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Predicting the changing marine climate, circulation and extremes off southeastern Australia into the 21st century

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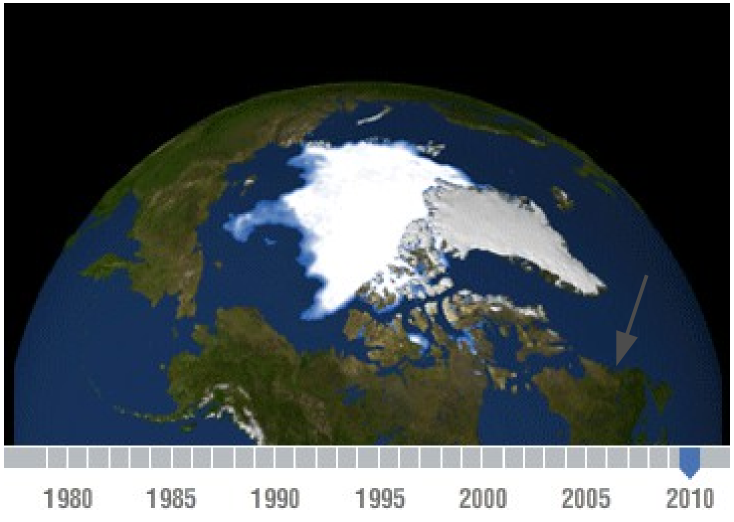
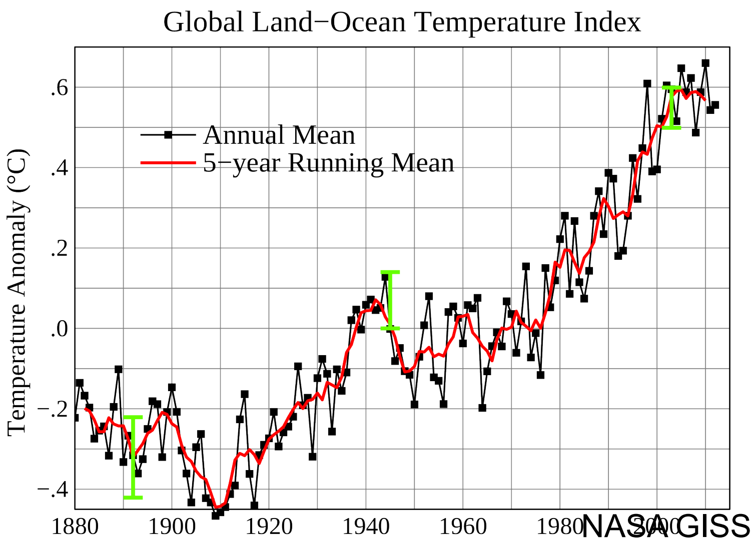
translatingnatureintoknowledge

Changing climate

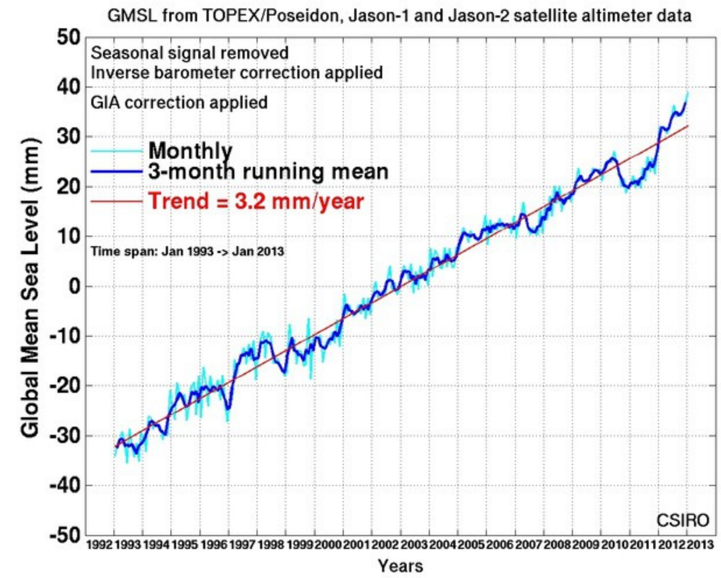
- The Earth is warming at an unprecedented rate
- Much of this warming can be linked to Human-related activities and projecting future warming is a major research area
- However, many aspects of the climate are changing in addition to air temperatures: sea level, sea temperature, circulation, habitat distribution

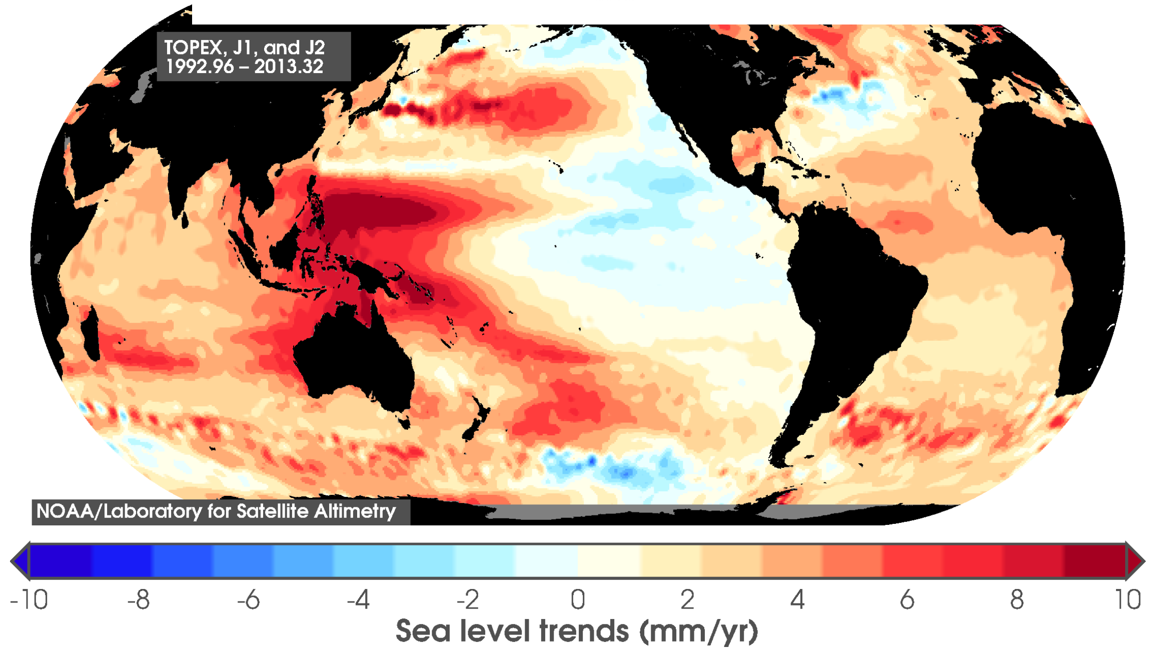




Marine climate change

- <u>Sea level</u>
  - Changes are occurring globally at a rate of ~1.7 mm/yr since 1950 and ~3 mm/yr since 1993.
  - Heterogeneous in space, e.g., change in West Pacific due to trade winds
  - Leads to elevated risk for coastal communities





http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html

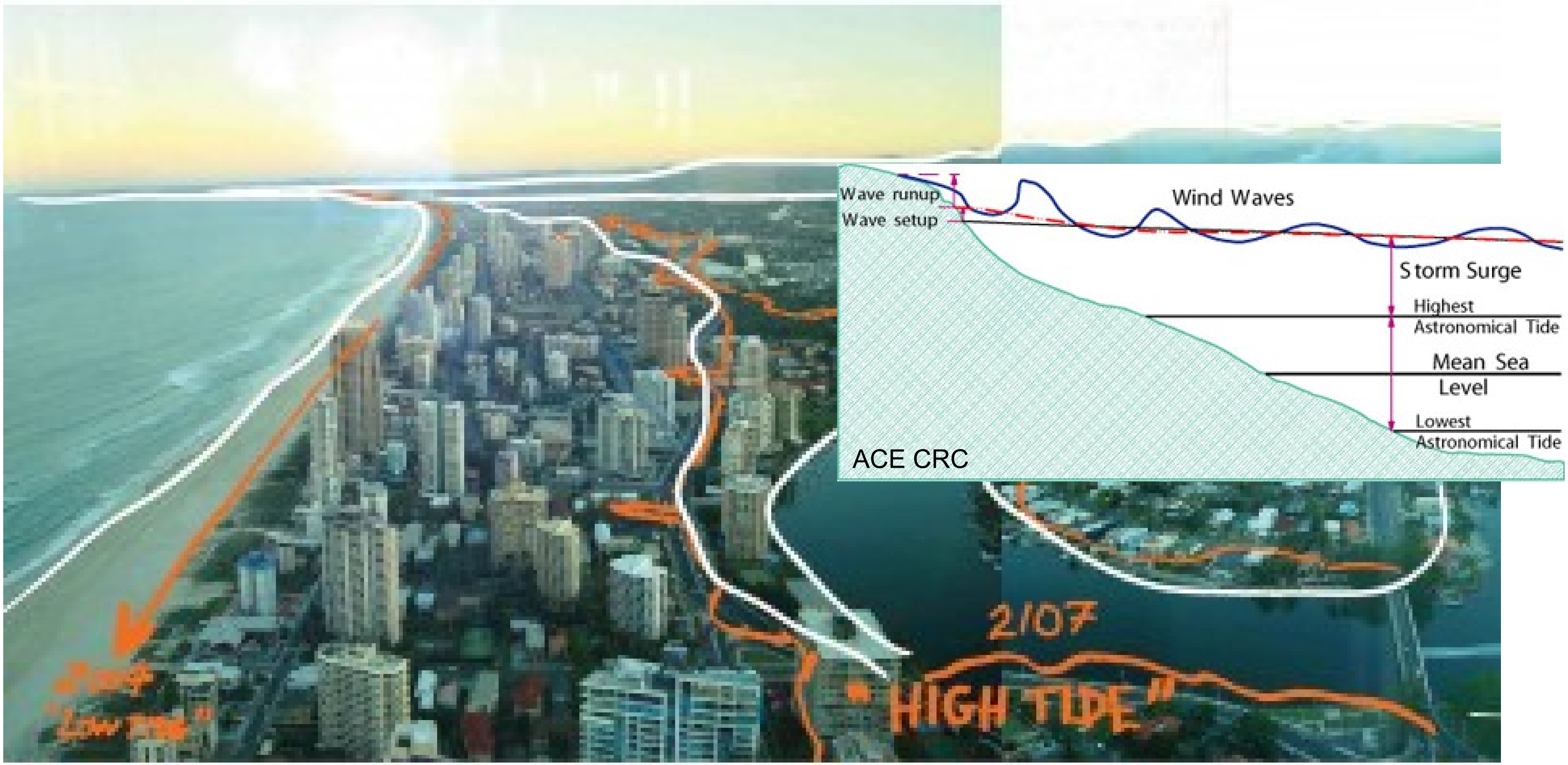
Marine climate change

Projected 2107 "low tide" and "high tide" for the Gold Coast

AECOM Research

Marine climate change

Projected 2107 “low tide” and “high tide” for the Gold Coast



AECOM Research

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Marine climate change

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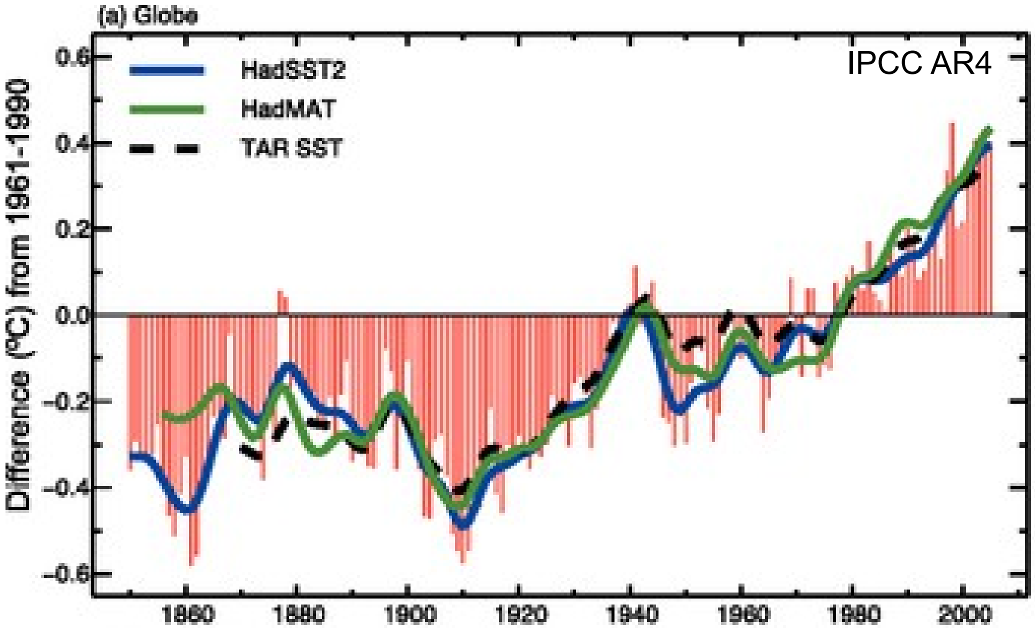
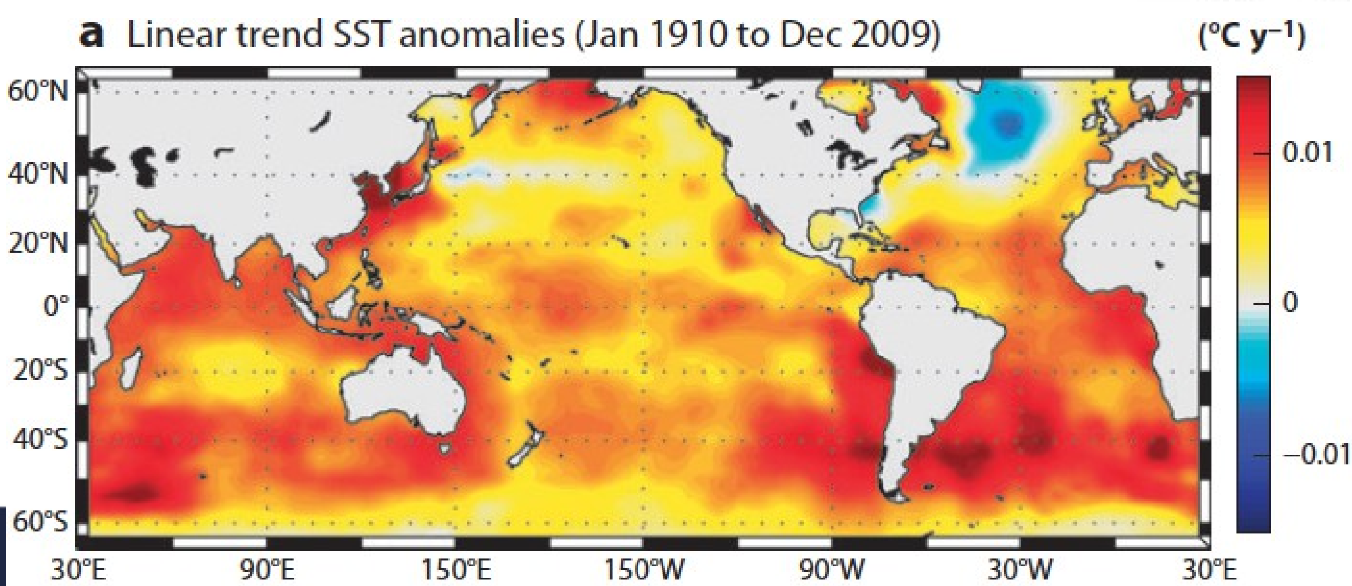
<u>Global sea surface temperature (SST)</u>

- Global SST increasing at a rate of 0.6 ^{0}C/century
- Tasman Sea hotspot: upper ocean heat increasing at nearly 4 times the global average! [Holbrook and Bindoff, 1997; Ridgway, 2007]





Chavez et al., 2011

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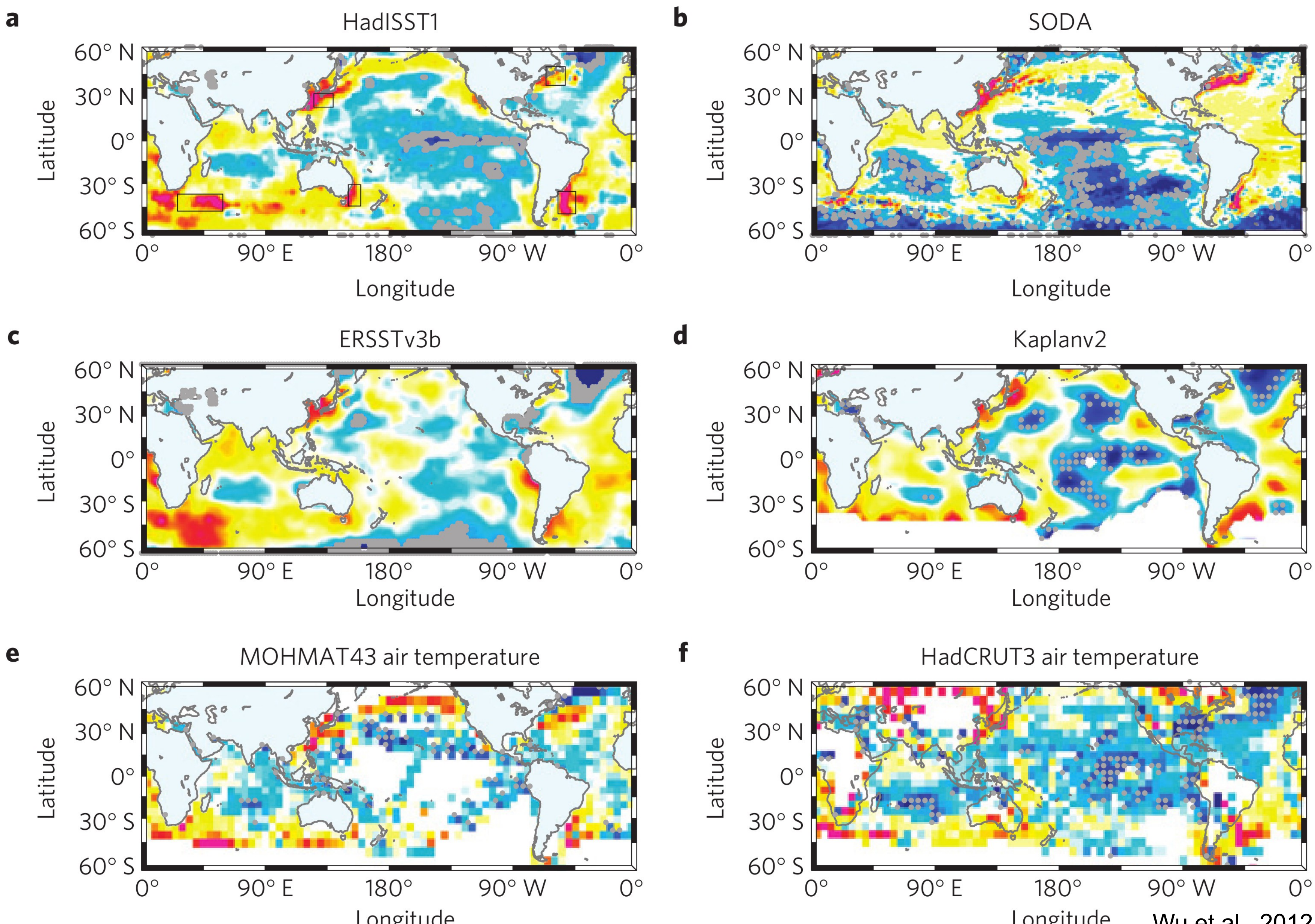
Marine climate change

UTAS

Part of a pattern of change in all Western Boundary Currents

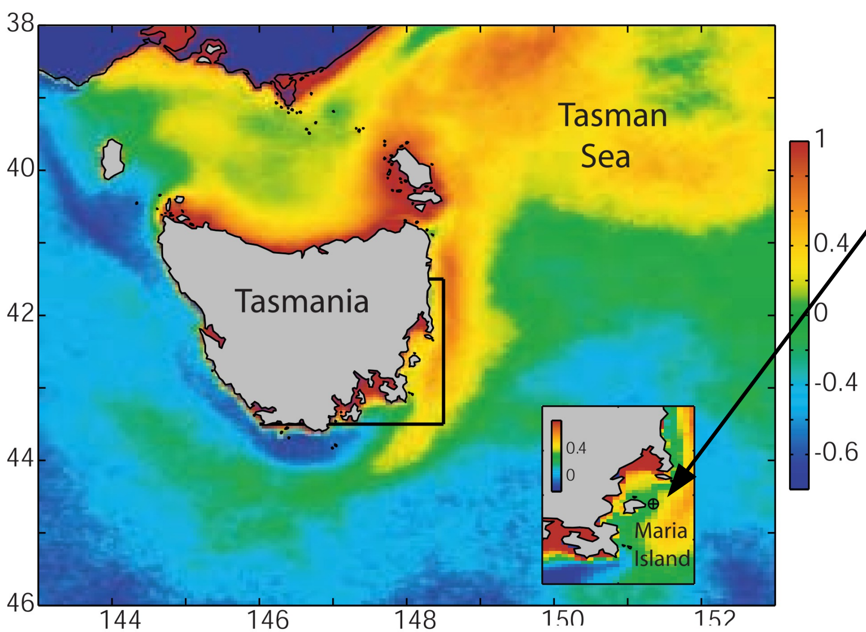


Wu et al., 2012

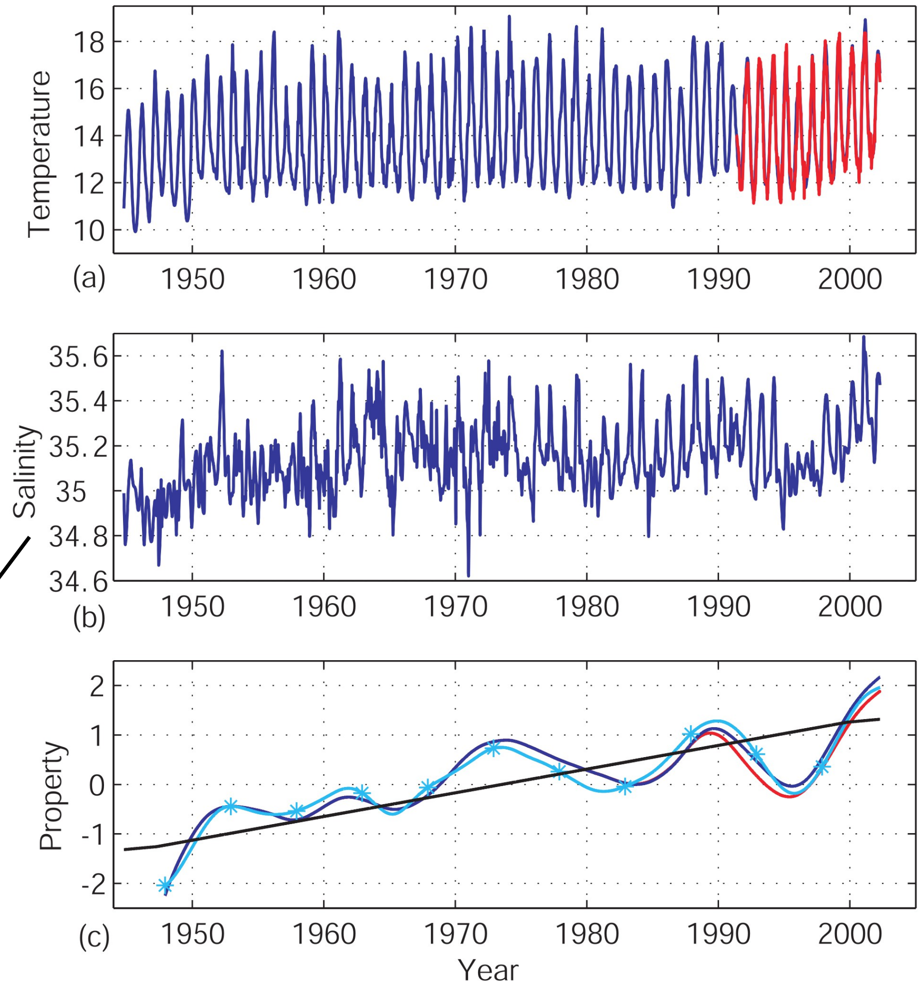
edge

Marine climate change

- <u>Circulation changes</u>
  - Locally, the East Australian Current appears to be penetrating deeper along the East coast of Tasmania
  - Bringing with it warm and salty (and nutrient-poor) water

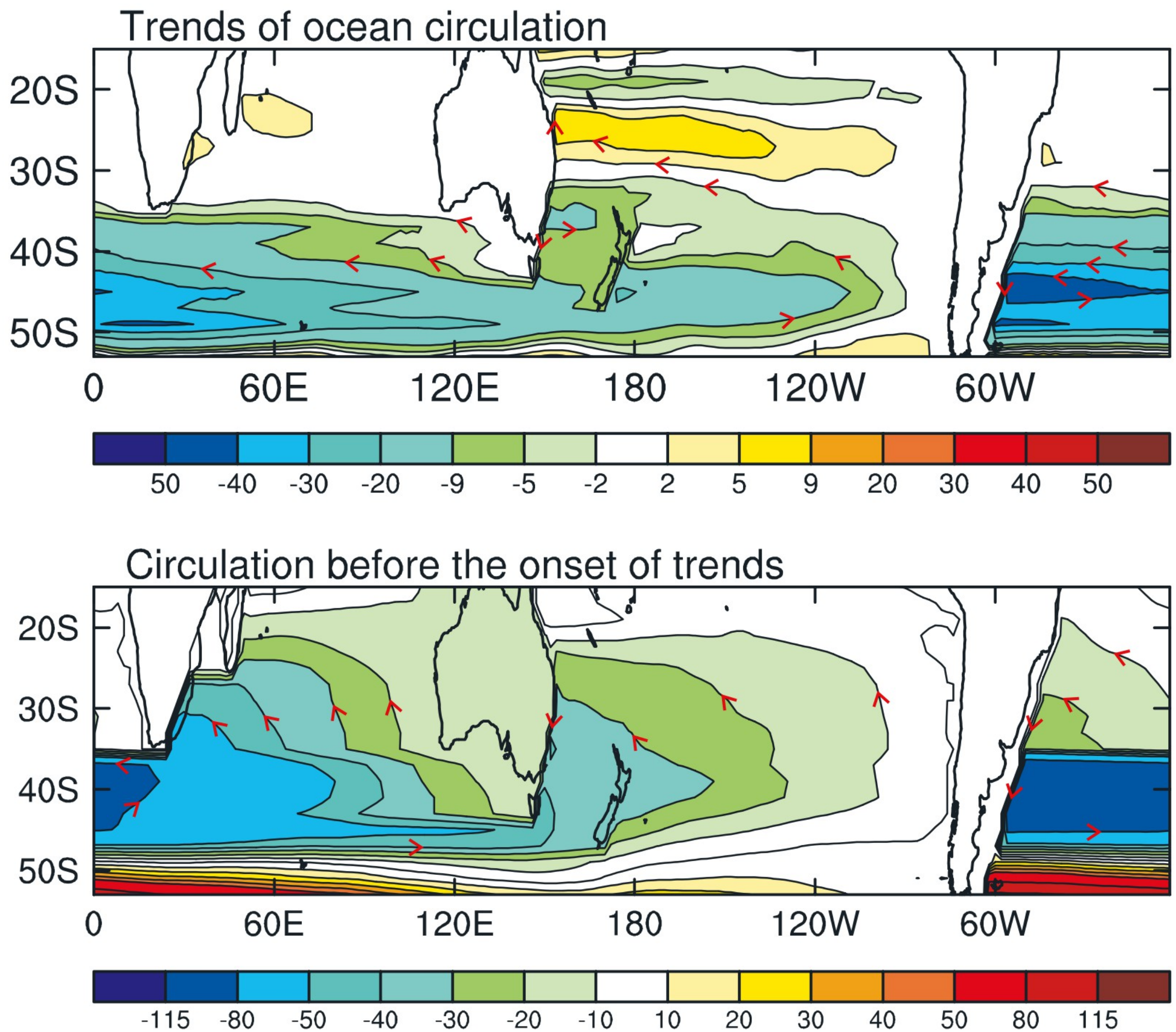


Ridgway, 2007



Marine climate change

Part of a greater spin-up of the South Pacific Gyre … and the supergyre?

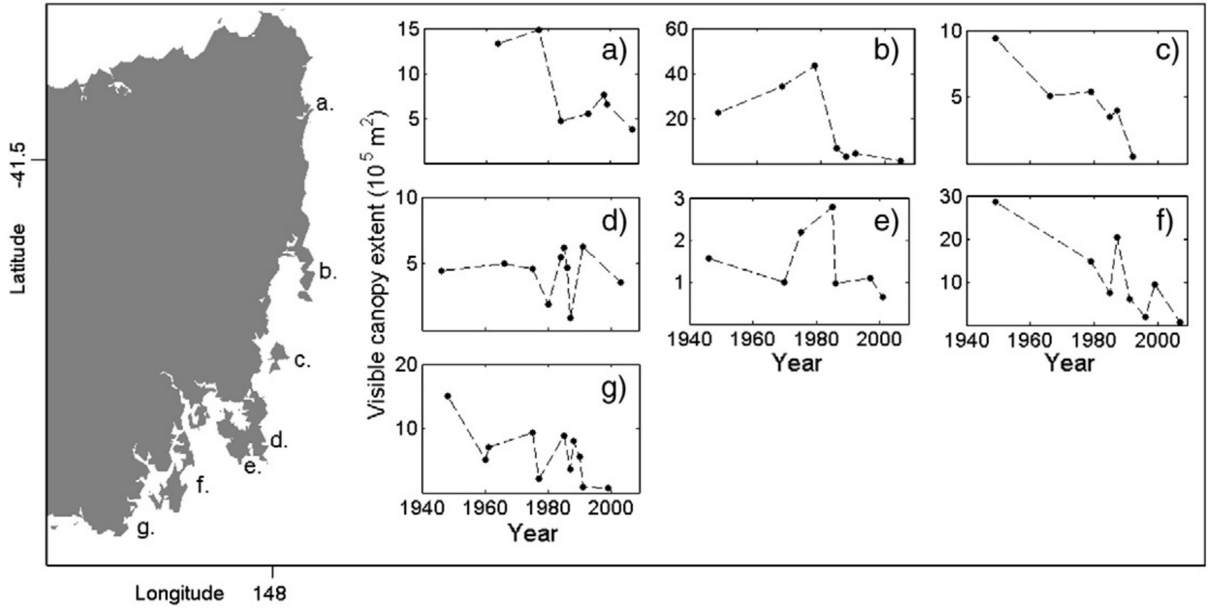


Cai, 2006

Marine climate change

- <u>Species habitat ranges</u>
  - Changes in the marine climate are leading to changes in ecosystem habitat ranges
  - For example, Johnson et al. (2011) documented shifts in species ranges off eastern Tasmania and linked it to shifts in the regional oceanography.
  - Extreme events can lead to "ratchet-like" change events

Change in visible surface kelp canopy (Macrocystis pyrifera)



Johnson et al. (2011)

Marine climate chang

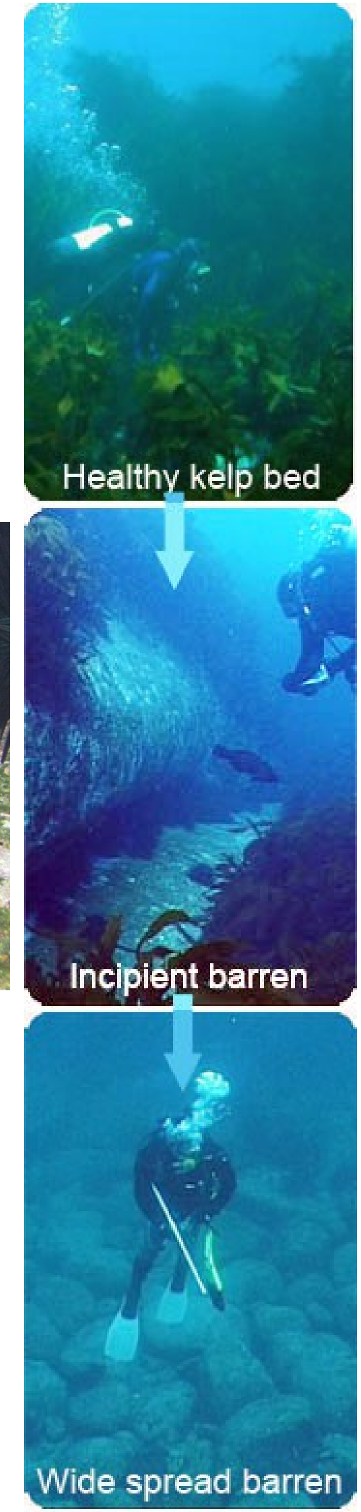
- Spiny sea urchins are displacing giant kelp along Tasmania's coastline

Kelp forests (Macrocystis pyrifera) off Tasmania

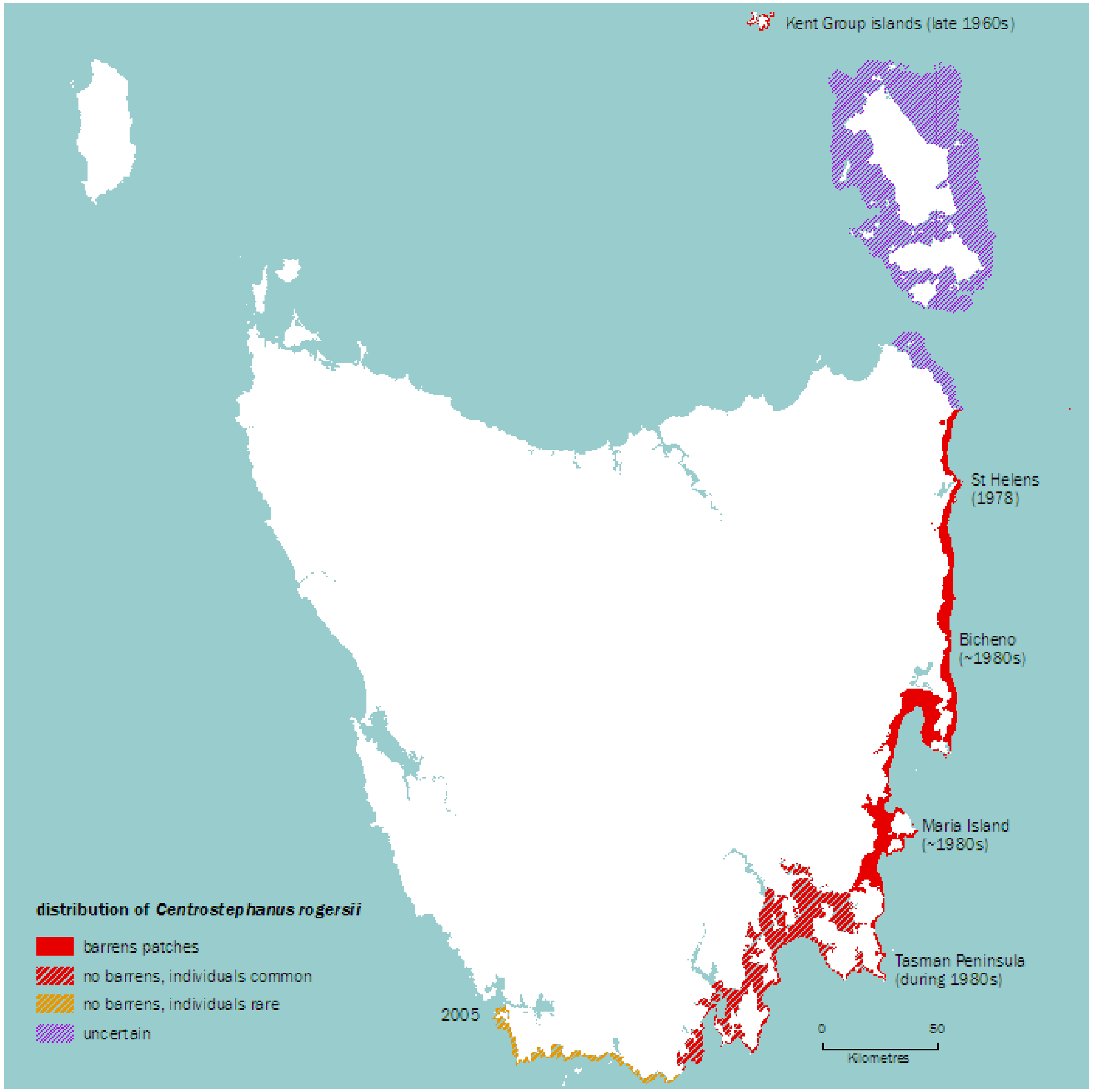
Neville Barrett

Spiny sea urchin
(C. rodgersii)

kelp become → urchin barrens



Marine climate change

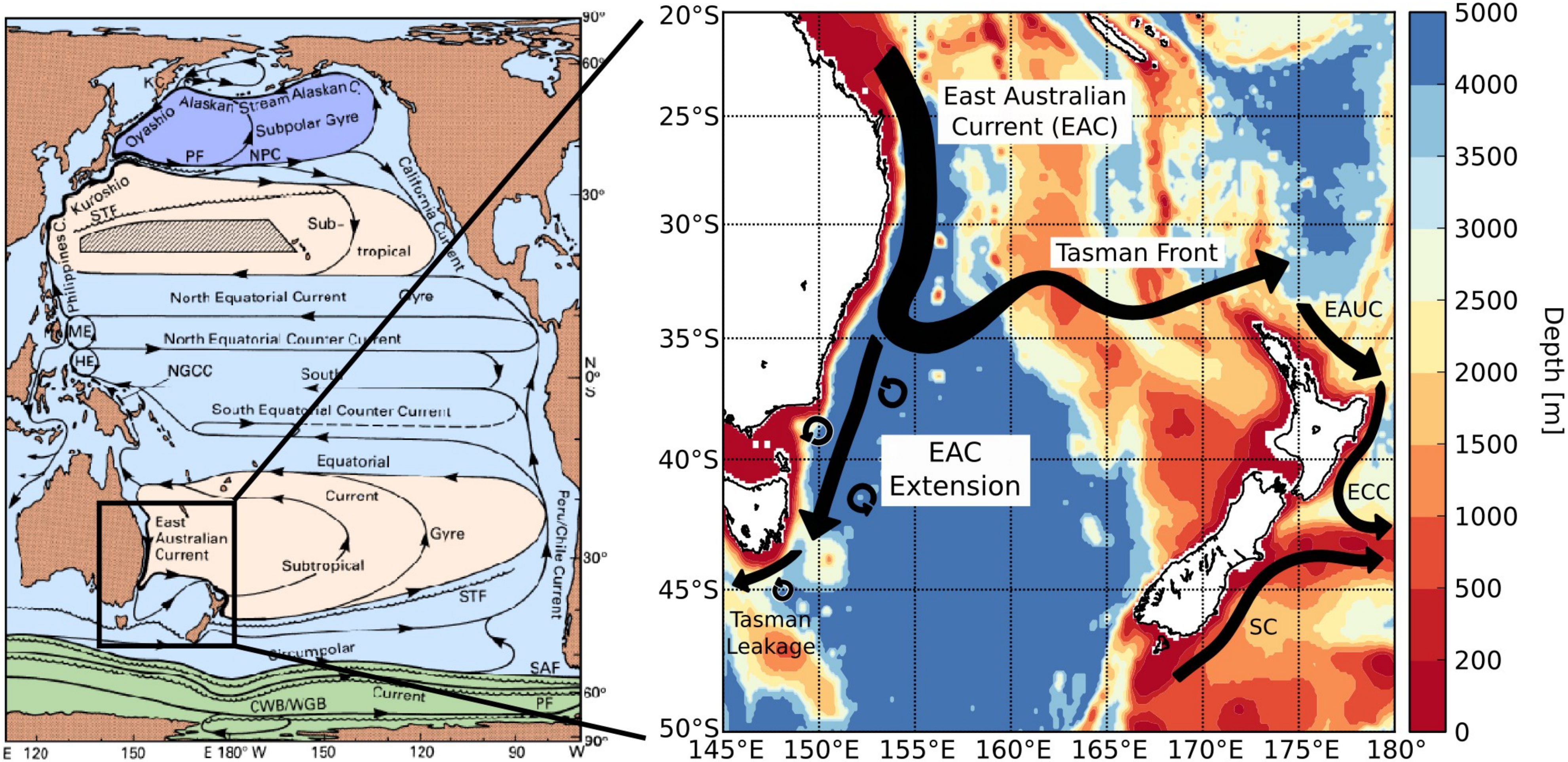


State of the Environment, Government of Tasmania

Southeastern Australia

- **Regional oceanography of the Tasman Sea**

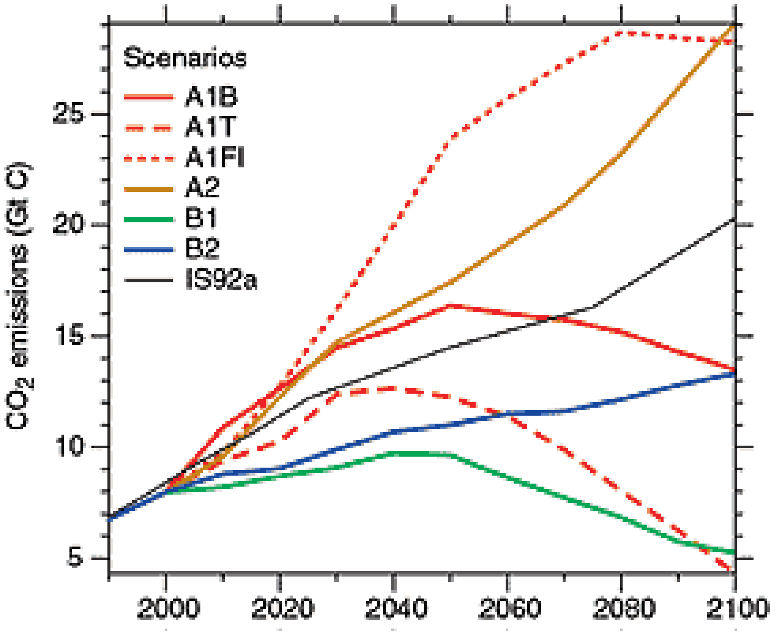
  western boundary current, eddy-rich region, complex bathymetry



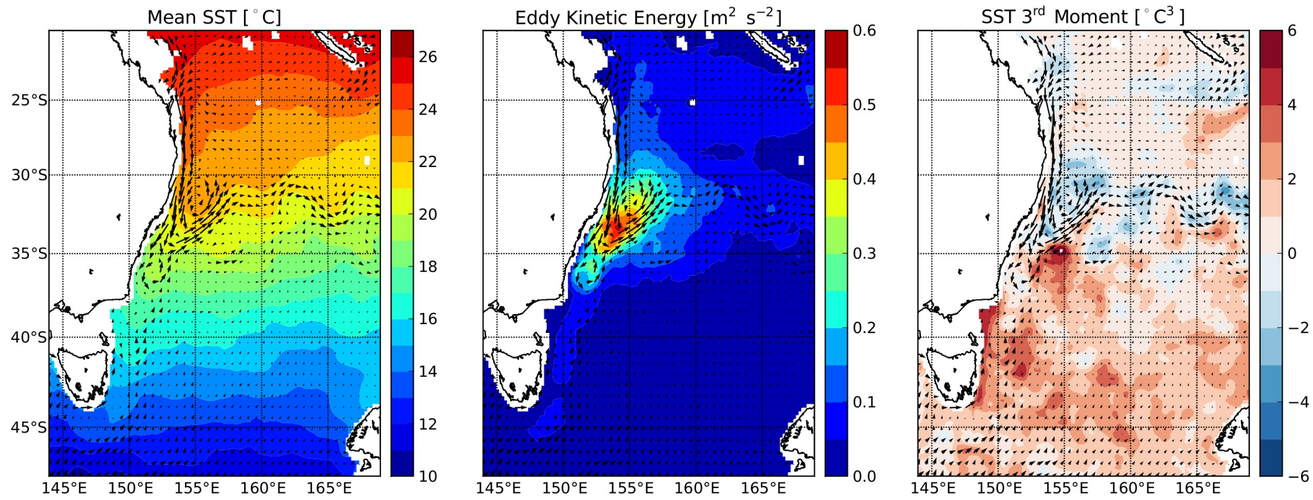
[Tomczak and Godfrey, 1994]

Ocean Models

- Two ocean model runs (Ocean Forecasting Australia Model; 70OS--70ON domain, 1/10^0 resolution around Australasia and decreasing elsewhere) were performed using forcing representative of the 1990s (CTRL) and the 2060s (A1B) [Chamberlain et al., 2010].
- Climate change scenario provided by CSIRO Mk3.5 GCM with an A1B emissions scenario
- Models represent well general circulation and temperature distribution around Australia, including seasonality [Sun et al, 2012; Matear et al., 2013].
- We examine marine climate statistics (e.g., means, variances, skewness of sea level, SST, and circulation) derived from these model runs



Ocean Models



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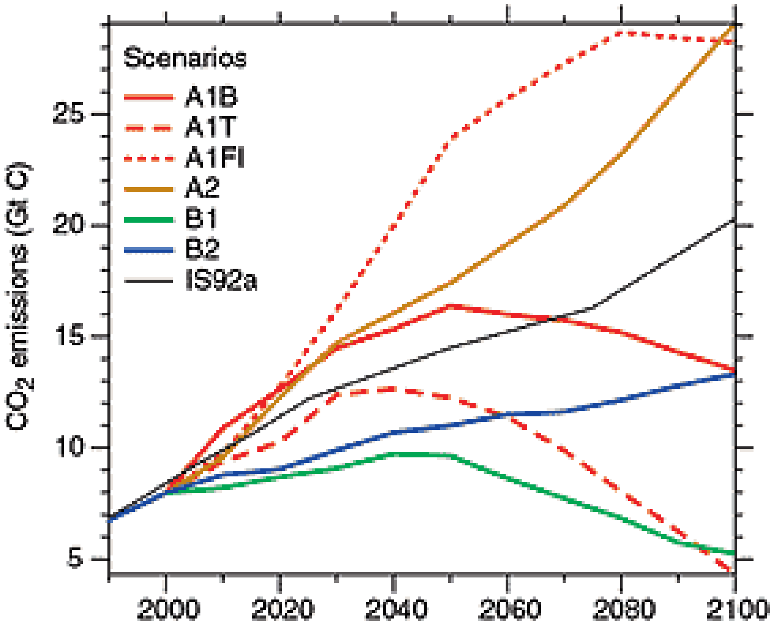
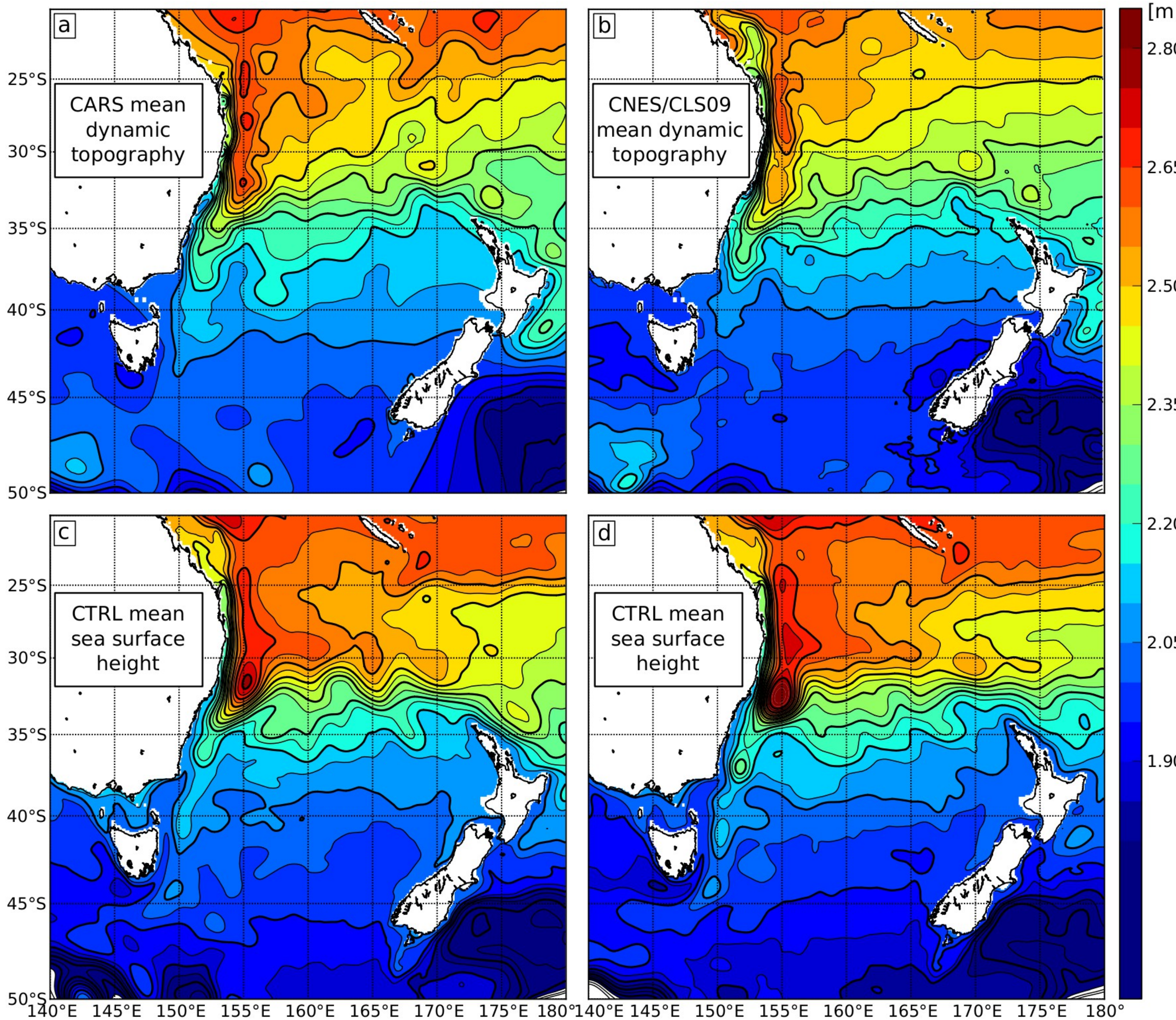


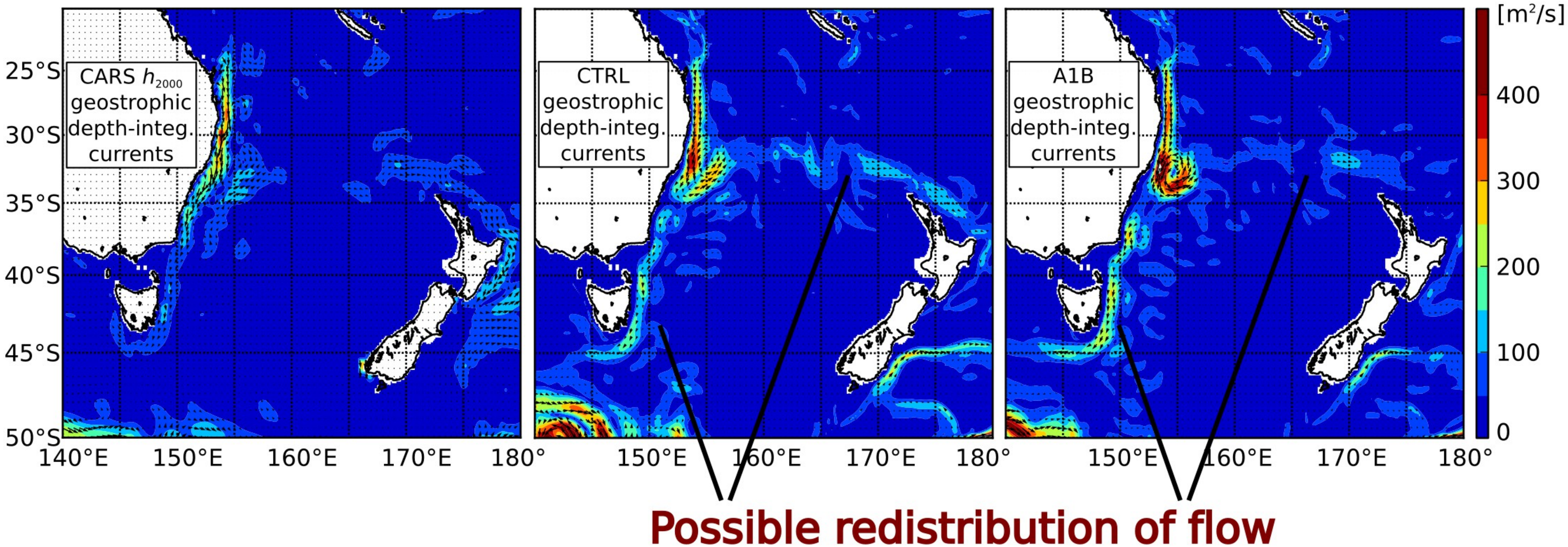
Mean Circulation

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



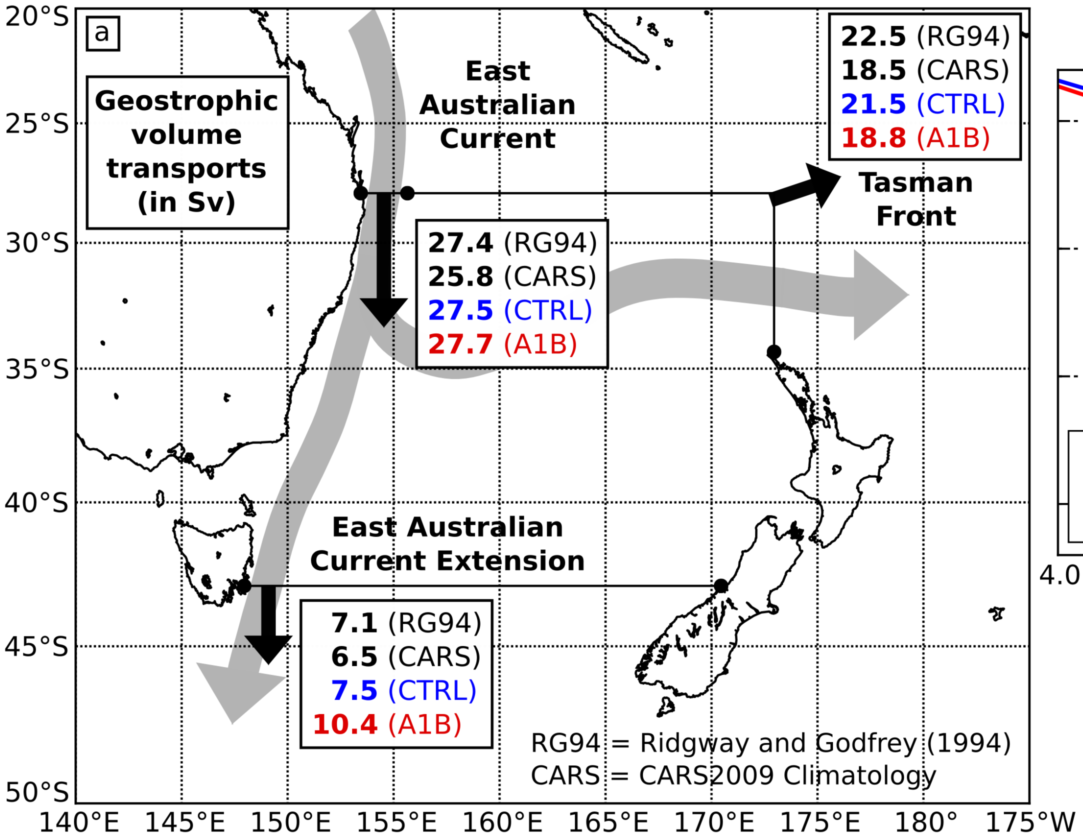
Mean Circulation

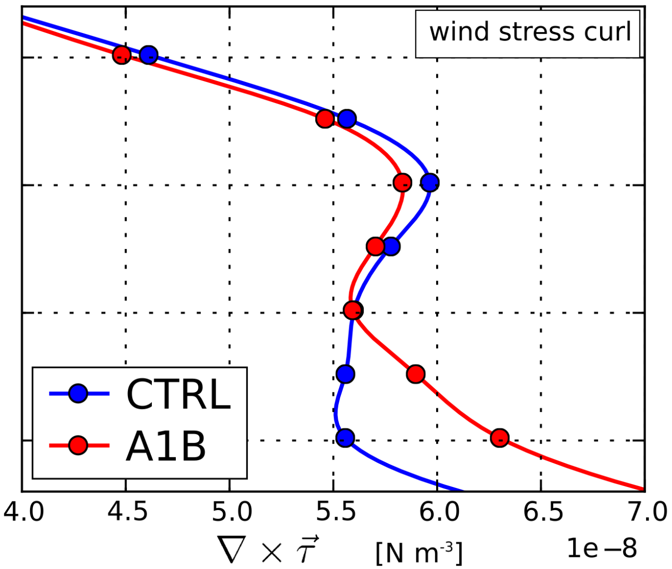
- Model simulated mean volume transport



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

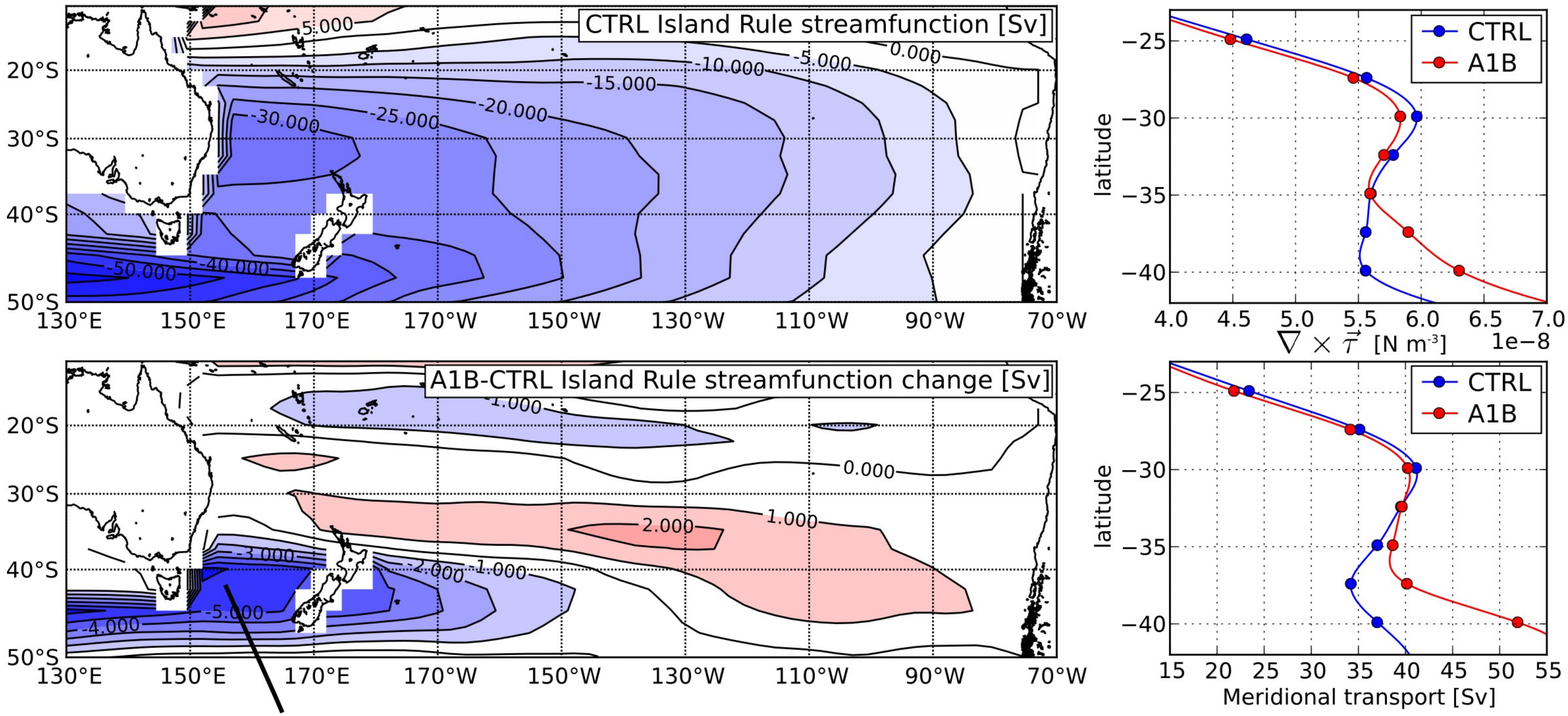
- **Simple linear, wind-driven, barotropic circulation model**
  - If the changes in mean circulation are simply due to changes in wind-stress, then we may be able to capture them with such a model
  - Sverdrup stream function $\psi(x,y)$ given by zonally integrating meridional flow according to $d\psi/dx=V$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

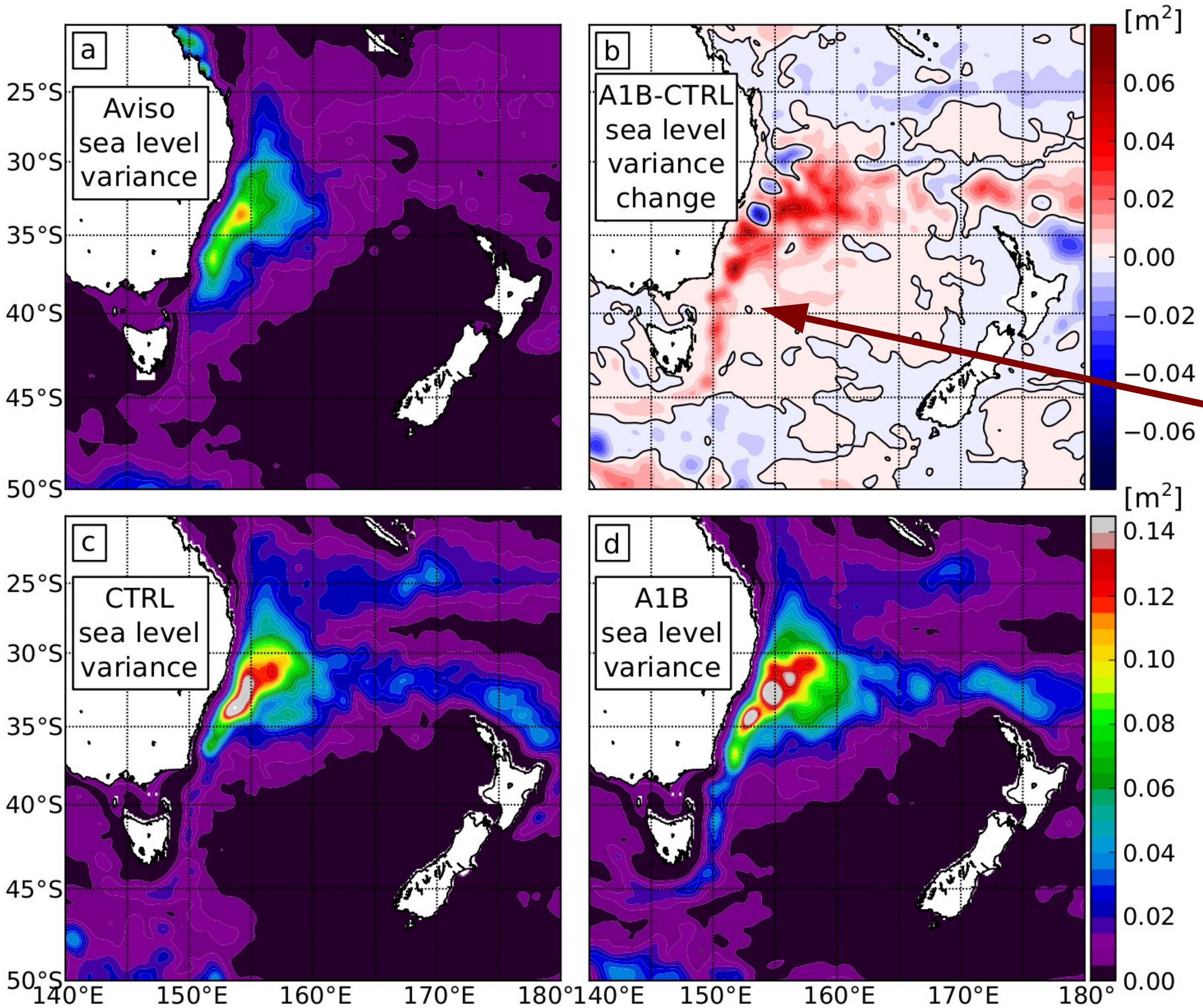
Wind-driven circulation

- 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)

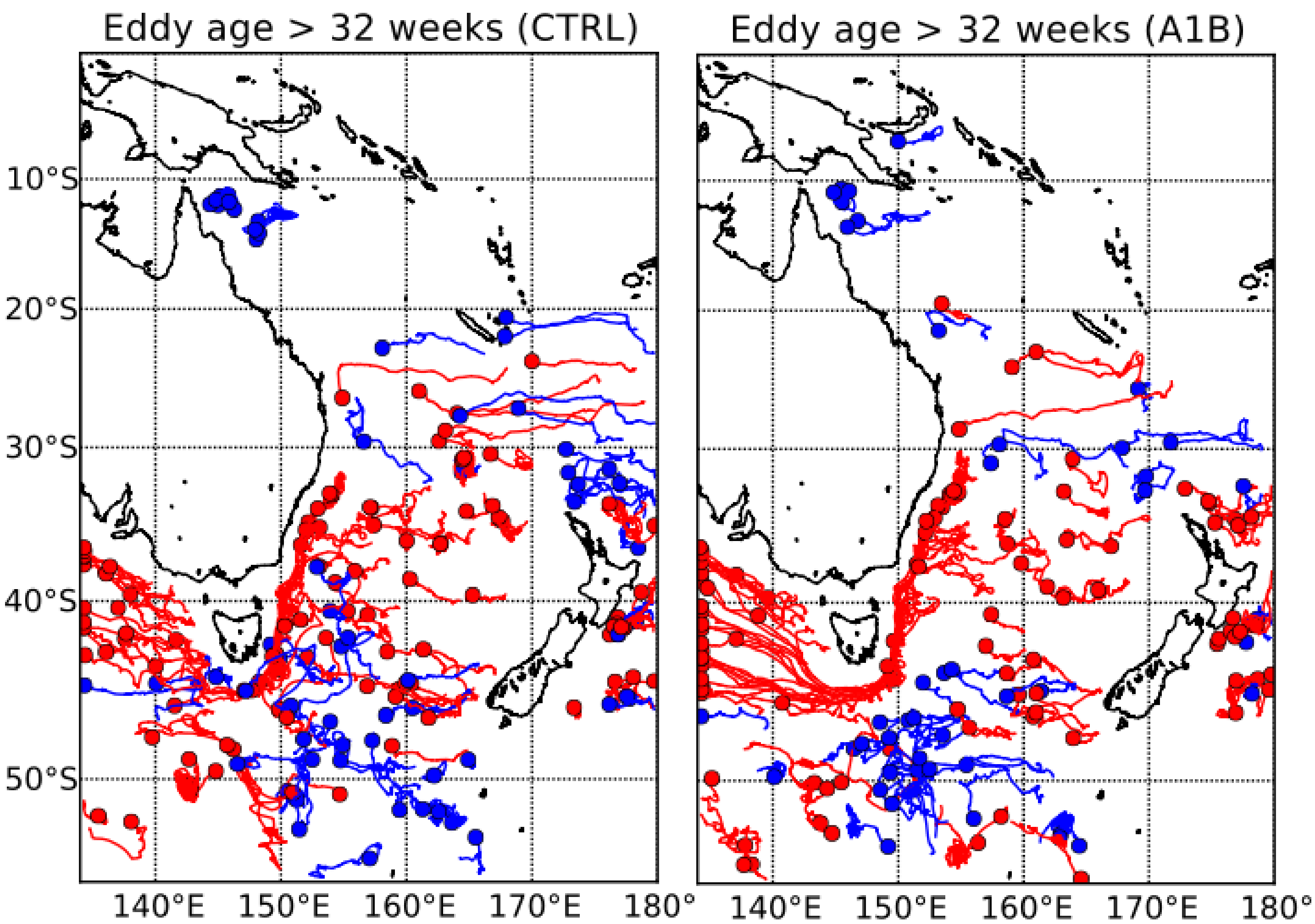
Eddy Kinetic Energy



- 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

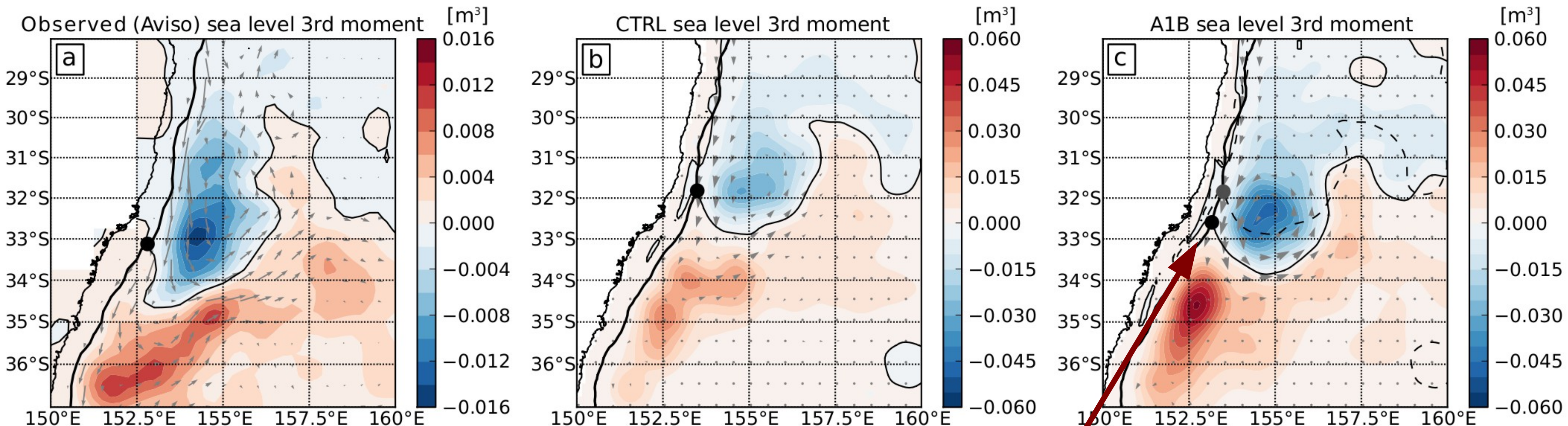
Cyclonic (blue) and **anticyclonic (red)** eddies tracked using Chelton et al. (2011) sea level algorithm:



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

EAC Separation Point

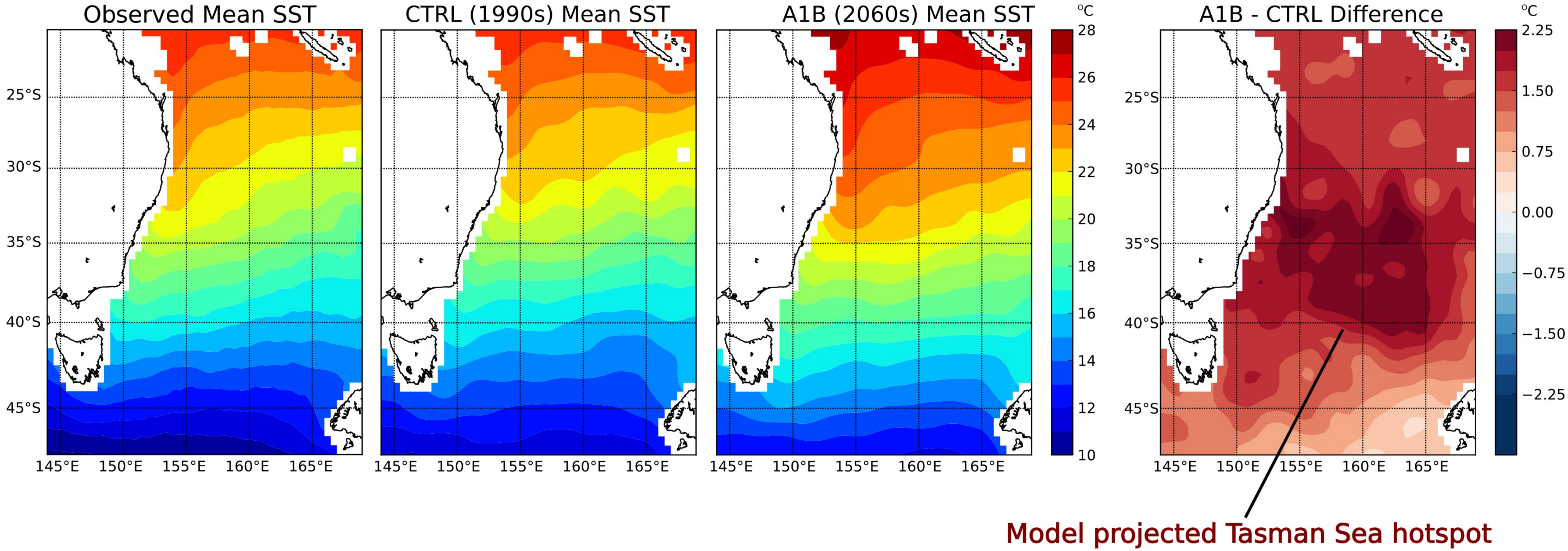
- The third moment of sea level (sea level skewness) can be used to map the mean path of a meandering jet, such as western boundary currents [Thompson and Demirov, 2006]
- The intersection of the mean jet path with the shelf break is used as a rough indicator of the mean EAC separation point



Approx 90 km southward shift in EAC separation

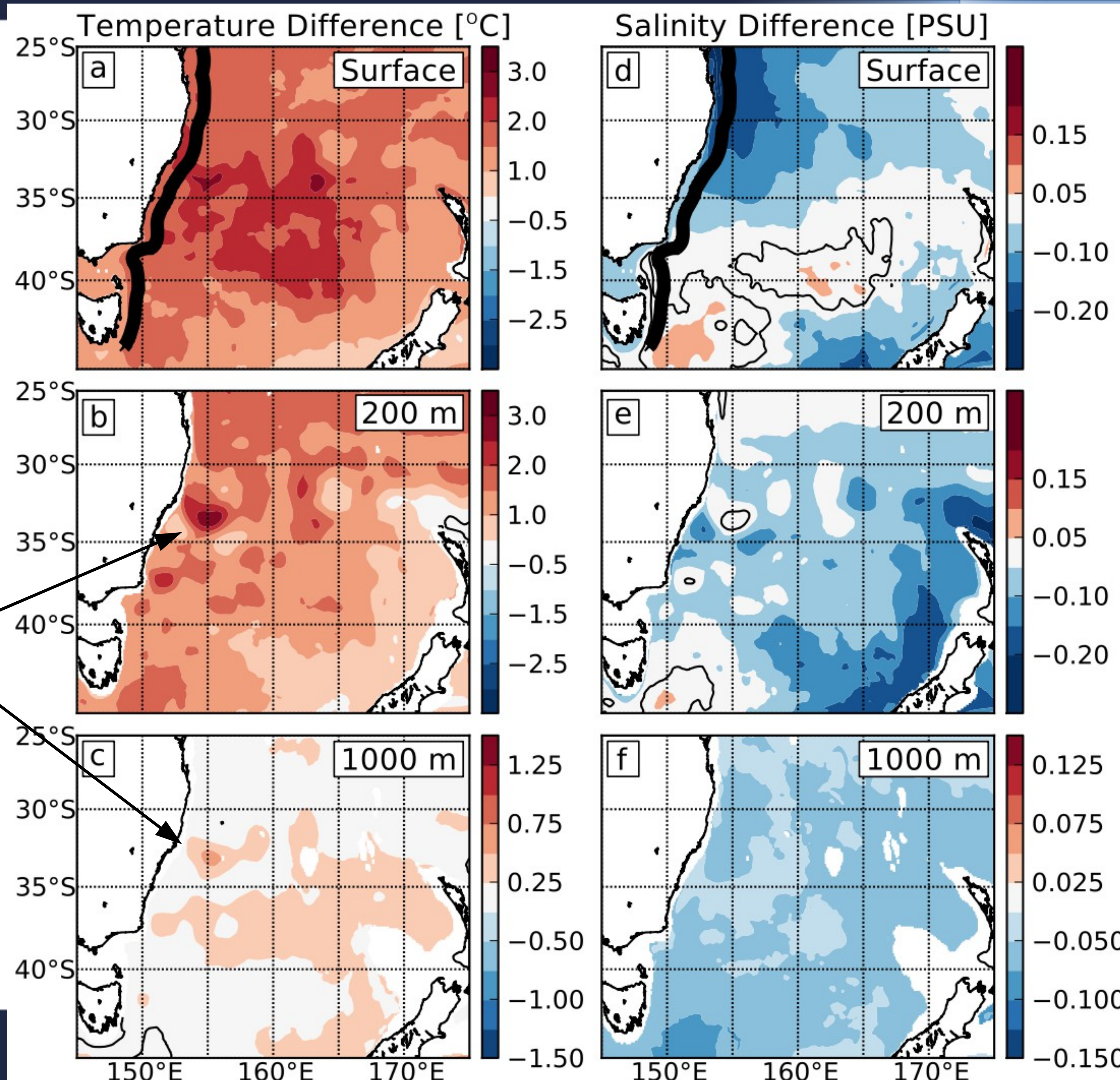
The Mean SST

- Model simulated mean SST



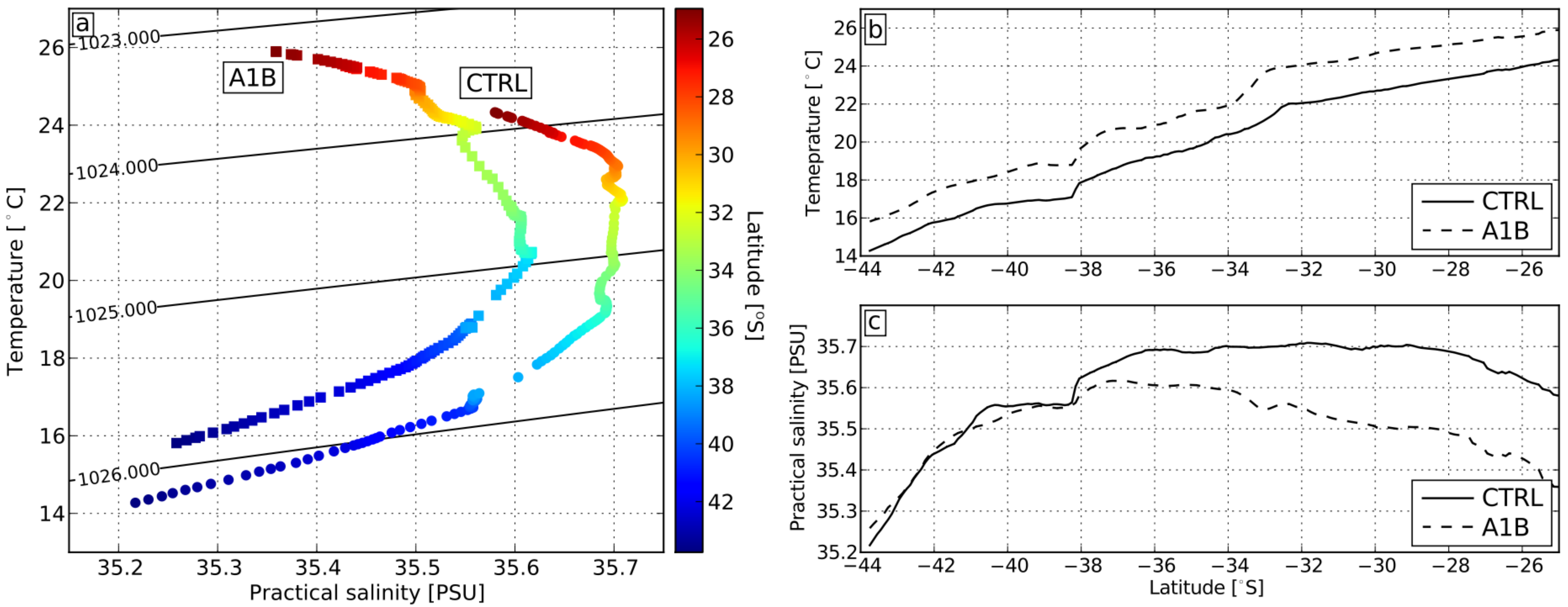
Changes at Depth

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



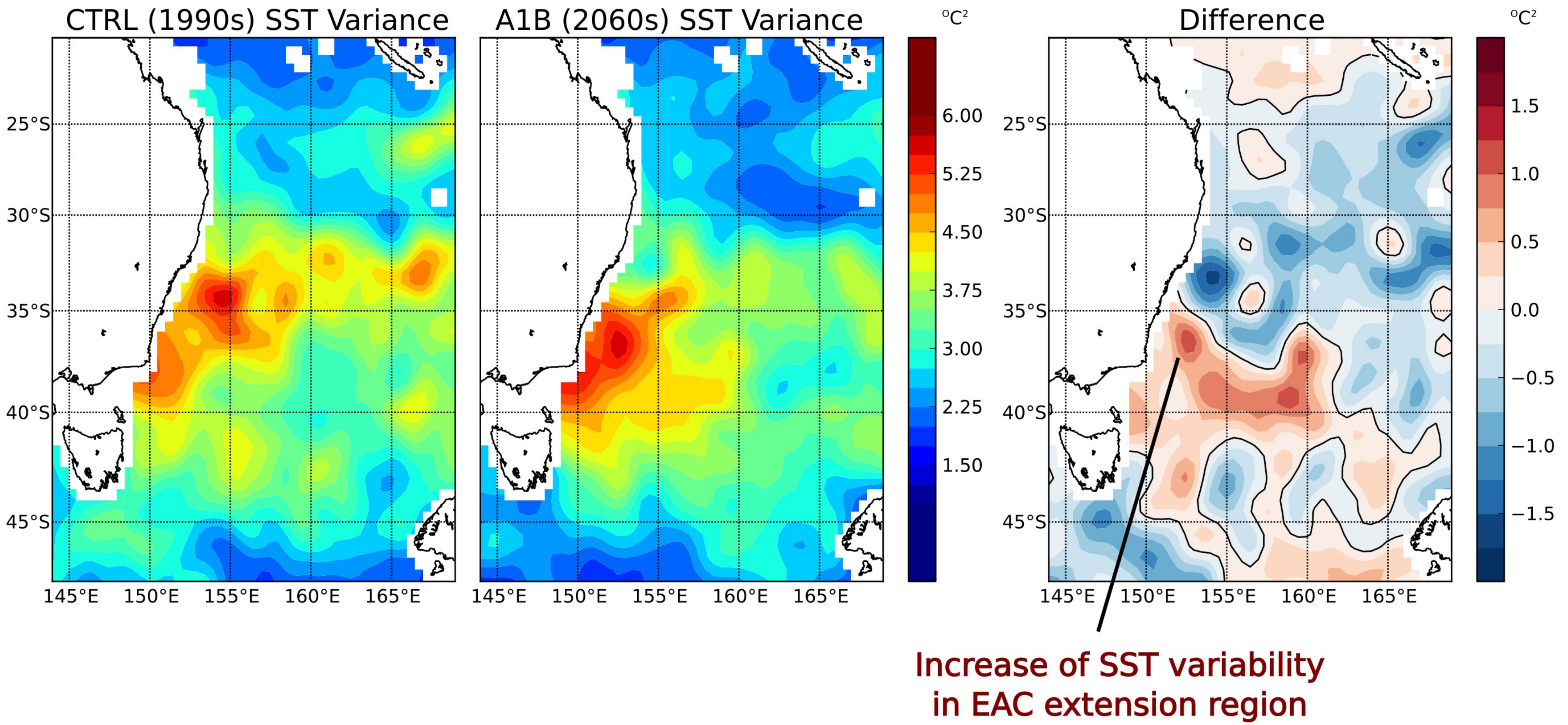
Shelf Break

- 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



SST Variability

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



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Marine Extremes

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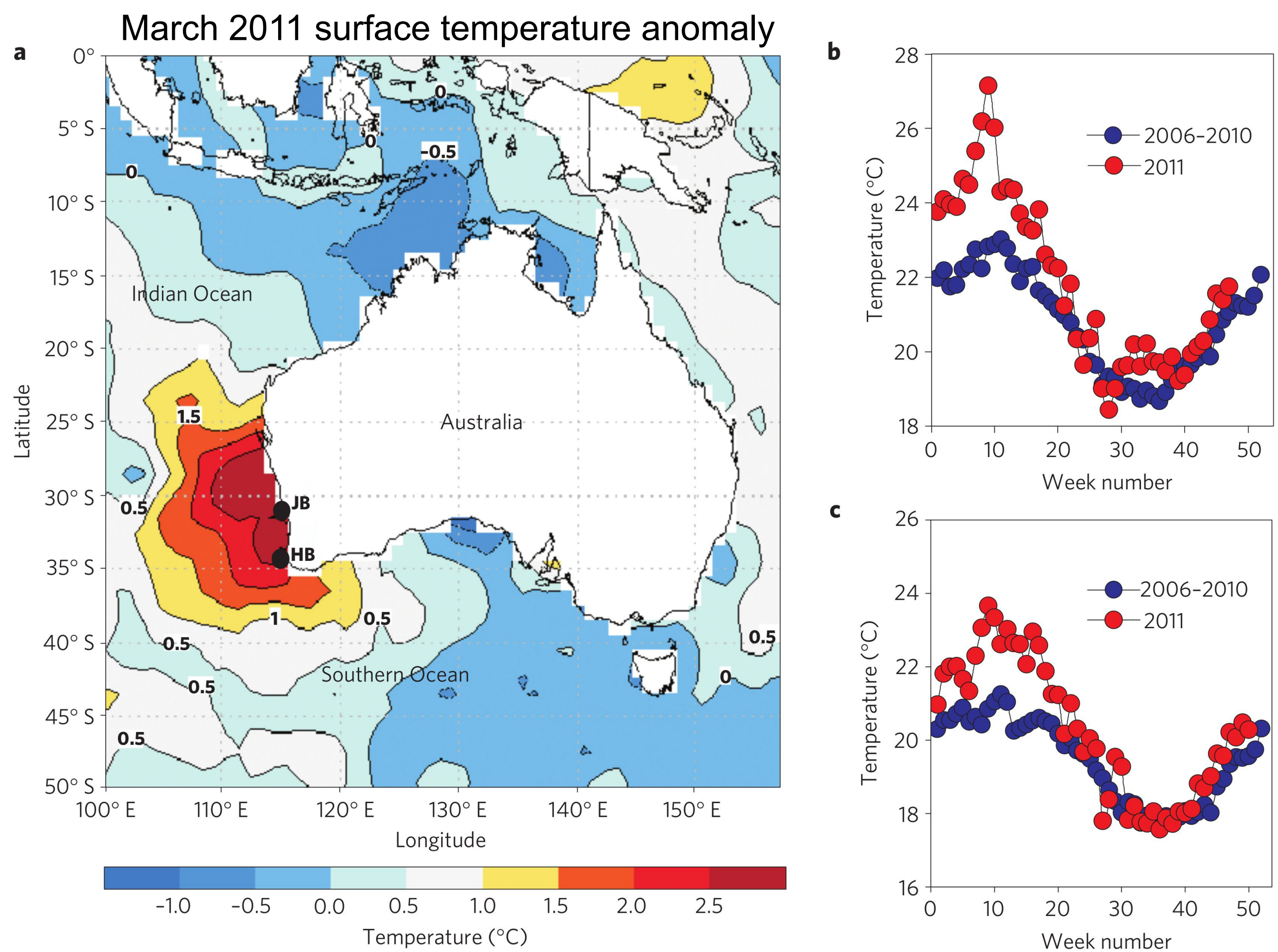
- Changes to extreme events have been recorded in the atmosphere and some have (at least partially) been linked to the changing climate:
  - Tropical cyclone intensities and numbers
  - Heat waves
  - Uncharacteristic winters (cold, snowy; e.g., Europe)
  - Droughts
- Extreme events in the marine environment have received relatively little attention, let alone studies on their potential change
- Likely to be important for species habitat and ecosystem change

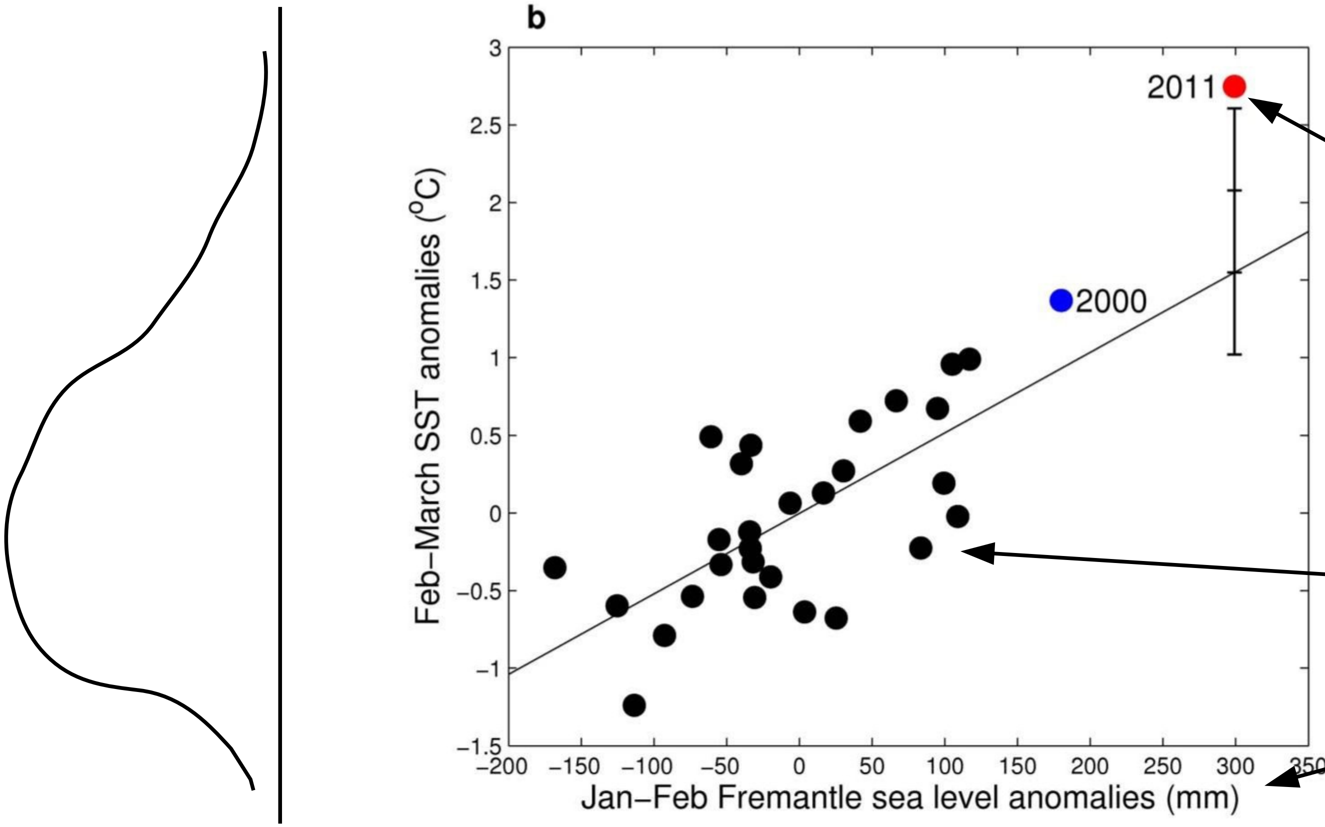
Marine Extremes

- In **2011**, a "**marine heat wave**" off of **Western Australia** was documented (Pearce and Feng, 2012; Feng et al., 2013)



Wernberg et al (2013)

Marine Extremes



Feng et al. (2013)

Now that's what we call an extreme event!!

Associated with a near-record La Nina event

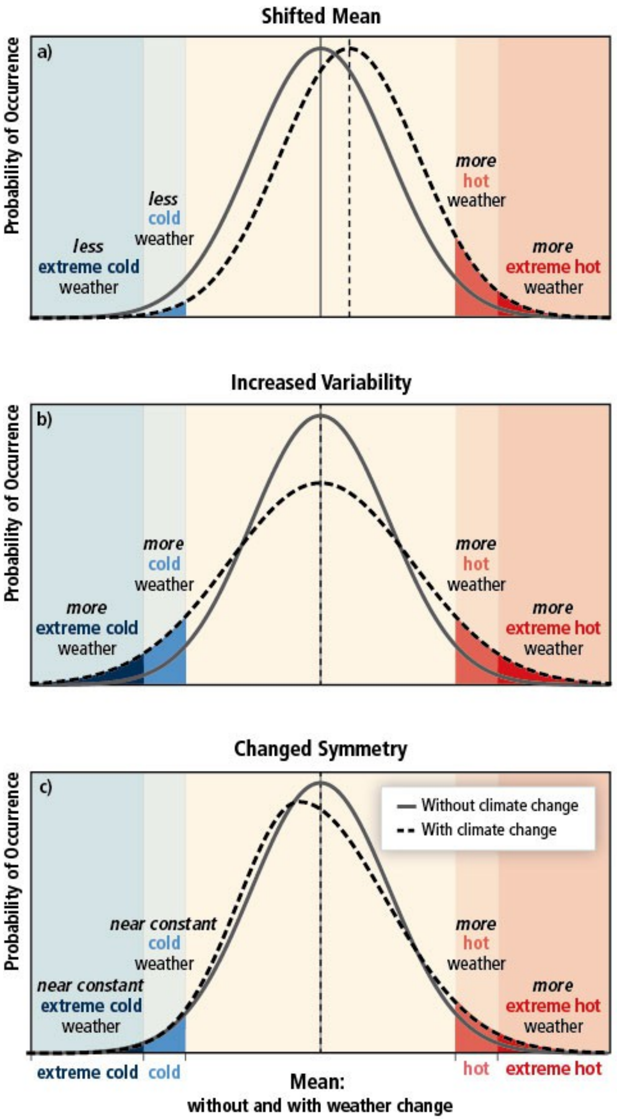
Individual years 1982 - 2011

Good indicator of ENSO variability

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

Climate change: It's all about the statistics!

- In terms of climate change, it is often the tails (the "extremes") that we are most interested in
- The downscaled ocean model runs do not properly represent the extreme events
- Intuitively, the tails of probability distributions are related to the central moments of the distribution – at least for events which are "not too extreme"
- Previous studies have shown that temperature extremes can be estimated using the central moments alone, e.g., [Griffiths et al., 2005, Ballester et al., 2010, Simolo et al., 2011, de Vries et al., 2012]



IPCC 2012 - SREX SPM

Extremes from central moments

Simple model for the 1990s:

- The CTRL run yields good estimates of large-scale ocean variability such as the main current systems and their variability [Sun et al., 2012] and the central moments (e.g., mean SST, SST variance, eddy kinetic energy, etc).
- Therefore, we can model the extremes as a function these statistics using a hierarchical Bayesian model.

Predictions for 2060s:

- Use the fitted model and the A1B climate statistics to get estimates of future extremes.
- This assumes stationarity of the model.

Hierarchical Bayesian model

Data layer

Assume that at each location j the annual maxima are distributed according to an extreme value distribution:

$$\mathbf{y}_j | a_j, \phi_j \sim F_{\mathrm{I}}(a_j, \phi_j)$$

Climate process layer

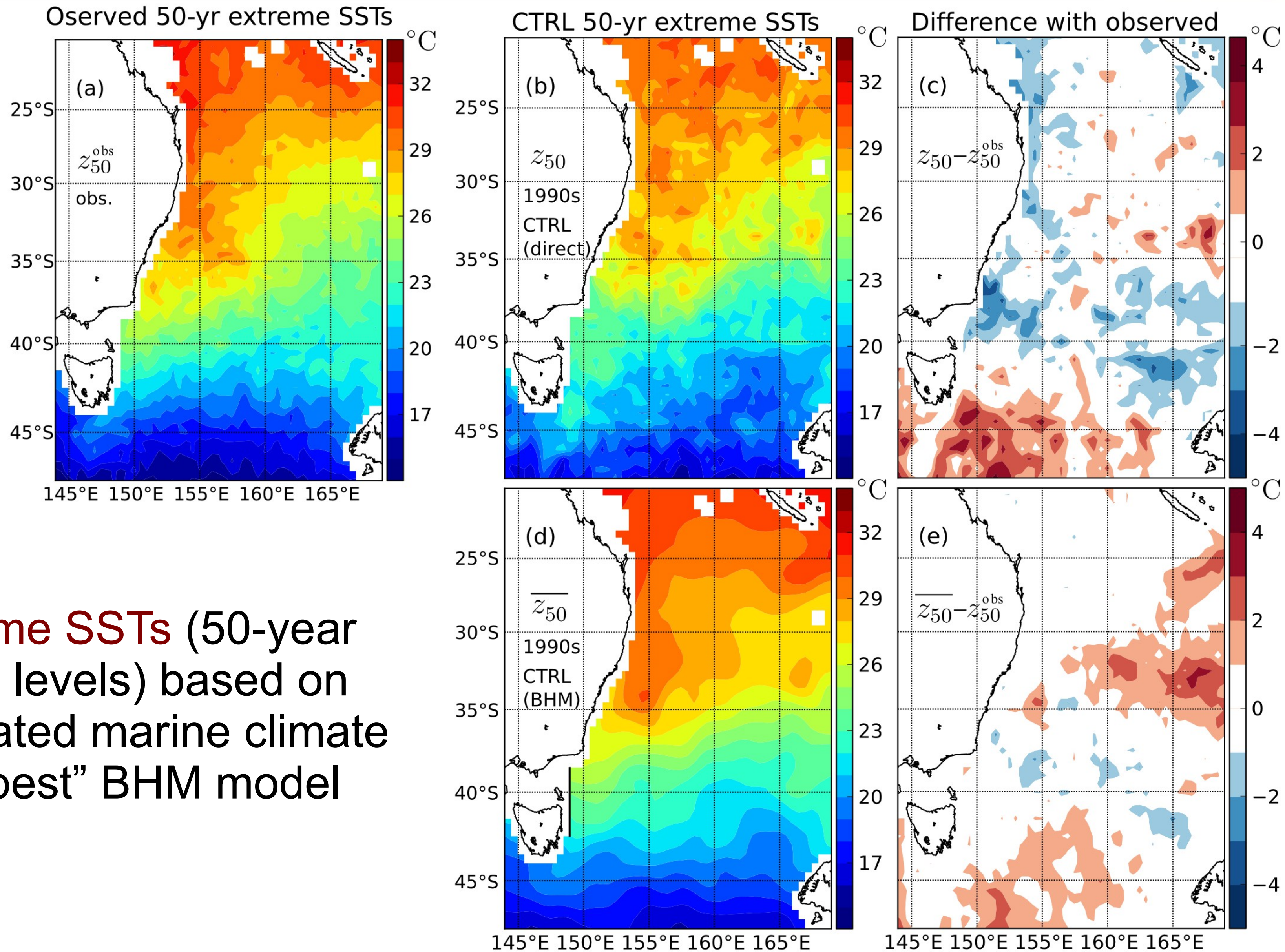
Assume that the model parameters a_j and ϕ_j are normally distributed with means that are linear combination of the covariates $\mathbf{X}$ at location j

$$\begin{aligned} a_j | \boldsymbol{\beta}_a, \tau_a &\sim \mathcal{N}(\mathbf{X}_j \boldsymbol{\beta}_a, \tau_a) \\ \phi_j | \boldsymbol{\beta}_\phi, \tau_\phi &\sim \mathcal{N}(\mathbf{X}_j \boldsymbol{\beta}_\phi, \tau_\phi). \end{aligned}$$

The $\boldsymbol{\beta}$s and τs are independent of location and describe the relationship between $\mathbf{a}$ and $\boldsymbol{\phi}$ and a *latent spatial process*.

$\boldsymbol{\beta}$s and τs are sampled using a Markov Chain Monte Carlo simulation.

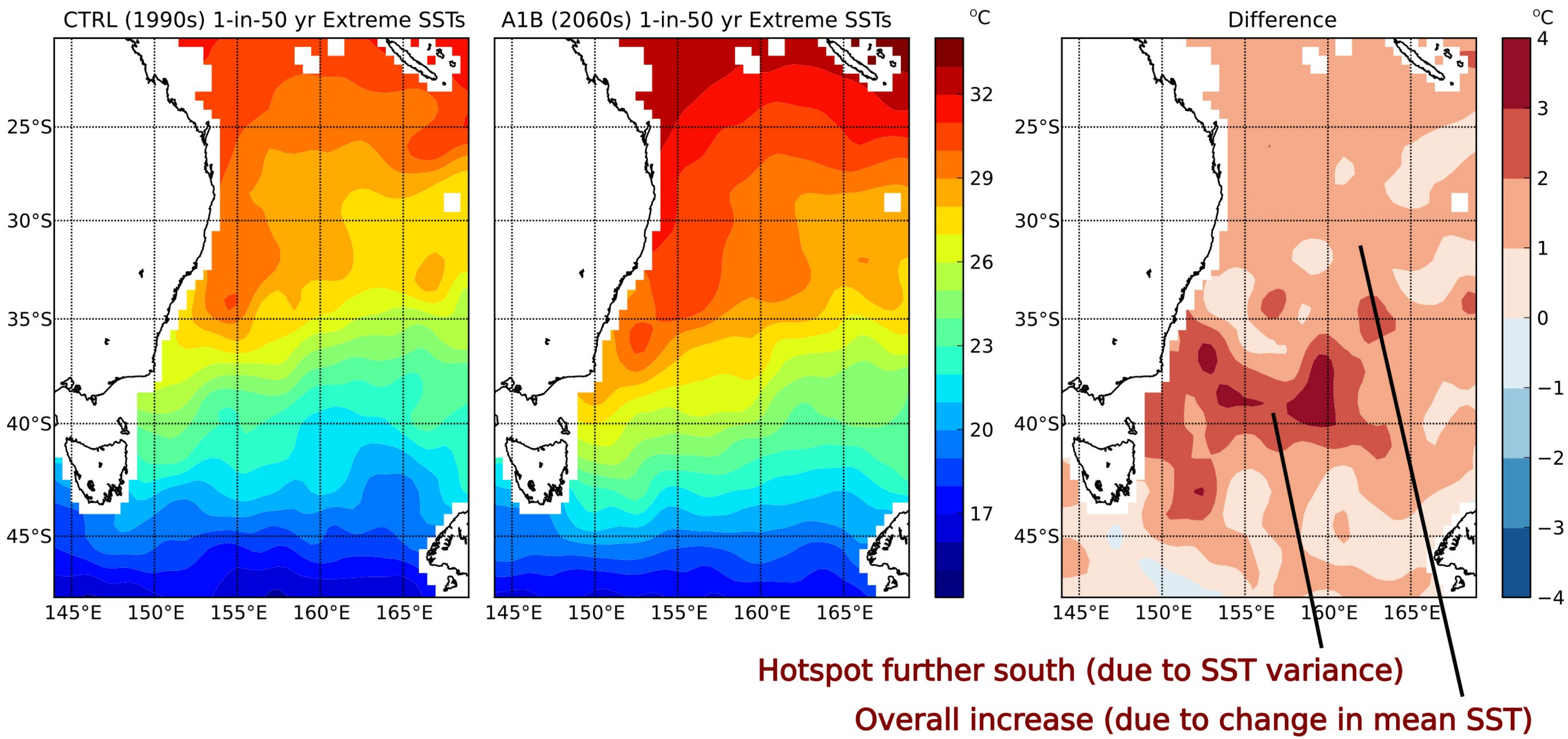
Extreme SSTs



Extreme SSTs (50-year return levels) based on simulated marine climate and "best" BHM model

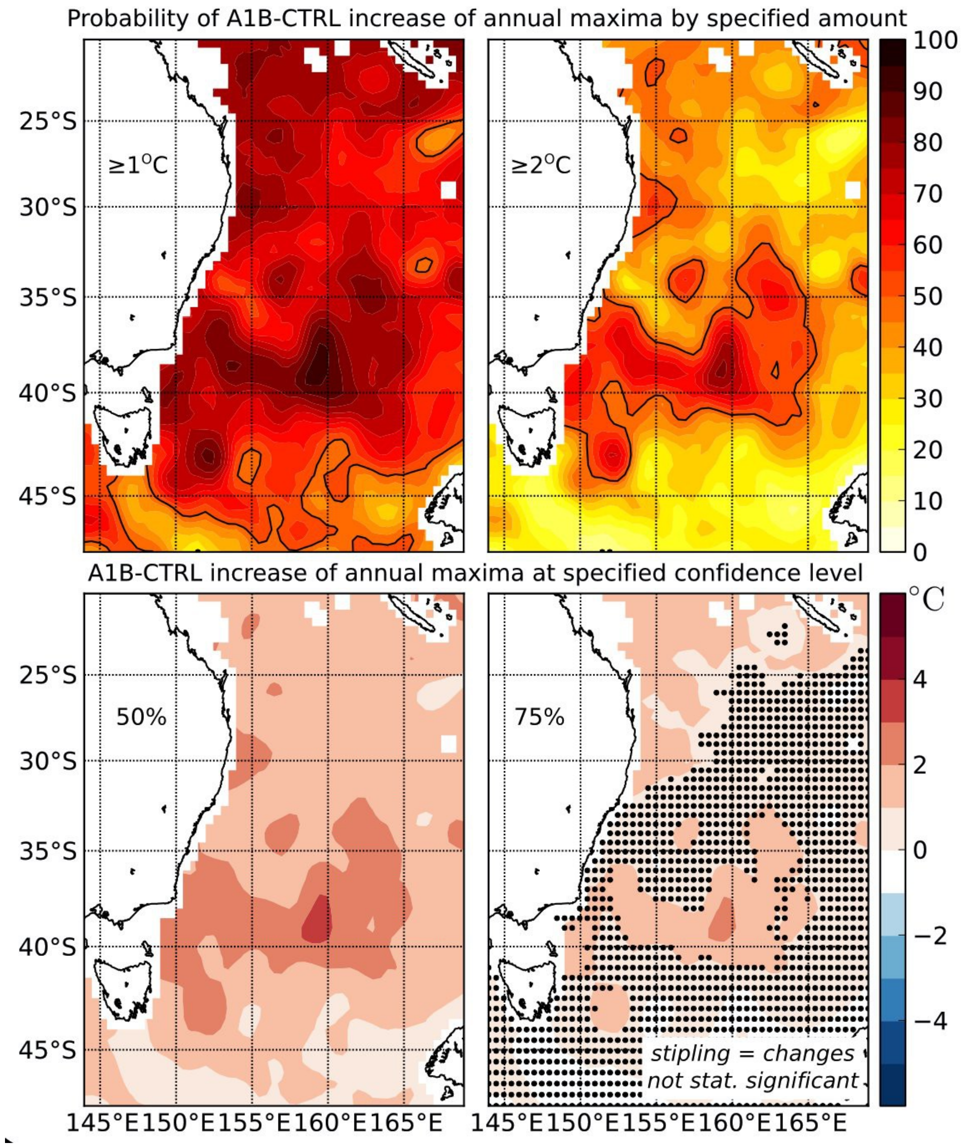
Extreme SSTs

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



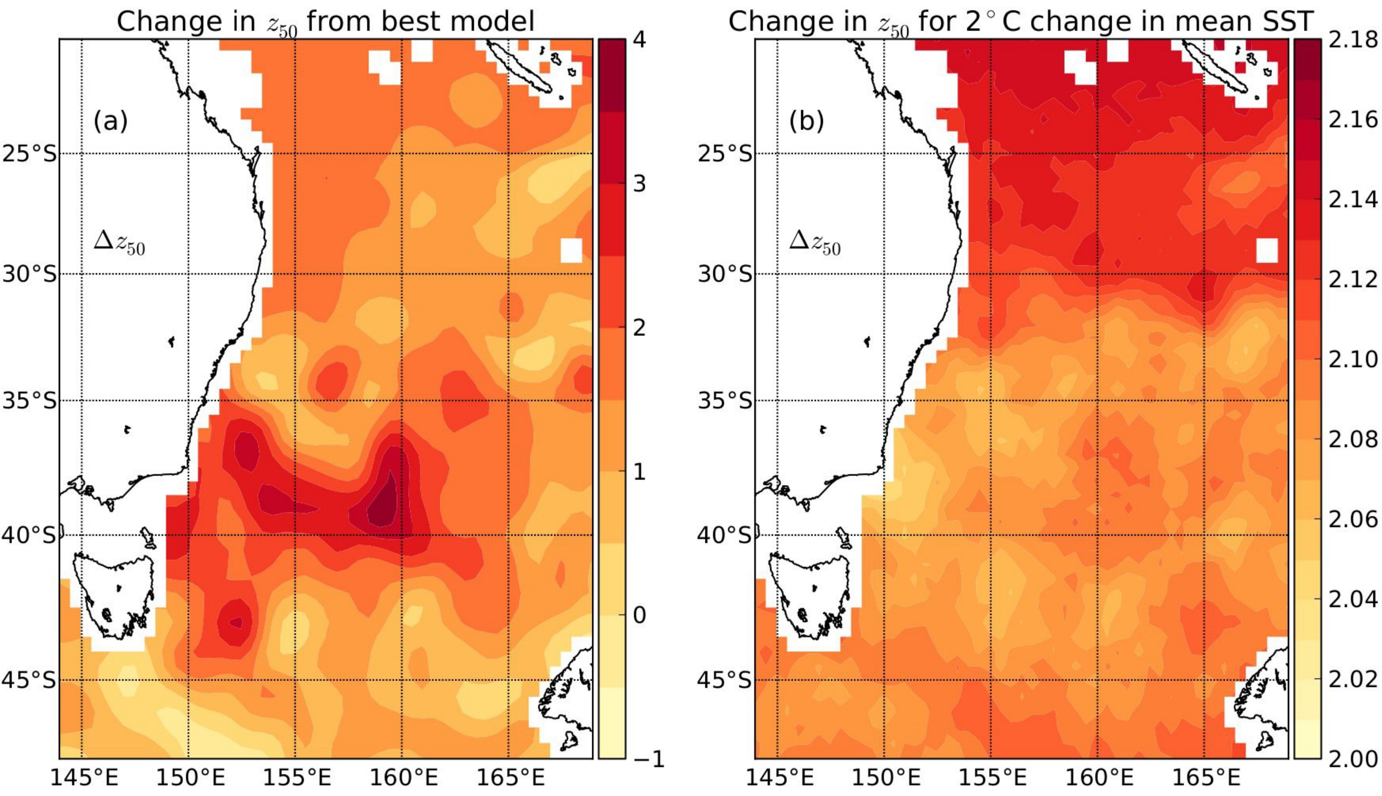
Extreme SSTs

- 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"
- Can test the response of the extremes to specified changes in climate



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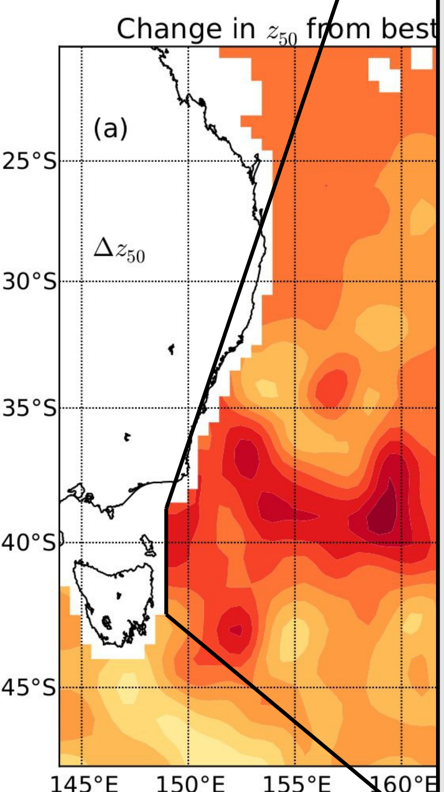
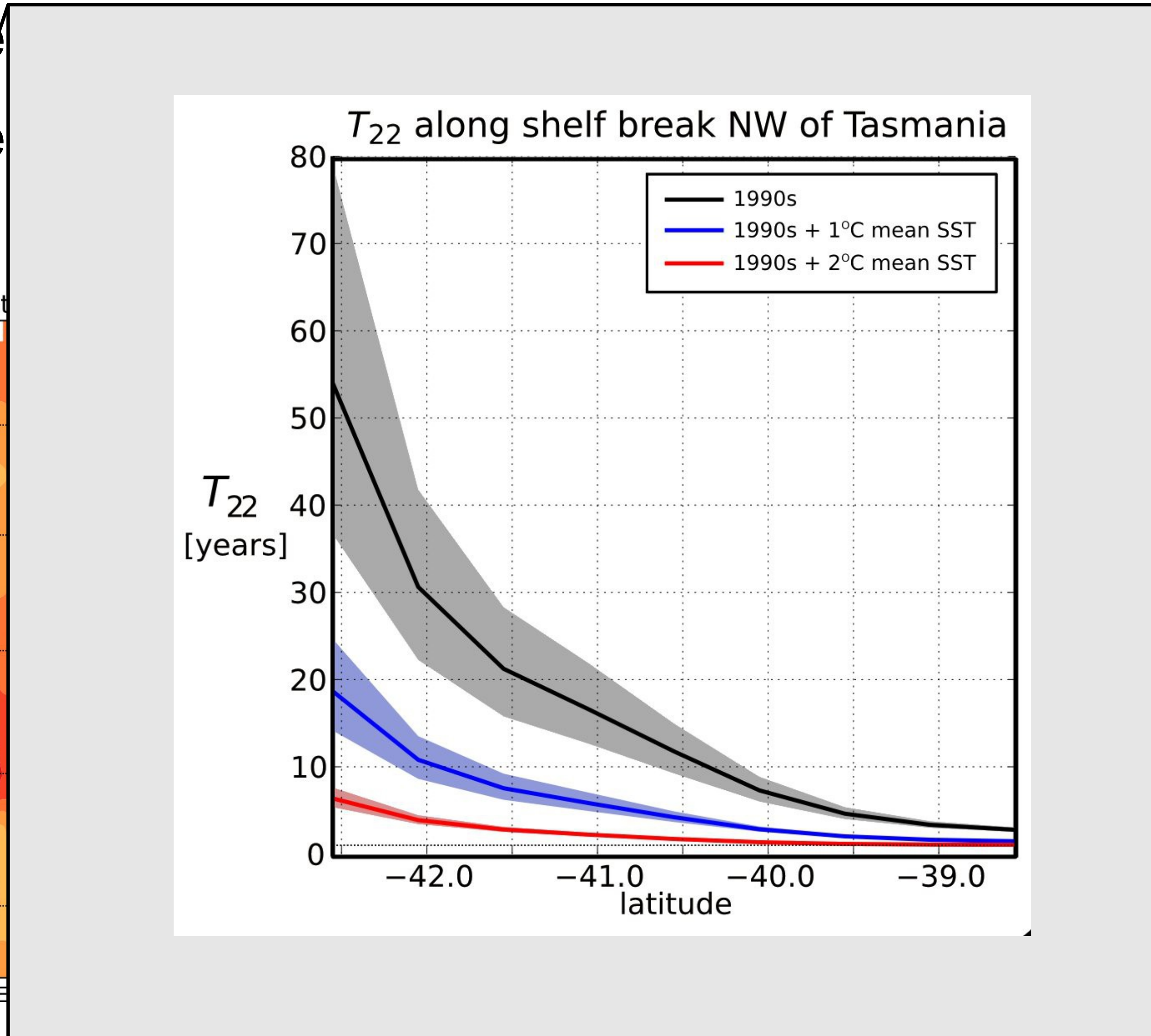
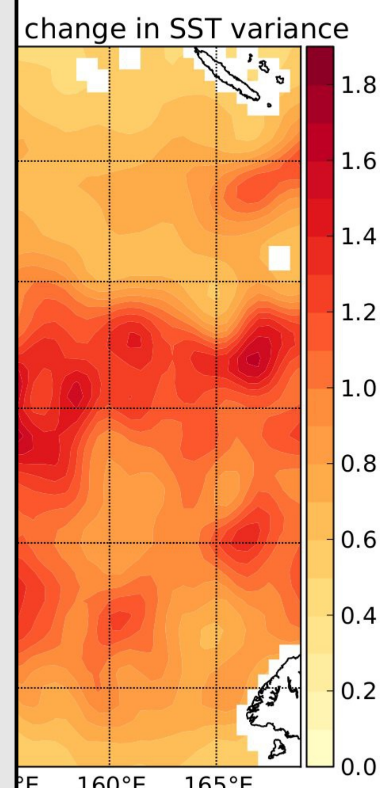
Extreme SSTs

UTAS

- Can use the
- Can test the ges in climate

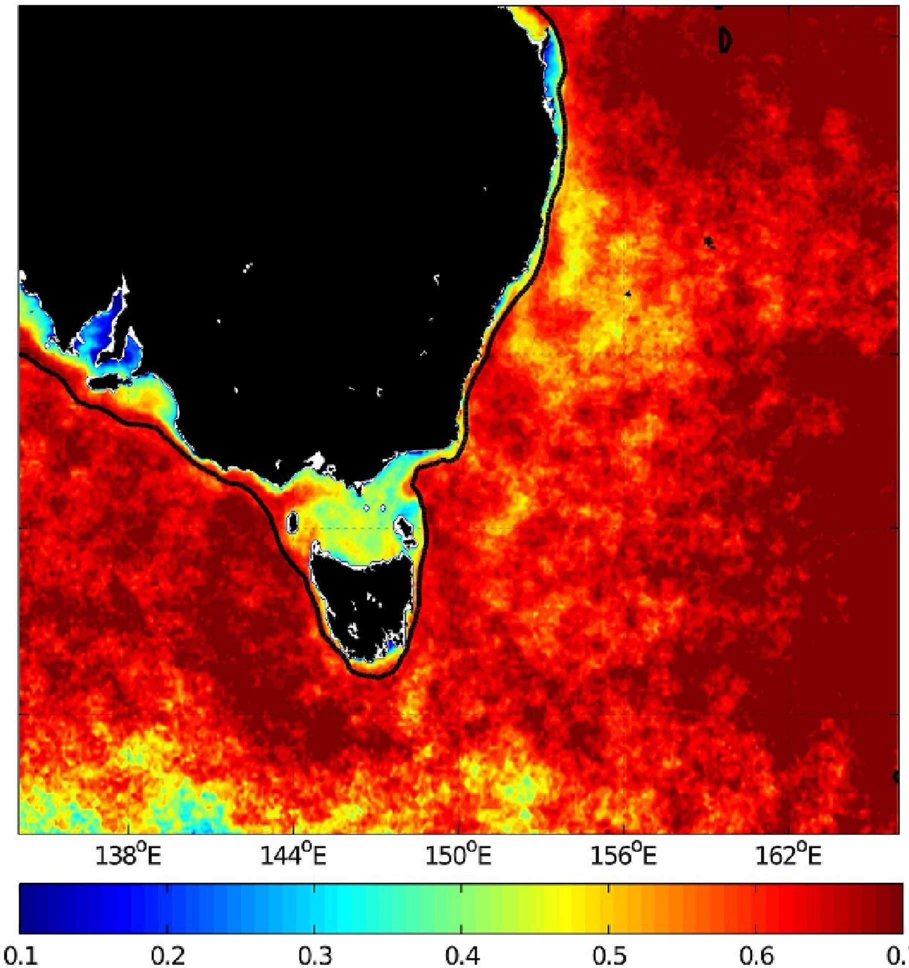






Coastal Marine Climate

- We would like to understand marine climate change over the continental shelf and in the coastal environment
- Unfortunately, global climate models and even high-resolution global ocean models (including OFAM) generally perform poorly in the near-shore environment.
- For example, the correlation between satellite and reanalysis (BRAN, based on OFAM) SST is very poor inside the 200 m isobath:



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

Linear statistical model

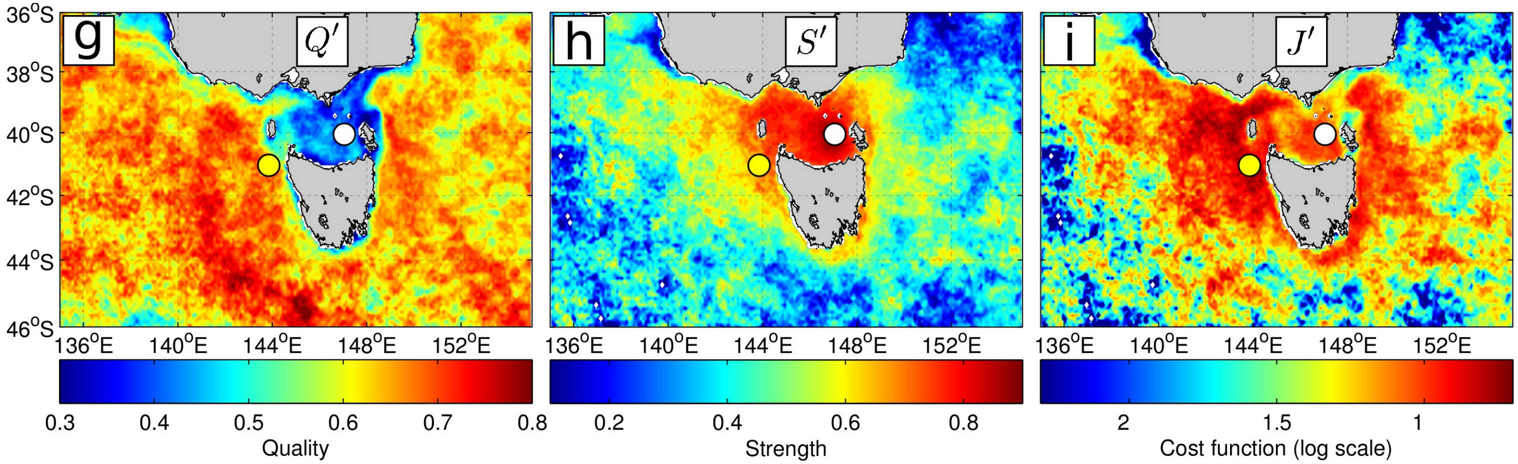
- Idea
  1. Build a model based on the (observed) statistical connection between off-shore and continental shelf SST.
  2. Use model/reanalysis estimates of the offshore SST, and the fitted model, to generate improved predictions of continental shelf SST.
- Divide SST time series into mean, seasonal cycle, and residual variability:

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

- Build seperate linear models for each component
- Choose the off-shore predictors optimally using three basic criteria: (i) data quality, (ii) strengh of off-shore–continental shelf SST relationship, and (iii) proximity of predictor and shelf region

Coastal Marine Climate

- Worked example: Bass Strait



Coastal Marine Climate

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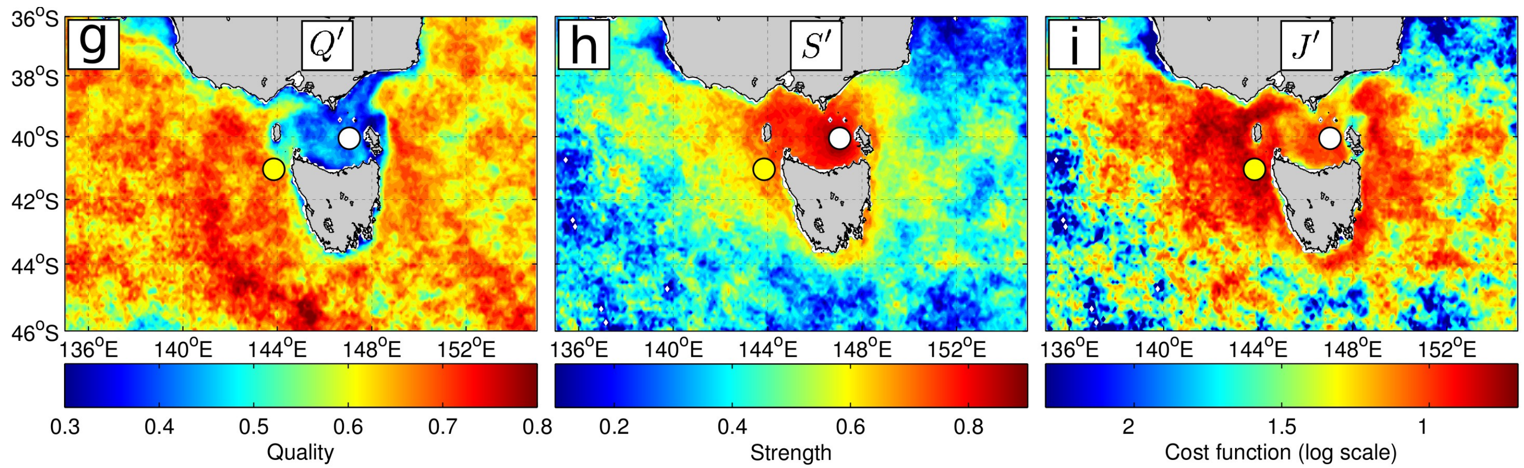
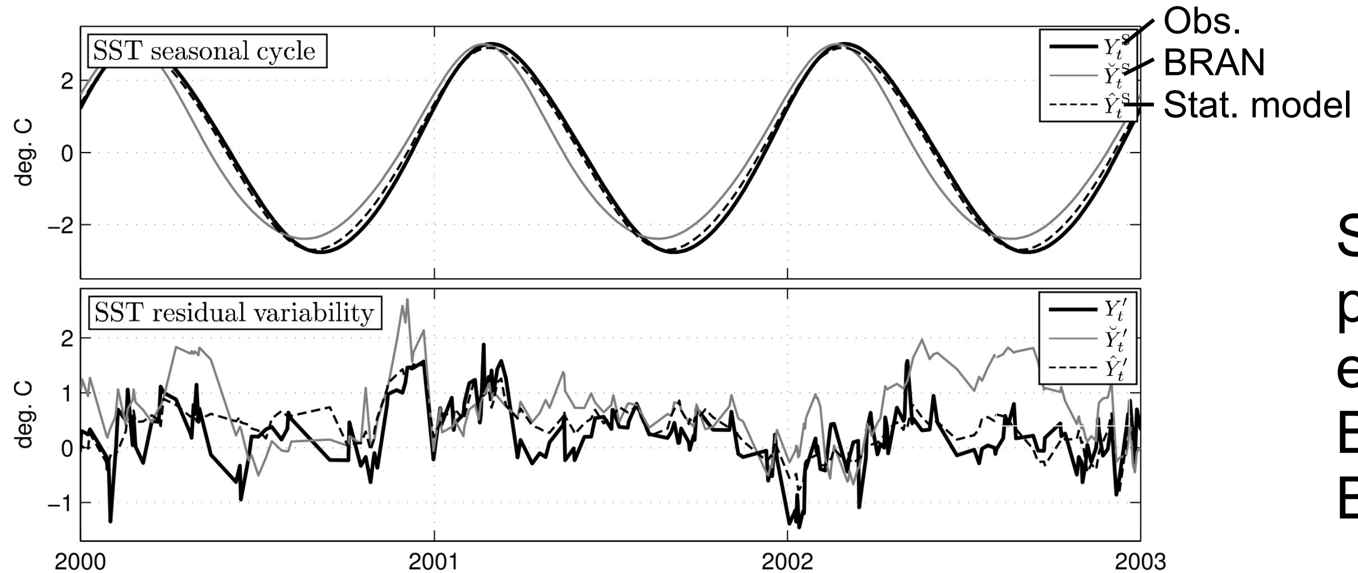
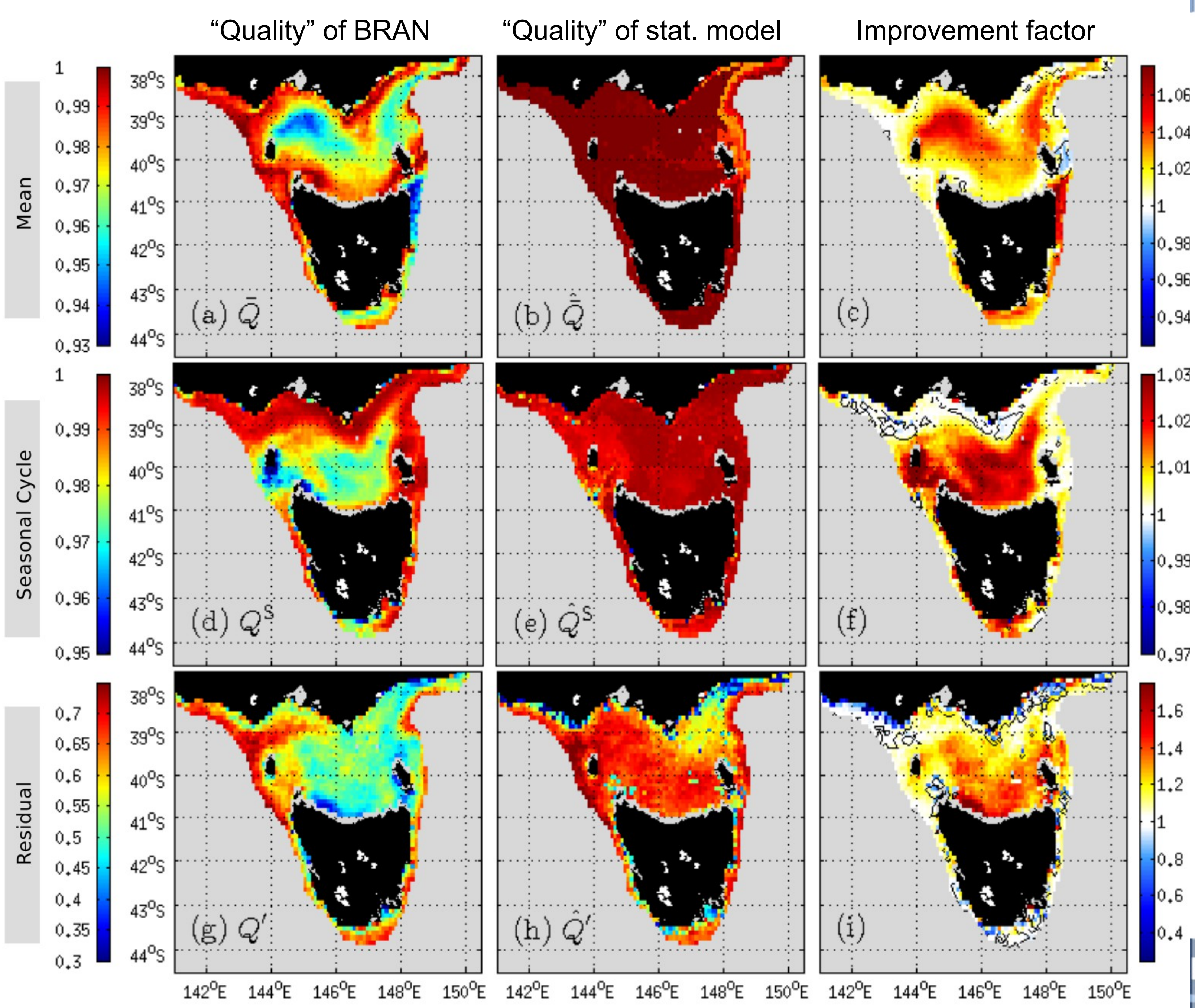




Correlation increased
RMSE decreased by factor of four

Statistical model provides better estimates of SST in Bass Strait than does BRAN

Coastal Marine Climate



knowledge

Coastal Marine Climate

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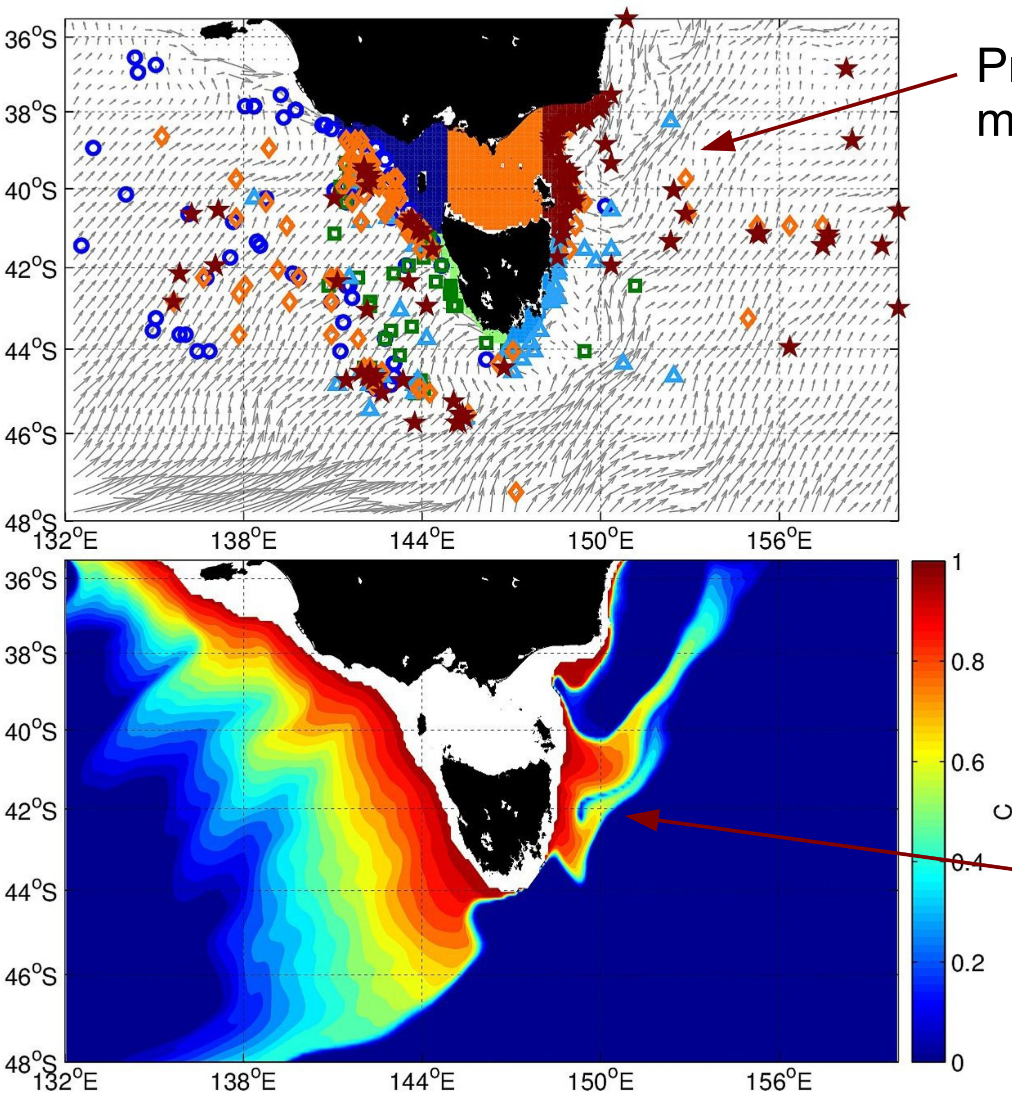

Predictor locations and mean surface currents

The inclusion of connectivity information leads to better and more robust near-shore SST estimates

→ a hybrid statistical-connectivity model

Off-shore ↔ on-shore connectivity statistics

Coastal Marine Climate

- Technique extended to the entire continental shelf for temperate Australia (>20^{O}S)
- Dataset (OH14) available online: `passage.phys.ocean.dal.ca/~olivere/OH14.html`
- Future plans to apply technique to 1990s and 2060s climate projections

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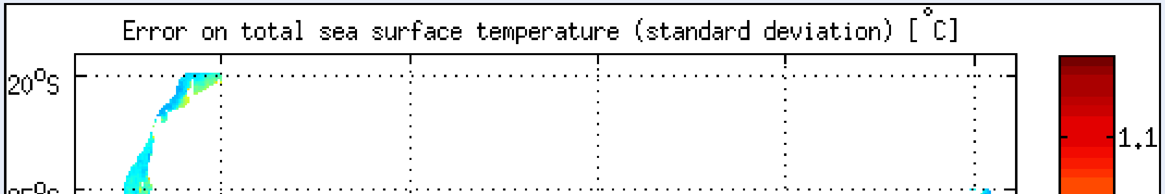
Statistical downscaling of Australian continental shelf sea surface temperatures

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:



Conclusions

- Ocean climate in the Tasman Sea is changing, rapidly relative to the global mean and the changes are not simply in the mean (mean SST, circulation) but in the variability also (eddy activity, SST variance)
- Predicted changes in the mean state: Tasman Sea SST hotspot and redistribution of transport through Tasman Sea
- Changes mean circulation broadly consistent with linear, wind-driven, barotropic model
- Eddy activity, SST variability, and SST extremes increase in EAC extension region – where the dynamics are dominated by mesoscale eddies
- Changes in SST extremes are not just simply due to changes in mean SST: spatial patterns are different, changes are due to a combined effect of the mean, the variance, and the skewness.
- The Bayesian hierarchical extremes model provides a general framework for estimating extremes from global climate model output using climate variables (bias correction)
- Future work: bring estimates of 2060s climate to the coast using "downscaling" model

Conclusions

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., 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. and N. J. Holbrook, Extending our understanding of South Pacific gyre 'spin-up': Modeling the East Australian Current in a future climate, *Journal of Geophysical Research* (available online)

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

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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