Identifying historical marine heatwaves off eastern Tasmania with a regional ocean model

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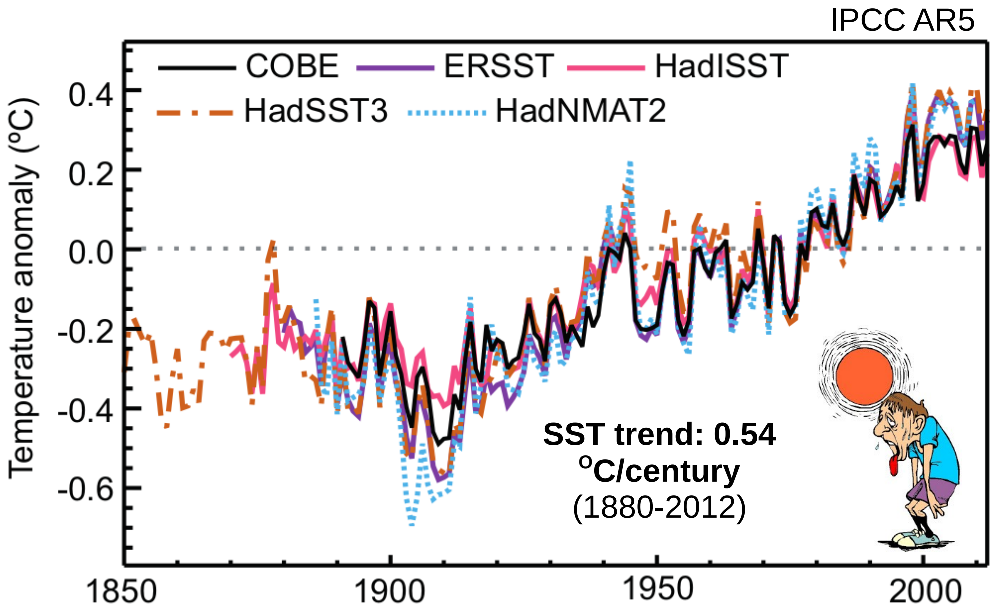
[2] Australian Research Council Centre of Excellence for Climate System Science
[3] Oceans and Atmosphere Flagship, CSIRO, Hobart, Australia

Eric is not here because … his baby girl **Coral was born** quite a bit earlier than expected and he’s off work caring for mum and bub

Overview

- Global marine climate is **warming**
- The SW Pacific (Tasman Sea) is a **hotspot of change**
- Ocean temperature extremes, or **marine heatwaves**, are often the first expression of climate change
- Impacts on **marine ecology** are already being felt
- Regional ocean modelling can help us understand historical marine heatwaves:
  - **Physical drivers**
  - **Variability**
  - **Long-term trends**



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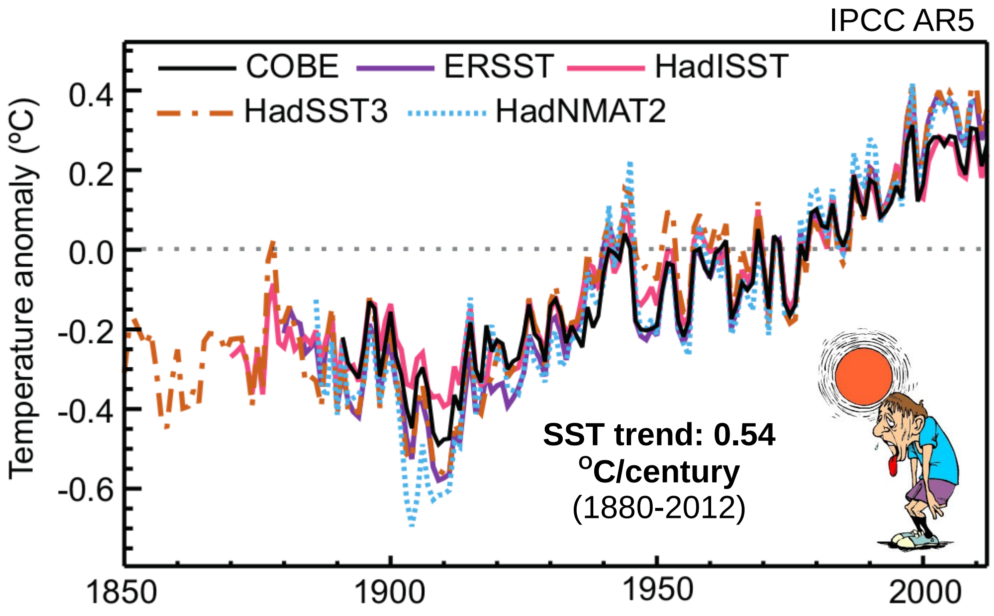
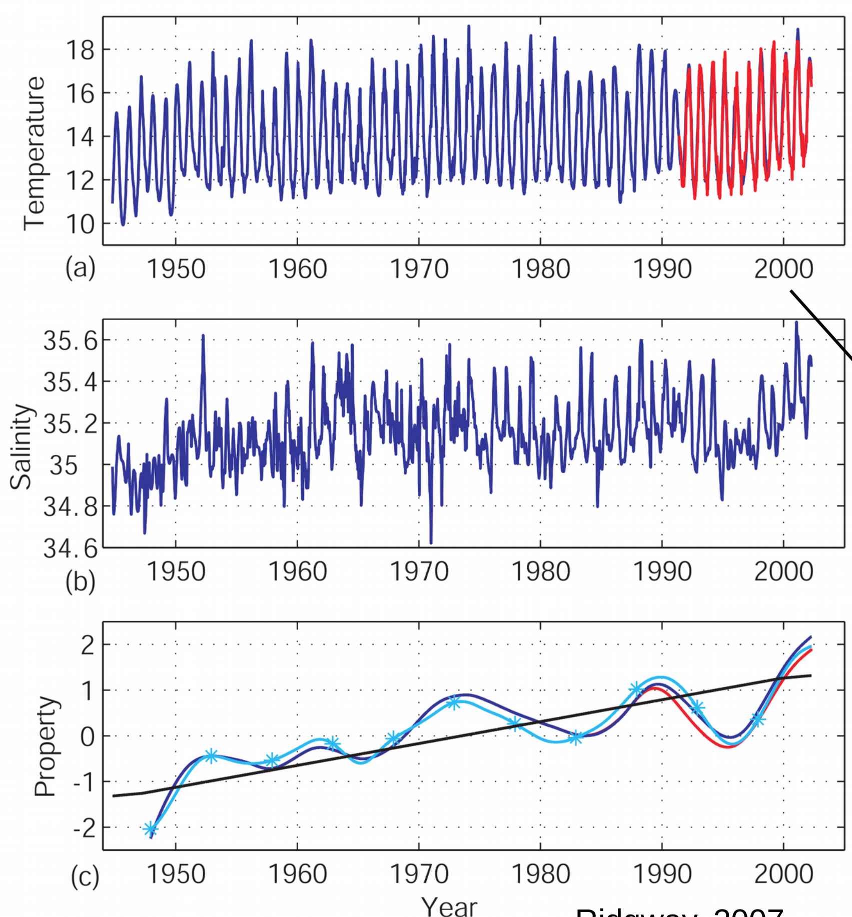
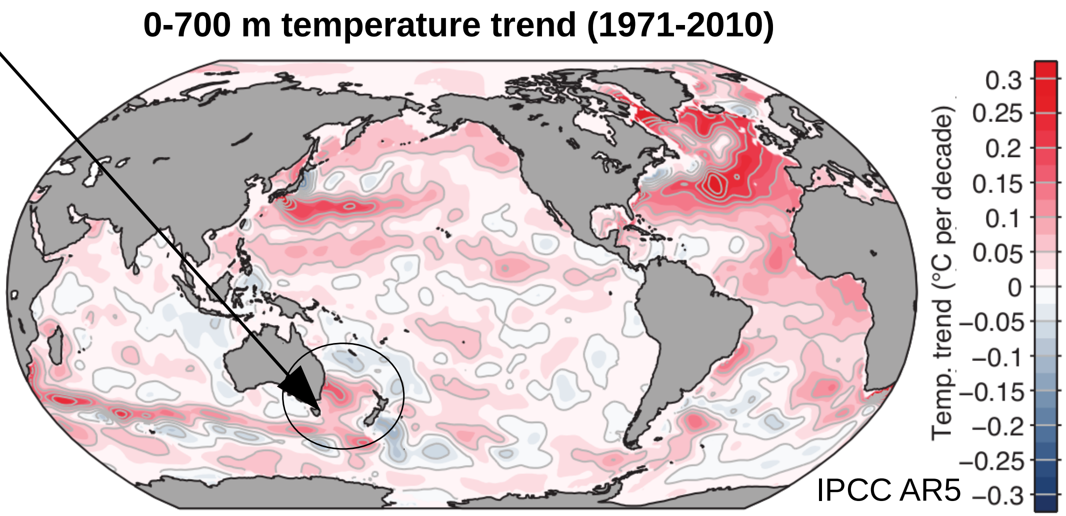




Ridgway, 2007



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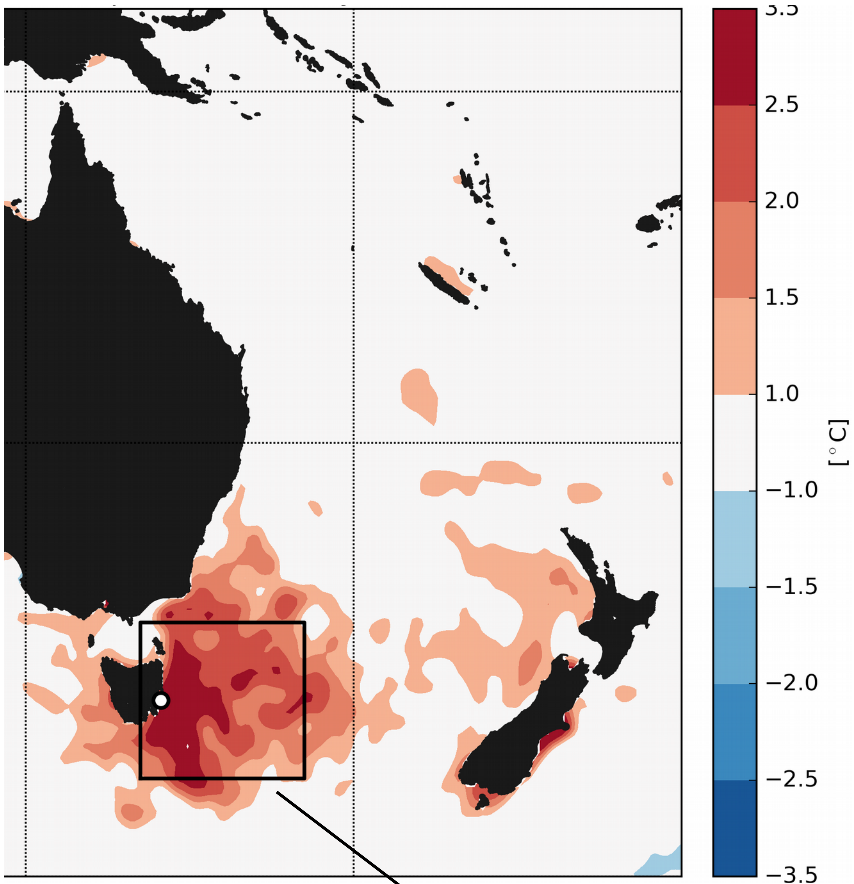
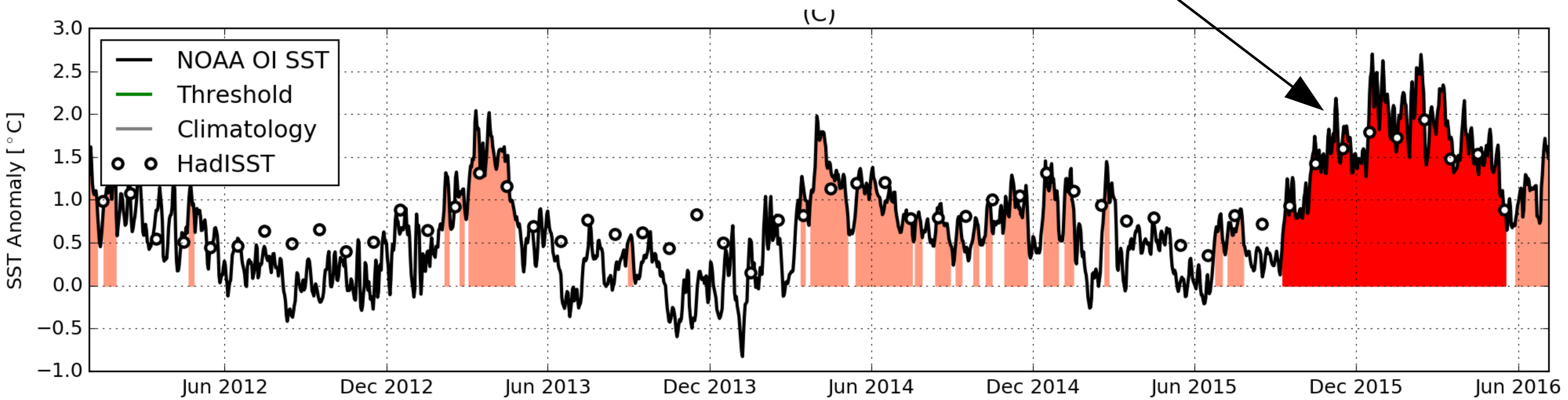


2015/16 Tasman Sea Marine Heatwave



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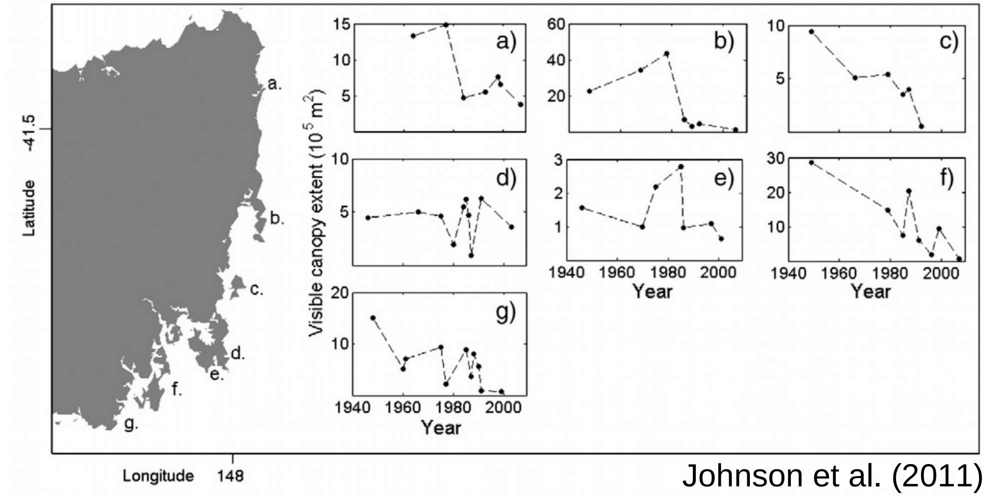
Long-term change in visible surface kelp canopy (Macrocystis pyrifera)



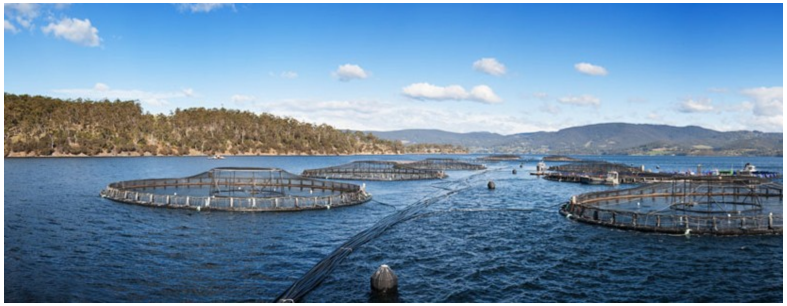
Johnson et al. (2011)

During 2015/16 event:

POMS in Oysters

Abalone mortality

Poor salmon performance



Tropical fish!

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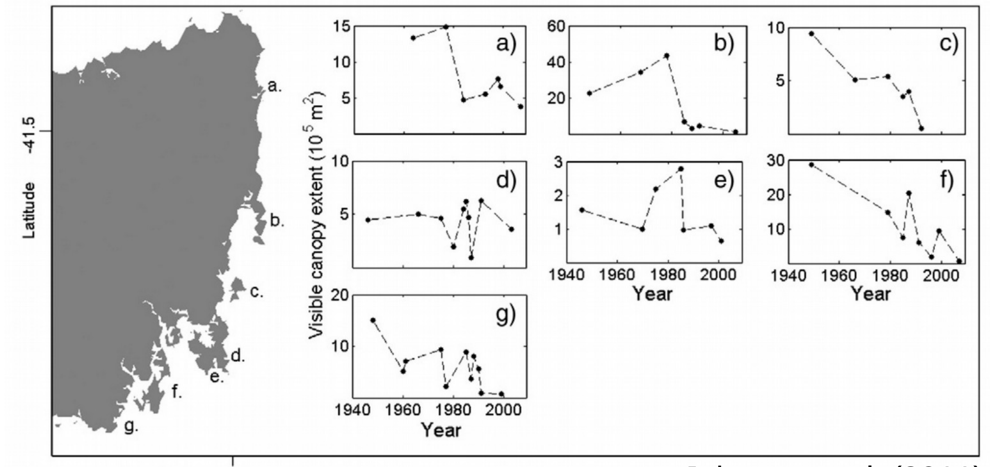

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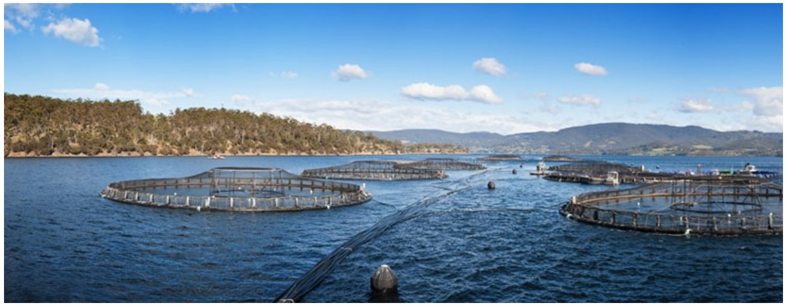

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ETAS Model

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- Domain: South Cape to ~Eddystone Point and seaward out to shelf break
- Bathymetry: Australian Geological Survey Organisation (AGSO) 2002 + SETAS
- Resolution: ~1.9 km resolution
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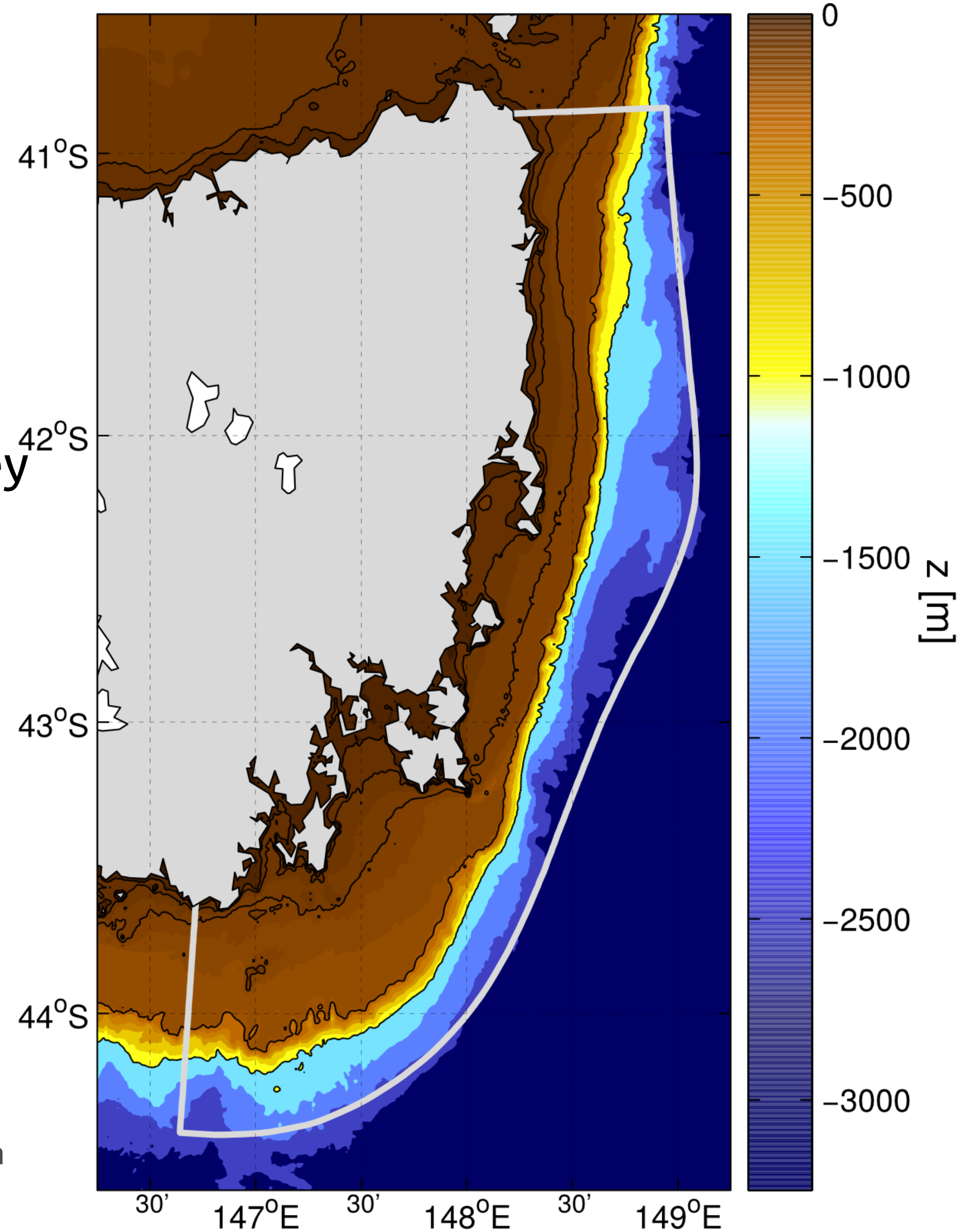

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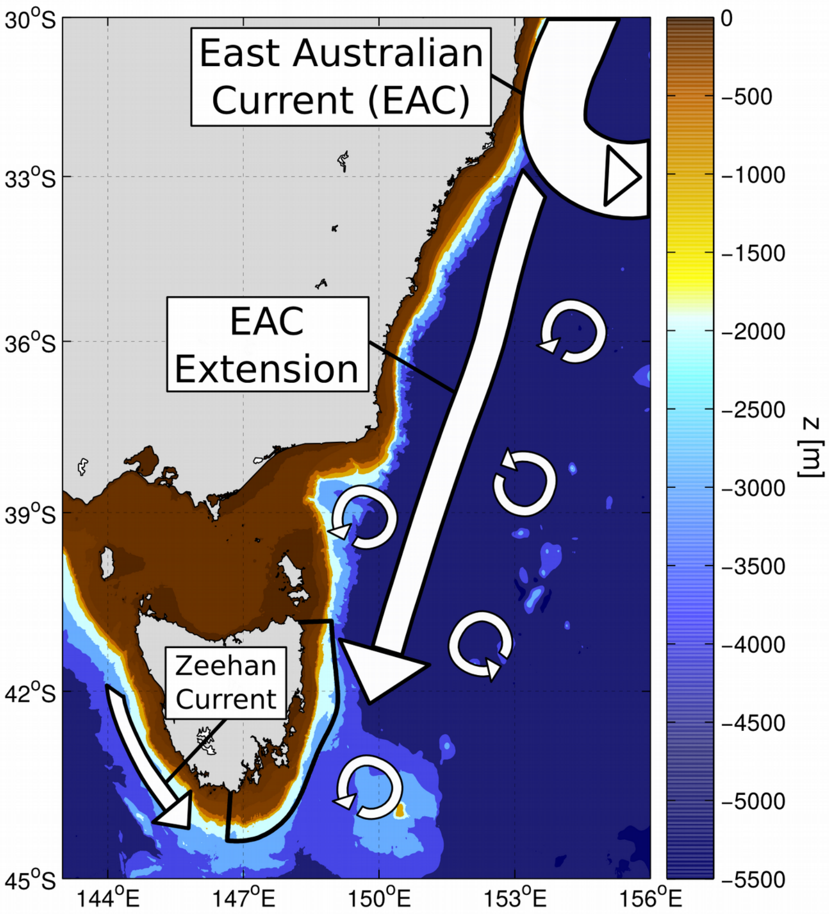
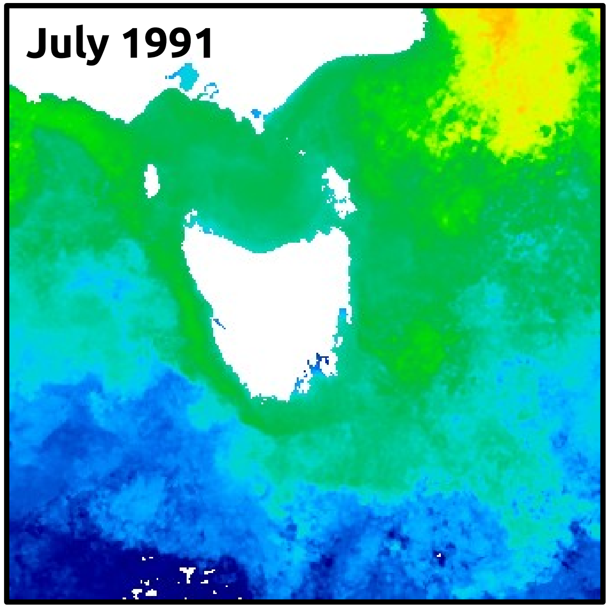
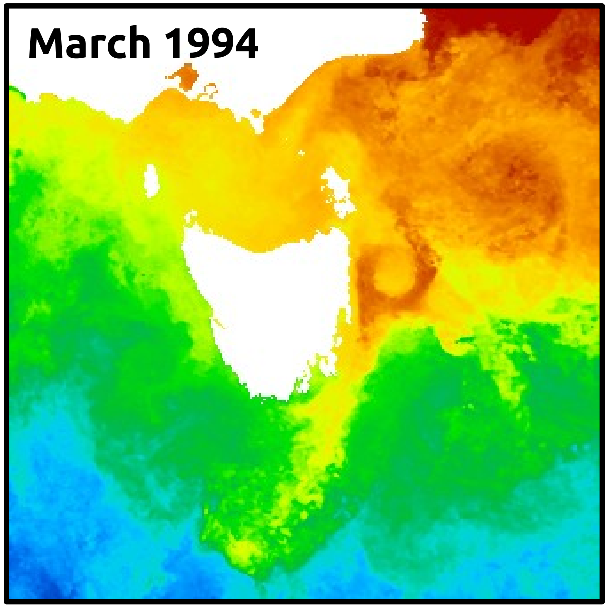
Herzfeld, M. (2006), An alternative coordinate system for solving finite difference ocean models, Ocean Modelling, 14 (3-4), 174-196

Regional Oceanography

- **East Australian Current (EAC)**, a quasi-steady western boundary current, separates from the coast ~33°S.
- The **EAC Extension** continues southward transport as far as Tasmania, but as an unsteady, eddy-rich "current"
- The **Zeehan Current (ZC)**, part of a current system extending all the way to WA, runs southward and eastward along the west and south coasts of Tasmania [Cresswell 2000]



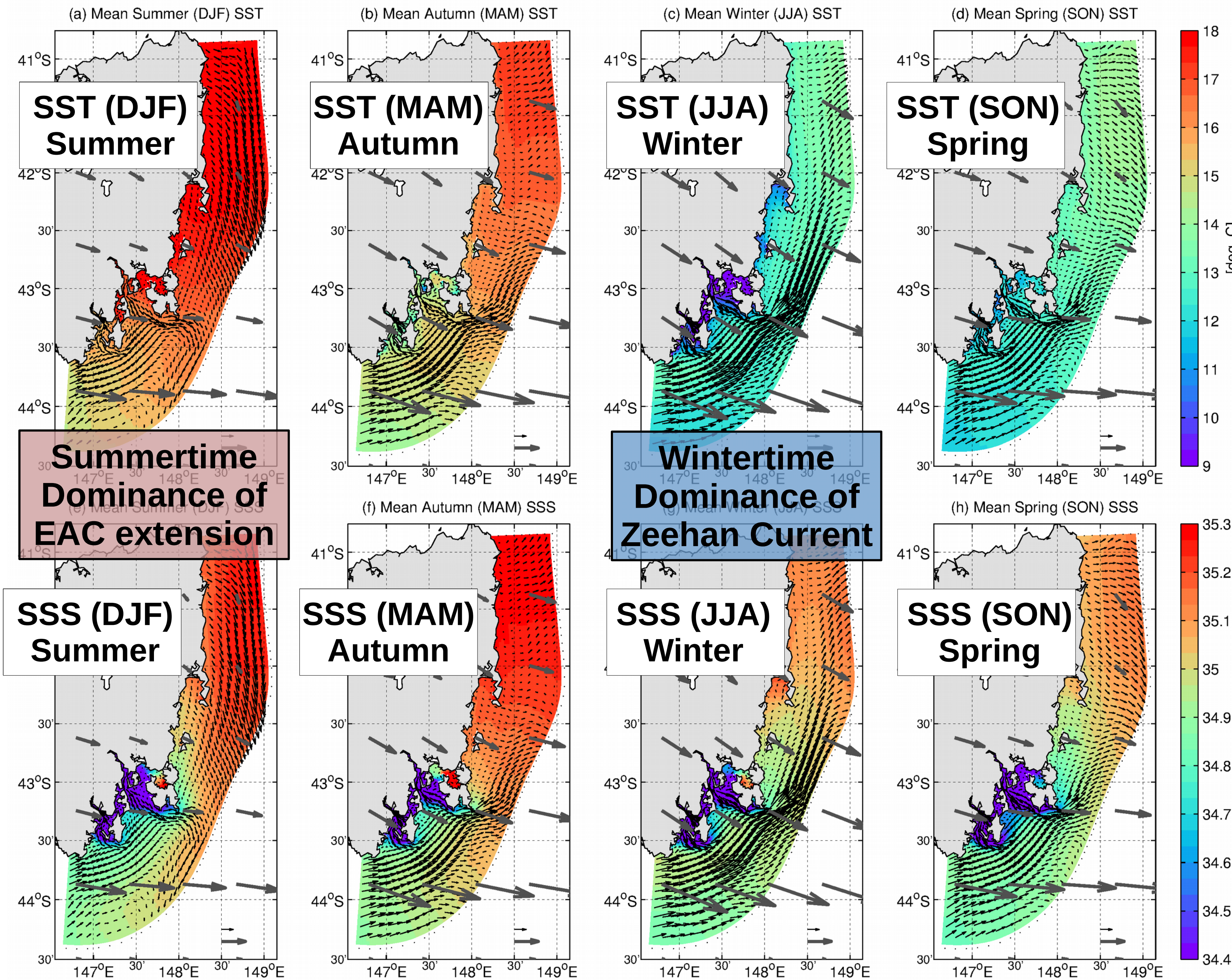




http://www.marine.csiro.au/~lband/yacht_races/yyzeecur.html

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

Surface Climatology



Oliver, Herzfeld and Holbrook, accepted for publication in *Cont. Shelf. Res.*

Marine Heatwave Definition

- A **marine heatwave (MHW) definition** has been proposed (Hobday et al., 2016)
- A MHW is defined to be **a discrete prolonged anomalously warm water event at a particular location**
  - **'anomalously warm'**: MHW temperatures are above a baseline 90th percentile climatology
  - **'prolonged'**: a MHW must persist for at least 5 days
  - **'discrete'**: a MHW event has well-defined start and end times

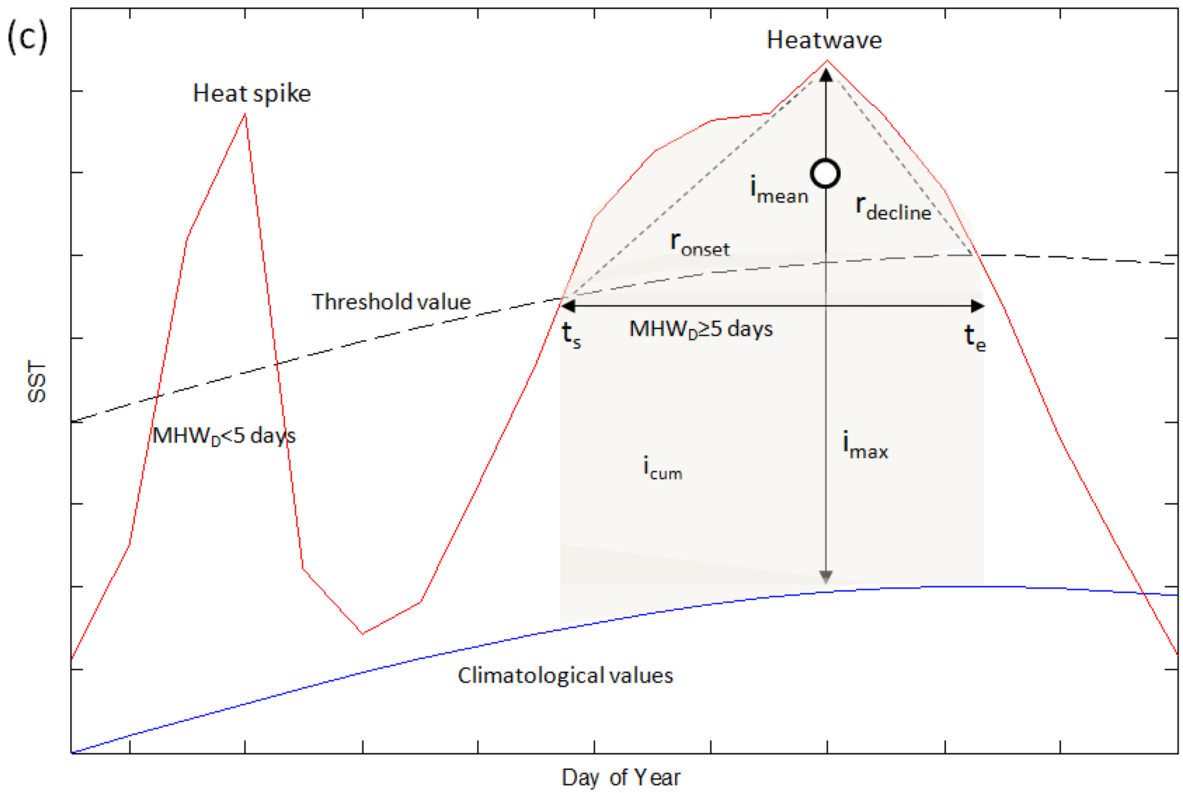


Figure from Hobday et al. (2016) *Prog. Ocean.*

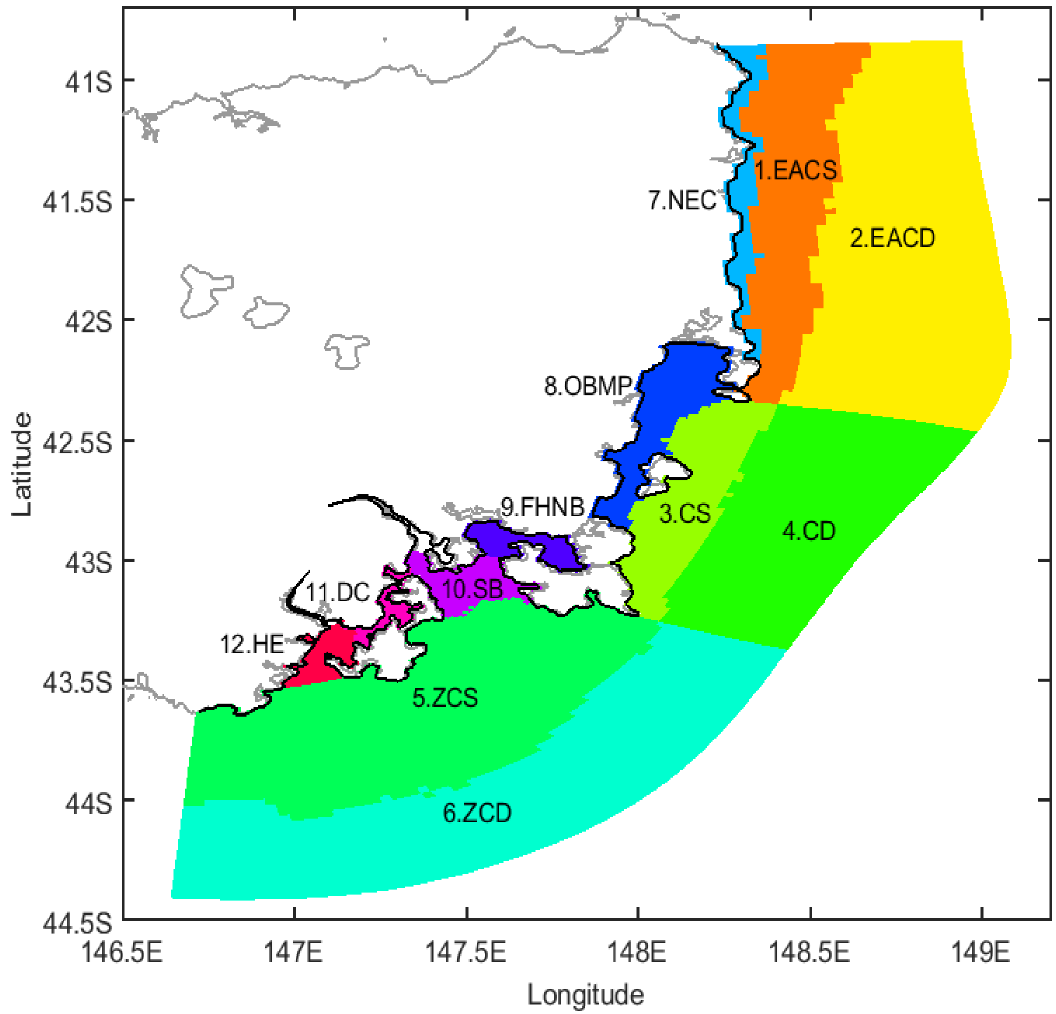
Definition includes a set of metrics, including:

- **Intensity** [^{o}C]
  - both maximum and event-mean
- **Duration** [days]
  - Time from start to end dates

Software implementation in Python freely available here:
`github.com/ecjoliver/marineHeatWaves`

ETAS Regions

- Domain was divided up into **12 sub-regions**:
  - 3 deep (D) regions (H>200m)
  - 3 shelf (S) regions (50m<H<200m)
    - **Split** in the along-shelf direction based on dominating influence of the **EAC** or the **ZC**, or in their **confluence**
  - 6 nearshore regions, defined by bays and estuaries
  - → 12 spatially averaged **daily SST time series** covering 1993-2015
  - MHW def'n applied to each

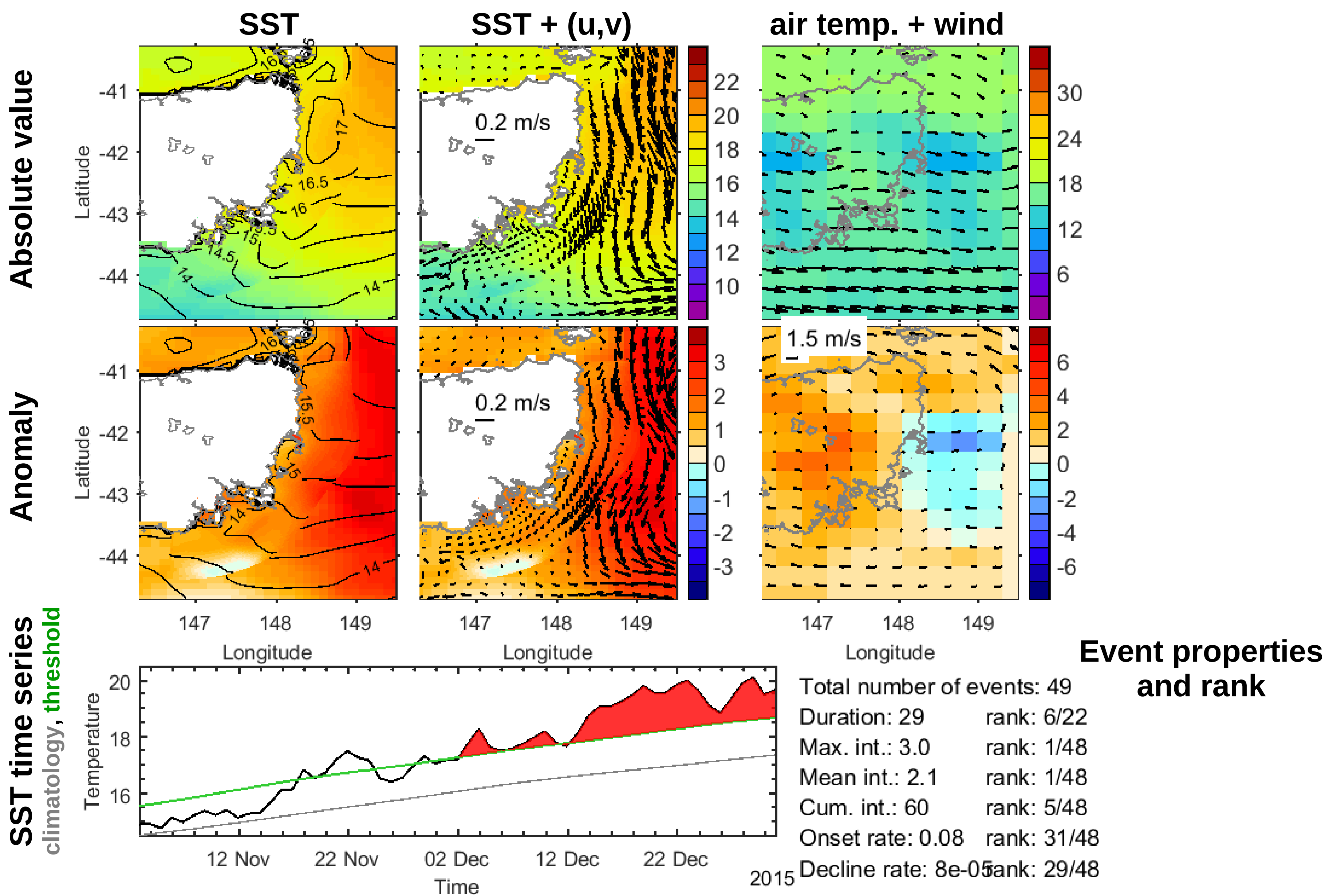


LEGEND

EAC+ = East Australian Current, **ZC+** = Zeehan Current, **C+** = Confluence
+D = Deep (H>200m), **+S** = Shelf (50m<H<200m)
NEC = Northeast coast, **OBMP** = Oyster Bay & Mercury Passage
FHNB = Frederick Henry and Norfolk Bays, **SB** = Storm Bay
DC = D'Entrecasteaux Channel, **HE** = Huon Estuary

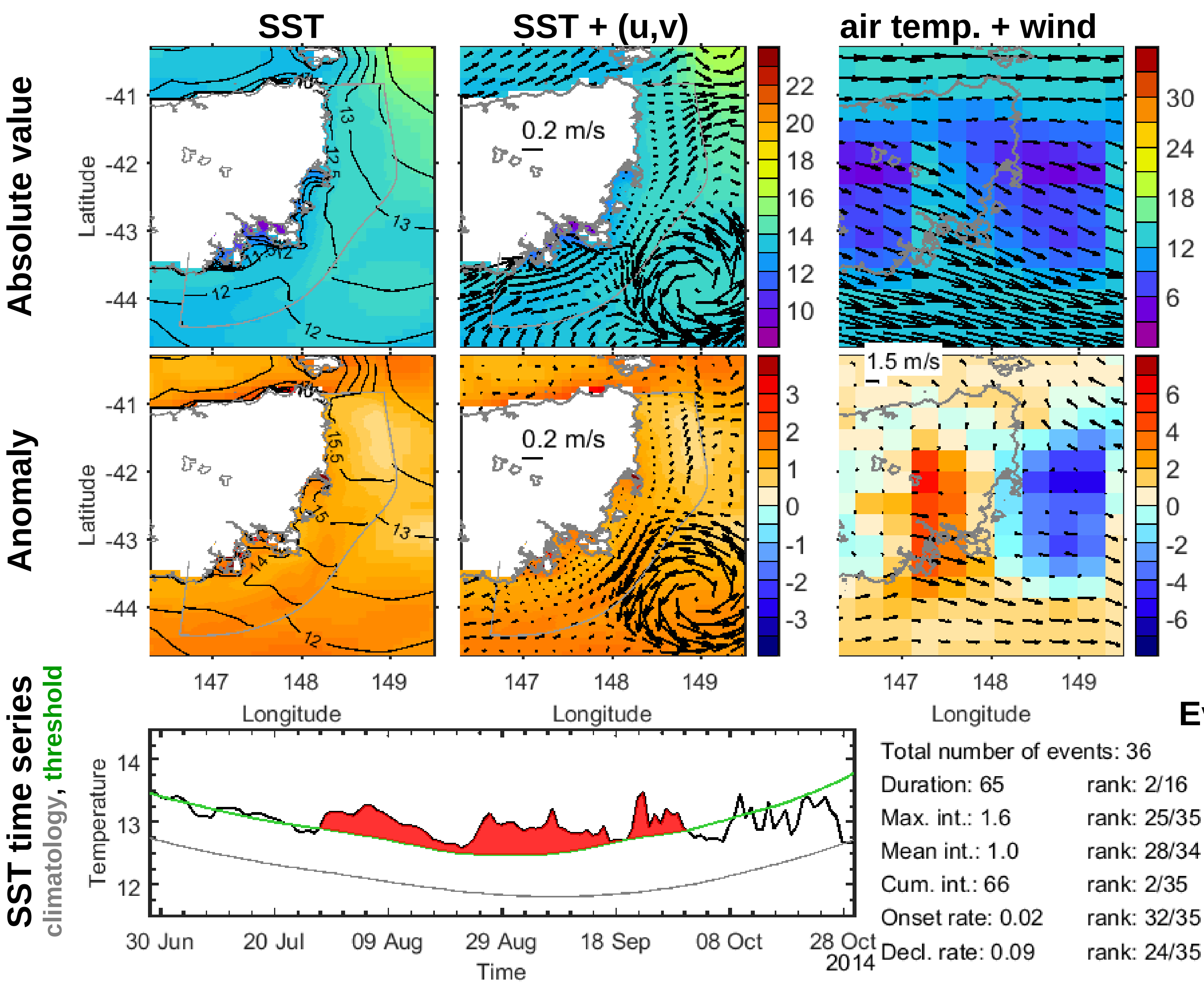
Individual events

- **Event 49 (of 49) in Region 2 (EACD, region with strongest EAC influence)**
- Also calculate regional SST, currents, air temp., wind averaged over event duration



Individual events

- **Event 32 (of 36) in Region 5 (ZCS, roughly the "Bruny Island bioregion")**
- Also calculate regional SST, currents, air temp., wind averaged over event duration

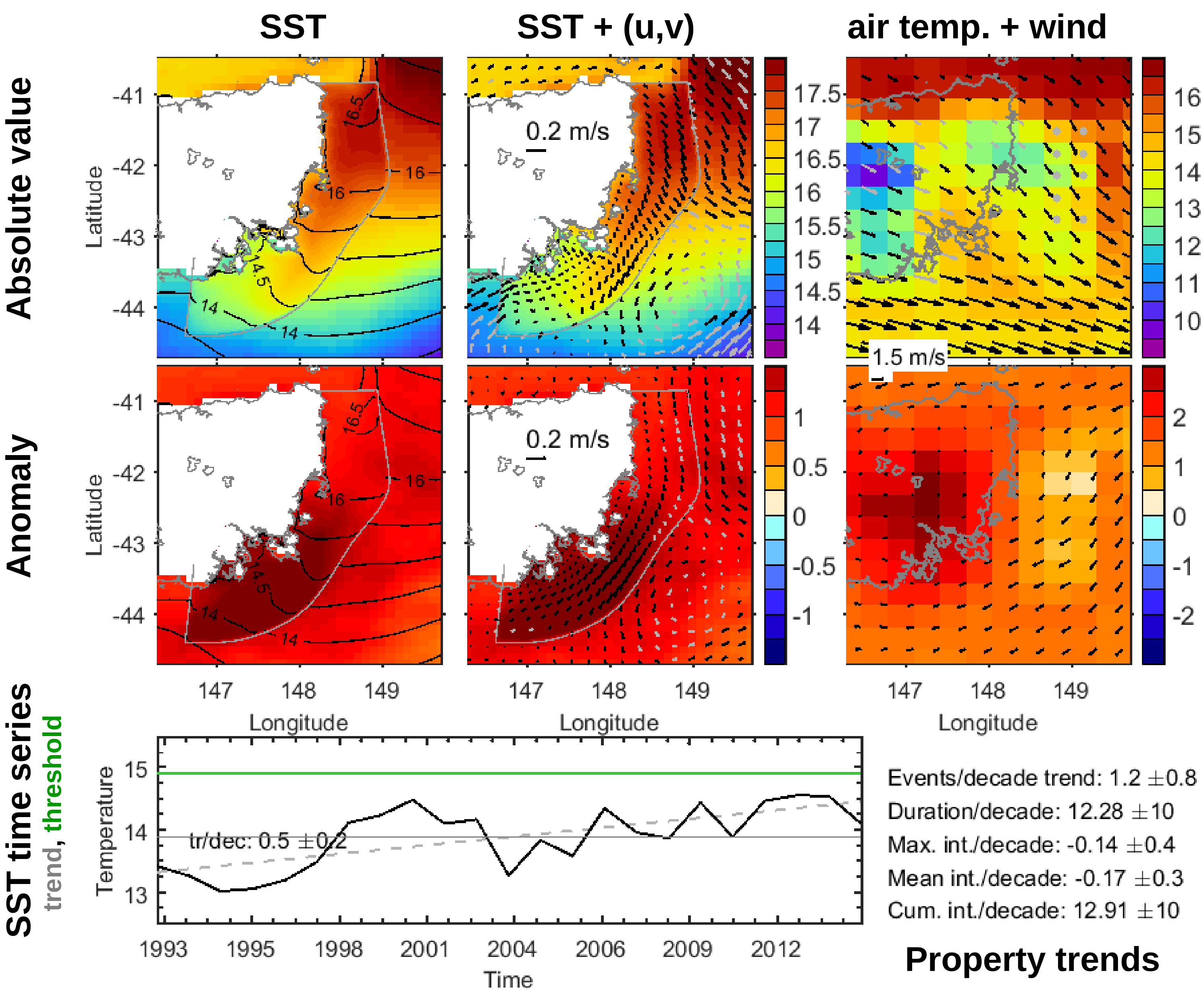


Event properties and rank

Total number of events: 36	
Duration: 65	rank: 2/16
Max. int.: 1.6	rank: 25/35
Mean int.: 1.0	rank: 28/34
Cum. int.: 66	rank: 2/35
Onset rate: 0.02	rank: 32/35
Decl. rate: 0.09	rank: 24/35

Average MHW conditions

- **Average across all events in Region 5 (ZCS, roughly the "Bruny Island bioregion")**
- Grey dots/arrows/± indicate statistical significance (95% confidence)



Events/decade trend: 1.2 ±0.8
Duration/decade: 12.28 ±10
Max. int./decade: -0.14 ±0.4
Mean int./decade: -0.17 ±0.3
Cum. int./decade: 12.91 ±10

Property trends

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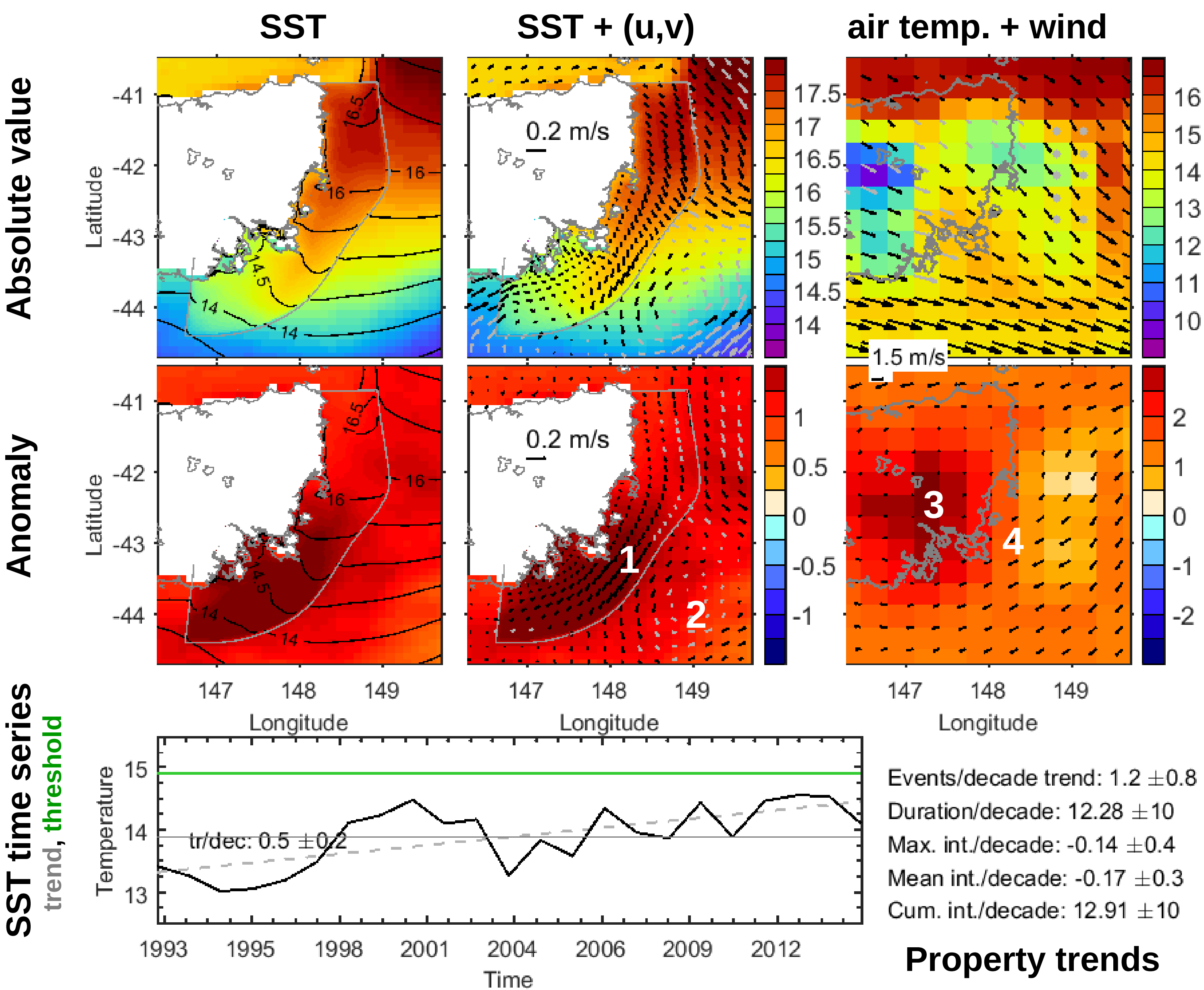

MHWs in the southeast tend to co-occur with:

1. Anomalously strong southward (EAC?) flow

2. An anticyclonic eddy of the SE of Tasmania

3. Warm air over the SE of Tasmania

4. Weak anomalous NE-erlies

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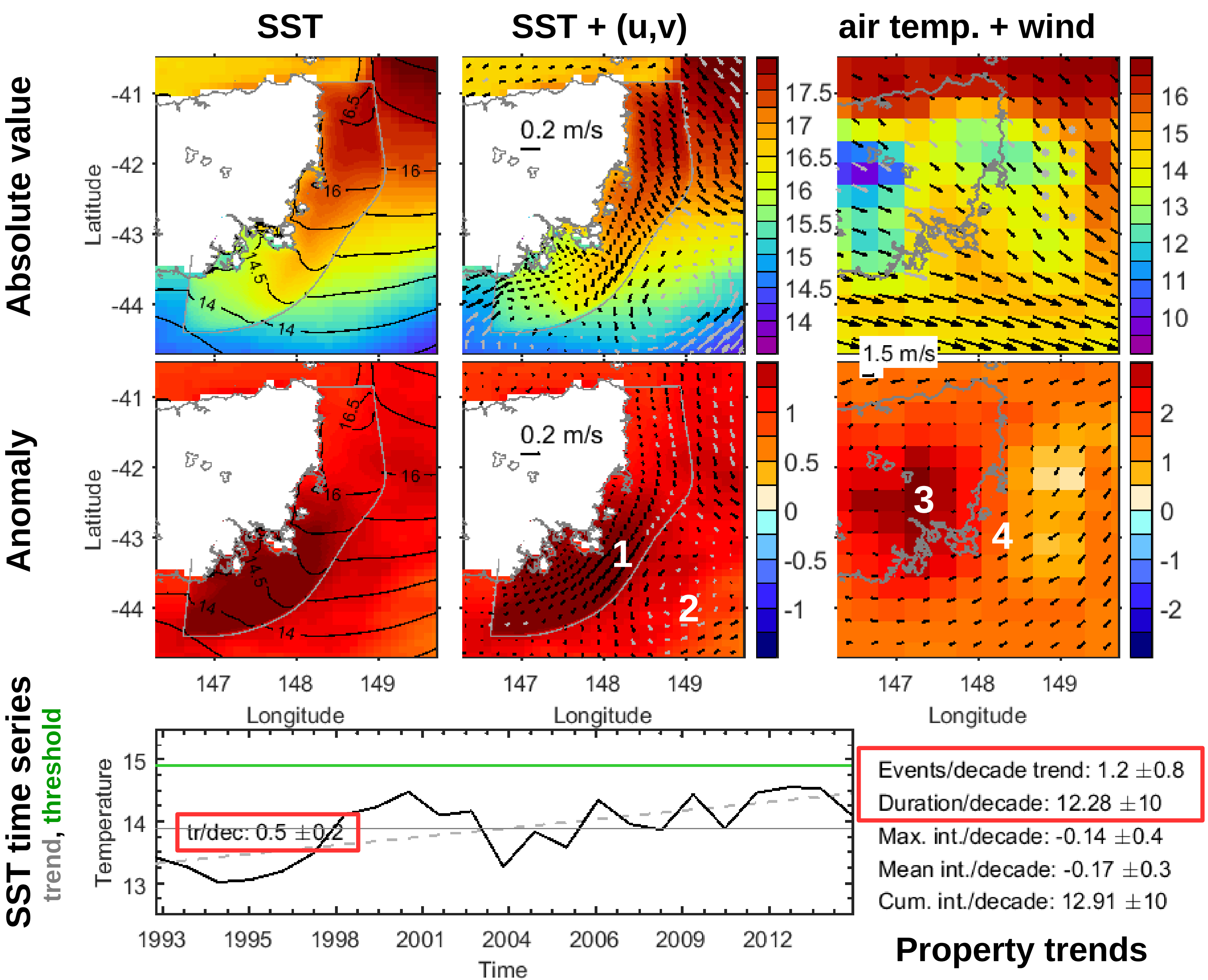

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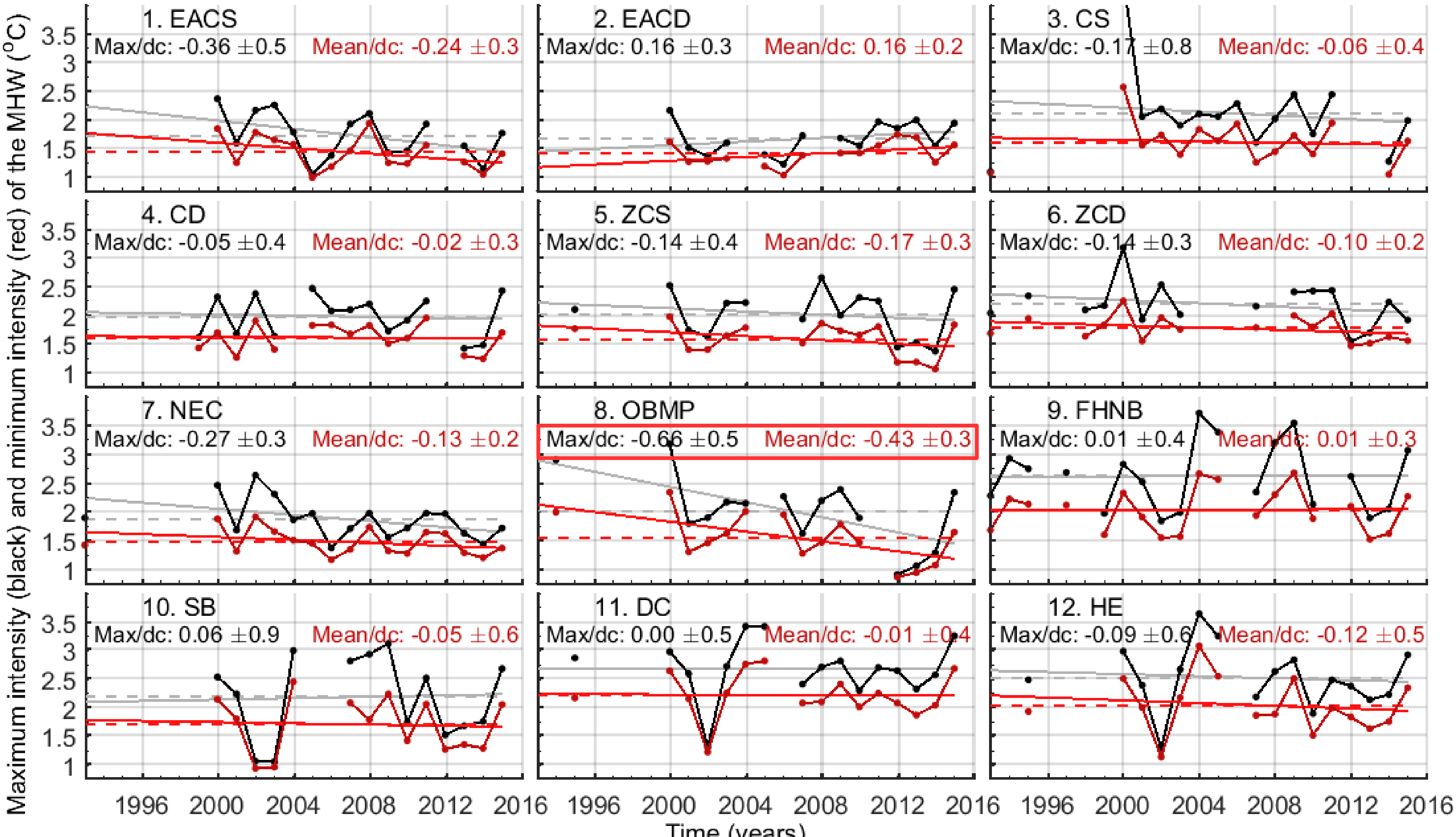
Significant linear trends in <u>SST</u>, <u>MHW frequency</u>, and <u>MHW duration</u>

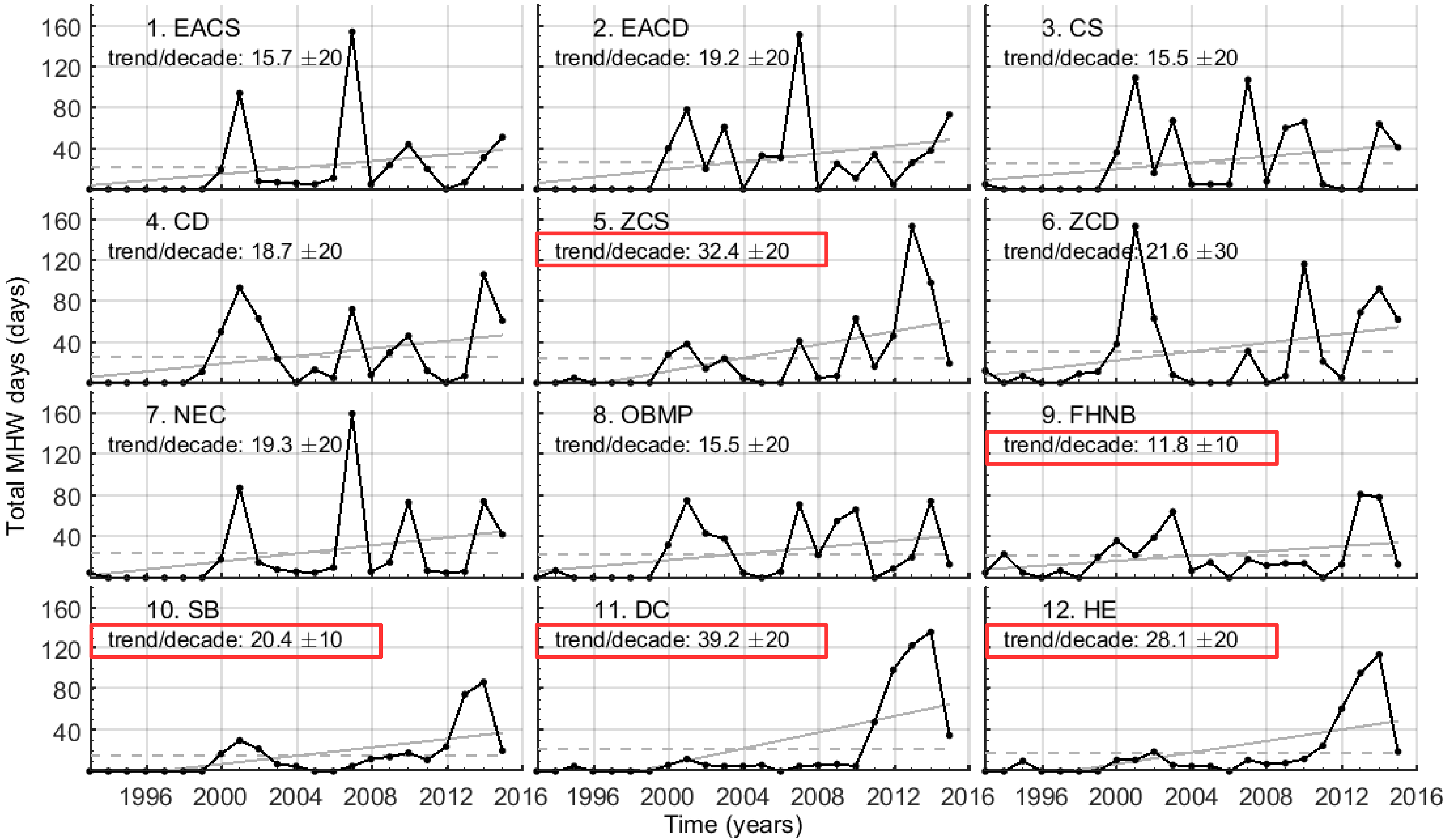
Annual Timeseries

- Annual time series' of **maximum and mean intensity** of MHWs
- No consistent trend in MHW intensity



Annual Timeseries

- Annual time series of **Total MHW days** i.e. “the count of MHW days in each year”
- **Spatial variation** in **linear trends**



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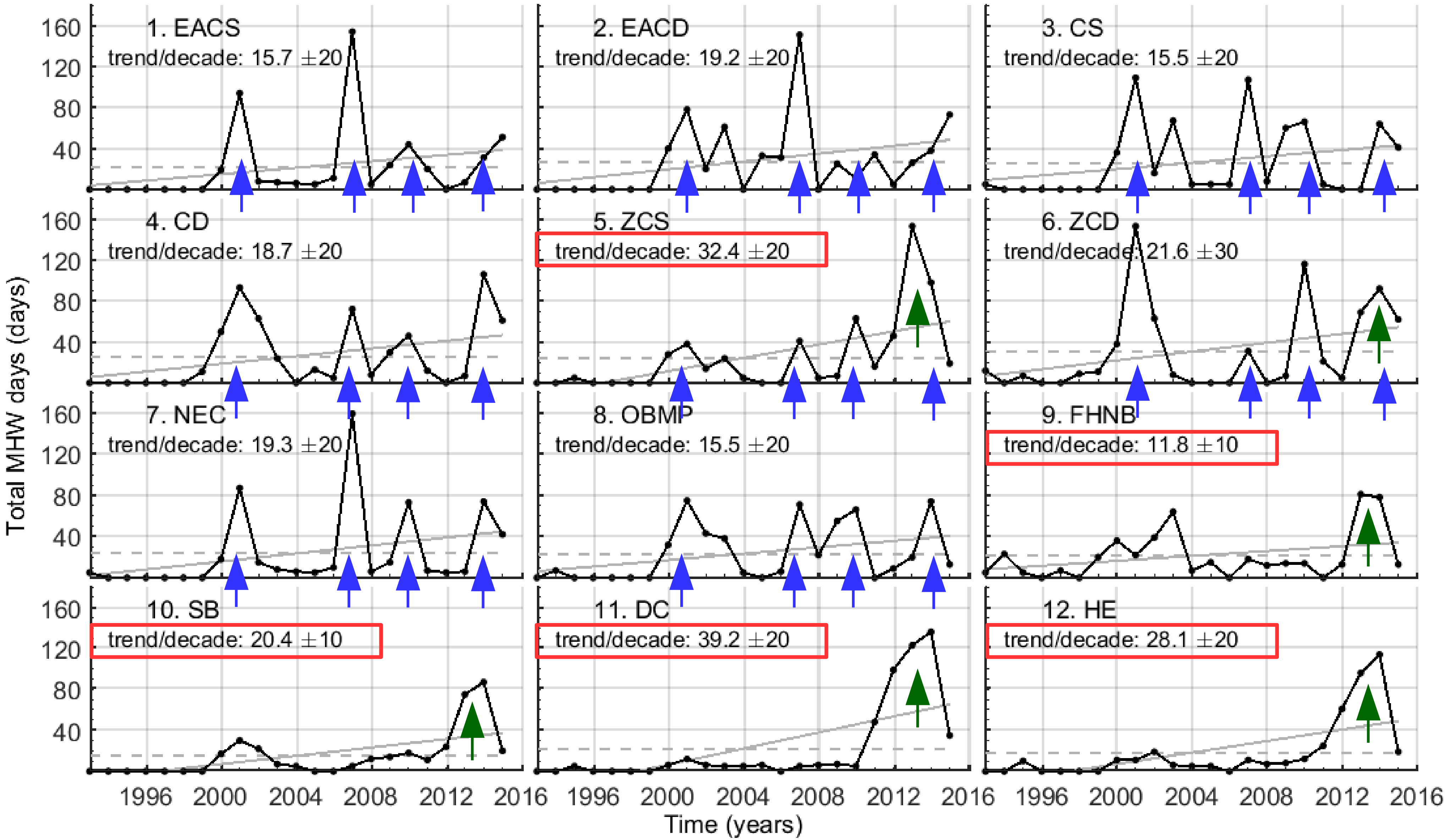
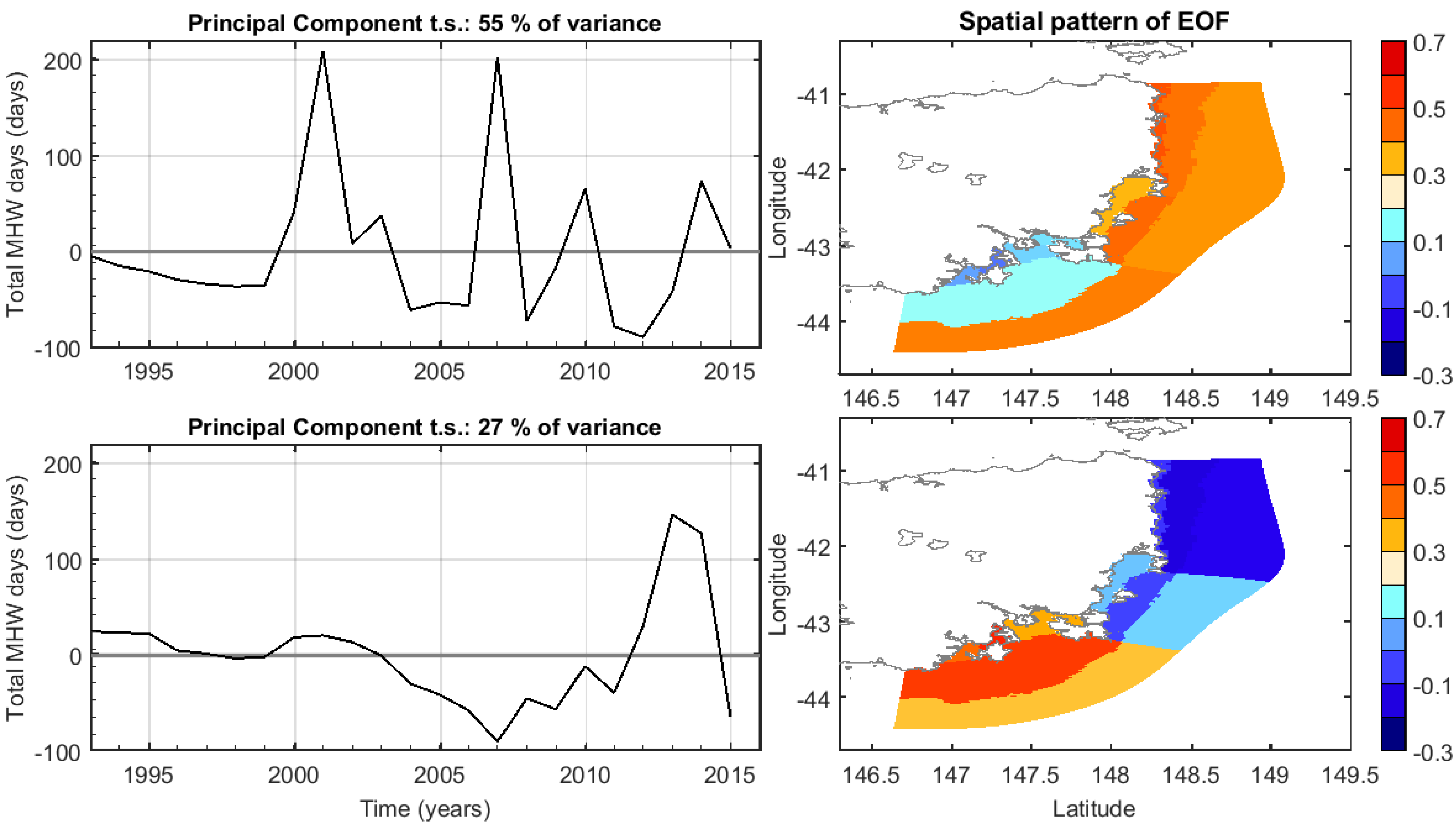
- **Spatial variation** in **linear trends** and **variability** → **(two modes?)**



Modes of Variability

- **Principal Component Analysis** of **Total MHW Days** (linear trend removed)
- Two modes of variability, spatially separated
  - **Mode 1:** *Interannual* mode picks 2001, 2007, 2010, 2014 for northern and eastern regions
  - **Mode 2:** Lower frequency mode (~*decadal*) picks up 2004-2011 low and 2012-2014 high for nearshore southeastern Tasmania



Summary and Future Work

- **ETAS** model can be used to identify and characterise all MHWs off eastern Tasmania over 1993-2015 period, including
  - MHW properties (intensity, duration, etc…)
  - Concurrent oceanographic and atmospheric and conditions
- **Averaging** across **events** in **all years or** in **a single year** tells us
  - **1.** Typical ocean and atmosphere forcing conditions
    - Clear role of the EAC Extension, possibly offshore eddies also
  - **2.** Long-term trends (strong increases in the southeast, “canary in the coalmine” for climate change?)
    - MHWs getting more frequent/longer but not more intense
- **Modes of variability** indicate two modes with different time scales (interannual, decadal) acting largely independently in two different zones off eastern Tasmania
- **Future work**: relative role of surface and boundary forcing, interaction between off-shore eddies and the shelf, influence of ENSO/other modes, quantifying EAC vs. ZC influence, individual case studies (e.g. 2015/16)

Acknowledgements: University of Tasmania Research Enhancement Grant Scheme (REGS) 2016 and ARC Super Science Fellowship and Centre of Excellence for Climate System Science. Modelling help and interpretation: Mike Herzfeld, John Andrewartha, Mark Baird, Farhan Rizwi (CSIRO), Jessica Benthuysen (AIMS)

Extra Slides:
Model set-up

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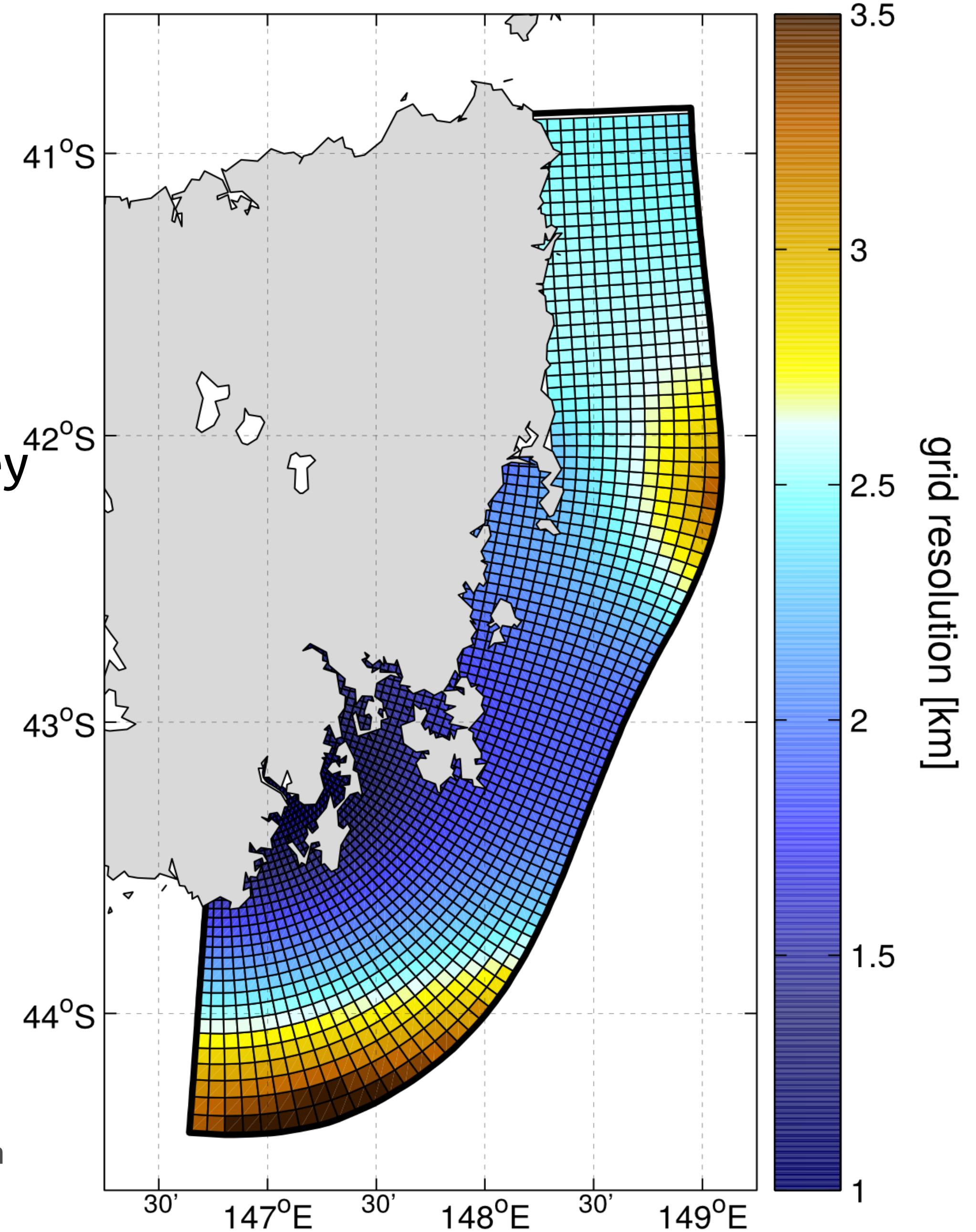

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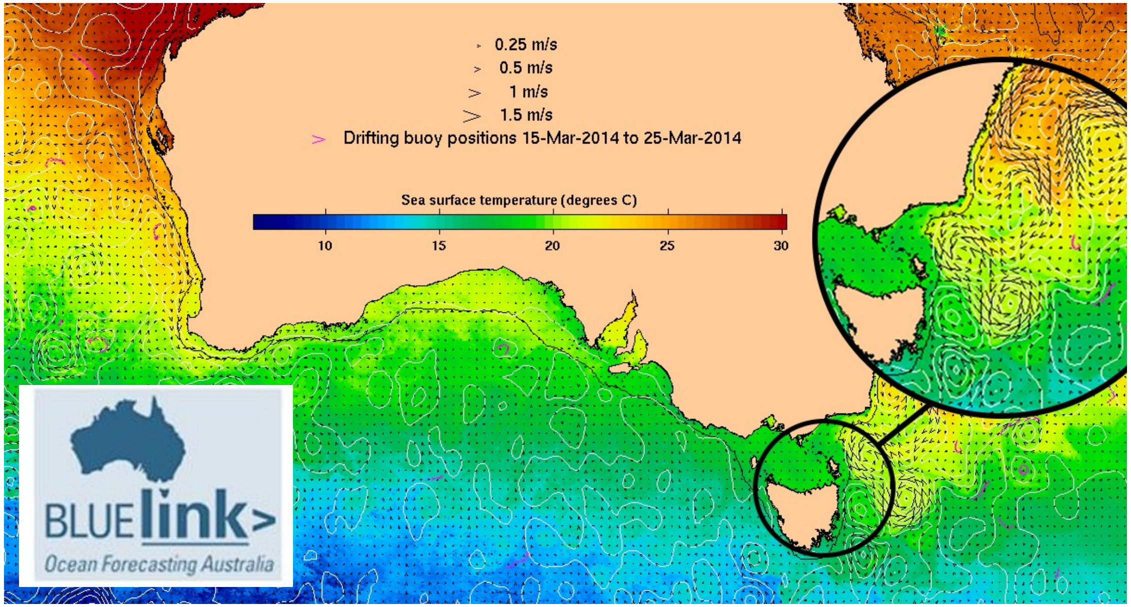
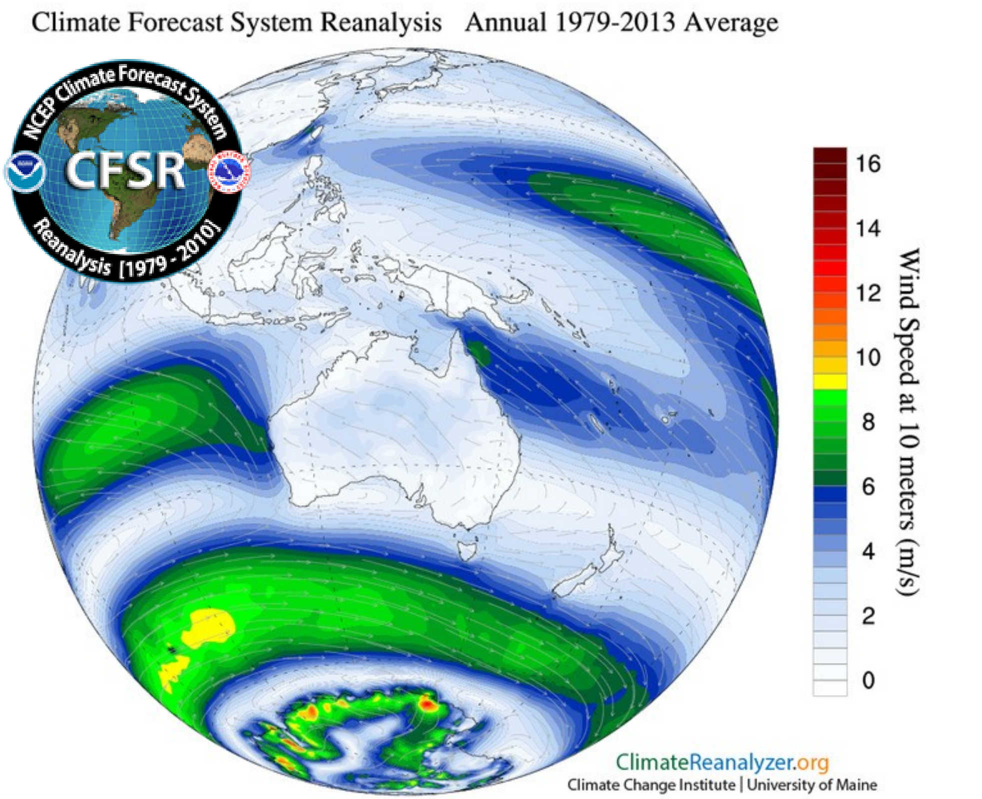
Forcing

- Boundary conditions used the recently-developed Dirichlet boundary condition of Herzfeld and Andrewartha (2012)
- Lateral boundaries were forced by velocities, temperature and salinity from **Bluelink** reanalysis and analysis fields
- Surface was forcing was provided from the **NCEP Climate Forecast System (CFS)** Reanalysis and Reforecast
- Coverage: 1993-2015





Herzfeld, M. and J. R. Andrewartha (2012), A simple, stable and accurate Dirichlet open boundary condition for ocean model downscaling, Ocean Modelling, 43-44, 1-21

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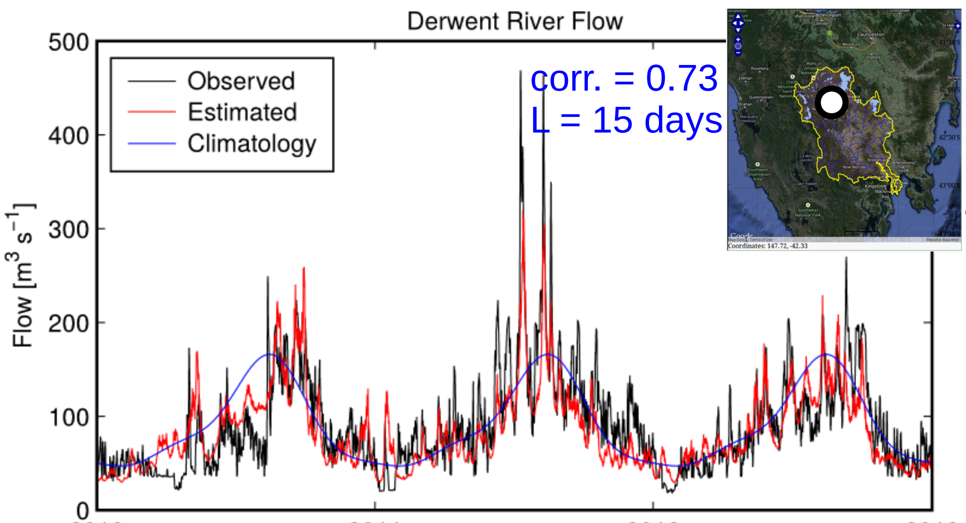
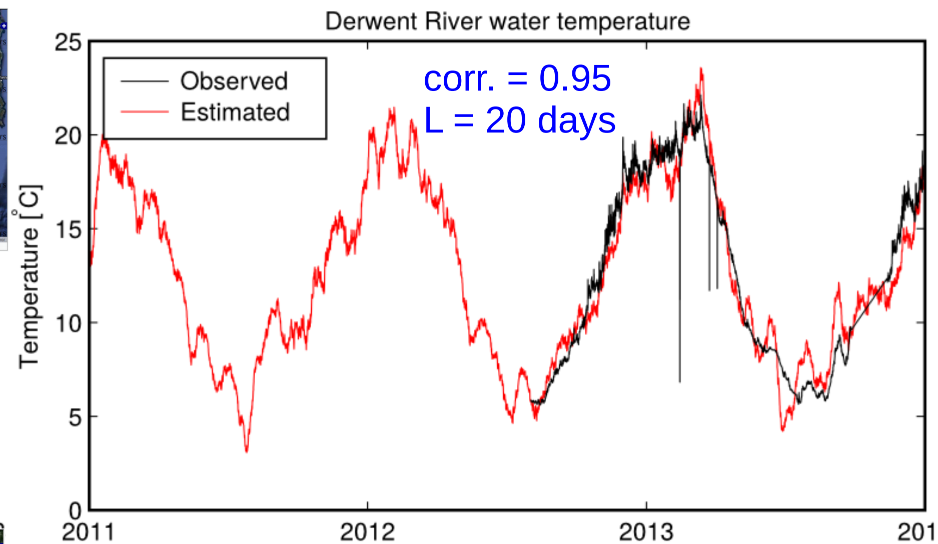
Model Parameters

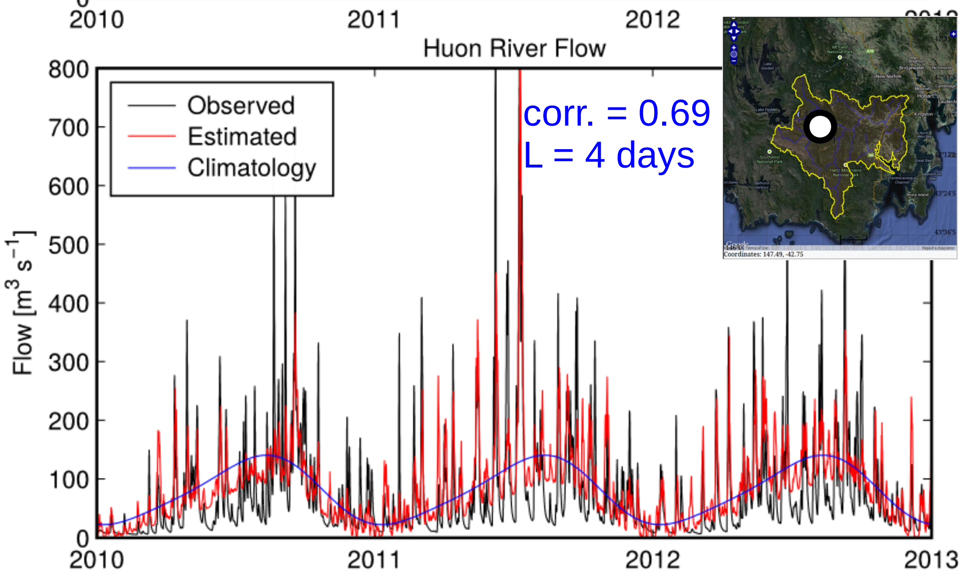
- Time steps
  - 3D: 60s (CFL: 72.8)
  - 2D: 3.75s (CFL: 4.2s)
- Horizontal mixing scheme
  - Smagorinsky (c=0.1) for diffusivity
  - Viscosity = 370 m^2/s for avg. grid size (~1.9 km)
  - Scaled over domain based on changing grid size
- Vertical mixing scheme
  - k-epsilon (Burchard et al. 1998)
  - Background diffusivity and viscosity = 10^{-5} m^2/s
- Bottom friction using drag law

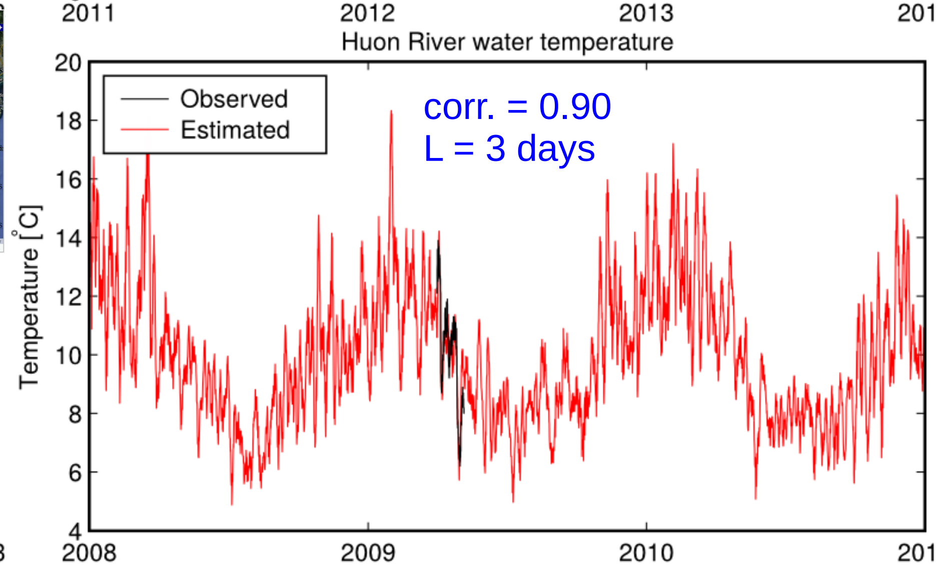
River Input

- 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 1993-2014









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

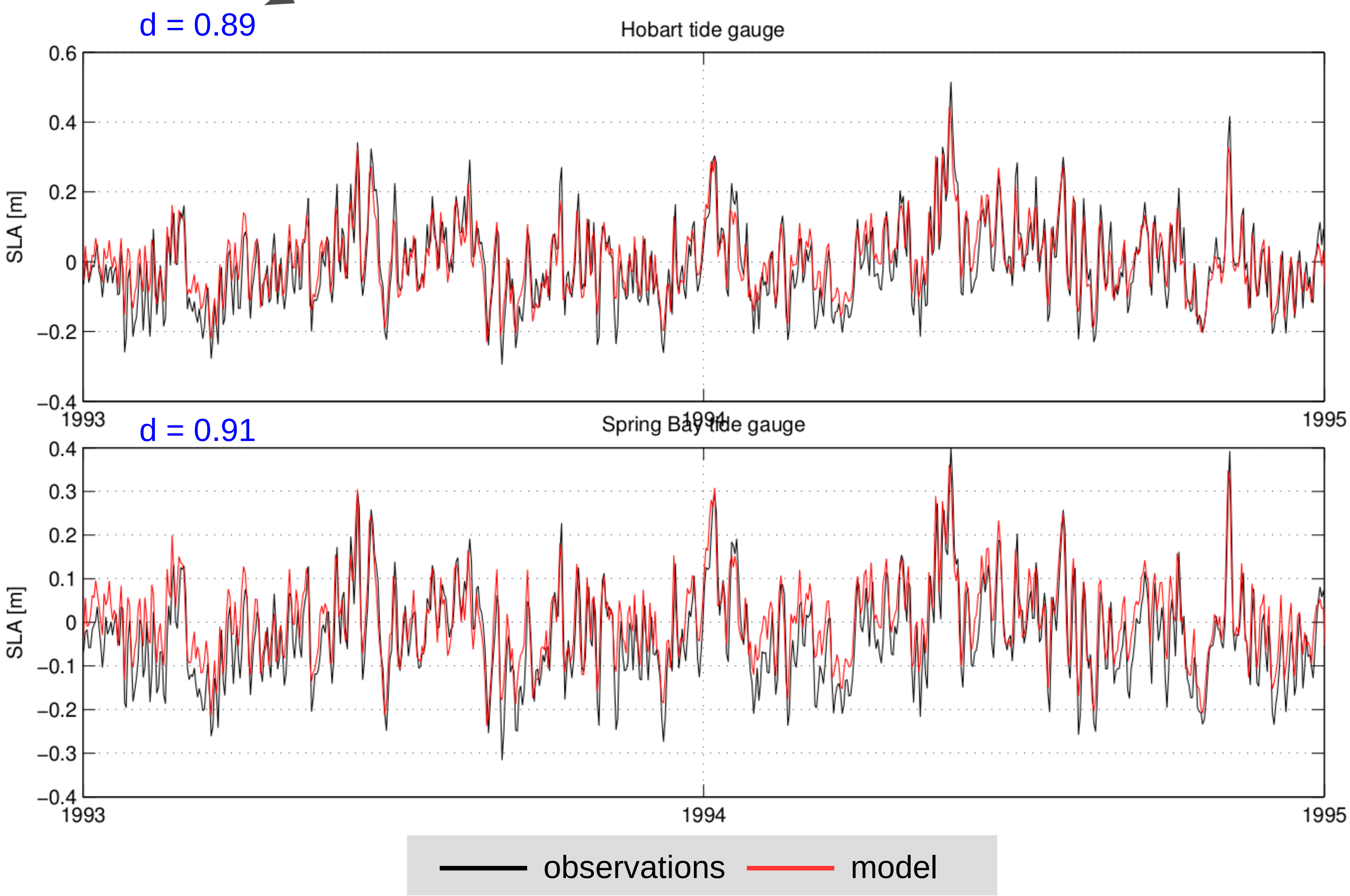
- A two-fold cross-validation was performed to determine which value of *L* provided the best fit
- Given a satisfactory fit, we used historical precipitation and air temperature from CFSR/CFSv2 to reconstruct river flow and temperature over the entire 1993-2013 period

Extra Slides:
Model validation

Tide Gauges

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

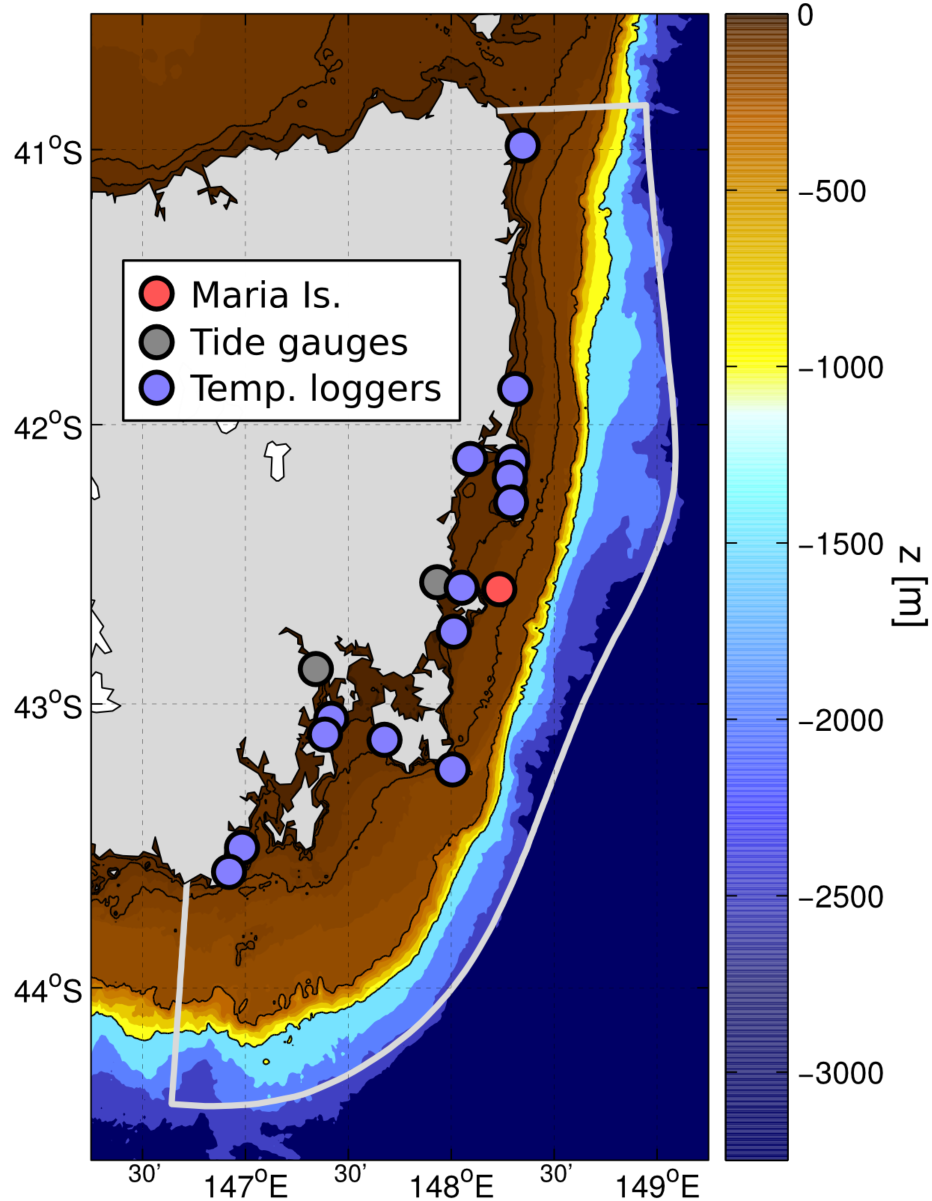
Willmott skill score (0 to 1)*



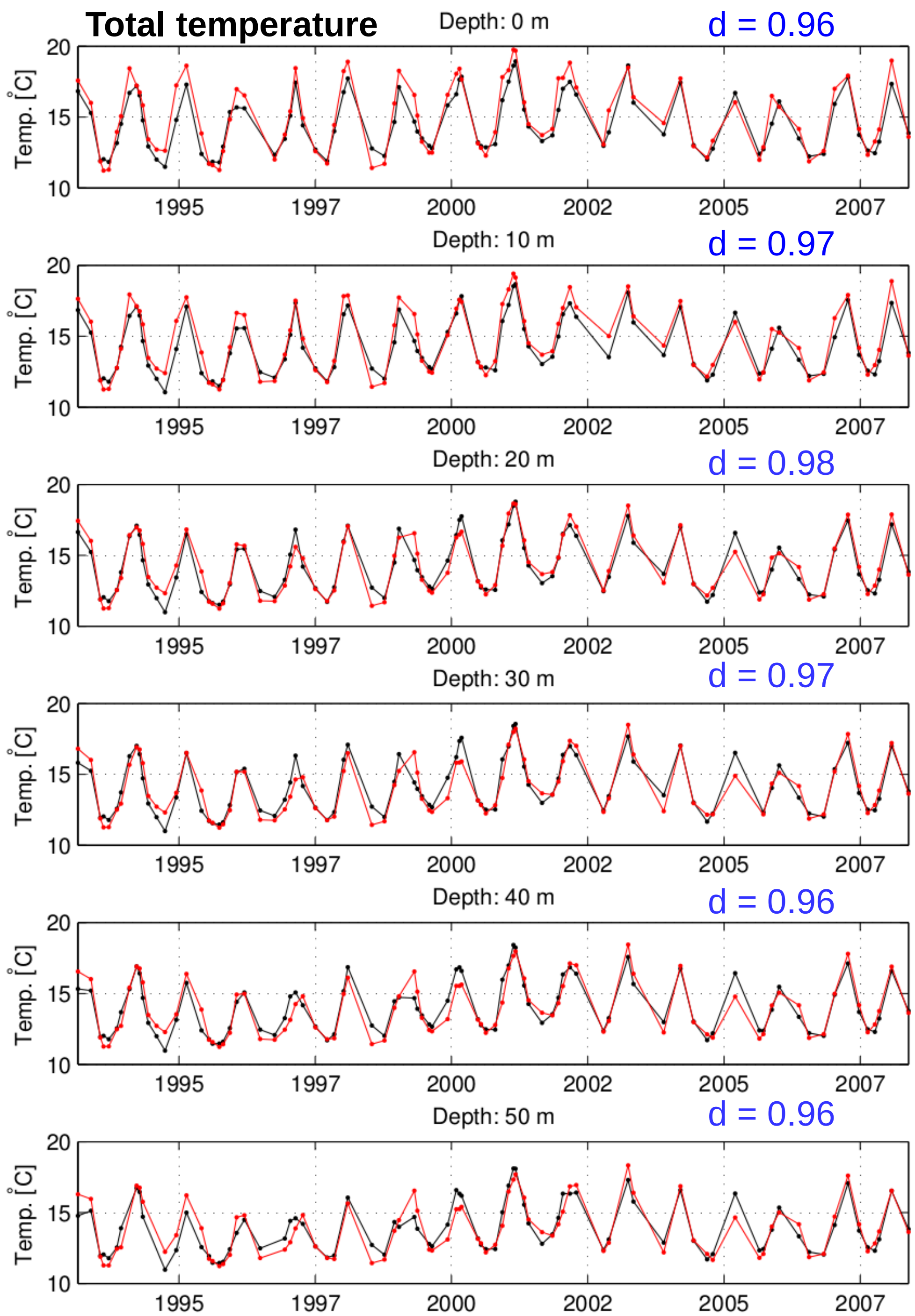
* Willmott, C.J. (1982) On the validation of models, *Physical Geography*, 2(2), 184-194

Validation Data

- <u>In-situ time series</u>
  - 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-ish
  - 2 Tide gauges (Hobart, Spring Bay) **[BLACK]**
    - Sea level
    - Hourly and daily, 1985 - 2012
- <u>Remotely sensed</u>
  - NOAA OI SST V2: daily, 1/4° x 1/4° resolution maps, 1982-2014



Maria Island Time Series



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  - The seasonal cycle

observations model

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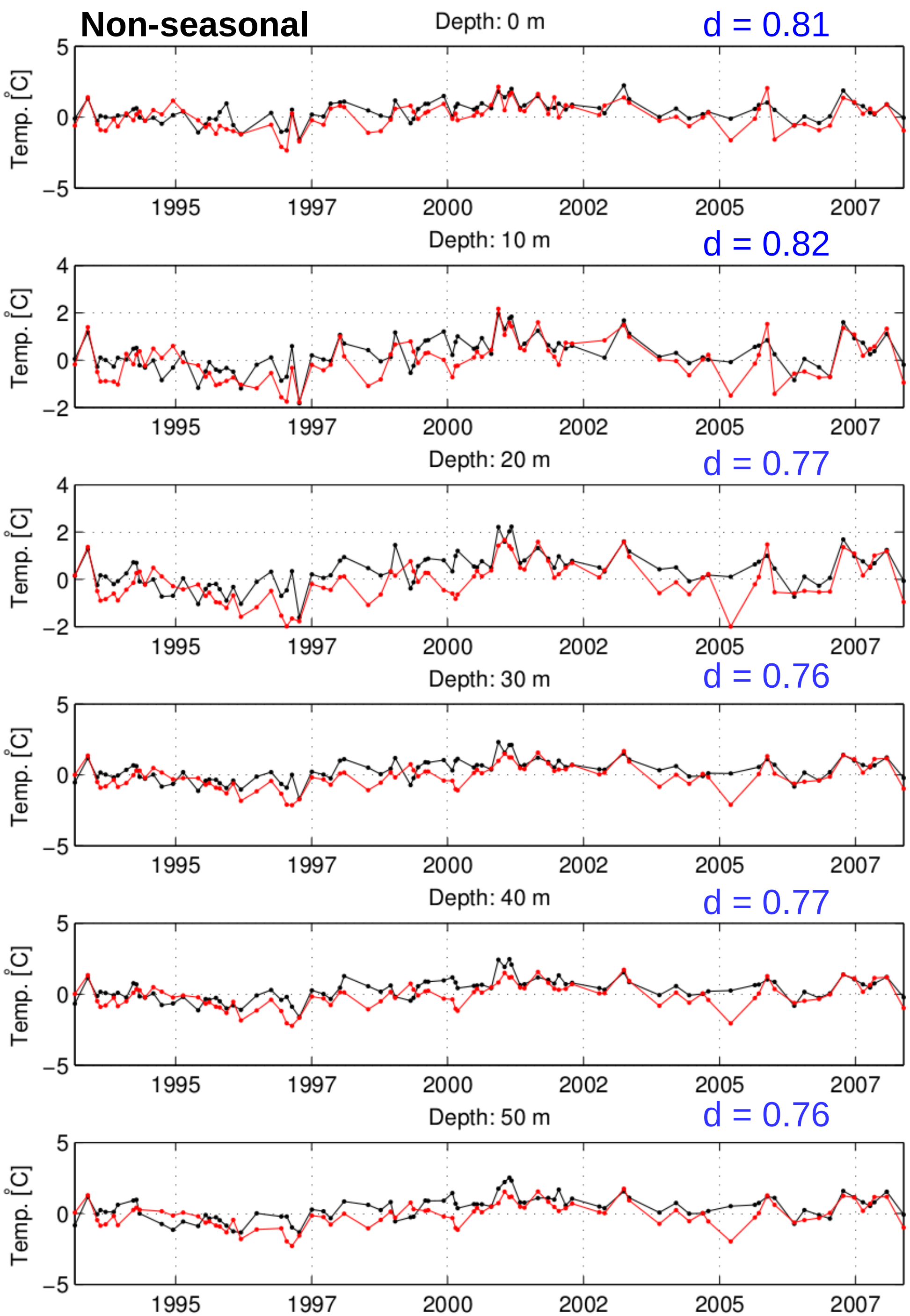

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  - The seasonal cycle
  - The non-seasonal variability

observations model

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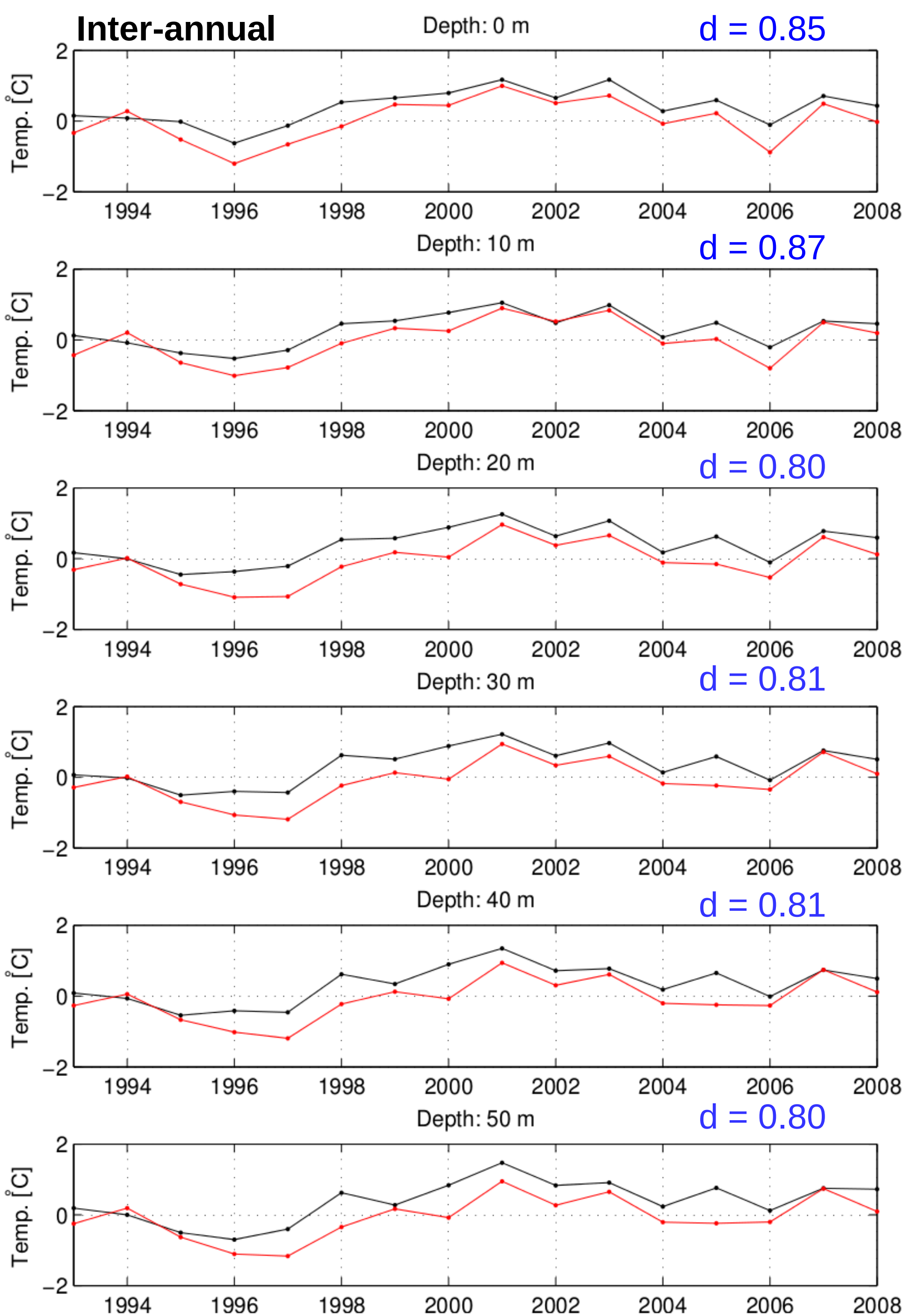
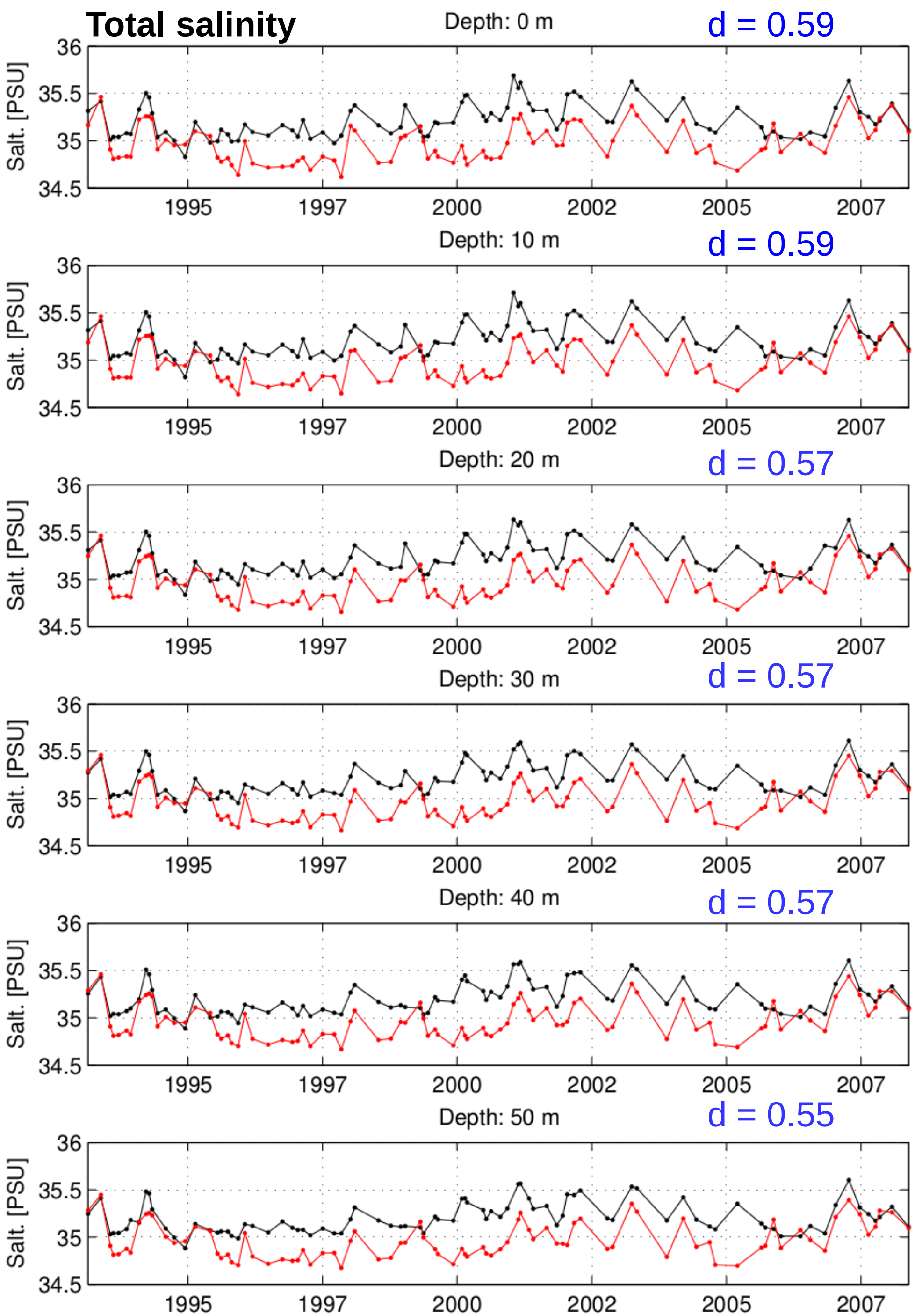


- **Maria Island Time Series**
- Temperature, model captures well:
  - The total variability at all depths
  - The seasonal cycle
  - The non-seasonal variability
  - The inter-annual variability

observations model

Maria Island Time Series



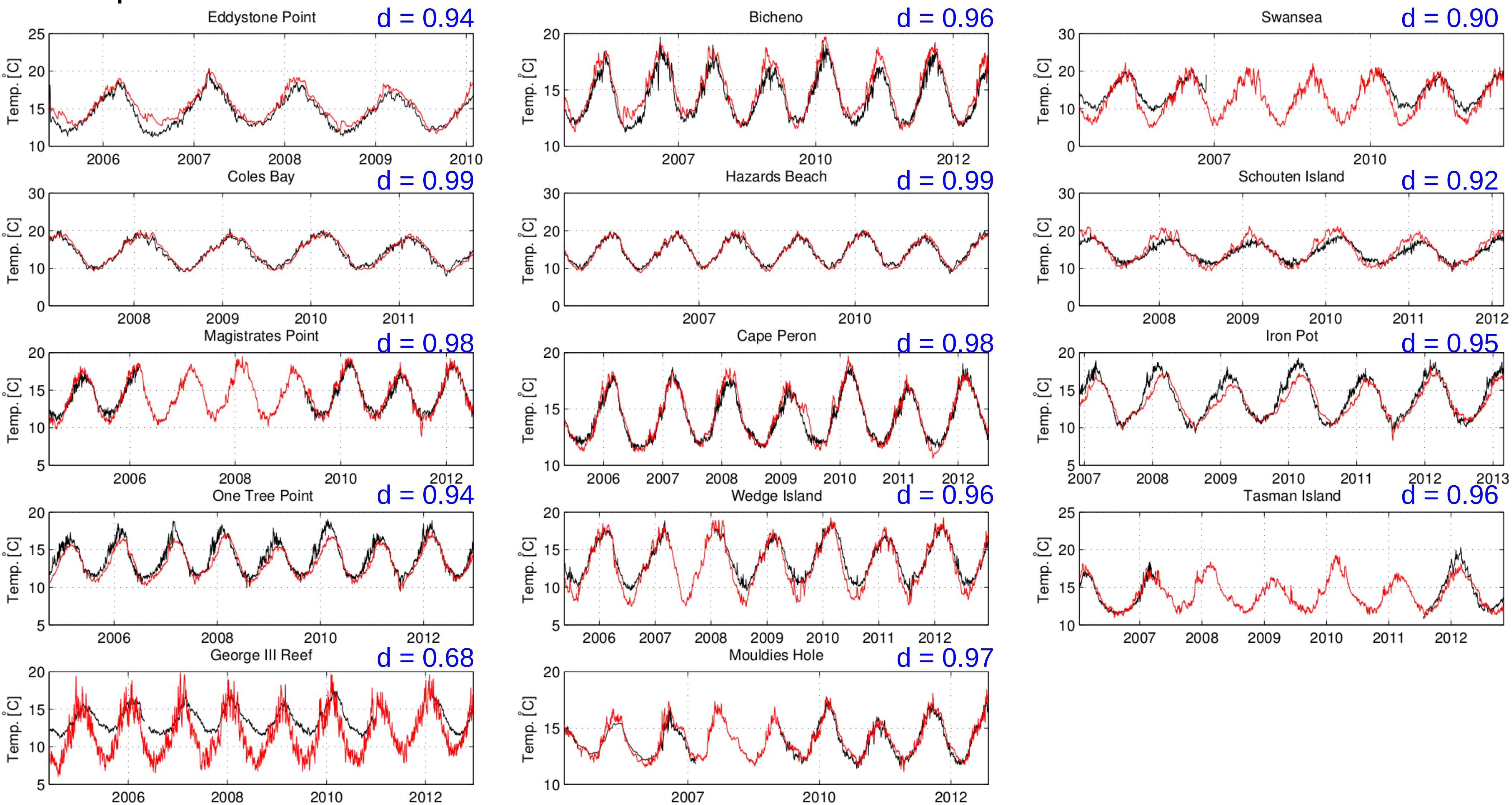
- **Maria Island Time Series**
- Temperature, model captures well:
  - The total variability at all depths
  - The seasonal cycle
  - The non-seasonal variability
  - The inter-annual variability
- Salinity:
  - A notable bias in mean salinity throughout the water column
  - May be related to salinity bias in BRAN3, transmitted through boundary conditions

observations model

Near-bottom temperatures

- **Near-bottom temperature loggers**
- Model captures well the total variability (incl. seasonal cycle)

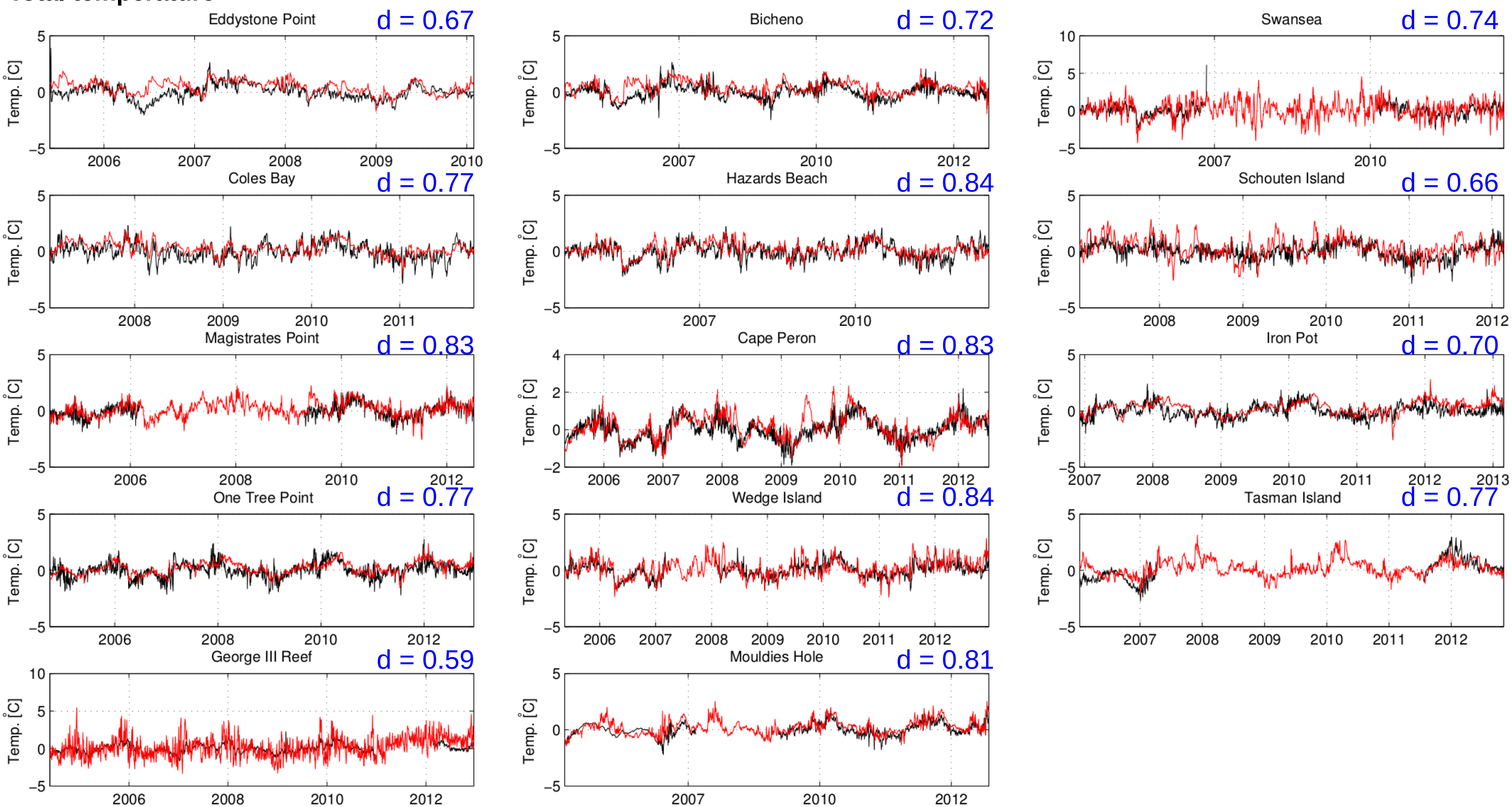
Total temperature



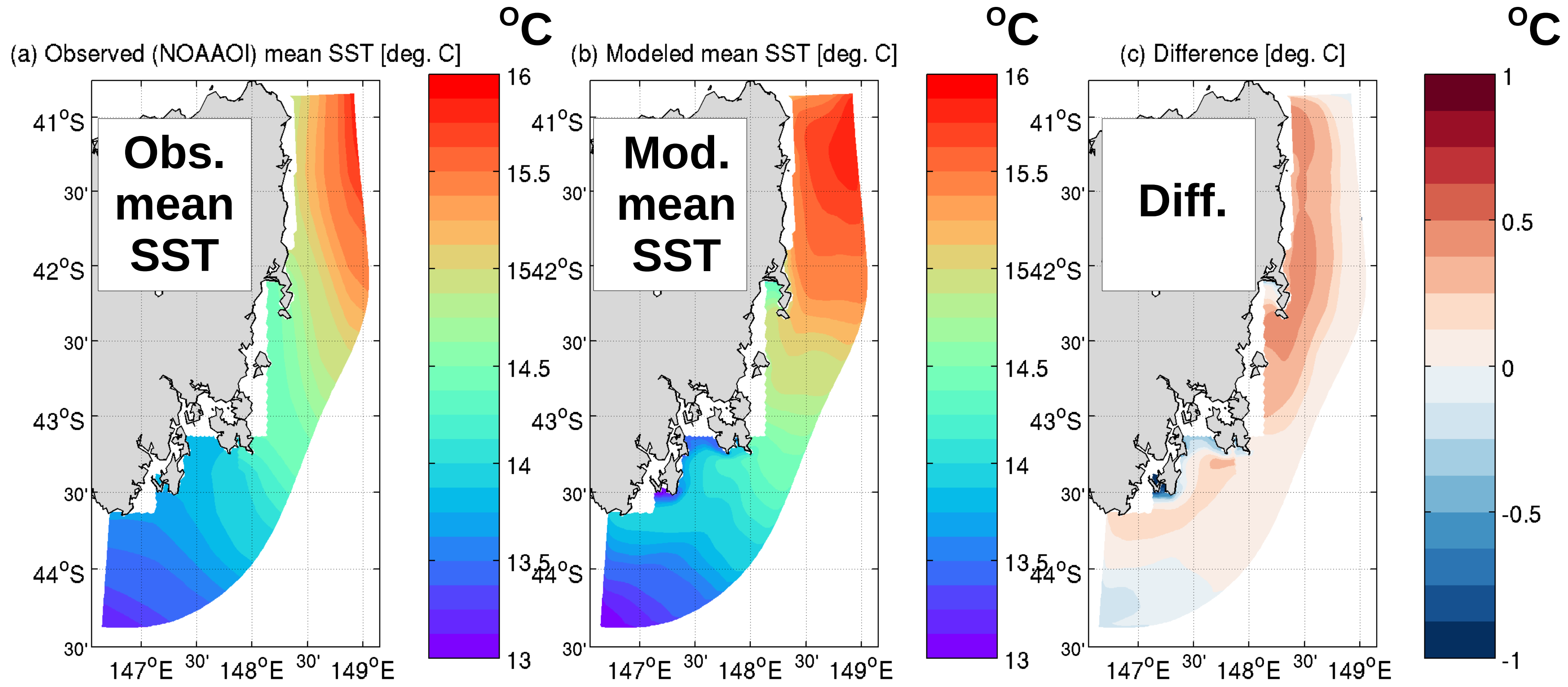
Near-bottom temperatures

- **Near-bottom temperature loggers**
- Model captures well the total variability (incl. seasonal cycle) and non-seasonal signal

Total temperature

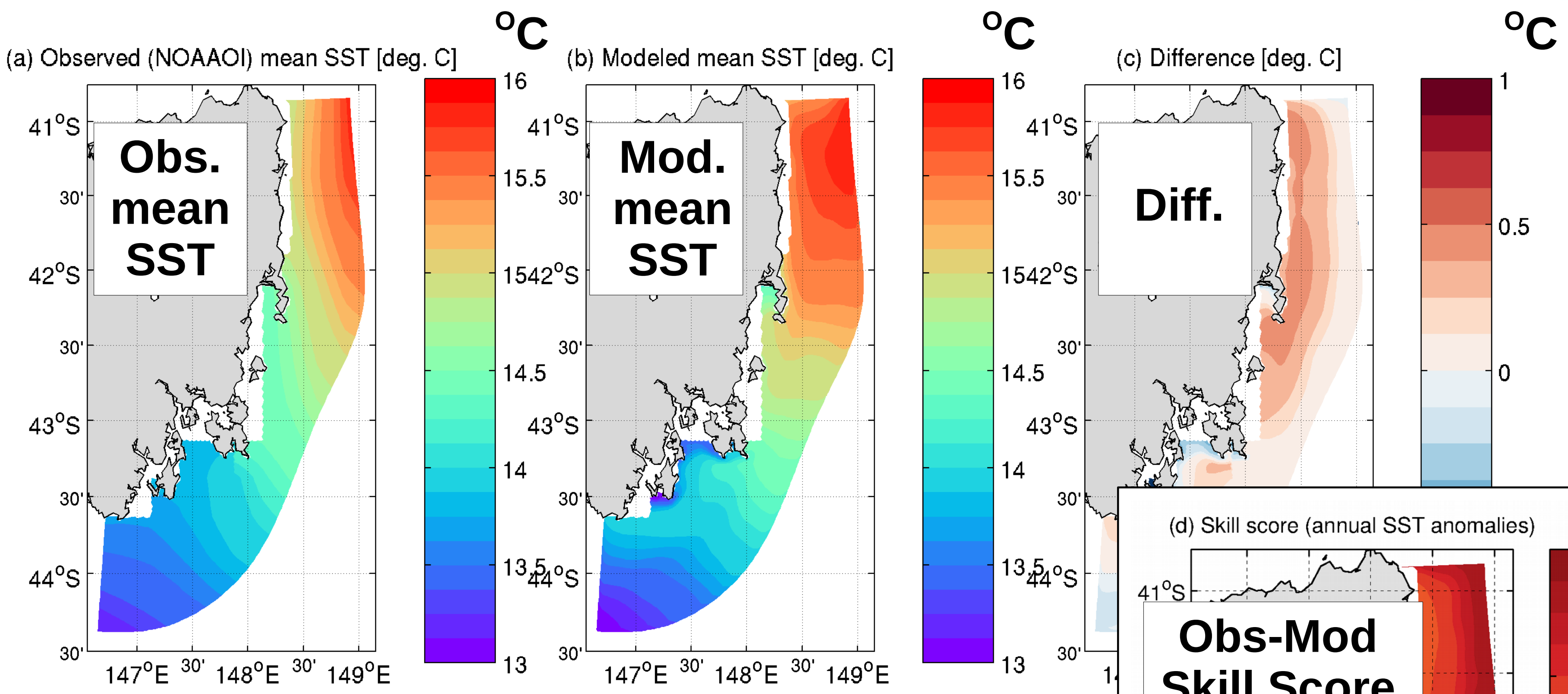


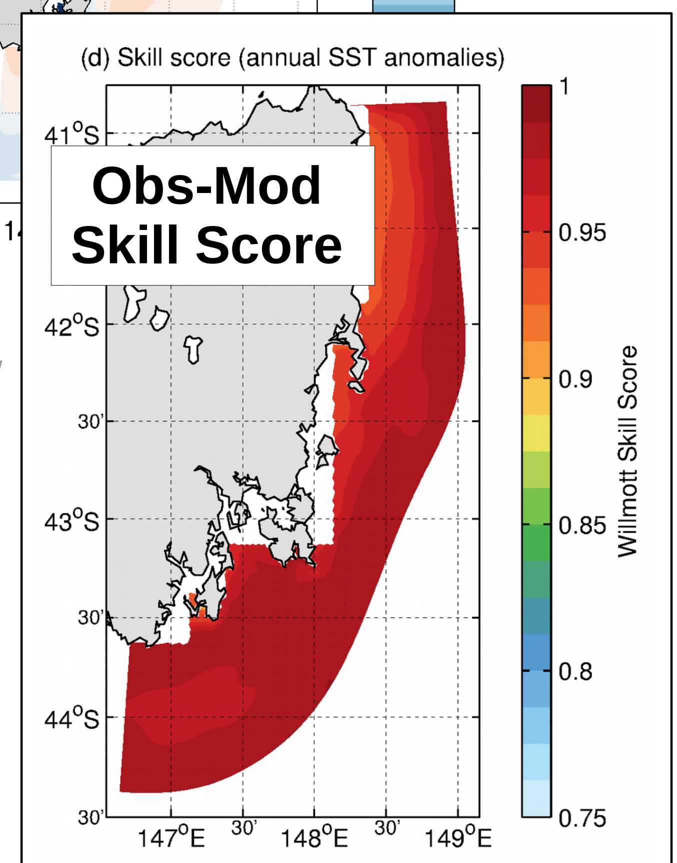
Remotely-sensed SST



- Model captures well mean SST remotely-sensed by AVHRR (gridded NOAA OI V2 product)
- A slight near-shore warm bias (0.5°C) in the northern 2/3 of the domain.

Remotely-sensed SST





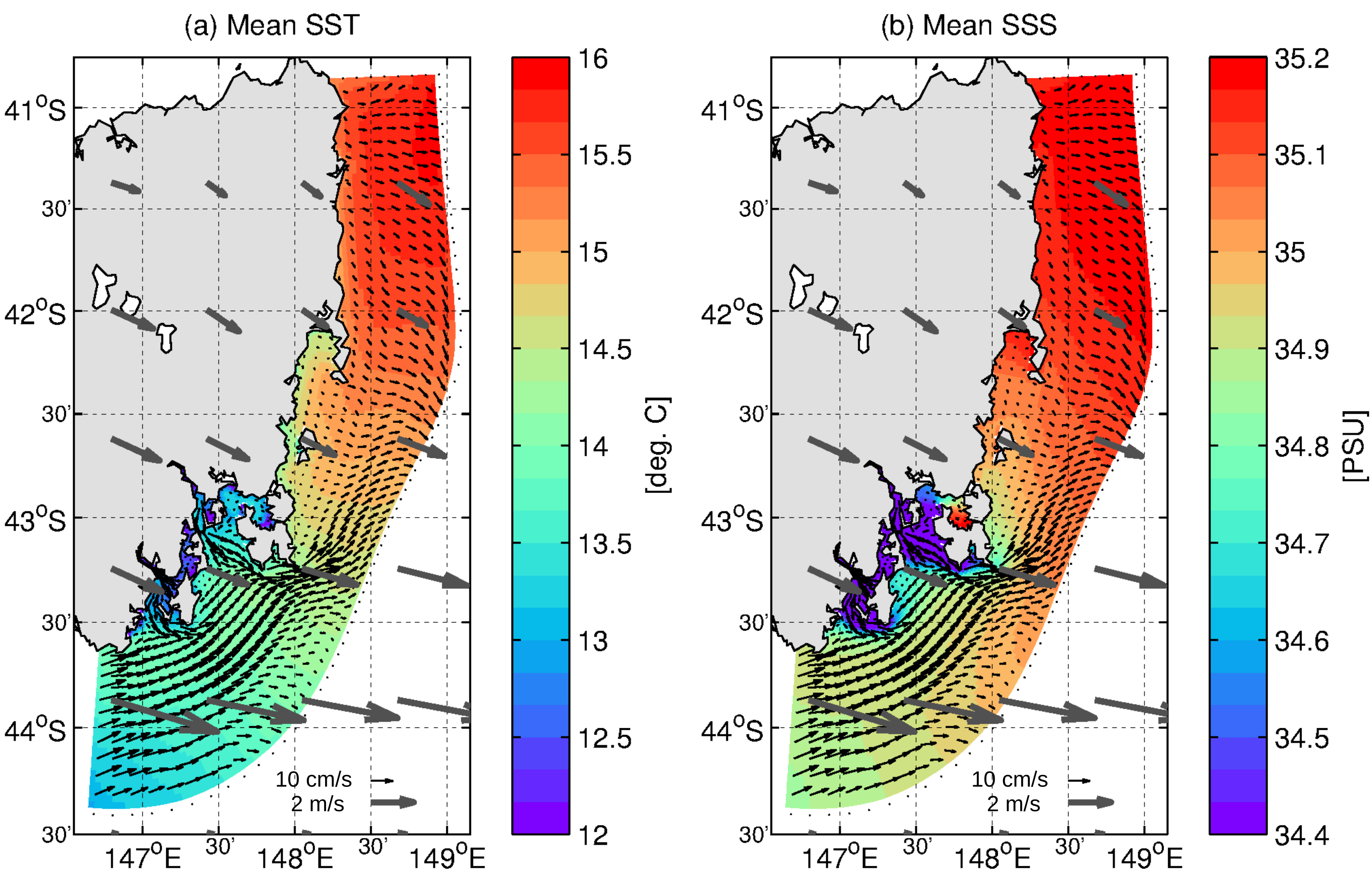
- Model captures well mean SST remotely-sensed by AVHRR (gridded NOAA OI V2 product)
- A slight near-shore warm bias (0.5^{O}C) in the northern 2/3 of the domain.
- Remotely sensed SST variations are also well captured with skill generally >0.9

Extra Slides:
Mean state & seasonal cycle

Surface Mean State

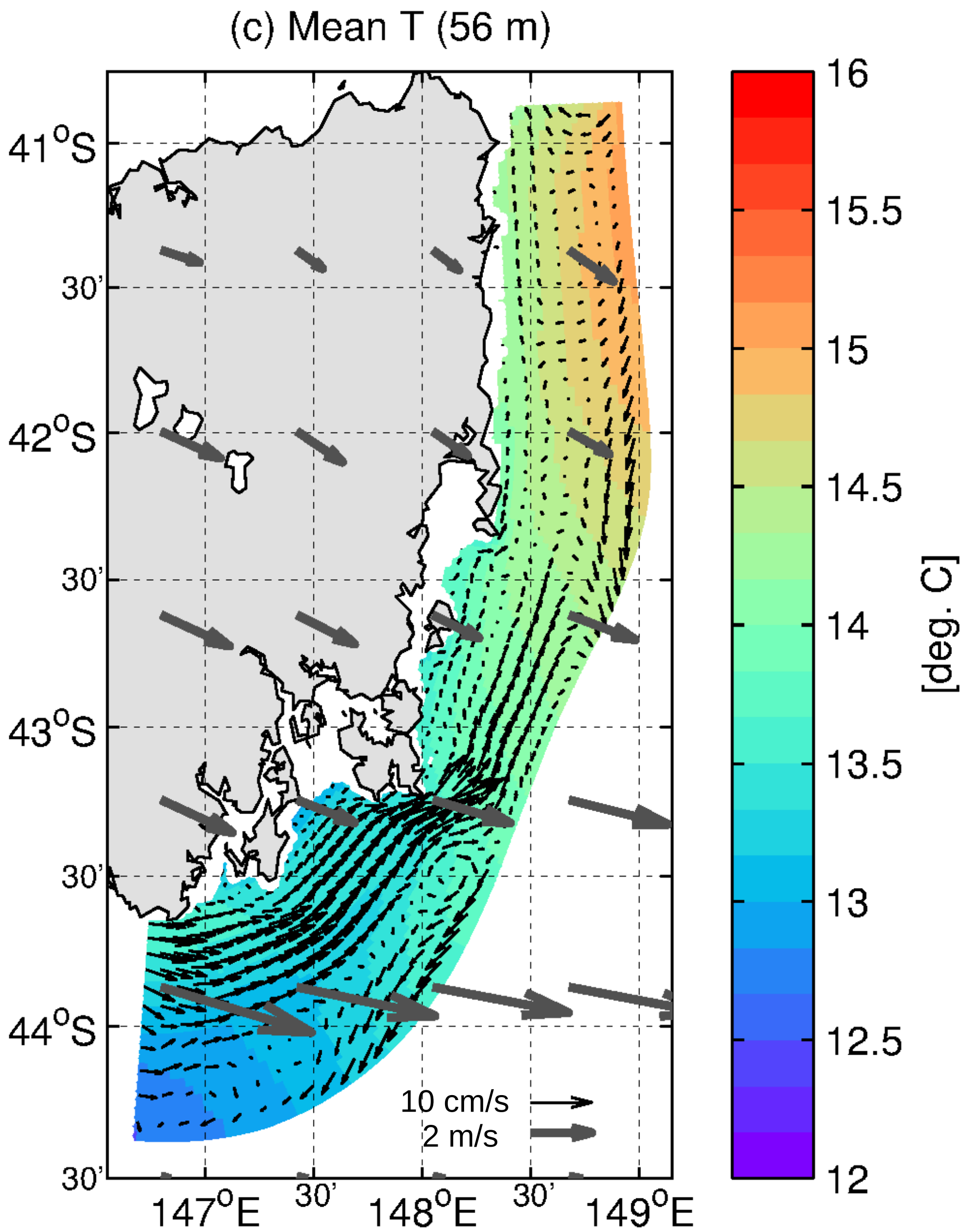
Mean SST and Circulation

Mean SSS and Circulation

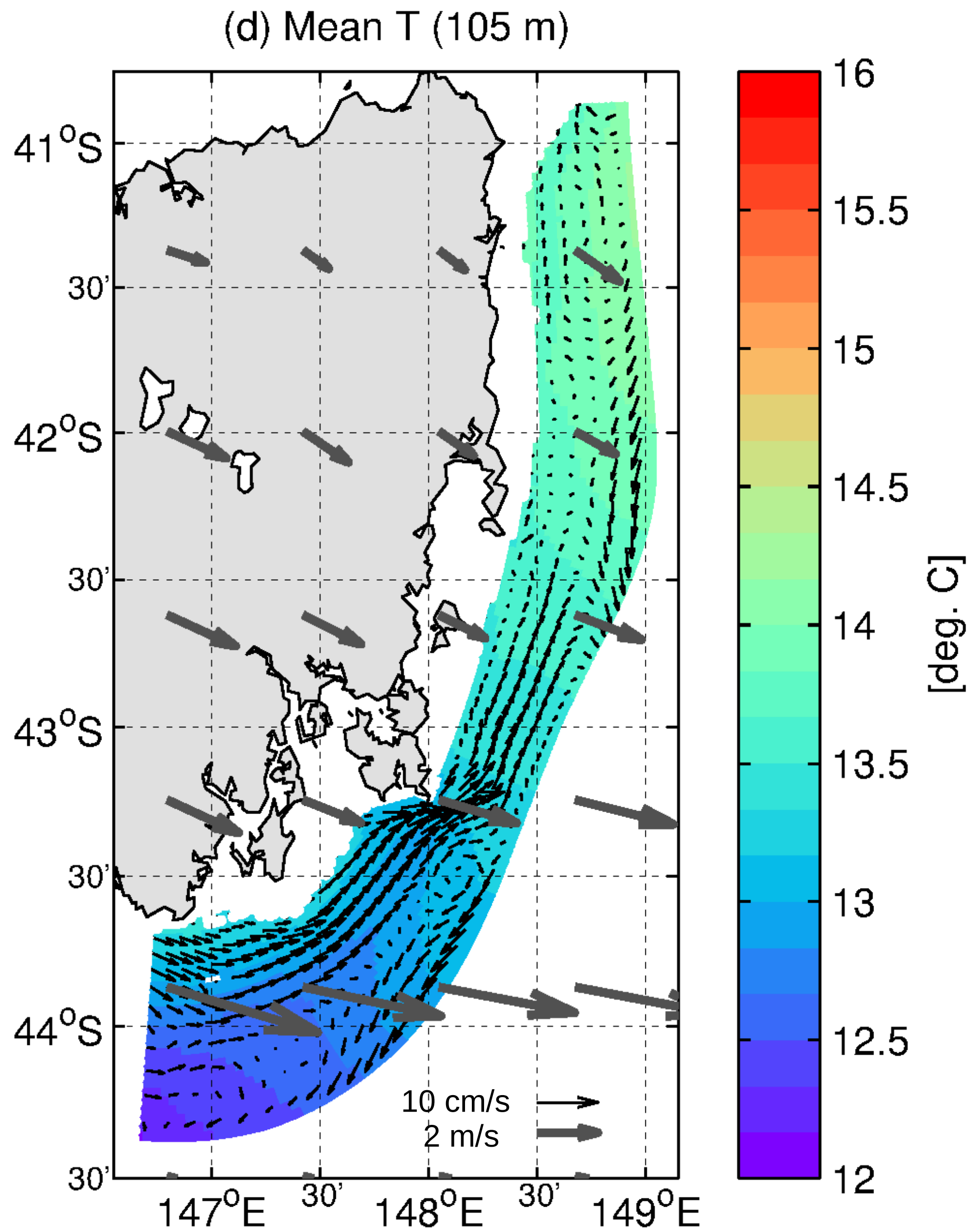


Subsurface Mean State

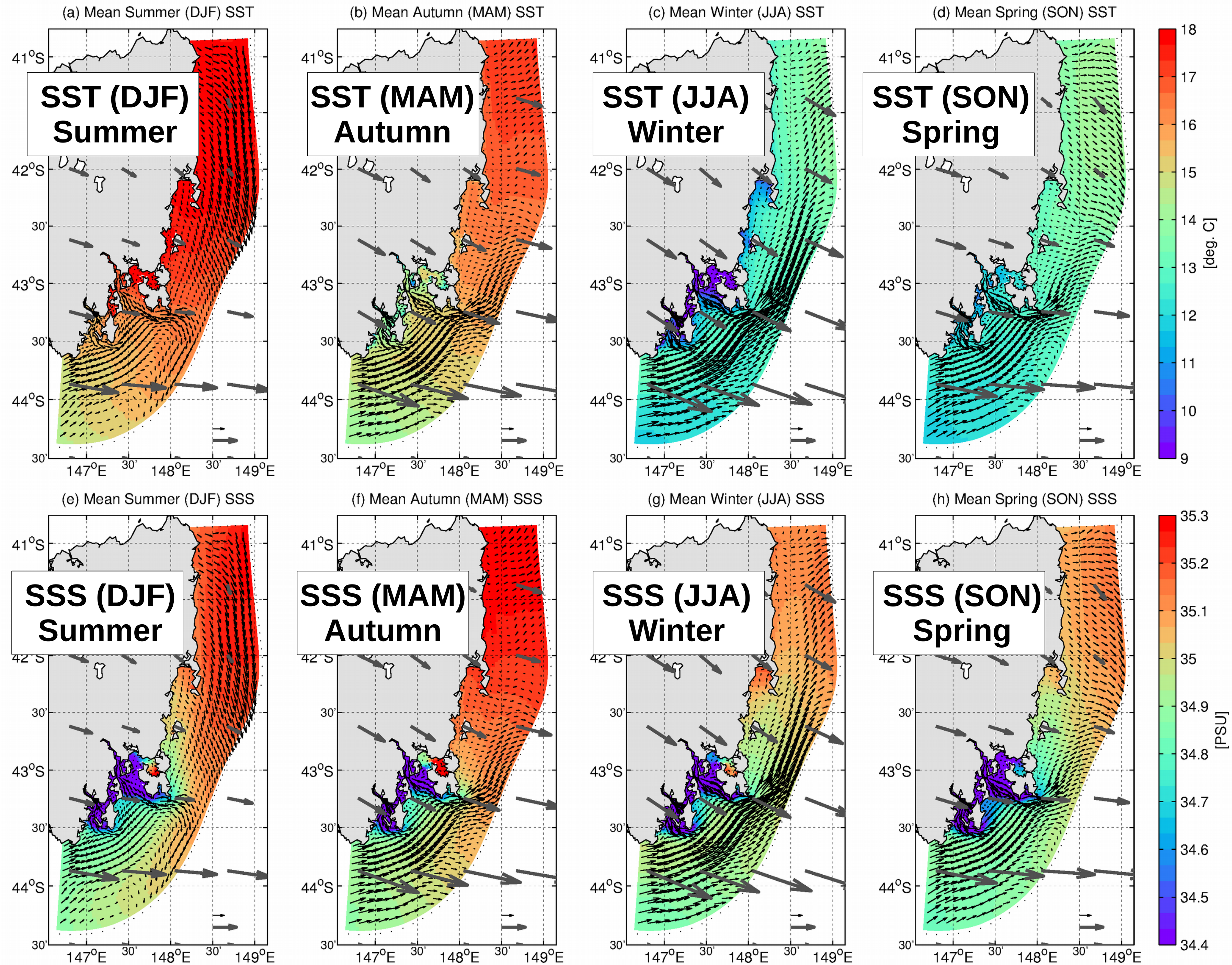
Mean T and Circulation @ 56 m



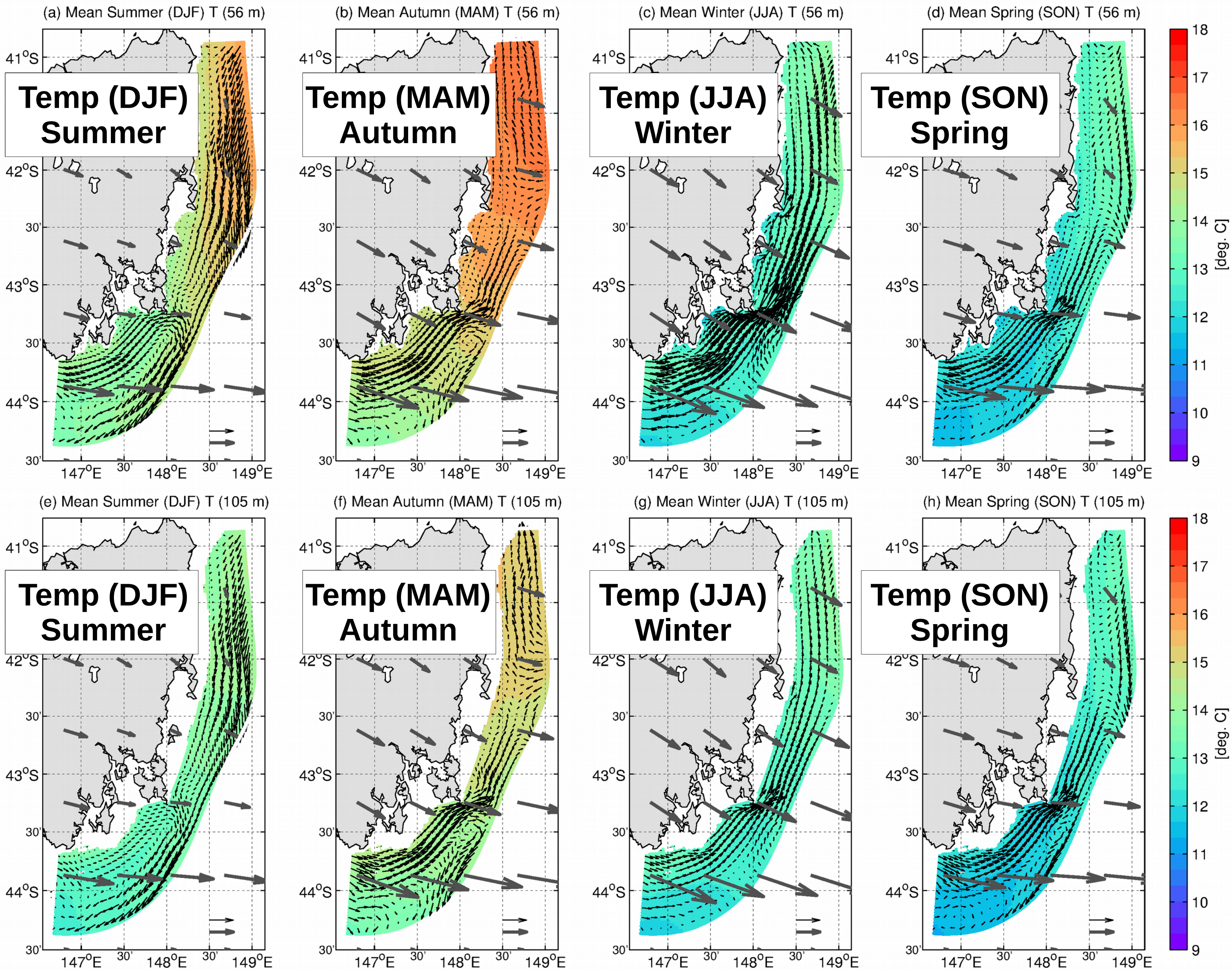
Mean S and Circulation @ 105 m



Surface Climatology



Subsurface Climatology



Cross-shelf Structure

- **Sections across shelf showing temperature (colours) and along-shelf currents (contours)**

- Seasonal alternation of Zeehan Current / EAC Extension, width depth-dependent and cross-shelf structure.