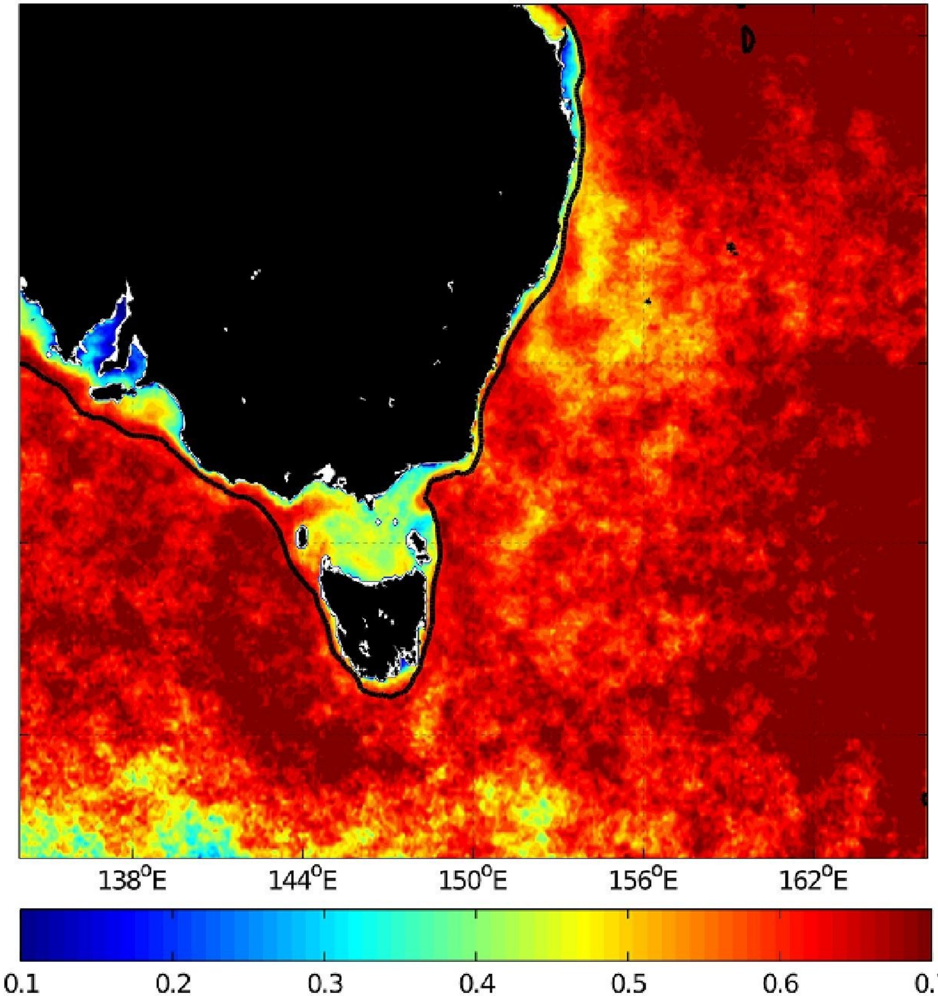
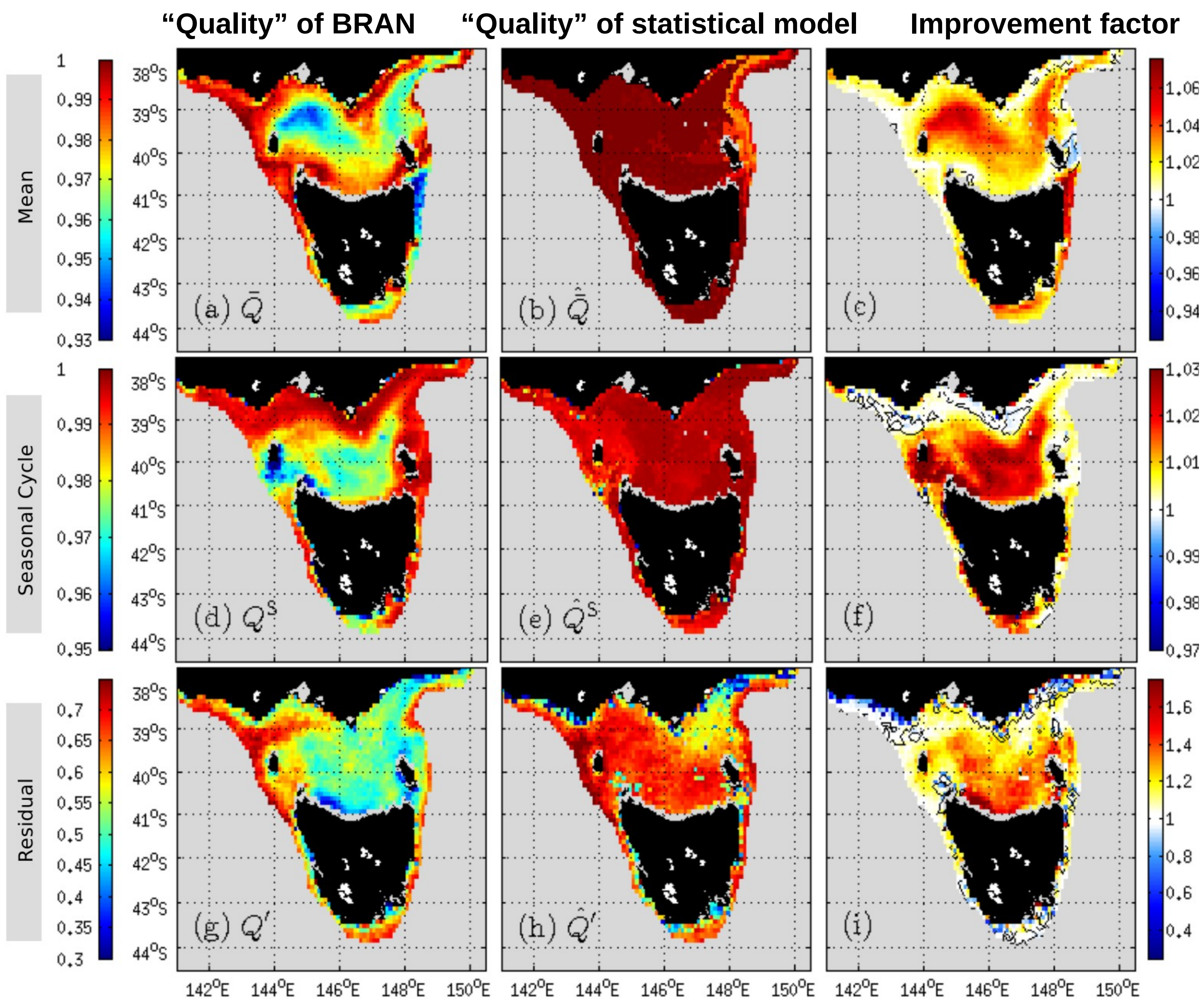


correlation between observed (AVHRR) and reanalysis (BRAN) SST

Statistical Downscaling

Oliver and Holbrook (2014; OH14) statistical technique improved estimates of shelf SST



Statistical Downscaling

- Technique extended to the entire continental shelf for temperate Australia (>20°S)
- OH14 dataset available online: **passage.phys.ocean.dal.ca/~olivere/OH14.html**
- Technique has been applied to 1990s and 2060s climate projections as well

Eric C. J. Oliver

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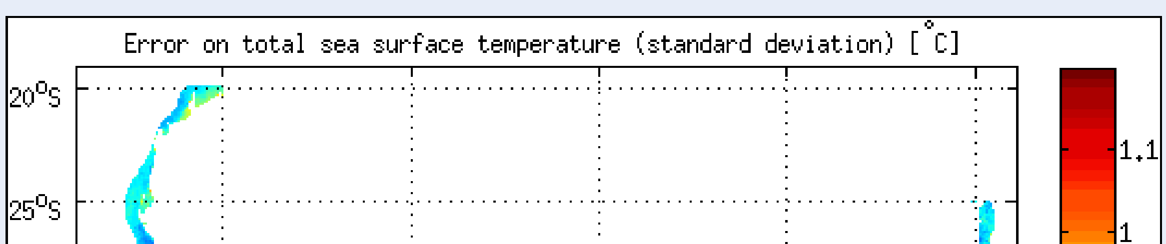
Statistical downscaling of Australian continental shelf sea surface temperatures

The Oliver and Holbrook (Journal Atmospheric and Oceanic Technology, 2014), or OH14, data set provides spatially and temporally homogeneous measurements of sea surface temperature (SST) variability at high resolution on the continental shelf around Australia.

- The data arises from a hybrid statistical-physical downscaling model designed to more accurately and robustly represent SST on the continental shelf informed by large-scale satellite observations and reanalysis data. The downscaled shelf SST is modeled using: (i) offshore SST from Bluelink ReANalysis (BRAN), (ii) the statistical relationship between inshore and offshore SST in observations from the Advanced Very High Resolution Radiometer (AVHRR), and (iii) the mean circulation which provides connectivity information between the shelf and the offshore regions. The SST time series' were separated into the mean, seasonal cycle, and the residual variability, and separate models were developed for each component.
- **The data are provided as a single NetCDF file, along with a User's Manual and MATLAB script for loading the data:** download data
- The data set provides total SST, mean SST, SST seasonal cycle, residual SST along with error estimates. Total SST is defined as the sum of the mean, seasonal cycle and residual. Mean SST and the error estimates are provided as a single value at each of the shelf locations, while the total SST, SST seasonal cycle, and residual SST are provided as daily time series (14 Oct 1992 to 13 May 2008) at each of the shelf locations. The error estimates are provided as a standard deviation and a map of the error for total SST, which also doubles as an indicator for which location data is provided, is shown below:

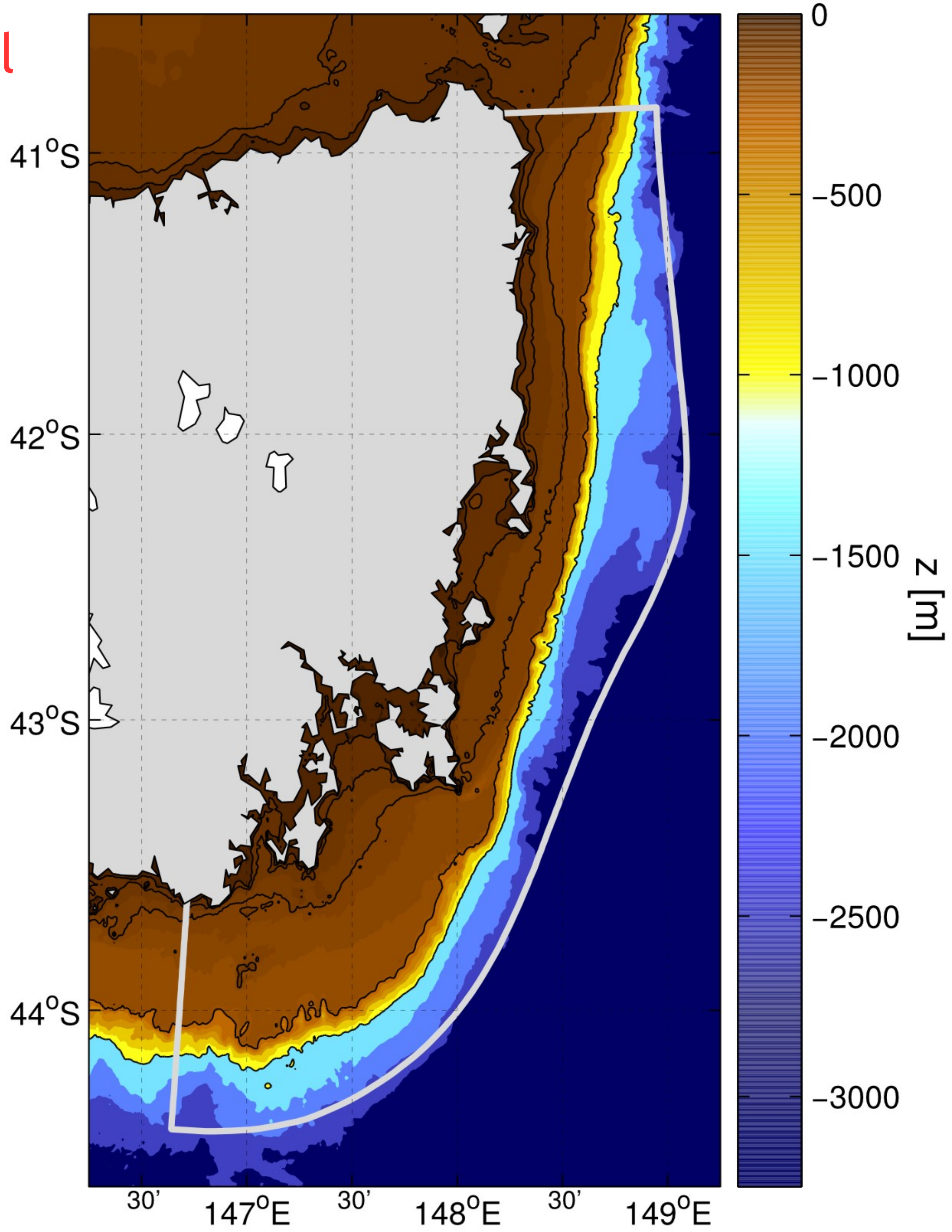


Dynamical Downscaling

- **Dynamical downscaling** uses numerical ocean models based on our theoretical understanding of ocean dynamics

---

- We modeled the eastern Tasmania continental shelf using the **Sparse Hydrodynamic Ocean Code (SHOC)** model [Herzfeld, 2006]
- Domain: South Cape to ~Eddystone Point and seaward out to shelf break
- Bathymetry: Australian Geological Survey Organisation (AGSO) 2002
- Resolution: ~1.9 km resolution
- 43 *z*-levels in the vertical



Herzfeld, M. (2006), An alternative coordinate system for solving finite difference ocean models, Ocean Modelling, 14 (3-4), 174-196

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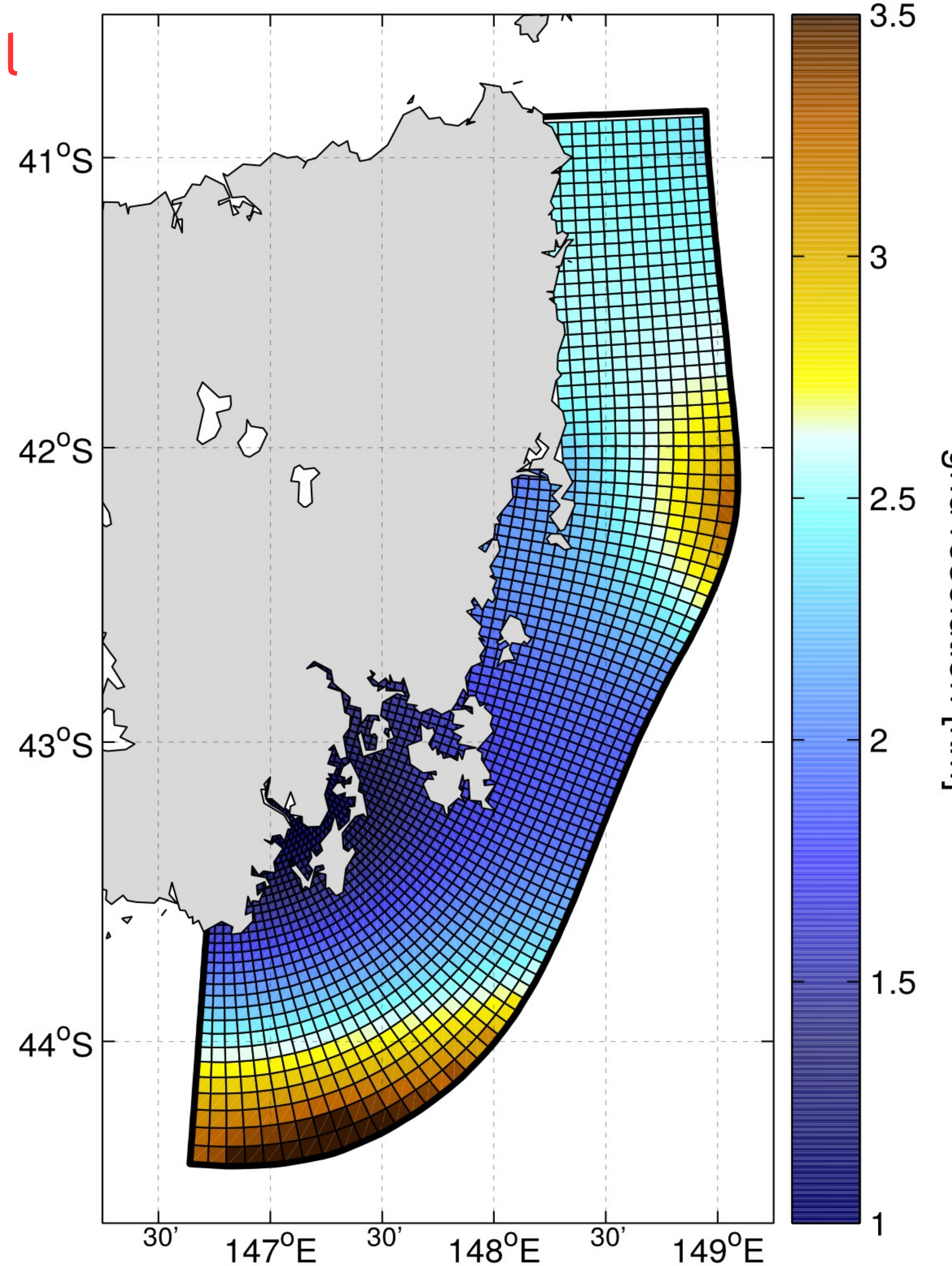

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Forcing: Ocean and Atmosphere

Model forced by realistic ocean and atmosphere at boundaries

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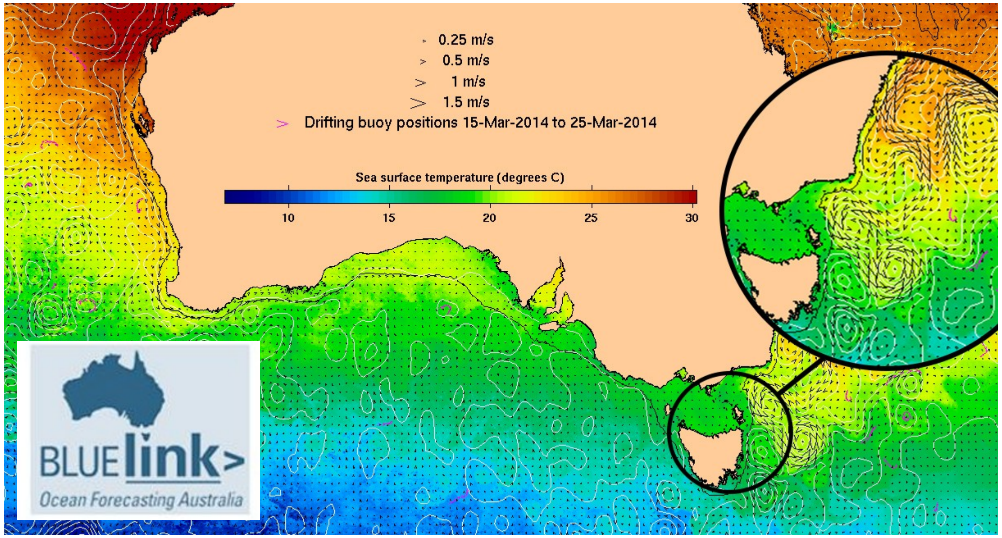

- Lateral boundaries were forced by velocities, temperature and salinity from **Bluelink** reanalysis and analysis fields [1,2]

[1] BRAN = Bluelink ReANalysis
[2] OceanMAPS = Bluelink Ocean Modelling, Analysis, and Prediction System

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Model forced by realistic ocean and atmosphere at boundaries

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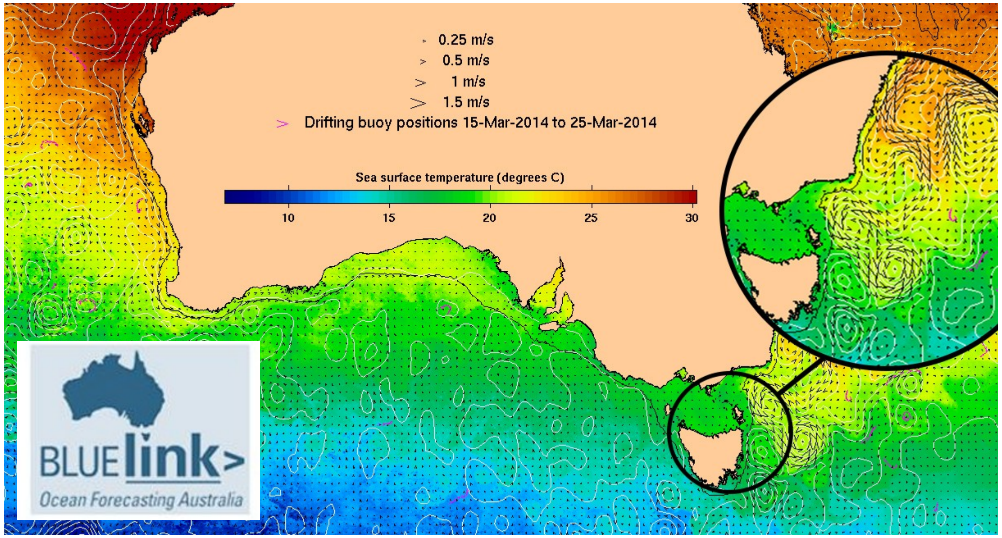

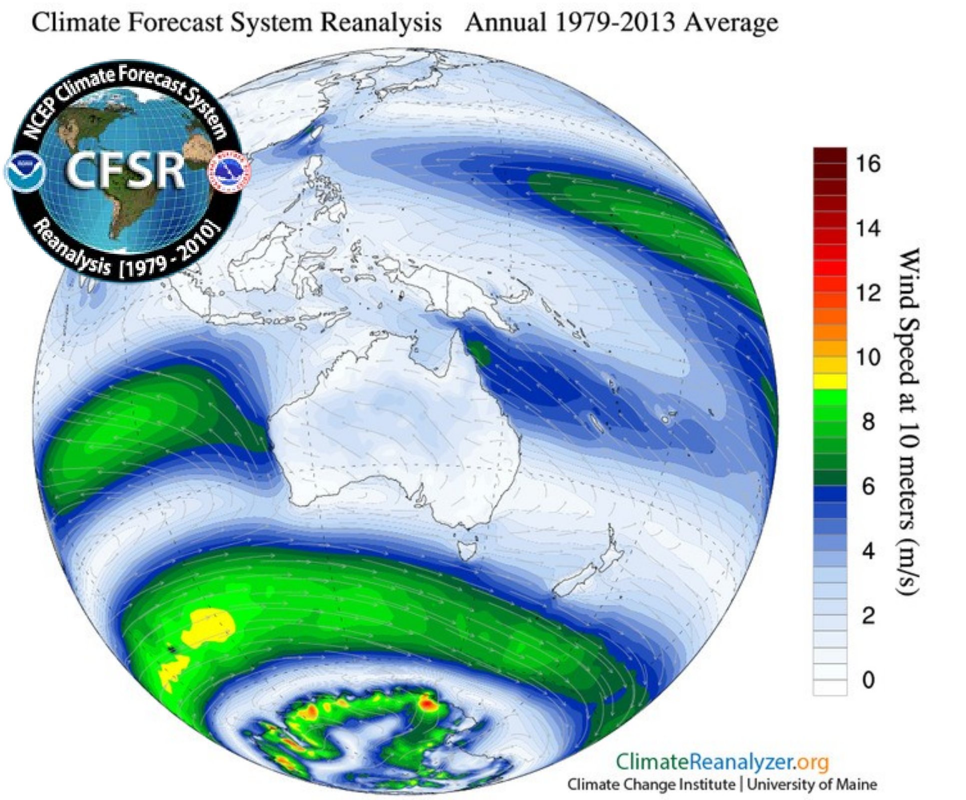

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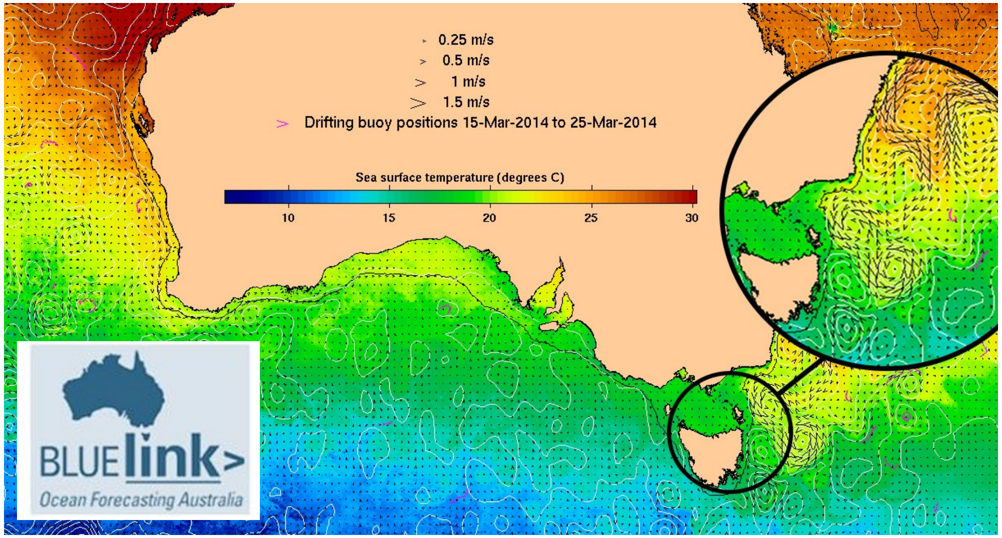
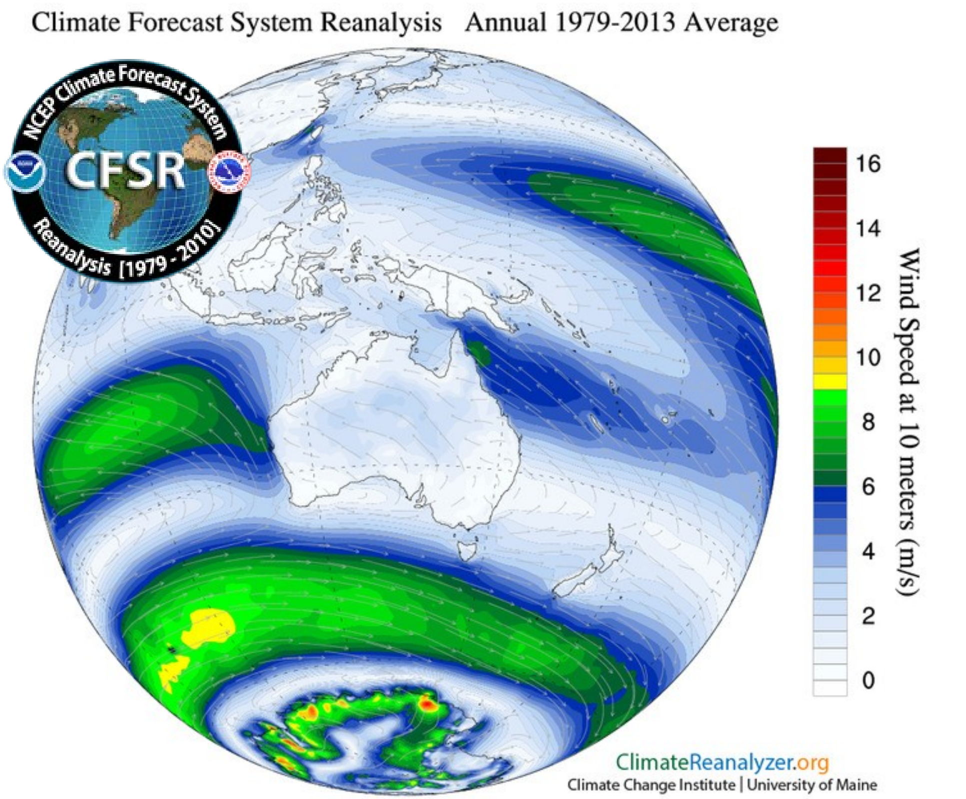
- River input was reconstructed from precipitation over catchments
- Coverage: 1993-2013





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Forcing: Ocean and Atmosphere

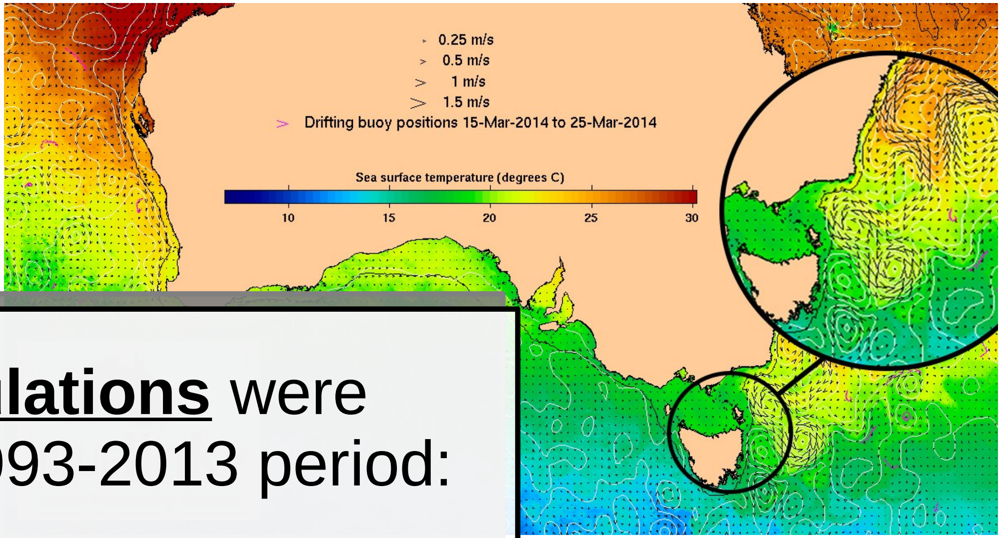
Model forced by realistic ocean and atmosphere at boundaries

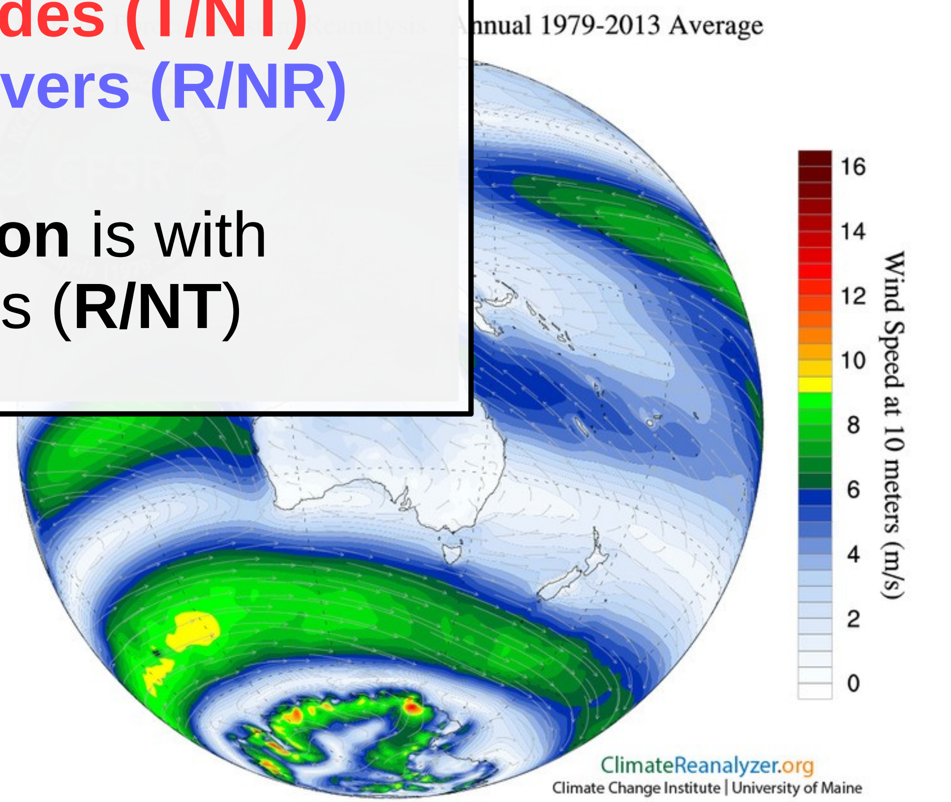
- Lateral boun... velocities, te... from **Bluelin...** analysis field...
- Surface was ... from the **NC...** **System (CFS...** Reforecast [3,4]
- River input w... precipitation ...
- Coverage: 1993-2013

Four **hindcast simulations** were performed for the 1993-2013 period:

- With and without tides (T/NT)
- With and without rivers (R/NR)

Base run for validation is with rivers and without tides (**R/NT**)





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Model Validation

In-situ time series

Maria Island time series **[RED]**

- Historical temperature and salinity @ surface and 5 depths
- Quasi-monthly, 1944 - 2008

Craig Mundy (IMAS-FAC, UTAS), near-bottom temperature gauges **[BLUE]**

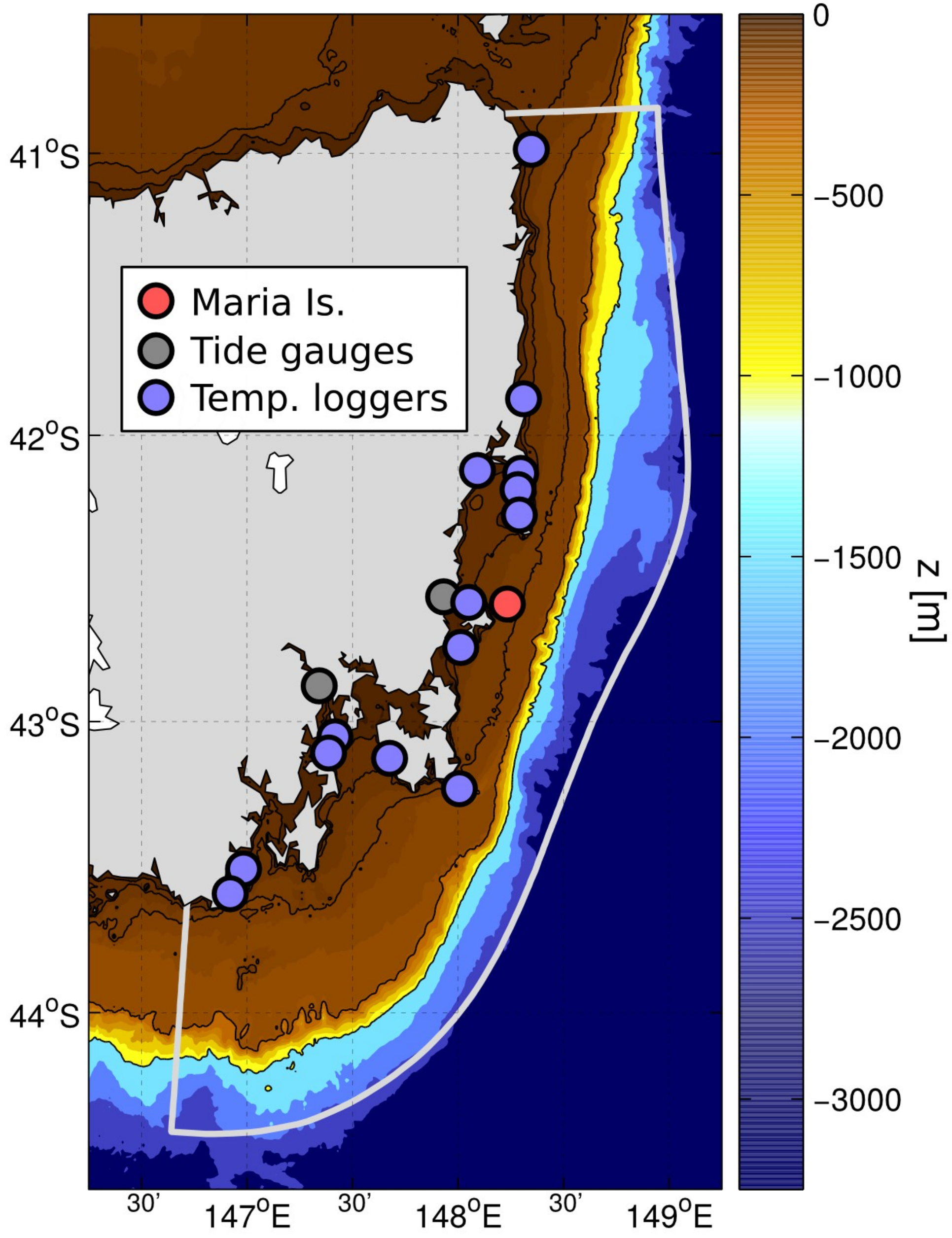
- Near-bottom temperature in 5-20 m water depths
- Daily, 2005 – present

2 Tide gauges (Hobart, Spring Bay) **[BLACK]**

- Sea level
- Hourly and daily, 1985 - 2012

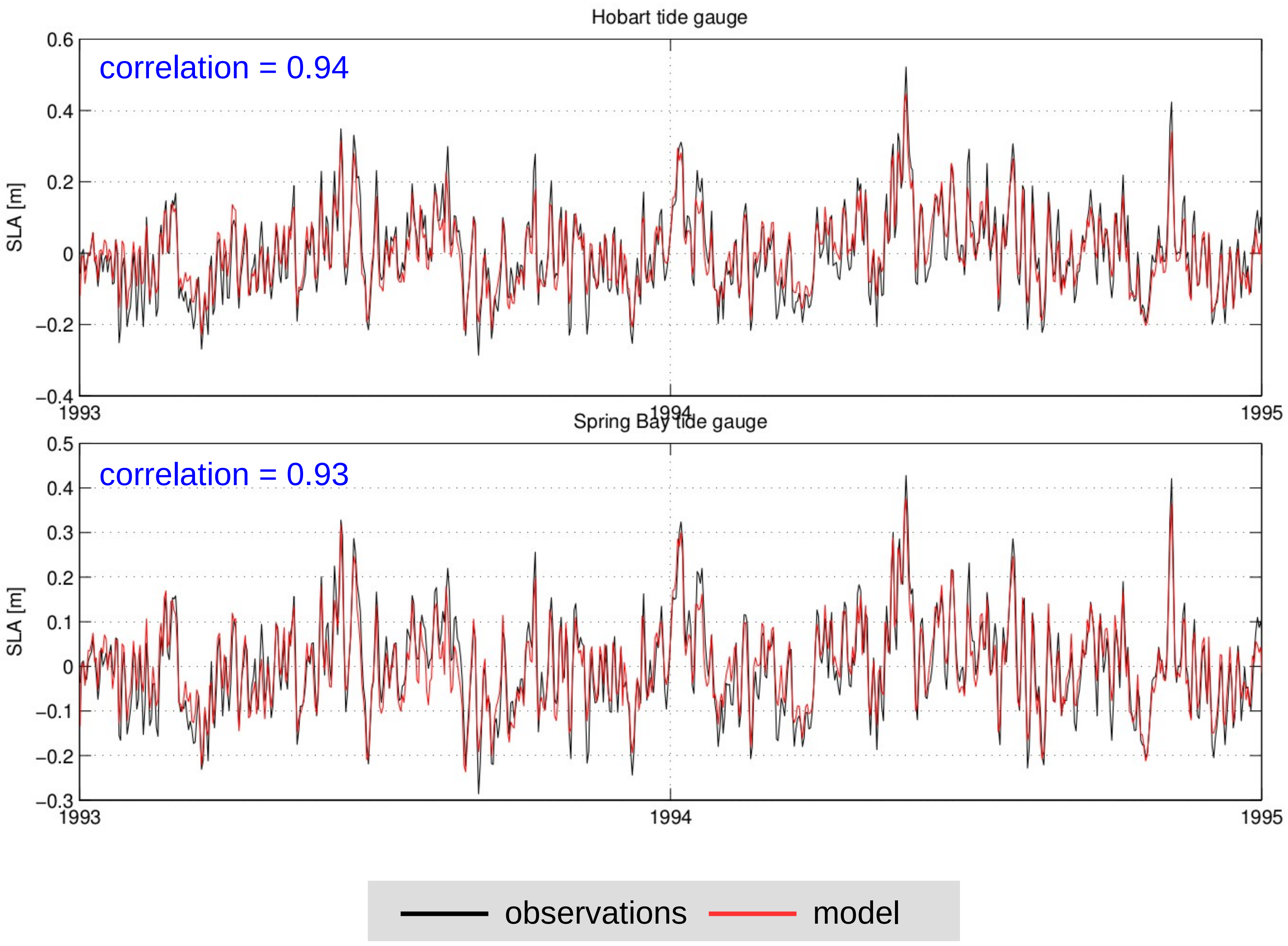
Remotely sensed

AVHRR: daily, 4 km maps, 1980-2012

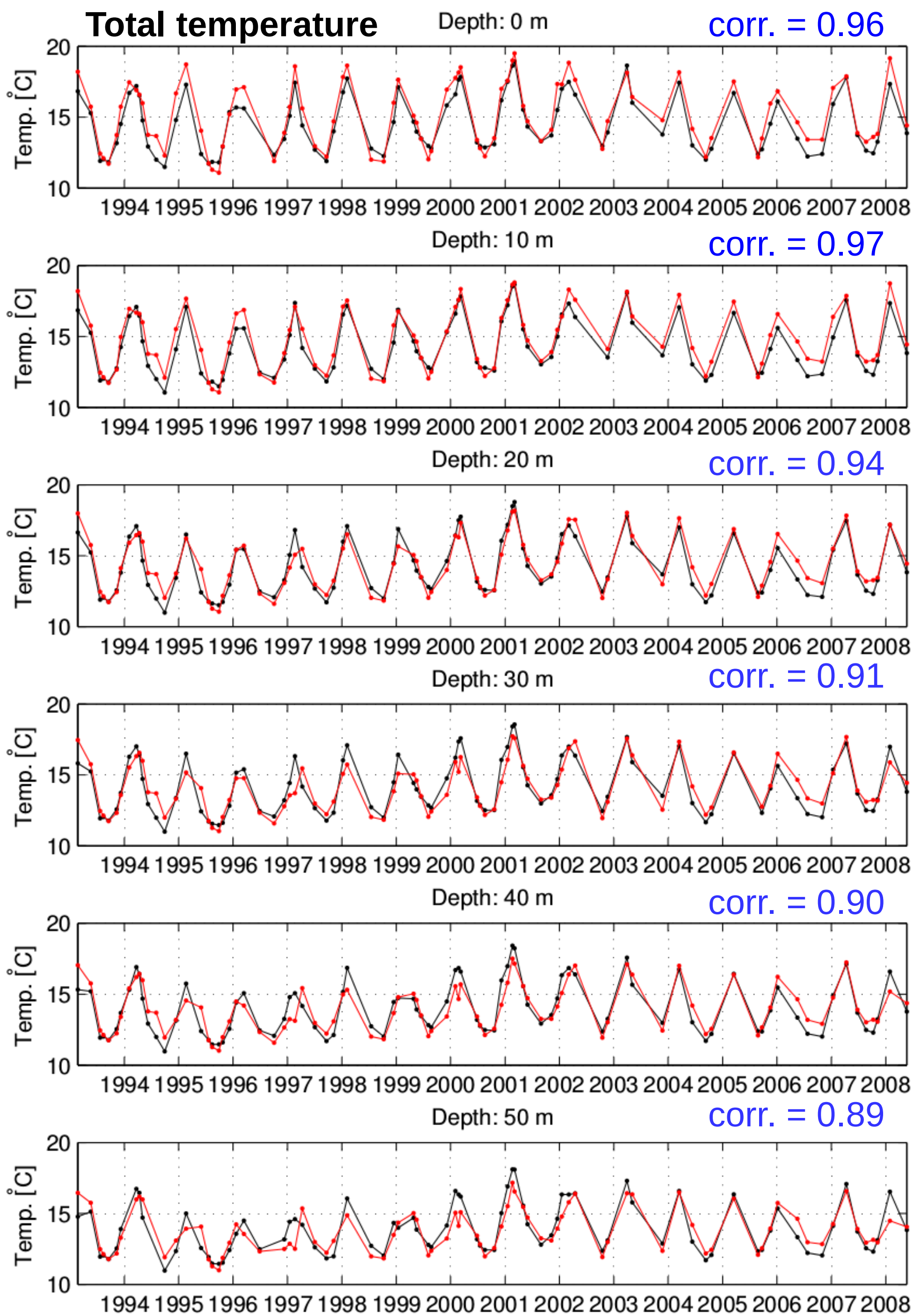


Tide Gauges

- Model captures well sea level at Hobart and Spring Bay tide gauges



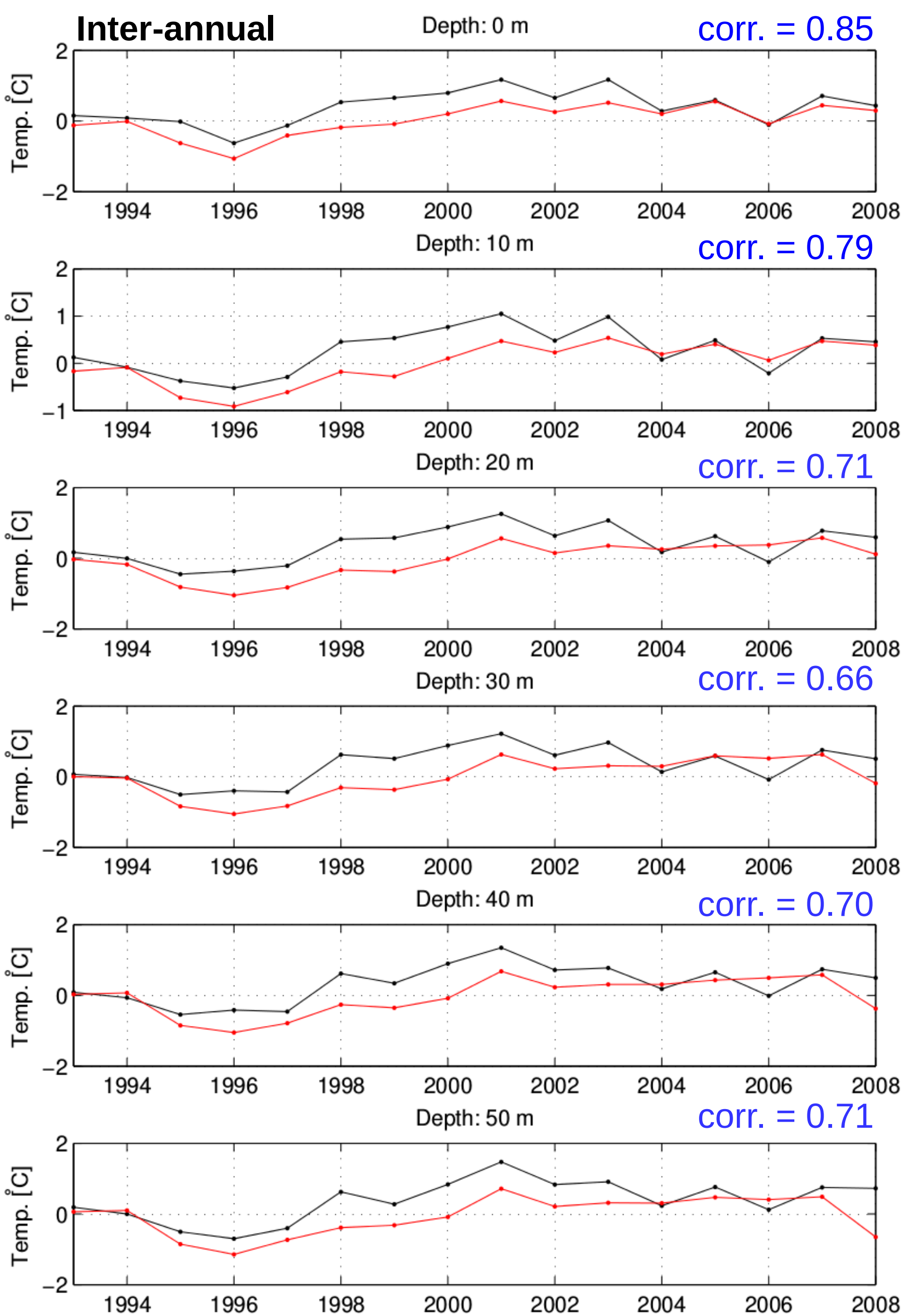
Maria Island Time Series



- **Maria Island Time Series**
- Temperature, model captures well:
  - The total variability at all depths
  - The seasonal cycle
  - The non-seasonal variability

observations model

Maria Island Time Series



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- Temperature, model captures well:
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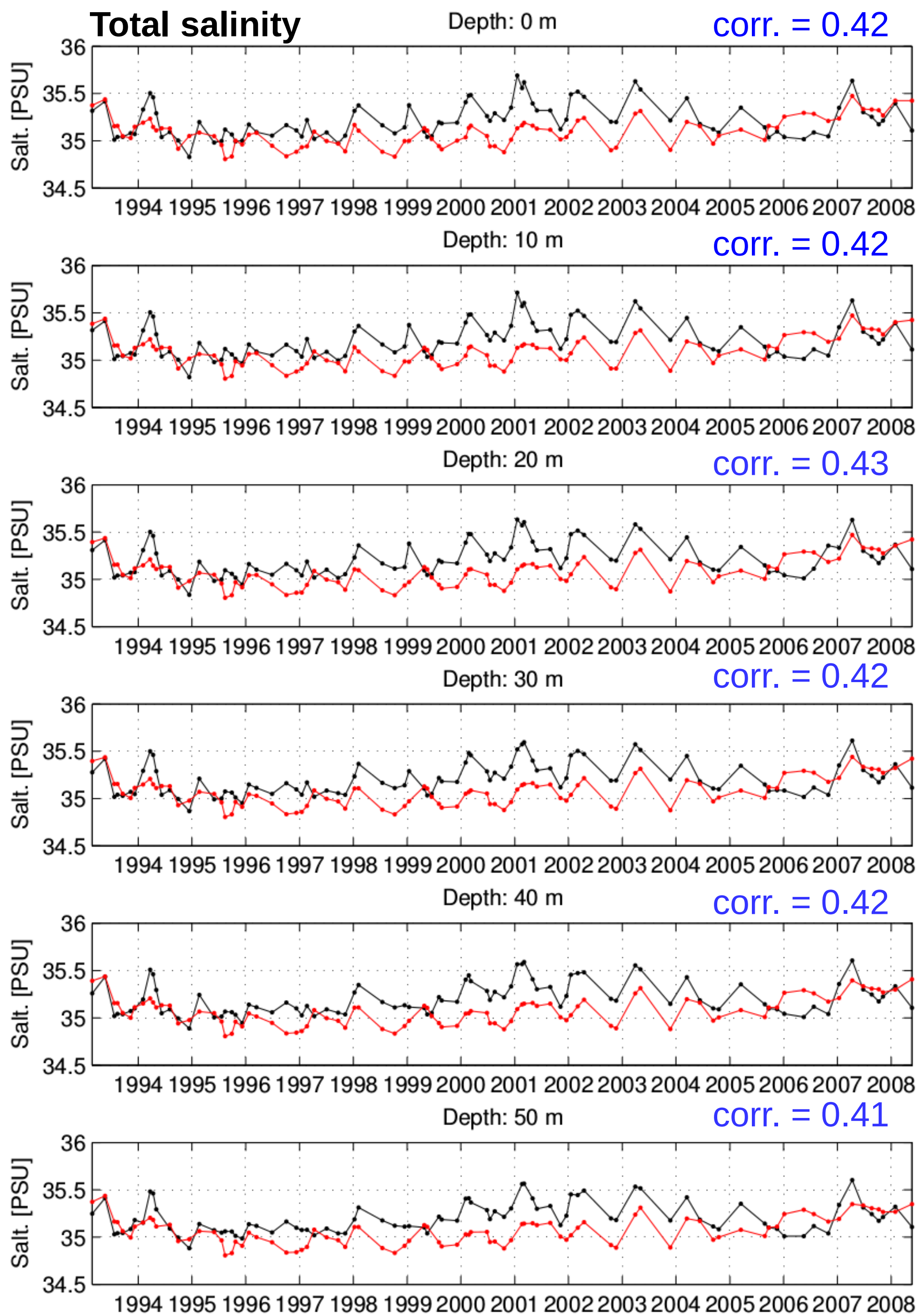
  - The inter-annual variability

observations model

Maria Island Time Series

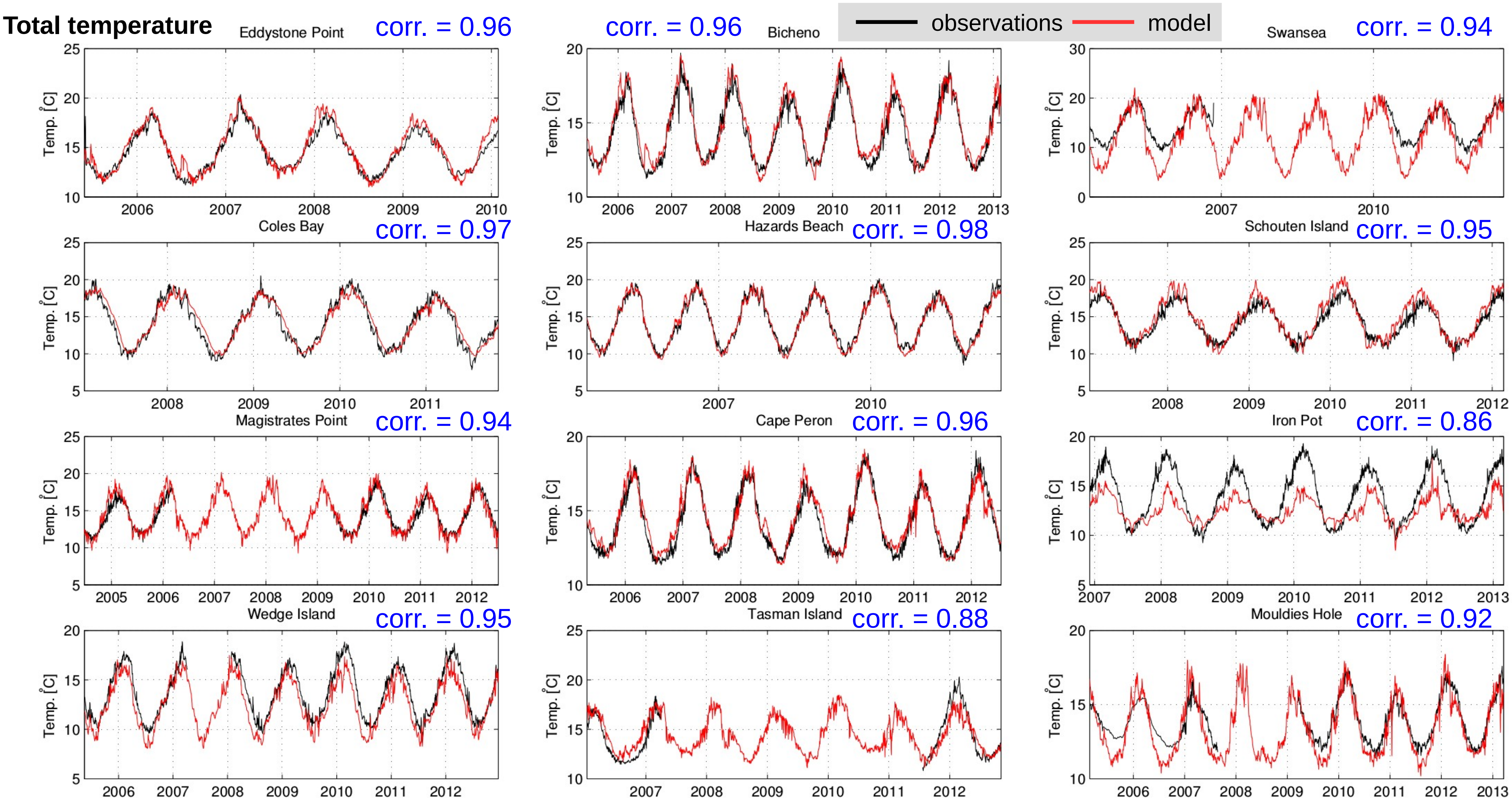


- **Maria Island Time Series**
- Temperature, model captures well:
  - The total variability at all depths
  - The seasonal cycle
  - The non-seasonal variability
  - The inter-annual variability
- Salinity:
  - A notable bias in mean salinity throughout the water column
  - May be related to poor representation of advection in earlier model versions

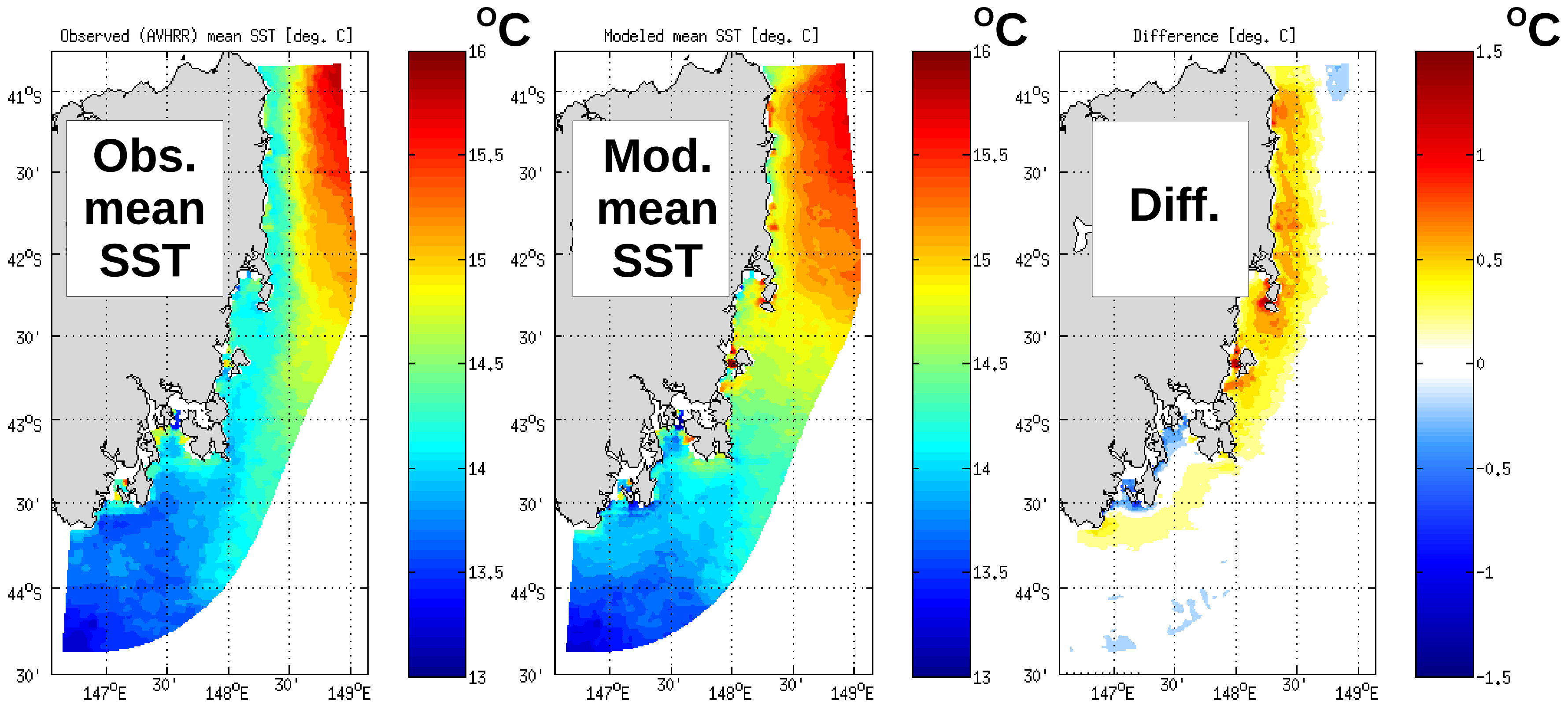
observations model

Near-bottom temperatures

- **Near-bottom temperature loggers**
- Model captures well the total variability, seasonal cycle, and non-seasonal signal



Remotely-sensed SST



- Model captures well mean SST remotely-sensed by AVHRR
- A slight near-shore warm bias (0.5°C) in the northern 2/3 of the domain.

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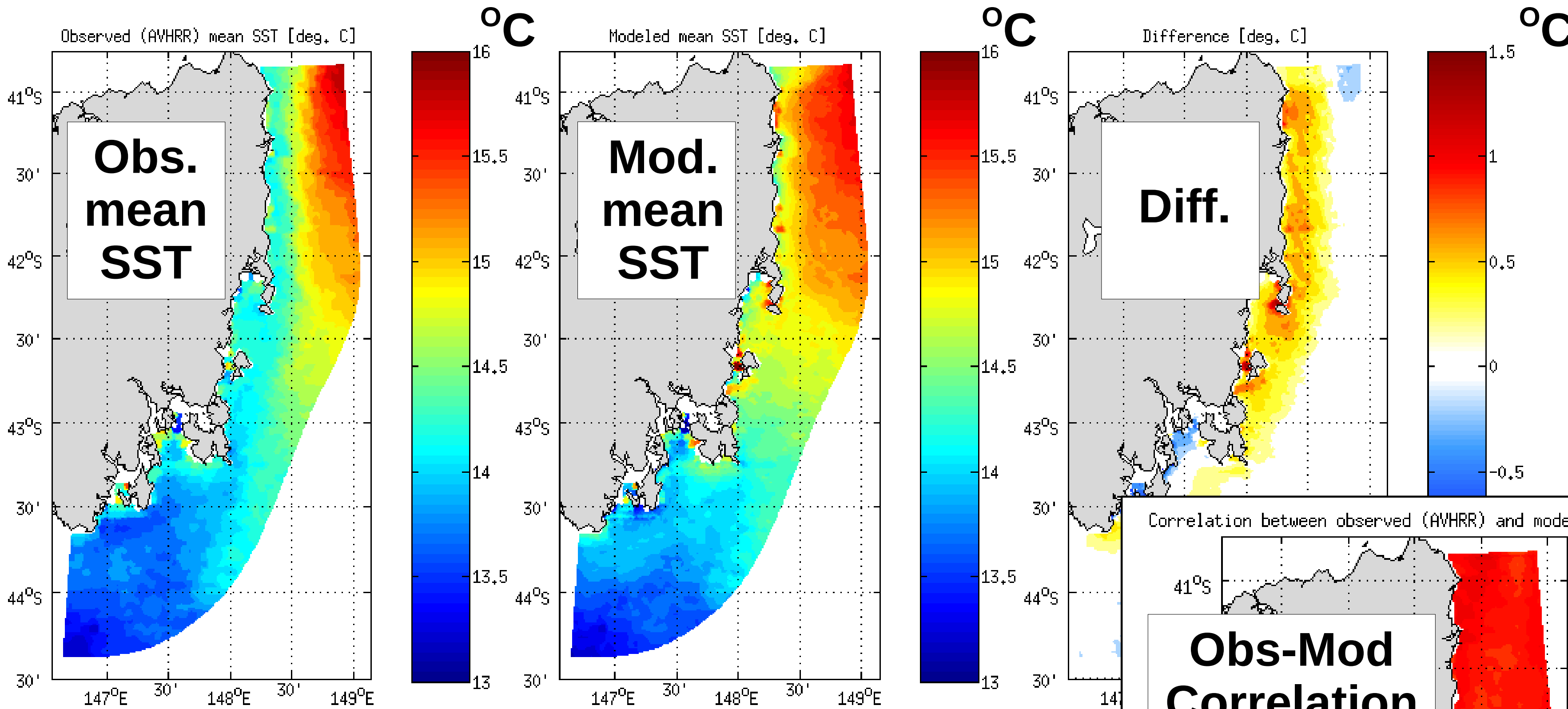
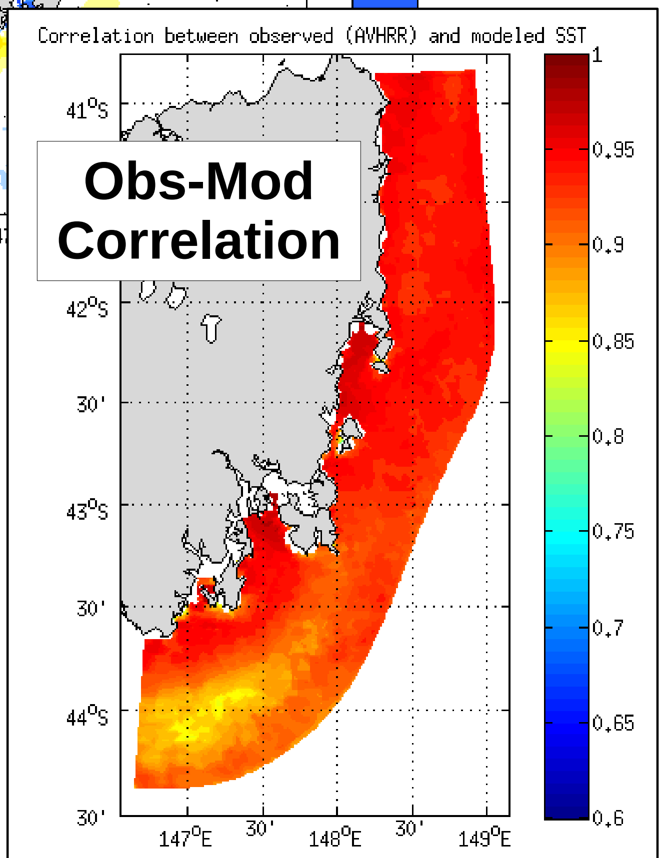
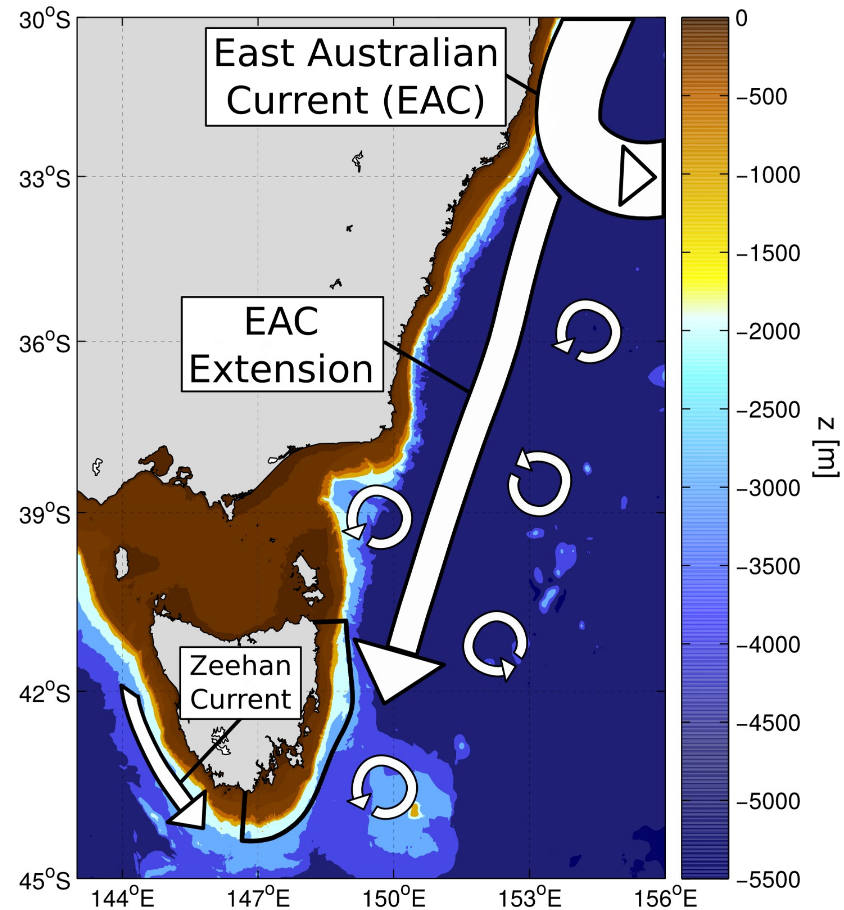


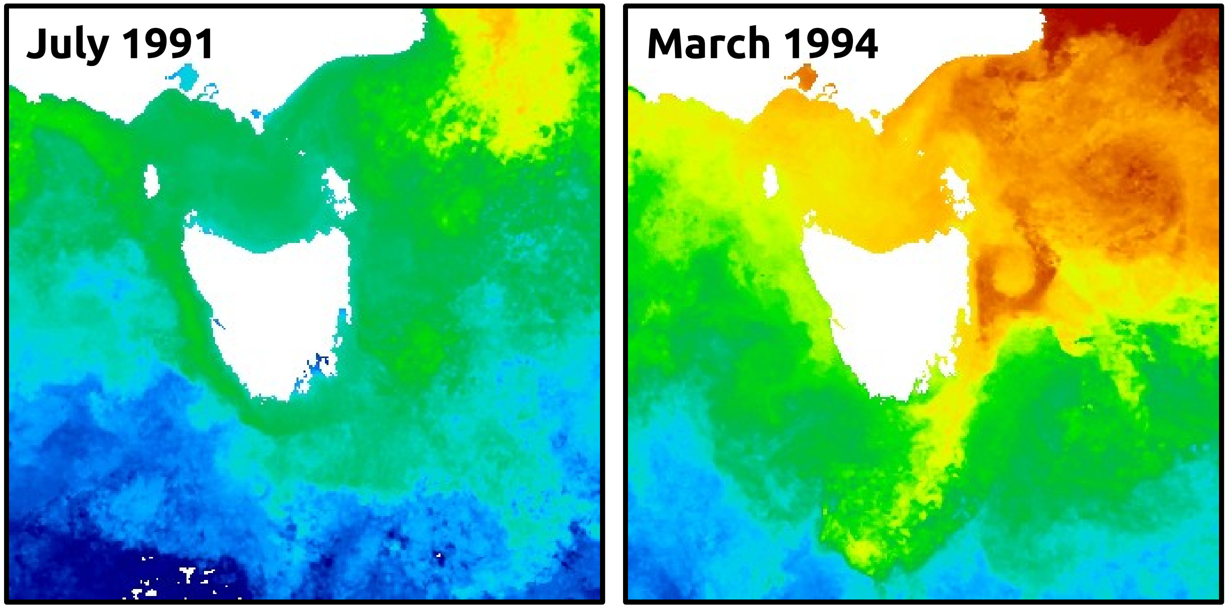


- Model captures well mean SST remotely-sensed by AVHRR
- A slight near-shore warm bias (0.5°C) in the northern 2/3 of the domain.
- Remotely sensed SST variations are also well captured with correlations generally >0.85.

The Zeehan Current

- **East Australian Current (EAC)**, a quasi-steady western boundary current, separates from the coast ~33^{O}S.
- The **EAC Extension** continues southward transport as far as Tasmania, but as an unsteady, eddy-rich "current"
- The **Zeehan Current**, part of a current system extending all the way to WA, runs southward and eastward along the west and south coasts of Tasmania [Ridgway and Condie, 2004]



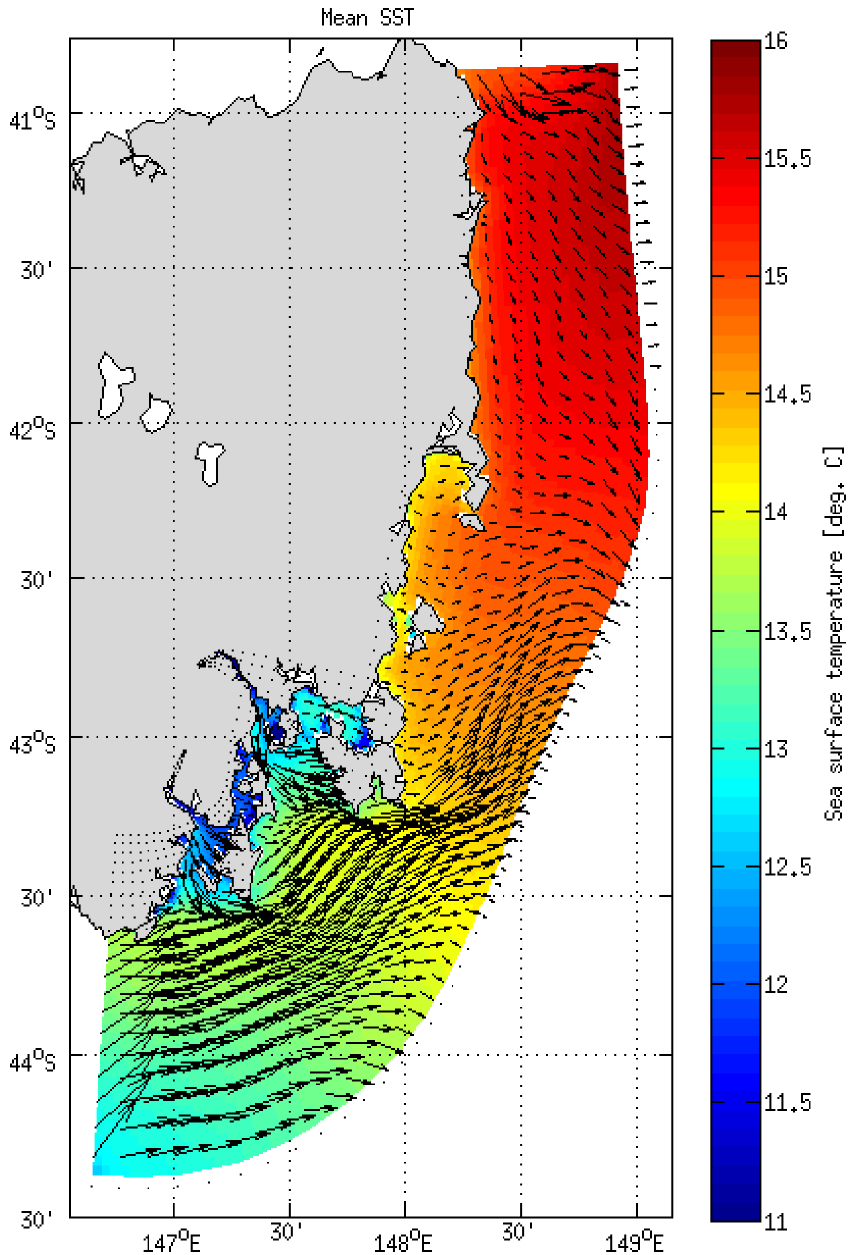


http://www.marine.csiro.au/~lband/yacht_races/yyzeecur.html

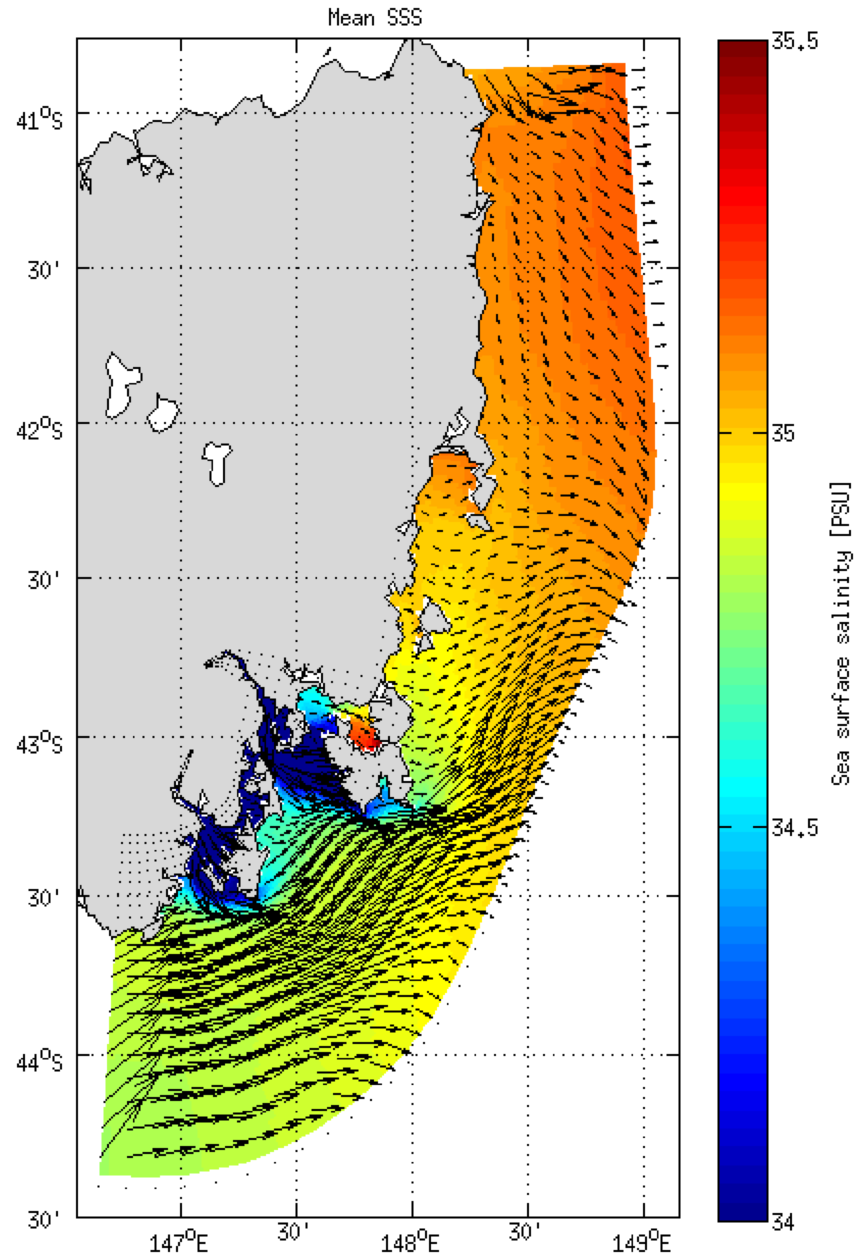
- Along the southeast coast of Tasmania, the **EAC Extension is dominant in summer** and the **Zeehan Current is dominant in winter**

Surface Climatology

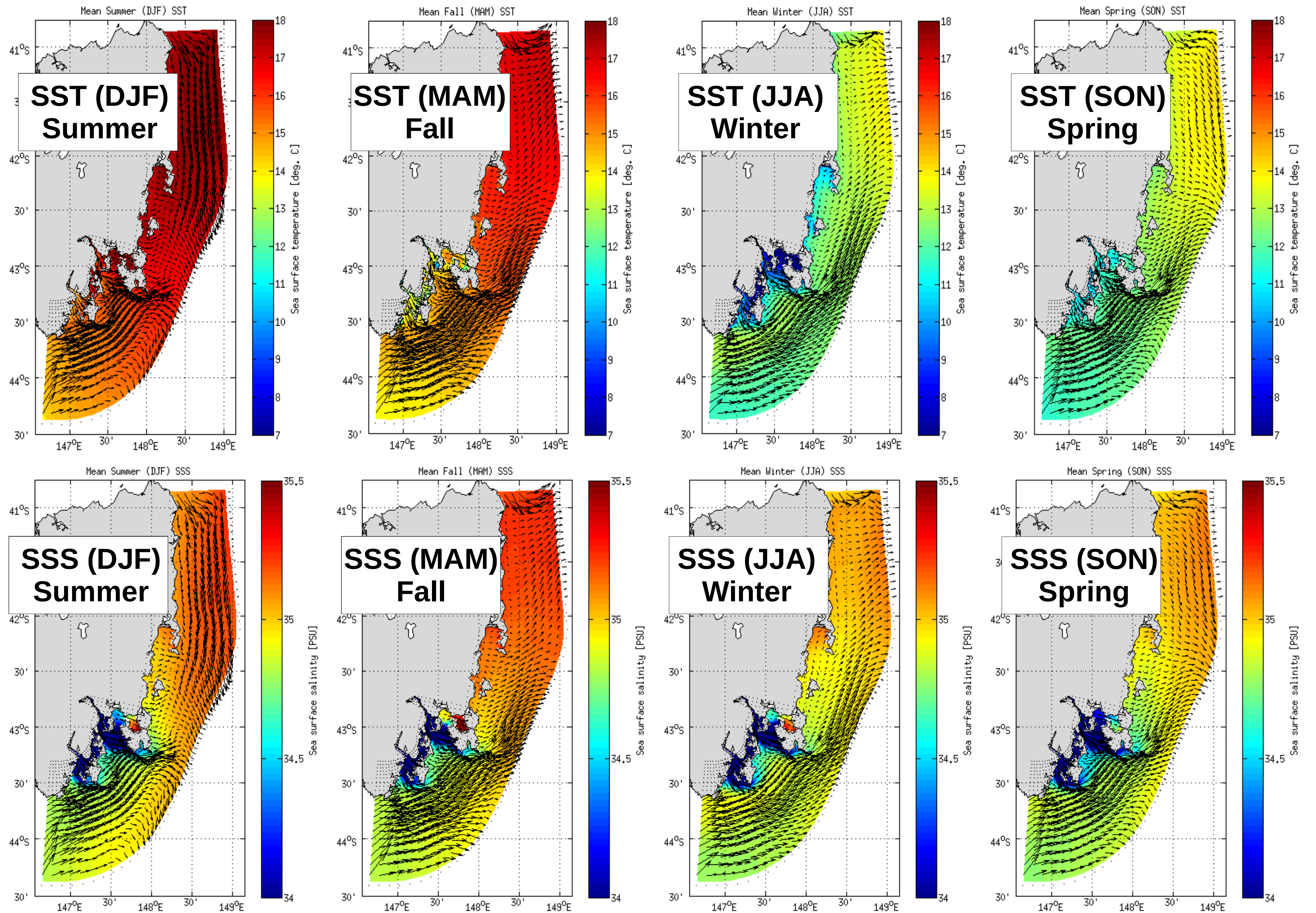
Mean SST and Circulation



Mean SSS and Circulation



Seasonal Climatology



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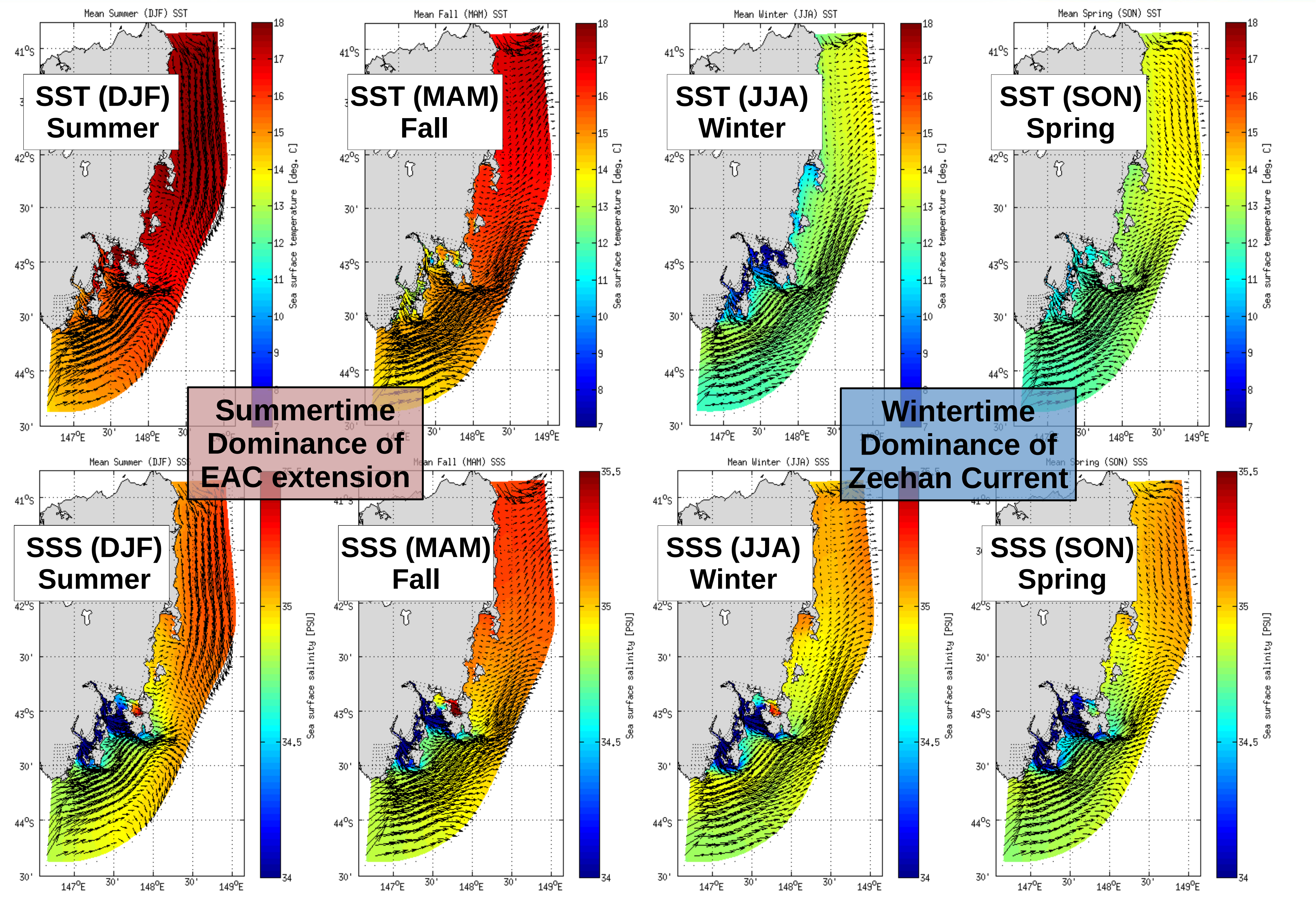
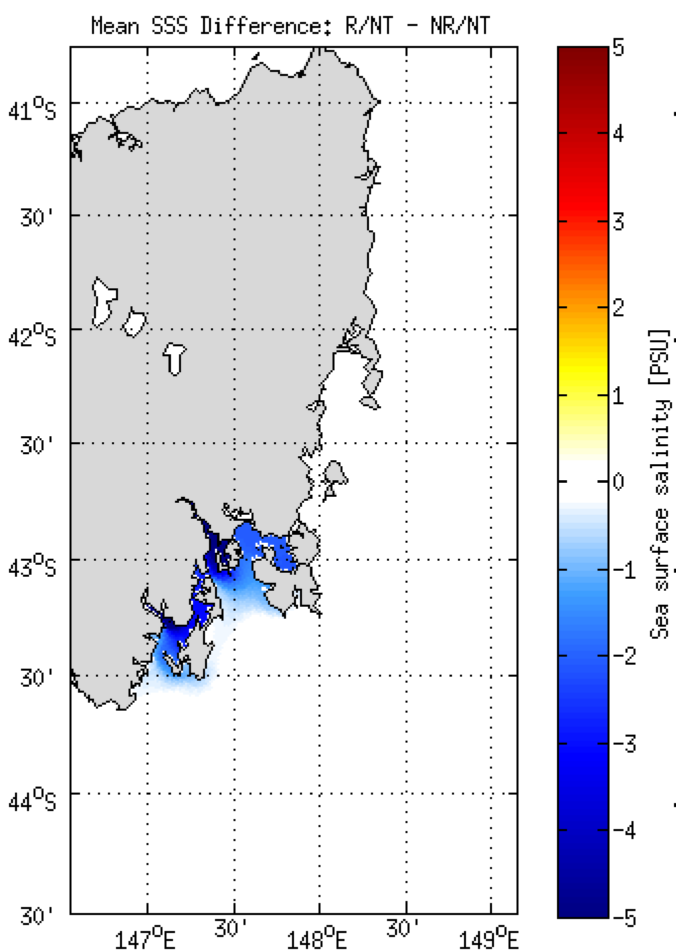
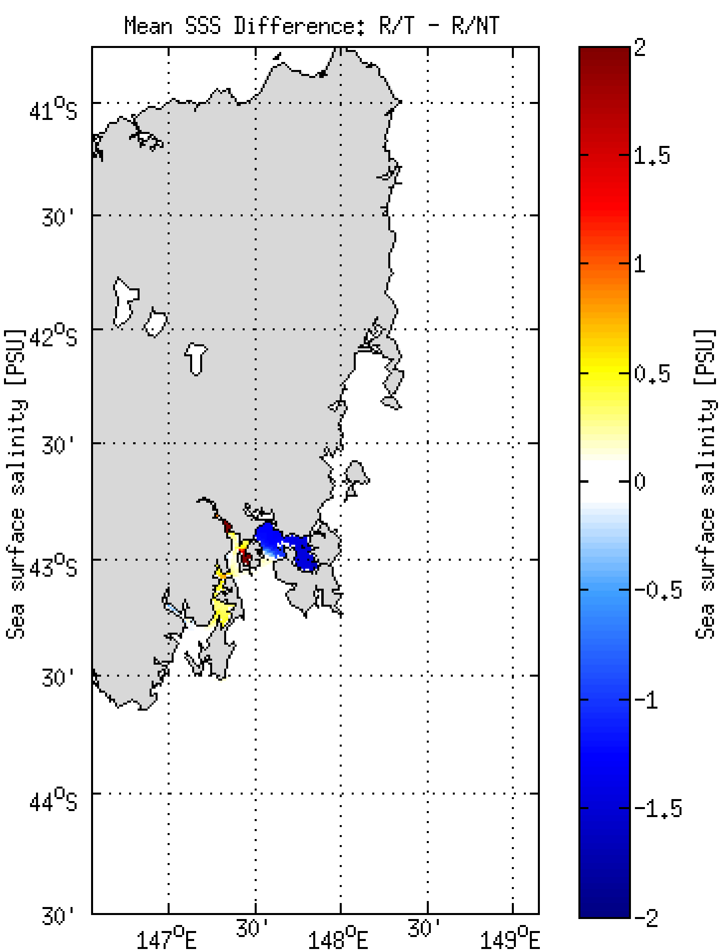


Roles of tides and rivers

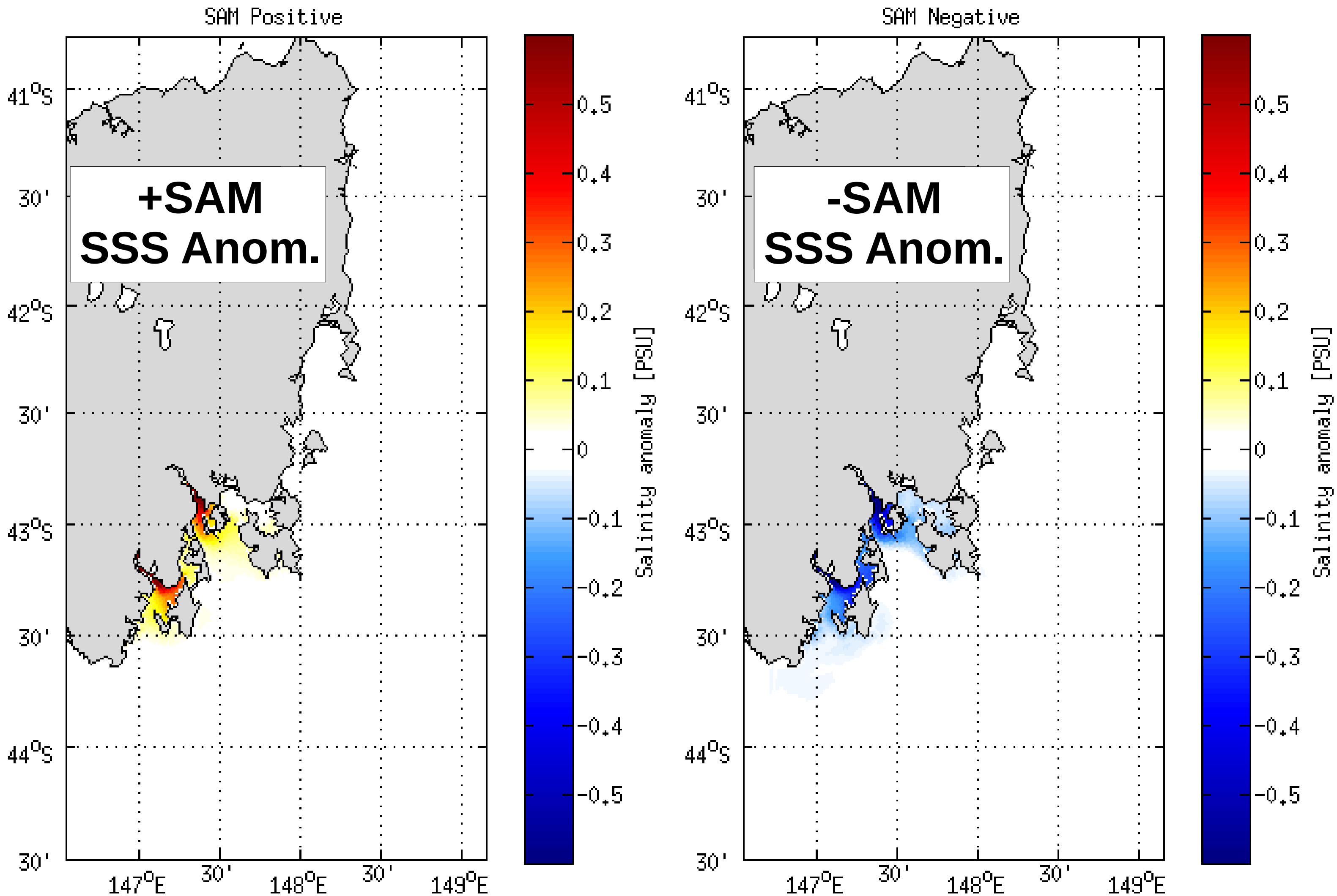
- **Role of the rivers** (*R/NT – NR/NT*):
  - Reduced salinity in Derwent and Huon estuaries
  - Presence of Derwent cools while the Huon warms (not shown)
- **Tidal interactions** (*R/T – R/NT*):
  - Tide-River interactions can be significant in and around river estuaries, Note: Frederick Henry Bay and Norfolk Bay





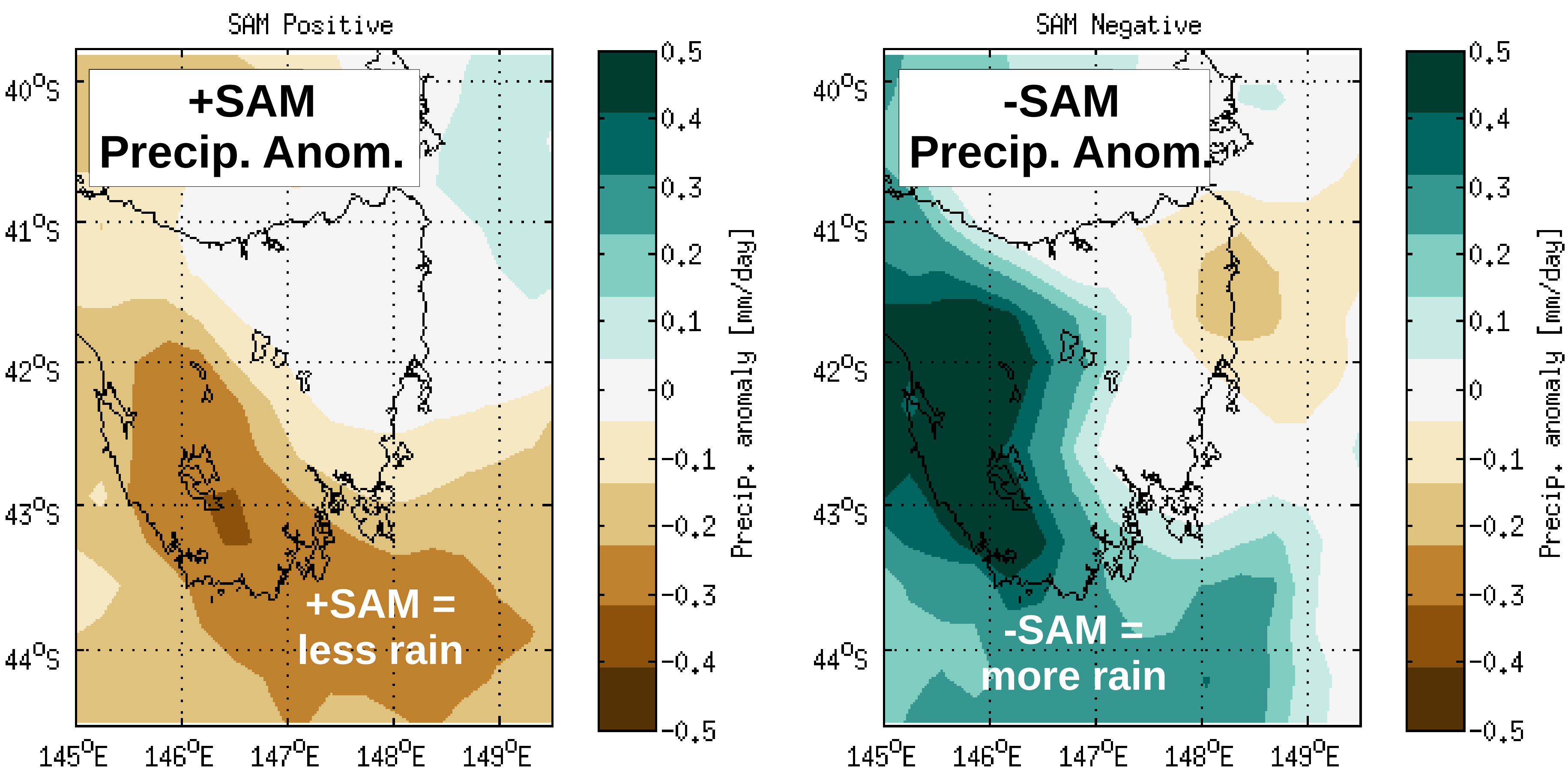
Modes of Variability

- Composite averages show a strong signature of **Southern Annular Mode (SAM)** on marine climate
- +SAM leads to increased salinity in the Derwent and Huon estuaries while -SAM leads to decreased salinity



Modes of Variability

- Composite averages show a strong signature of **Southern Annular Mode (SAM)** on precipitation over the catchment
- +SAM leads to decreased rainfall while -SAM leads to increased rainfall over SW Tasmania



Conclusions – Part II

- **ETAS** model compares well against observed coastal sea level, historical Maria Island time series, near-bottom temperature at a number of sites, and remotely-sensed SST across the shelf
- Model captures **seasonal alternation** between dominance of Zeehan Current in Winter (JJA) and EAC Extension in Summer (DJF)
- Roles of rivers, tides, and climate modes:
  - **Rivers** freshen and cool estuary waters
  - **Tides** can interact with the rivers in a complex way
  - **Climate mode (SAM)** plays a role in modulating near-shore marine climate through precipitation and thus river inputs
- **Future work**: relative role of surface and boundary forcing, interaction between off-shore eddies and the shelf, influence of ENSO and Tasman Sea blocking, modulation of shelf circulation by climate modes

Acknowledgements

- **Neil Holbrook** (IMAS) – post-doc supervisor
- **Simon Wotherspoon** (IMAS) – statistics mathemagician
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IMAS INSTITUTE FOR MARINE AND ANTARCTIC STUDIES

UTAS

Australian Government
Australian Research Council

Publications

Oliver, E. C. J. and N. J. Holbrook (2014), Extending our understanding of South Pacific gyre 'spin-up': Modeling the East Australian Current in a future climate, *Journal of Geophysical Research*, 119, 2788-2805

Oliver, E. C. J., S. J. Wotherspoon and N. J. Holbrook (2014), Estimating extremes from global ocean and climate models: A Bayesian hierarchical model approach, *Progress in Oceanography*, 122, 77-91

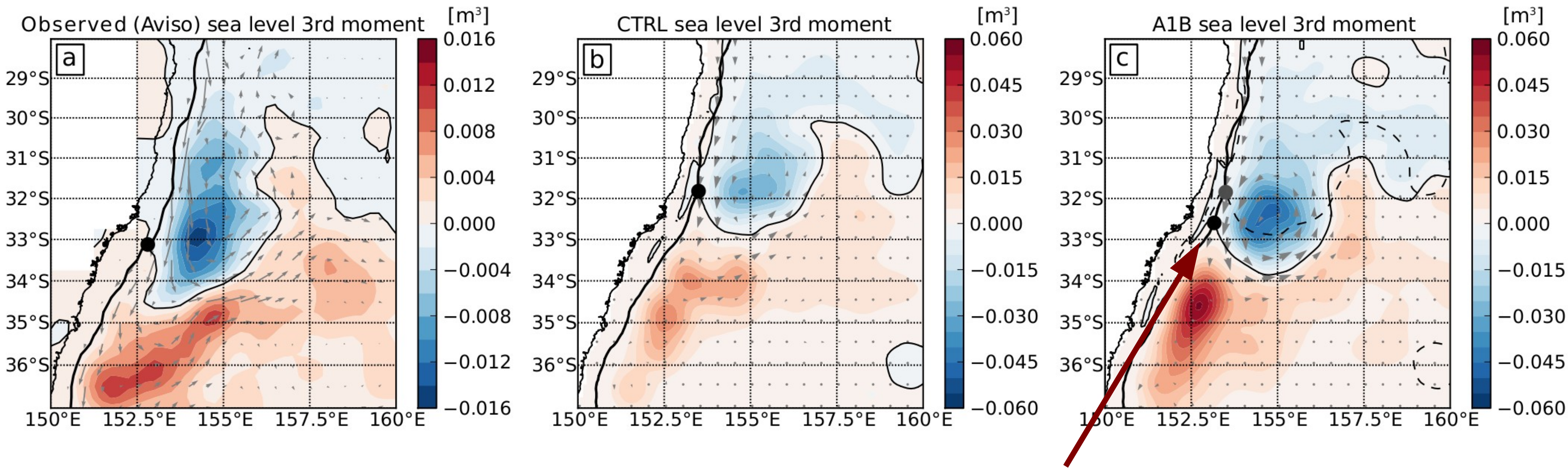
Oliver, E. C. J., S. J. Wotherspoon, M. A. Chamberlain and N. J. Holbrook (2014), Projected Tasman Sea extremes in sea surface temperature through the 21st century, *Journal of Climate*, 27(5), 1980-1998

Oliver, E. C. J. and N. J. Holbrook (2014), A statistical method for improving continental shelf and nearshore marine climate prediction, *Journal of Atmospheric and Oceanic Technology*, 31, 215-232

Extra Slides…

EAC Separation Point

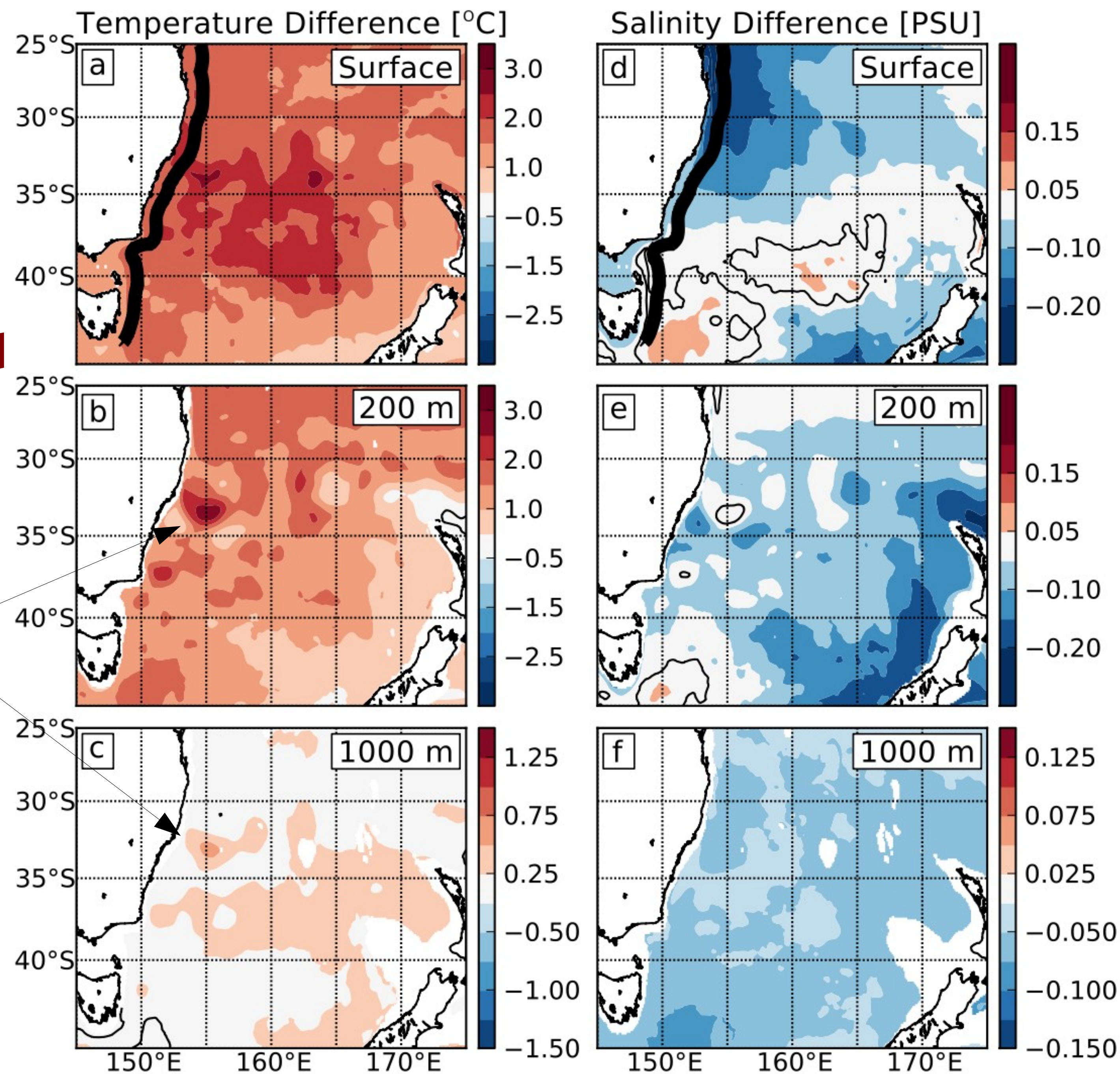
- The third moment of sea level (sea level skewness) can be used to map the mean path of a meandering jet, such as western boundary currents [Thompson and Demirov, 2006]
- The intersection of the mean jet path with the shelf break is used as a rough indicator of the mean EAC separation point



Approx 90 km southward shift in EAC separation

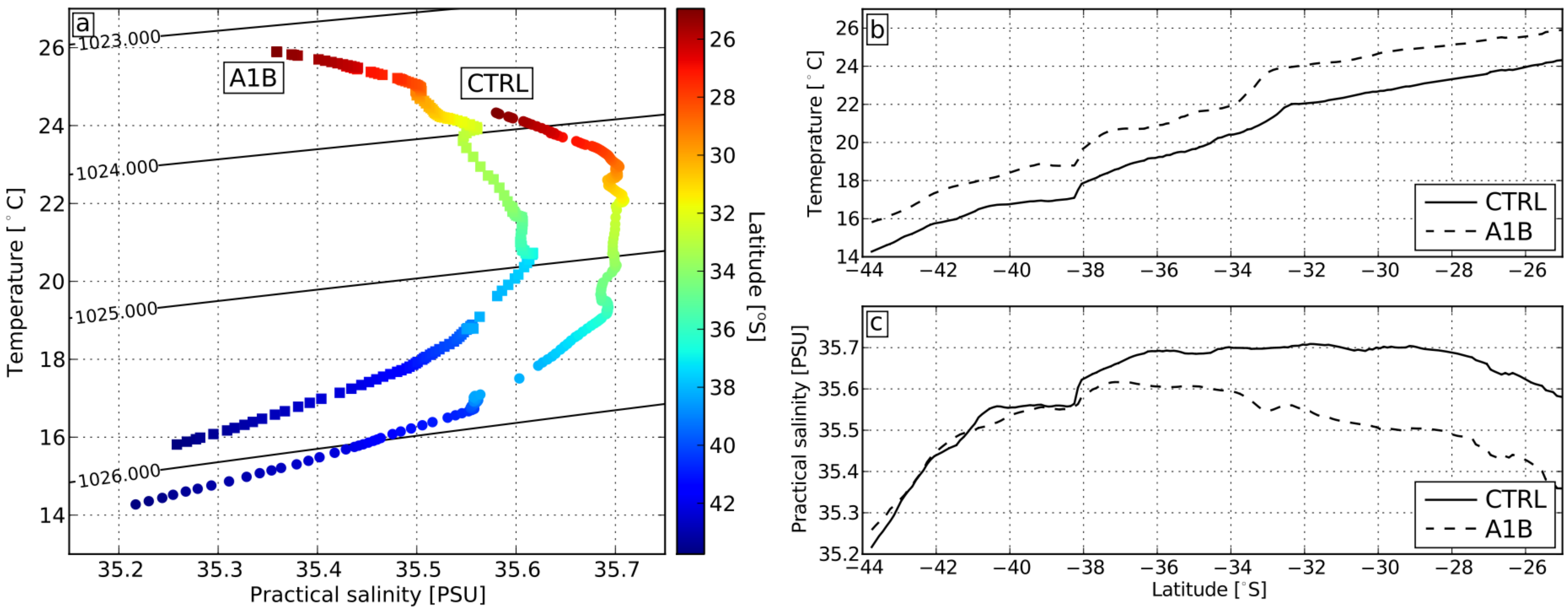
Changes at Depth

- Changes present throughout the water column: a general warming and freshening of the Tasman Sea
- Deepening of EAC anticyclonic recirculation near separation point?



Shelf Break

- Surface changes along the shelf break indicate a consistent warming of ~2^{0}C and freshening only north of Bass Strait and increasing with latitude



Model Stationarity

Fundamental relationship

We posit that there exists a relationship between the extremes and climate parameters $\mathbf{X}$:

$$\text{“extremes“} = f(\mathbf{X})$$

This relationship expresses fundamental aspects of the climate system which do not change with time.

Role of βs and τs

Effectively, we have performed a linear approximation to $f(\mathbf{X})$:

$$f(\mathbf{X}) = \mathbf{X}\beta + O(\mathbf{X}^2)$$

Therefore, the βs (and τs) are stationary since $f(\mathbf{X})$ is stationary

River Input

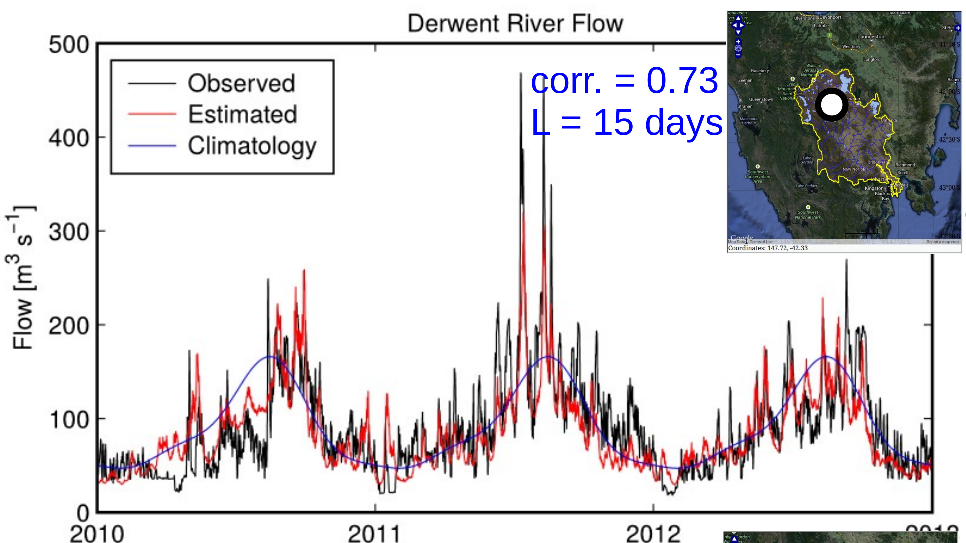
- We also require river input (flow rate and water temperature) for the two major rivers in SE Tasmania: Derwent River and Huon River
- We have observed records of flow (m^3/s) and water temp for both rivers, but records very short and very recent (Nov/2009 -late/2013; shorter for temp) and we require these quantities over the entire 1993-2013 period
- Therefore, we modeled river flow (F) using precipitation (P) over the river catchments (from CFSR/CFSv2) as a predictor in a multiple lag-regression model:

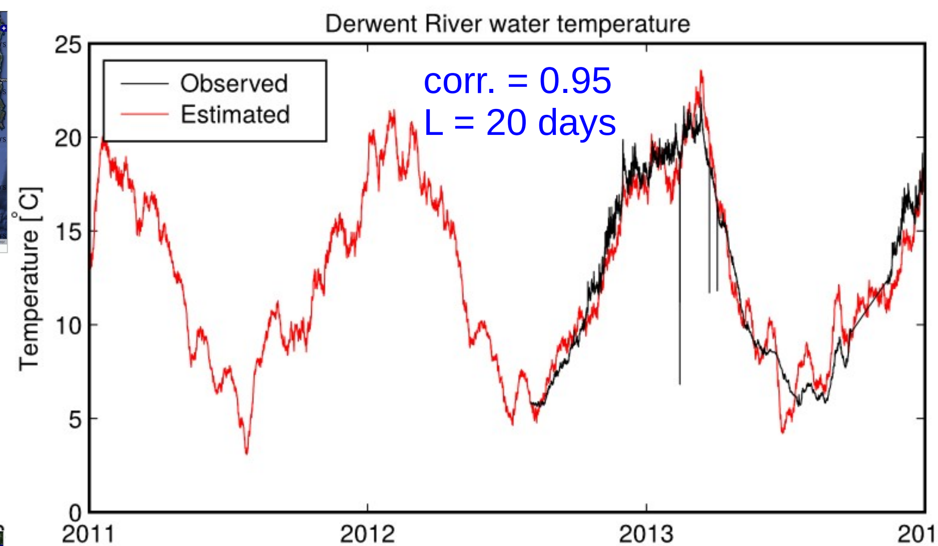
$$\log(F_t) = \alpha + \sum_{l=0}^{L} \beta_l \log(P_{t-l})$$

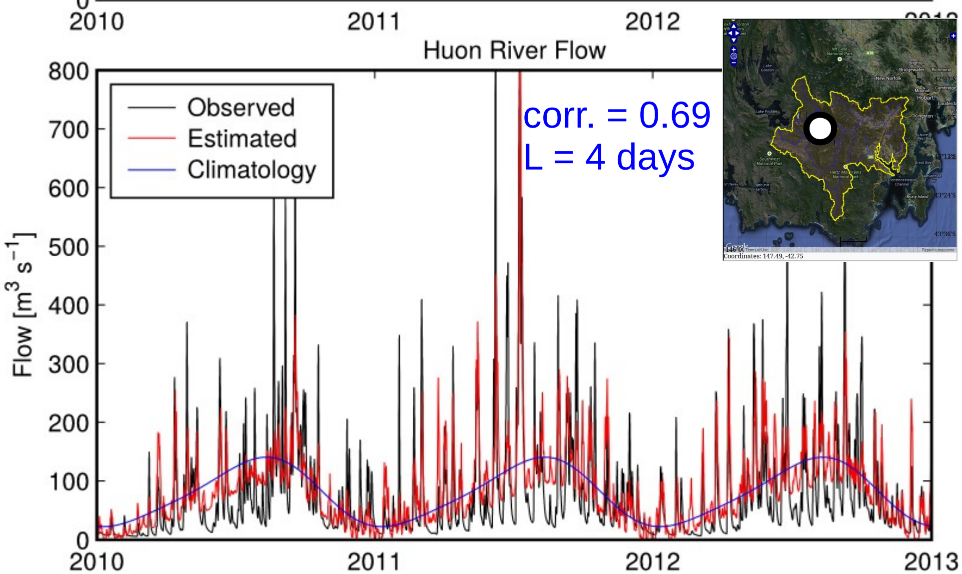
  And a similar model (without log-transforms) to estimate river temperature from local air temperature
- A two-fold cross-validation was performed to determine which value of L provided the best fit
- Given a satisfactory fit, we used historical precipitation and air temperature from CFSR/CFSv2 to reconstruct river flow and temperature over the entire 1993-2013 period

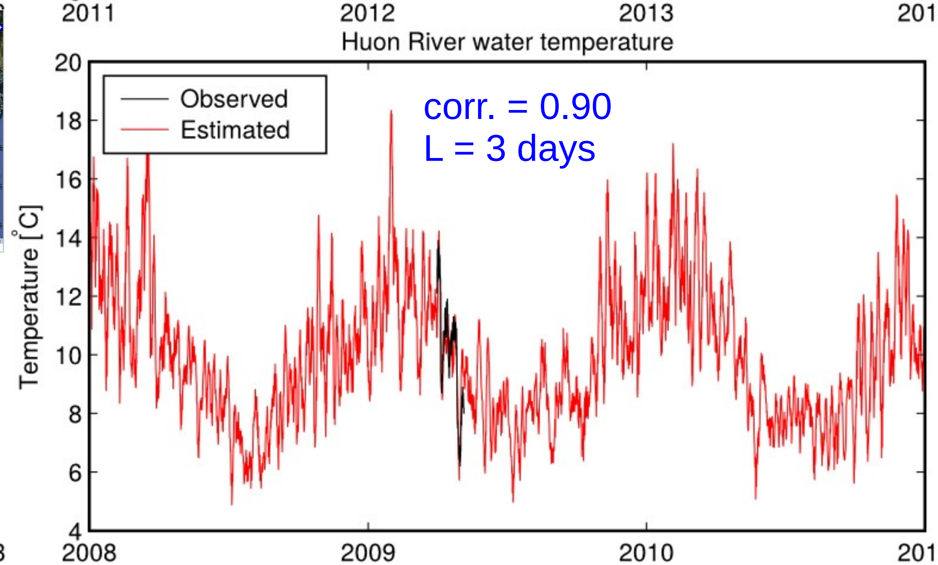
River Input

- River input (flow rate and water temperature) required for Derwent River and Huon River
- River inputs predicted from precipitation and air temperature using a lag-regression model and then reconstructed over 1993-2013









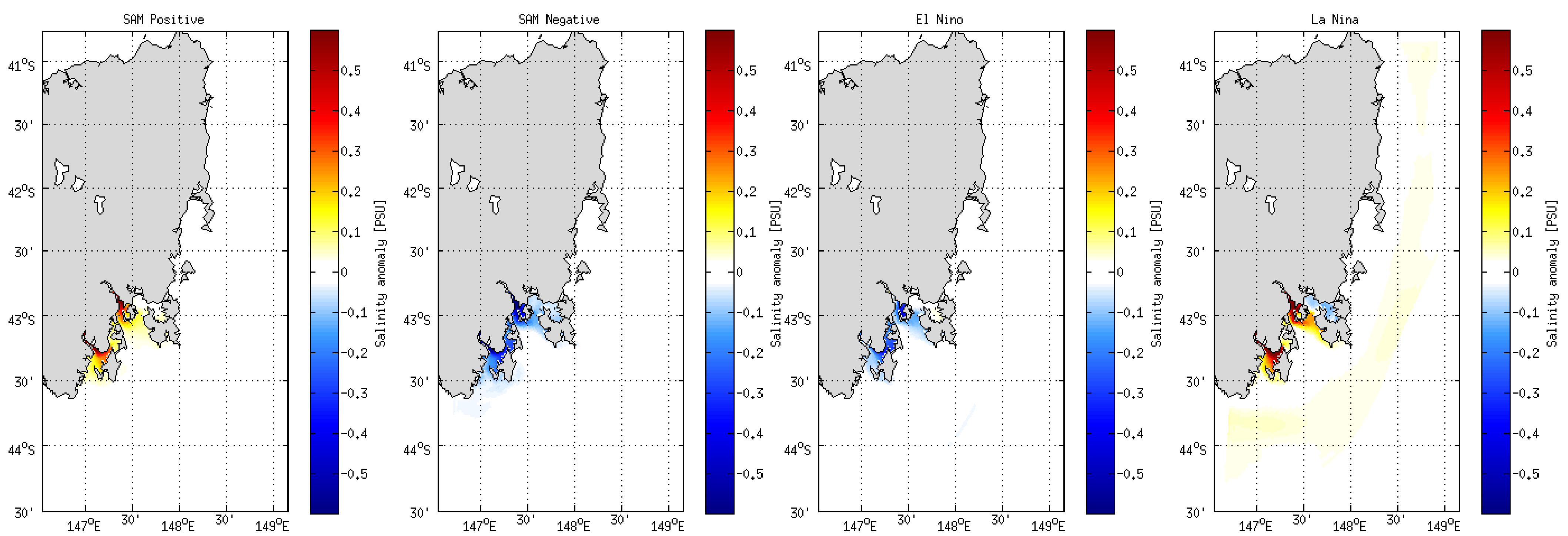
Hindcast Simulations

- Spin-up: model was spun up for 5 years using normal year forcing*, initialized from Bluelink on 1/1/1993
- Historical hindcast: model was then forced by realistic forcing over the 1993-2013 period
- Four runs were performed for all combinations
  - **with and without tidal forcing (T and NT)**, and
  - **with and without river inputs (R and NR)**
  - The **base run for validation** was with river input and no-tides (R/NT)

* NYF: climatological seasonal cycle, subseasonal variability from 1995, mean of 1993; following *Large and Yeager (2004)*; rivers are climatological only

Modes of Variability

- Composites of surface salinity modes of climate variability show a strong signature of **ENSO** and **SAM** on marine climate
- +SAM and La Nina lead to increased SSS in the Derwent and Huon estuaries while -SAM and El Nino lead to decreased SSS
- Signal disappears in NR runs: must be **related to river input**
- SAM and ENSO are related to a +/- 6–8 m^3/s modulation of river flow, which is up to 10% of the mean flow

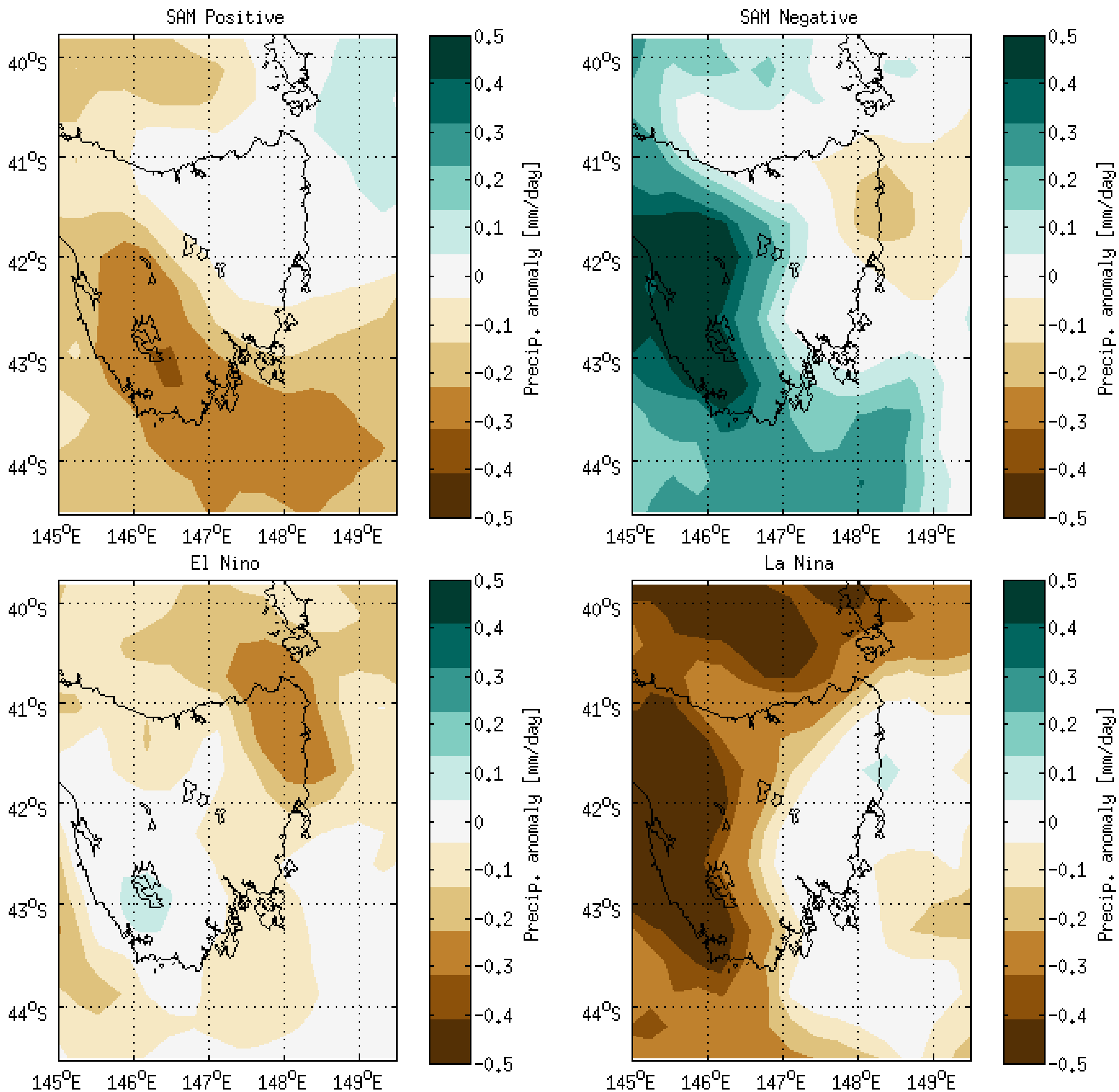


Modes of Variability

- Clearly related to SAM/ENSO relationship with precipitation over river catchments:

+SAM = less rain

-SAM = more rain



El Nino = more rain

La Nina = less rain