Marine heatwaves off eastern Tasmania

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Véronique Lago[1,2,3]
Alistair J. Hobday[3]
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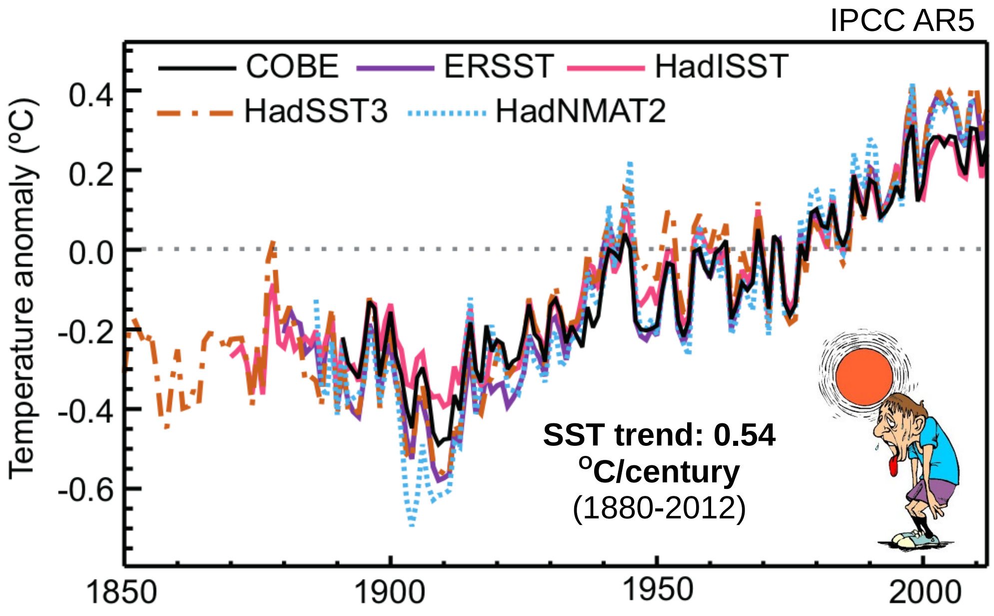
UTAS IMAS INSTITUTE FOR MARINE AND ANTARCTIC STUDIES ARCCSS NESP CSIRO UNSW AIMS

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
- **Ocean dynamics and climate modelling can help us understand historical marine heatwaves:**
  - **Physical drivers**
  - **Variability**
  - **Anthropogenic climate change**



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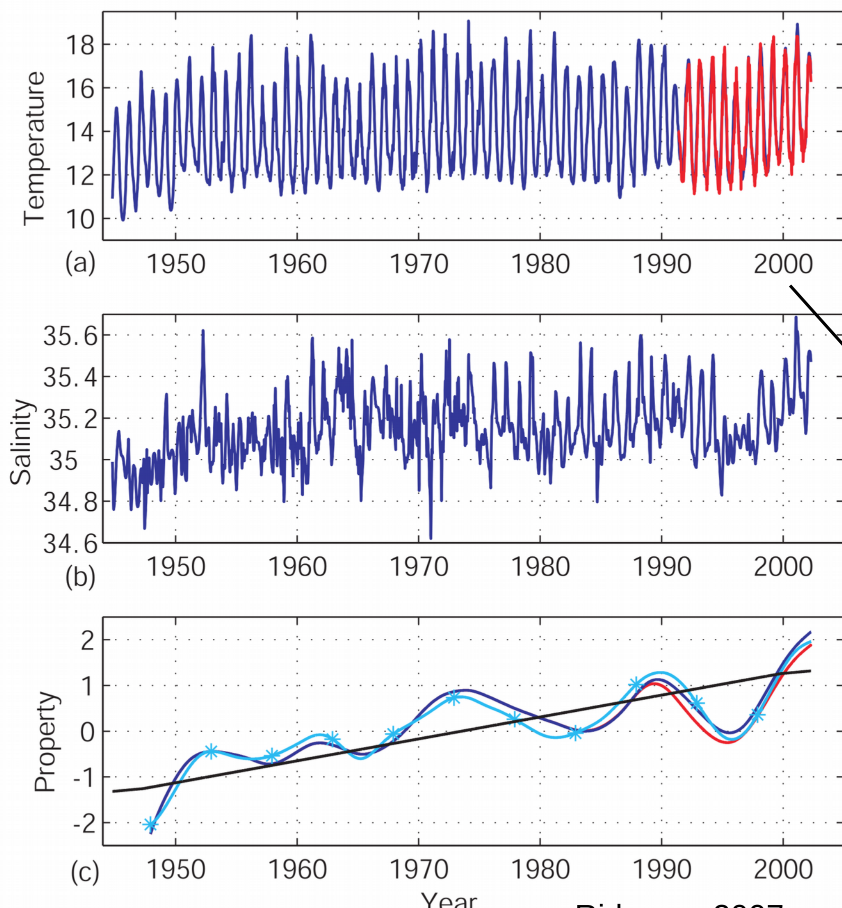
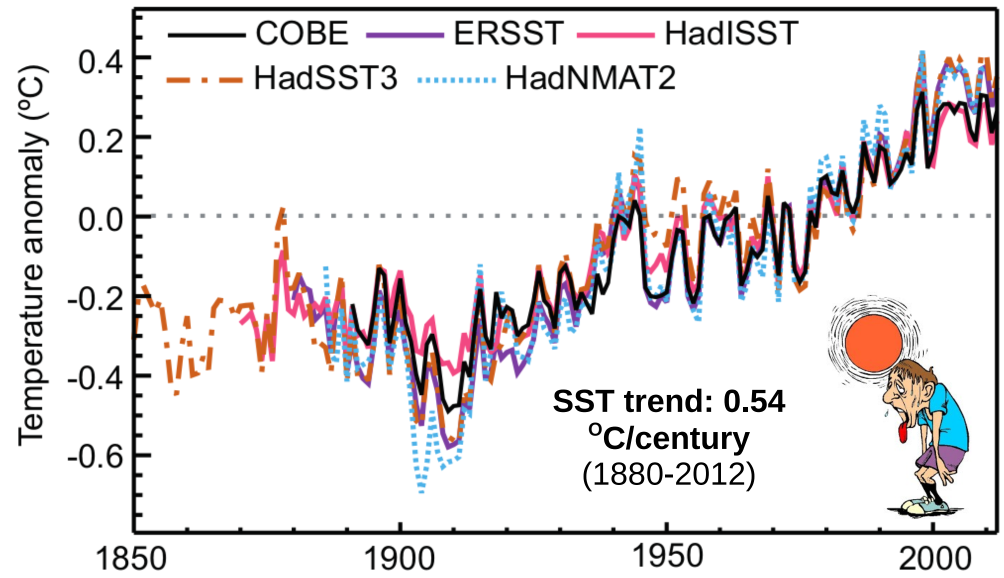
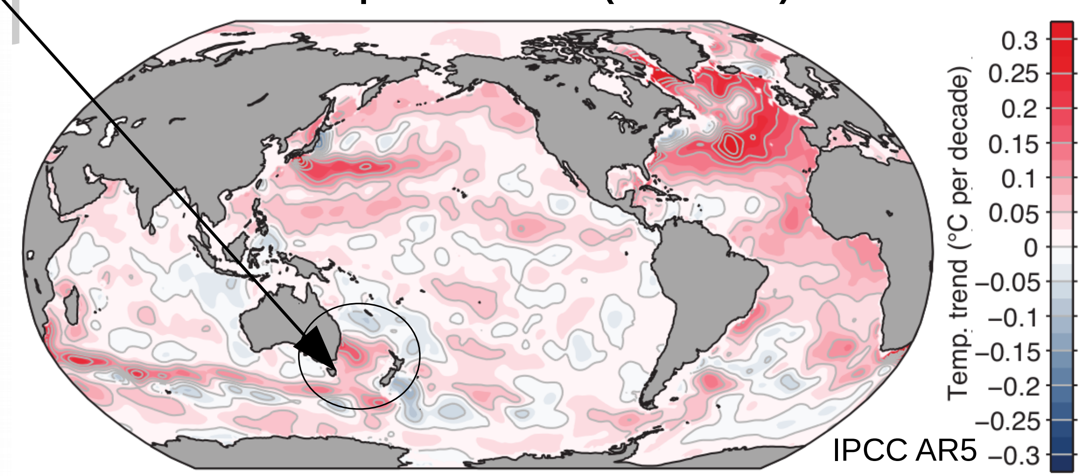


Ridgway, 2007

IPCC AR5



0-700 m temperature trend (1971-2010)



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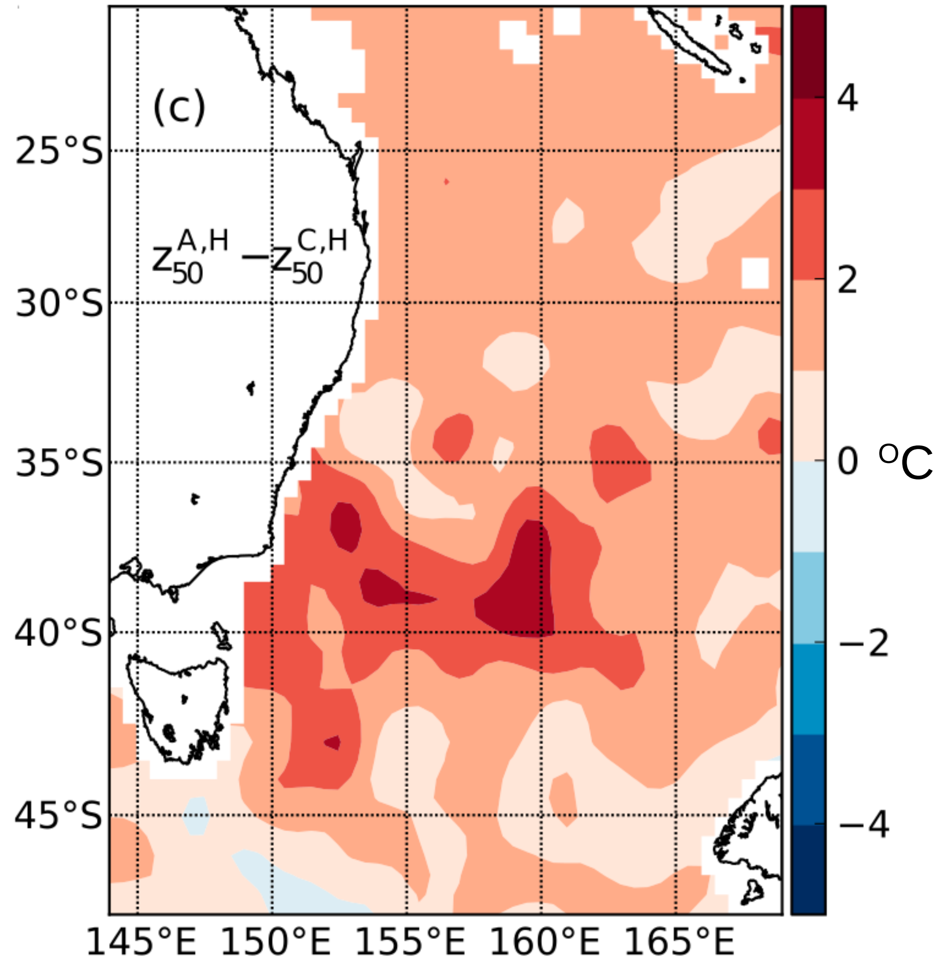
Projected increase in extreme SSTs 2060s - 1990s



Oliver et al., *J Clim*, 2014

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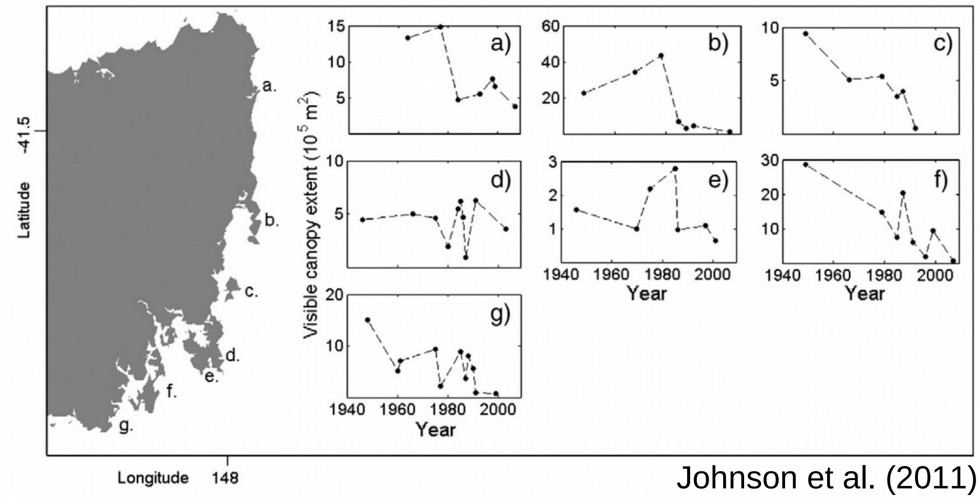
Long-term change in visible surface kelp canopy (Macrocystis pyrifera)



Johnson et al. (2011)

During 2015/16 event:

POMS in Oysters

Abalone mortality

Poor salmon performance

Tropical fish!

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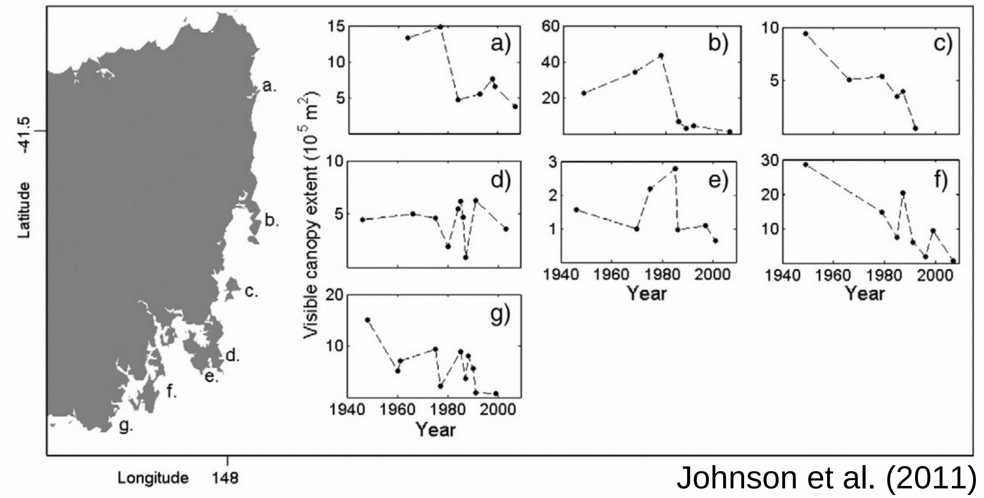

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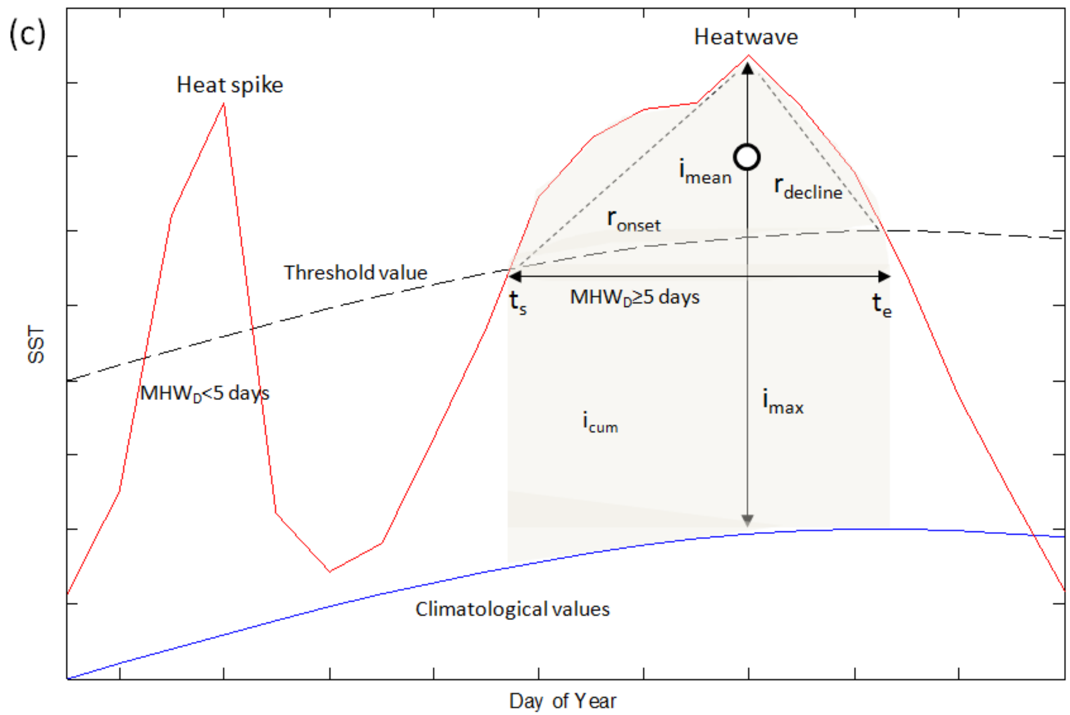
Part II

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

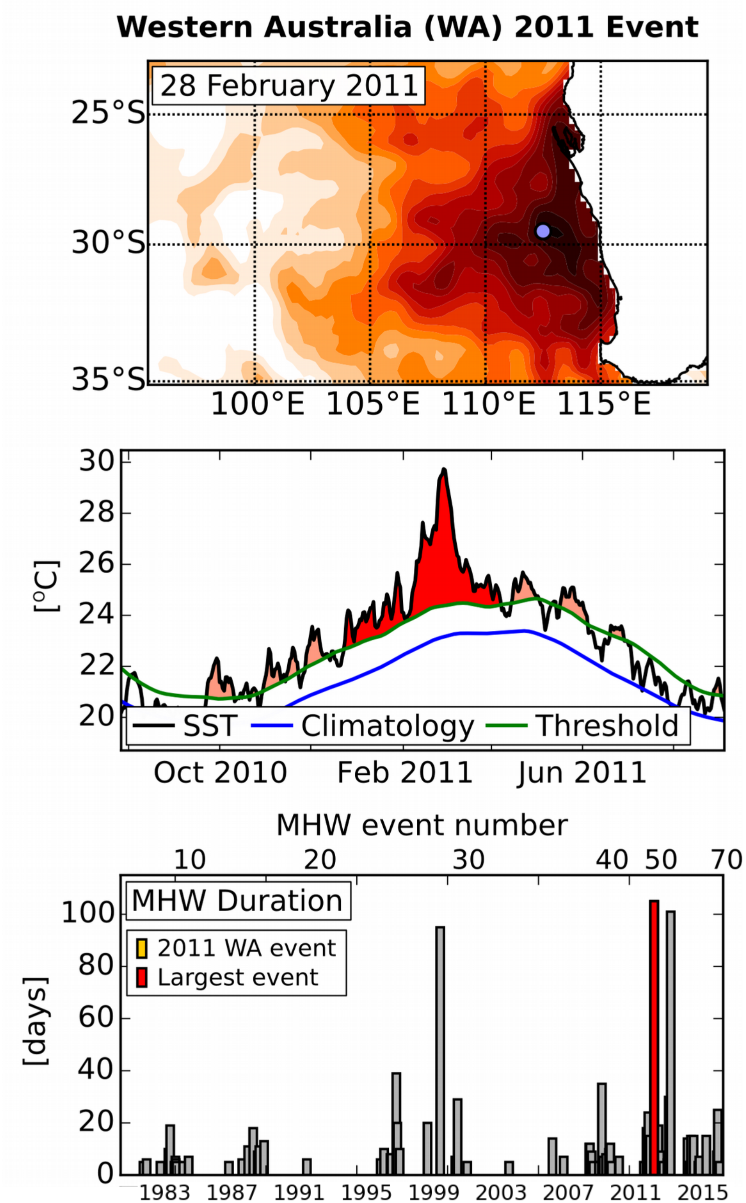
Oliver, Lago, Holbrook, Hobday, Mundy and Ling, *REGS 2016 Project* + manuscript (in prep.)

What is a Marine Heatwave?

- A **marine heatwave** (MHW) is defined to be **a discrete prolonged anomalously warm water event at a particular location** (Hobday et al., 2016)
- Specifically, **SSTs above the seasonally-varying 90th percentile** that persist **for at least 5 days**.
- Definition includes a set of **metrics**, including:
  - **Intensity** [^{O}C]
  - **Duration** [days]



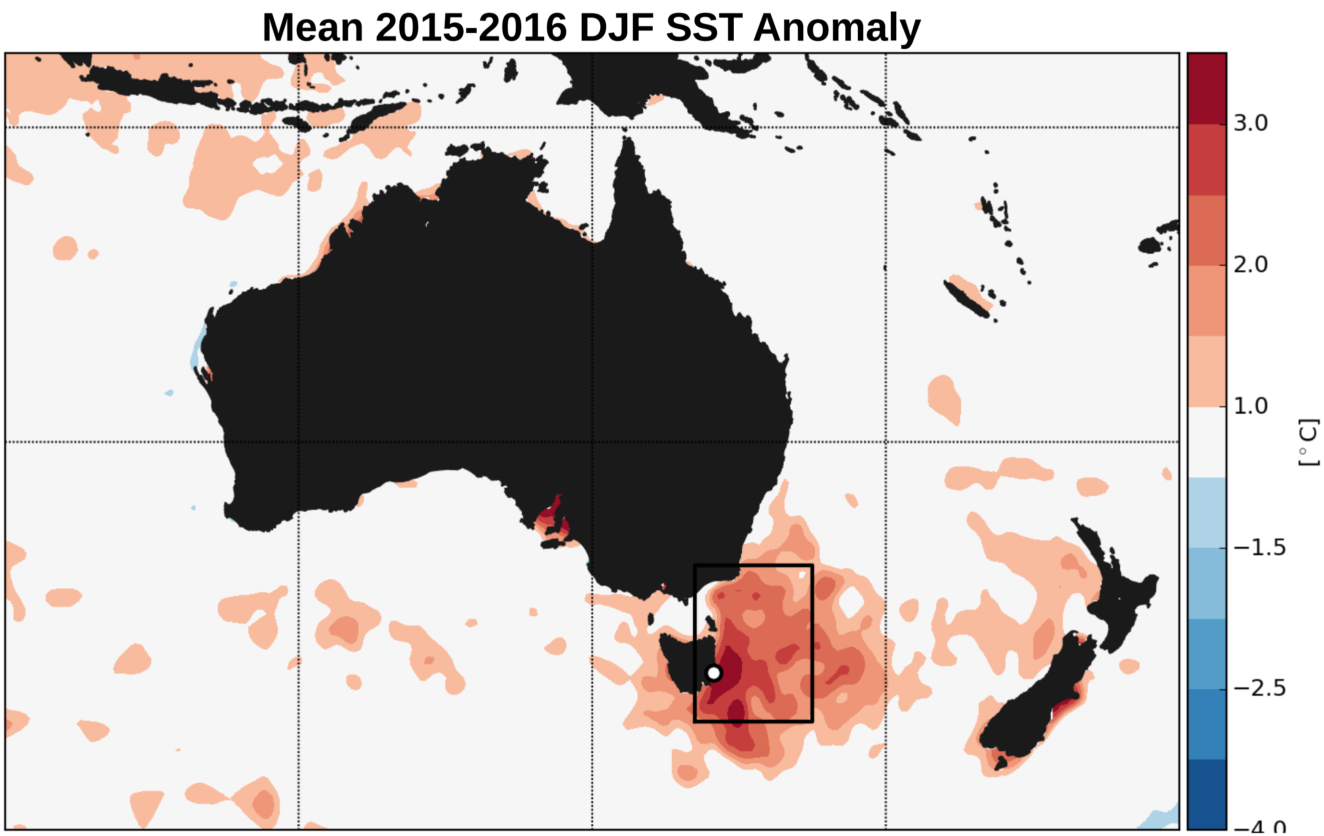
Software implementation free-ly available in Python here: `github.com/ecjoliver/marineHeatWaves`
and in R here: `github.com/cran/RmarineHeatWaves`

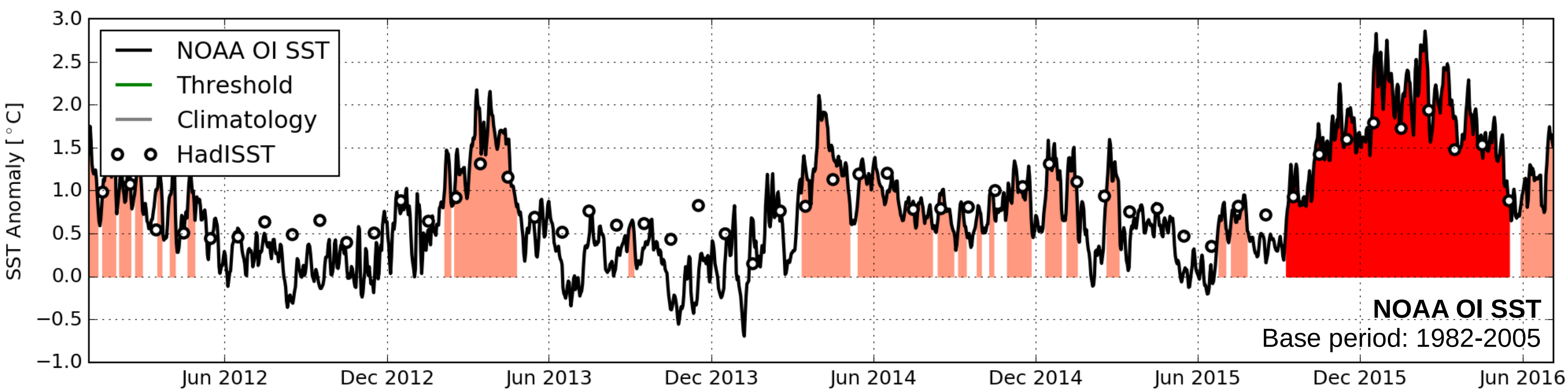


Figures from Hobday et al. (2016) *Prog. Ocean.*

2015-2016 SE Australia MHW

- There was a **marine heatwave** that occurred in **Austral Summer 2015/16** off southeastern Australia: *9 Sep 2015 – 16 May 2016*
- It is unprecedented in
  - **Duration (251 days)**
  - **Intensity (2.9°C max)**
- **Impacts**: POMS (Oysters), dead abalone, poor salmon farm performace, strange fish intrusions, kelp thinning…





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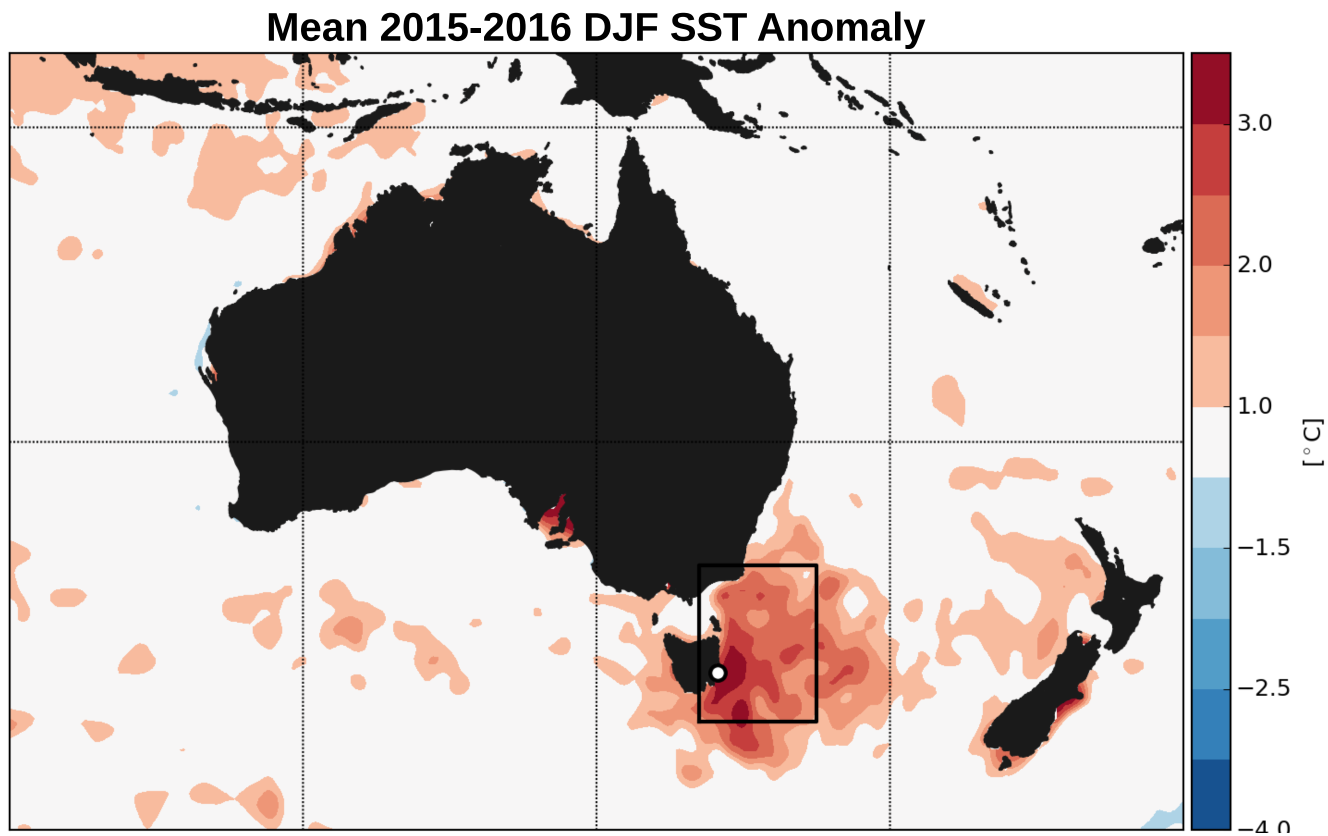
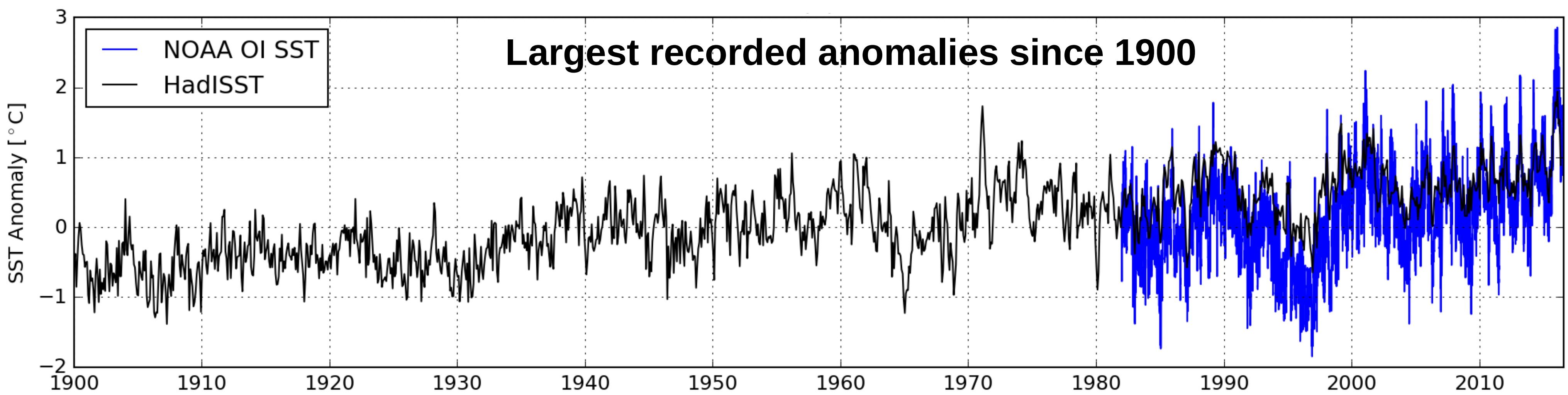
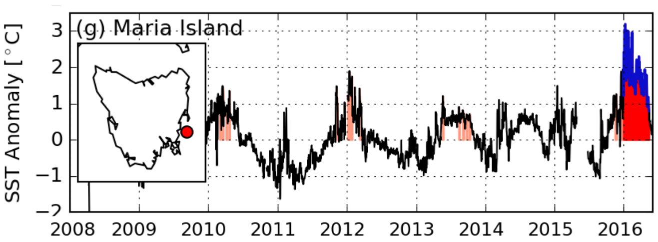




Nearshore Records

- ***IMOS Maria Island NRS***
  - 20 m temperature
  - Full-depth velocities
- ***IMAS Nearshore Temperature Monitoring***
  - A number of sites in 6-20 m depth
- This event was **record strength** (**red**) and duration (**blue**) in the ~10-year coastal records
- Record **southward flows**, possible indication of **forcing mechanism**



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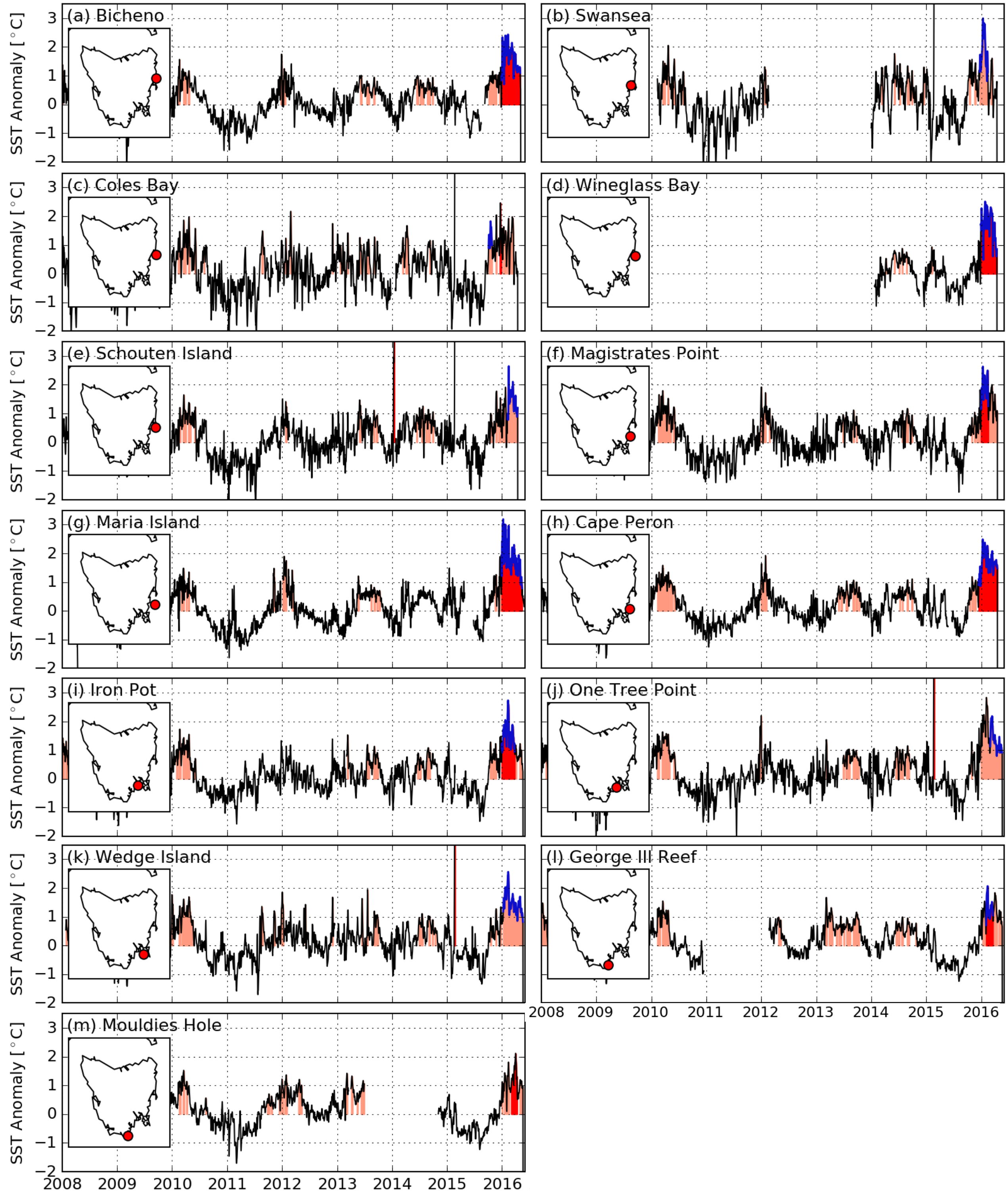

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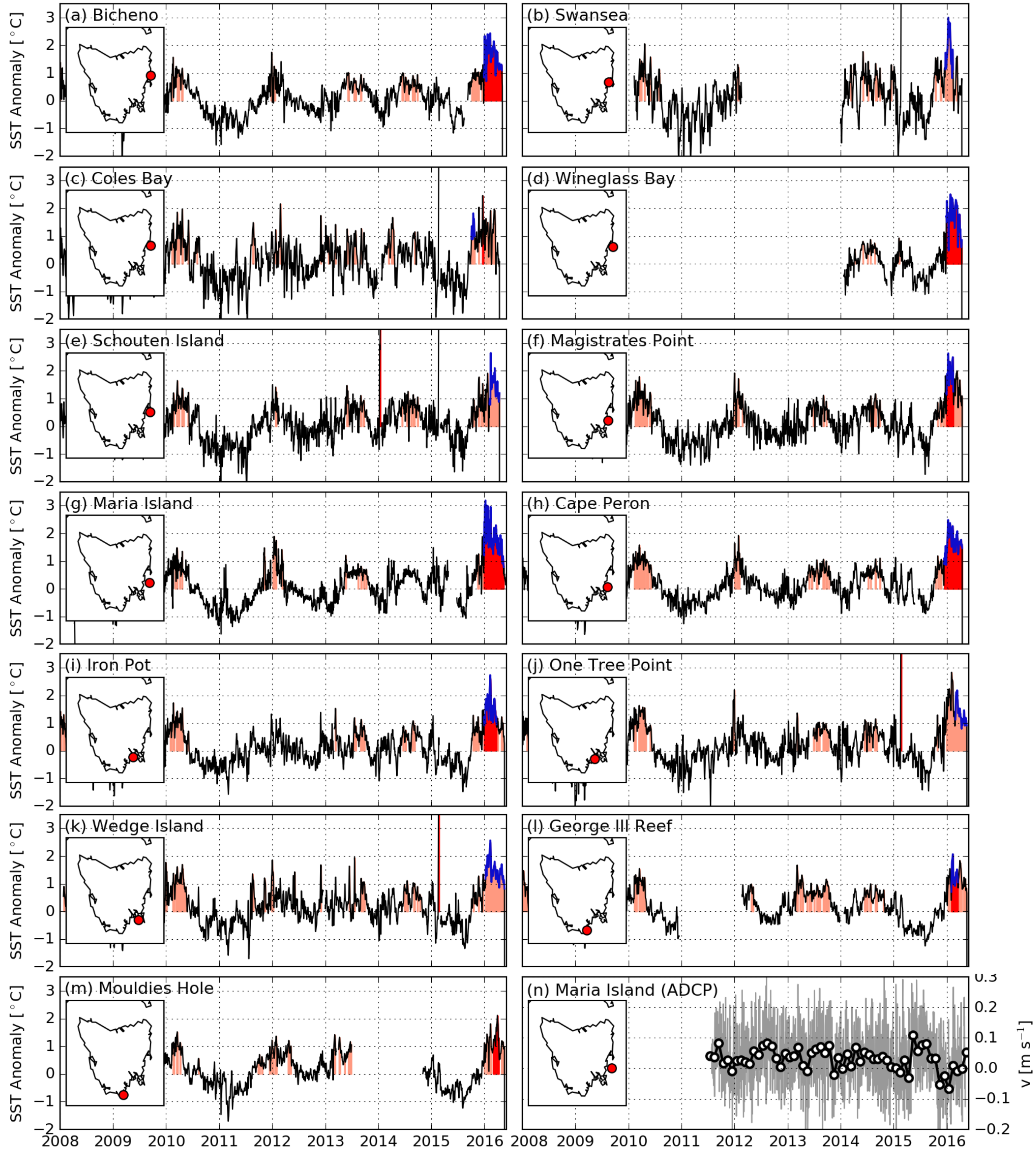
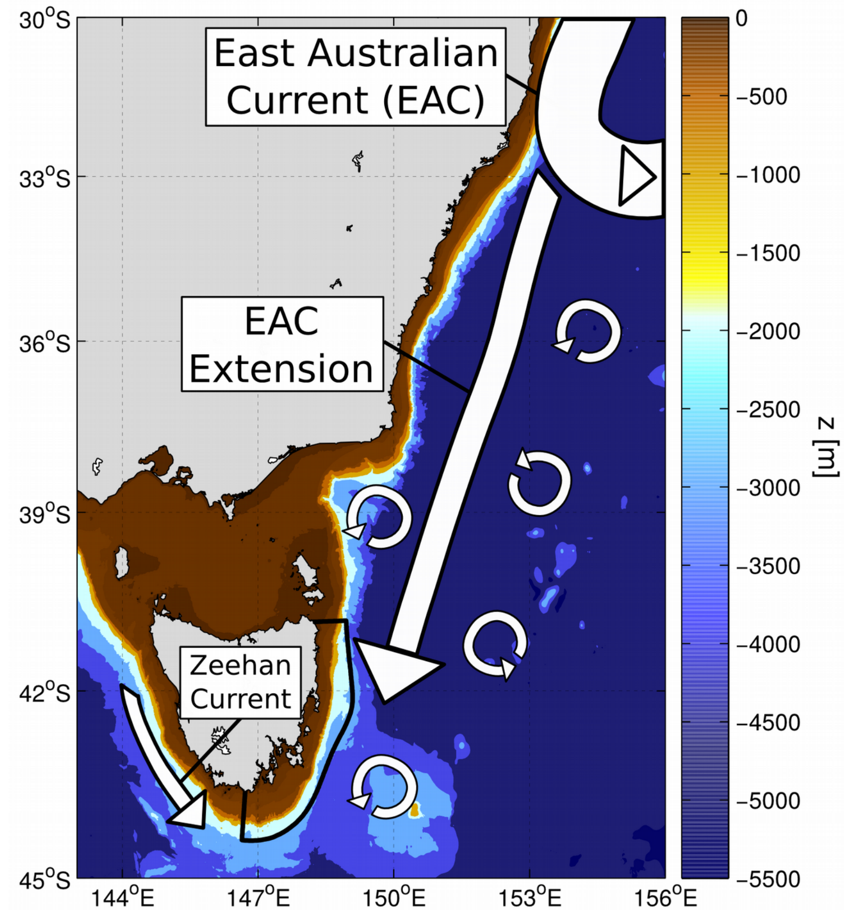
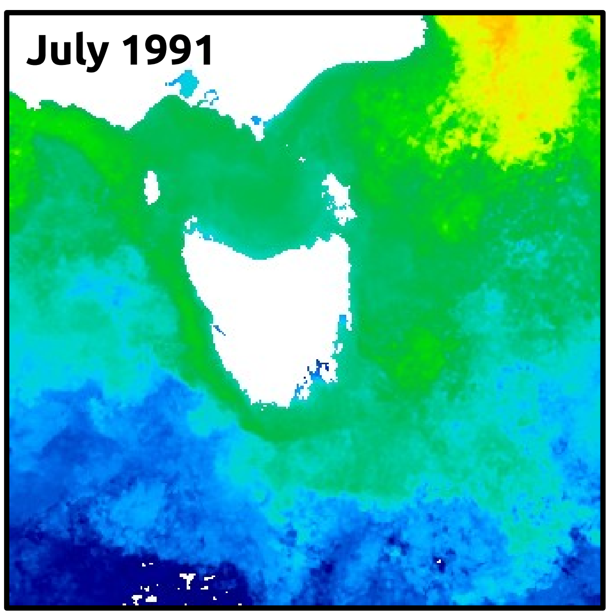
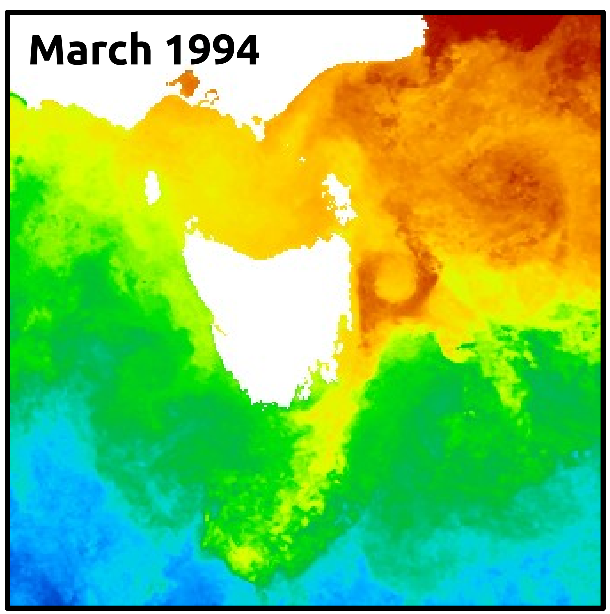


Regional Oceanography

- **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 (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]





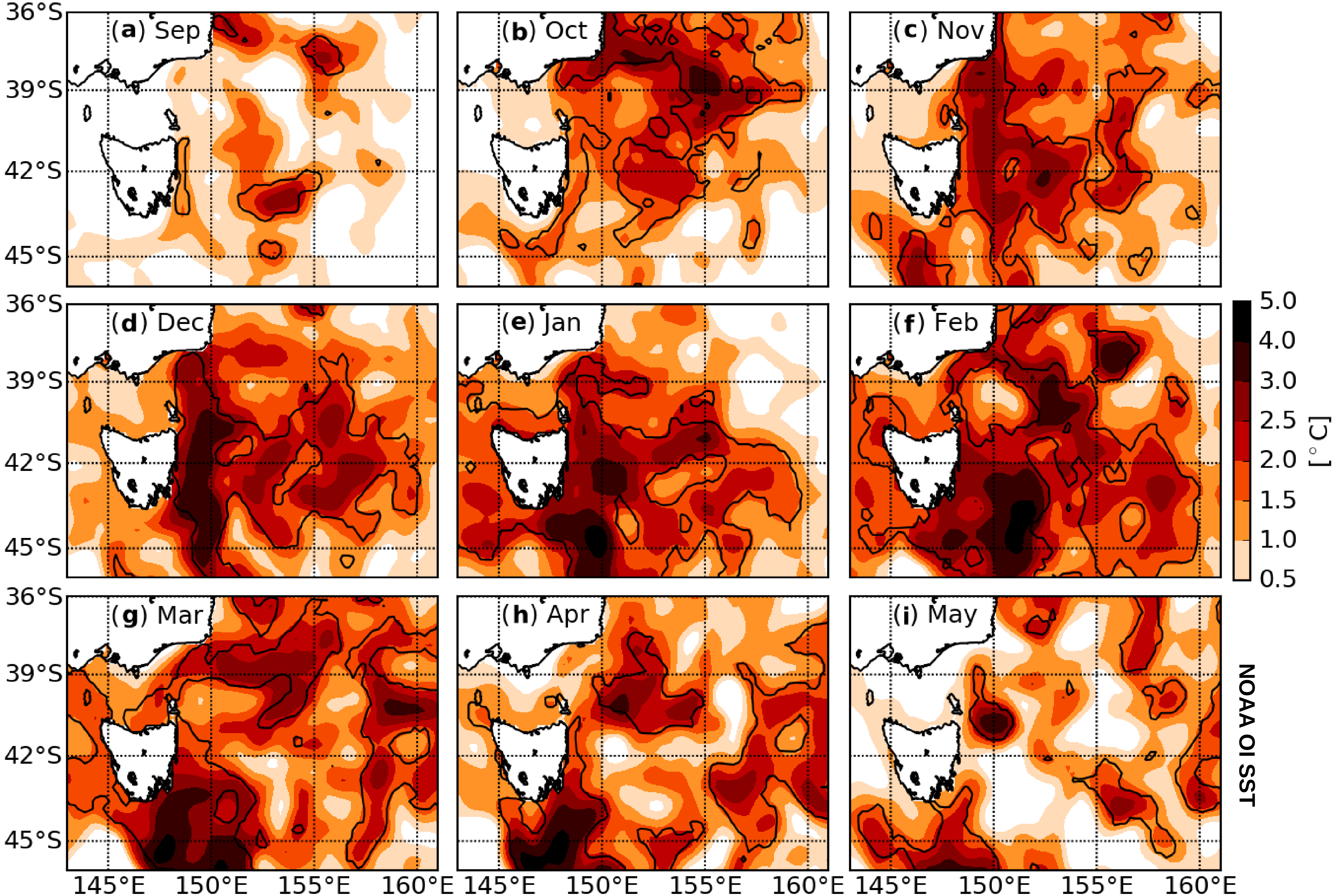


http://www.marine.csiro.au/~lband/yacht_races/yyzeecur.html

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

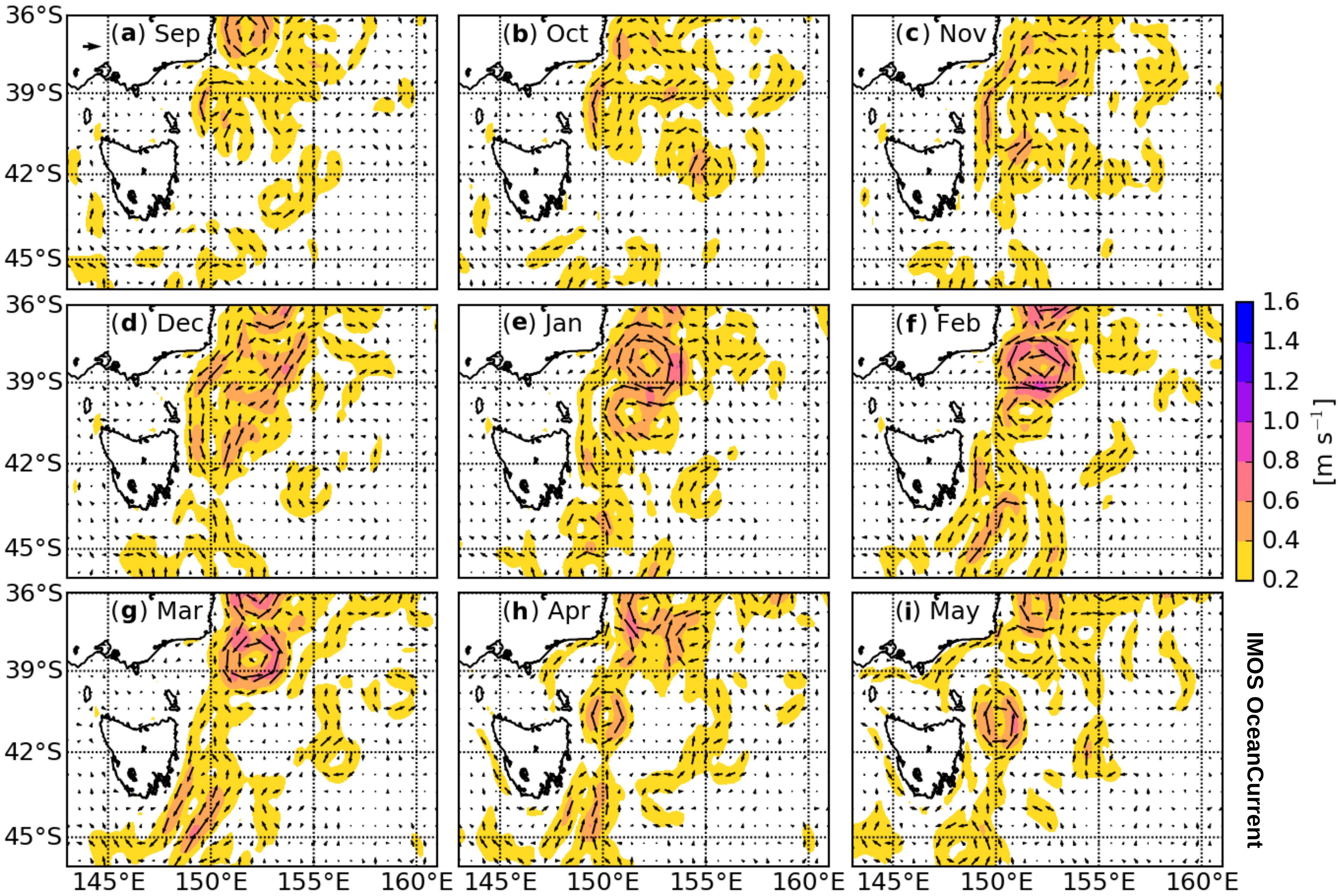
Evolution of the event

Monthly SST anomalies: contour encloses areas that were detected as MHWs for >90% of that month



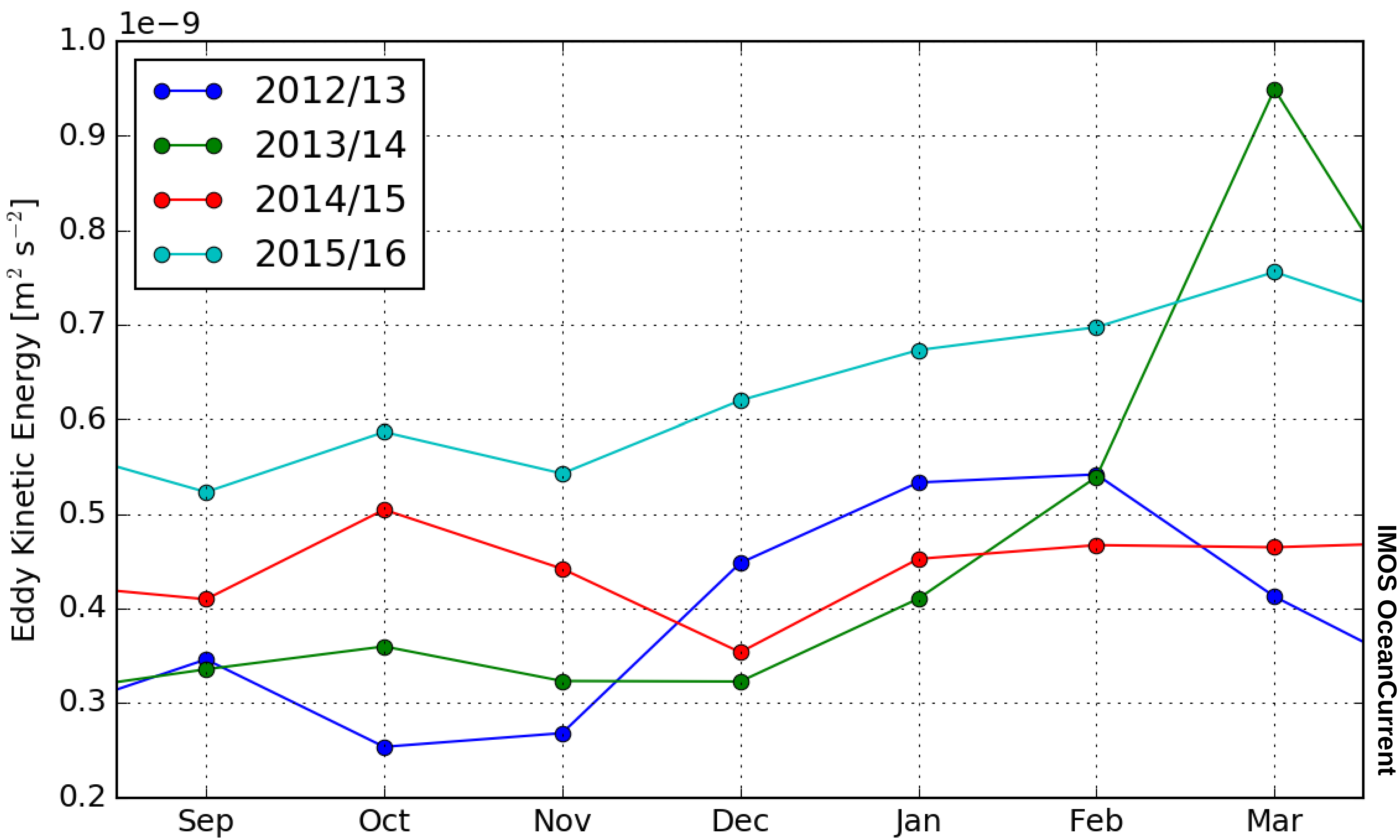
Evolution of the event

Monthly surface currents (*u*, *v*) (IMOS OceanCurrent)



Evolution of the event

Monthly surface Eddy Kinetic Energy (*EKE*) (IMOS OceanCurrent)



Physical drivers

- **<u>Upper ocean temperature budget</u>**, following:
  - Benthuysen et al. (*CSR*, 2014) for 2011 West. Aus. MHW
  - Chen et al. (*JGR*, 2015, 2016) for the 2012 NW Atlantic MHW
- **Volume averaged temperature** tendency equation:

$$\frac{dT}{dt} = -u_{\mathrm{H}} \cdot \nabla_{\mathrm{H}} T + \frac{1}{A}\int_{\mathrm{A}} \frac{Q}{\mathrm{H}} dA + \mathrm{Residual}$$

Horizontal temperature advection

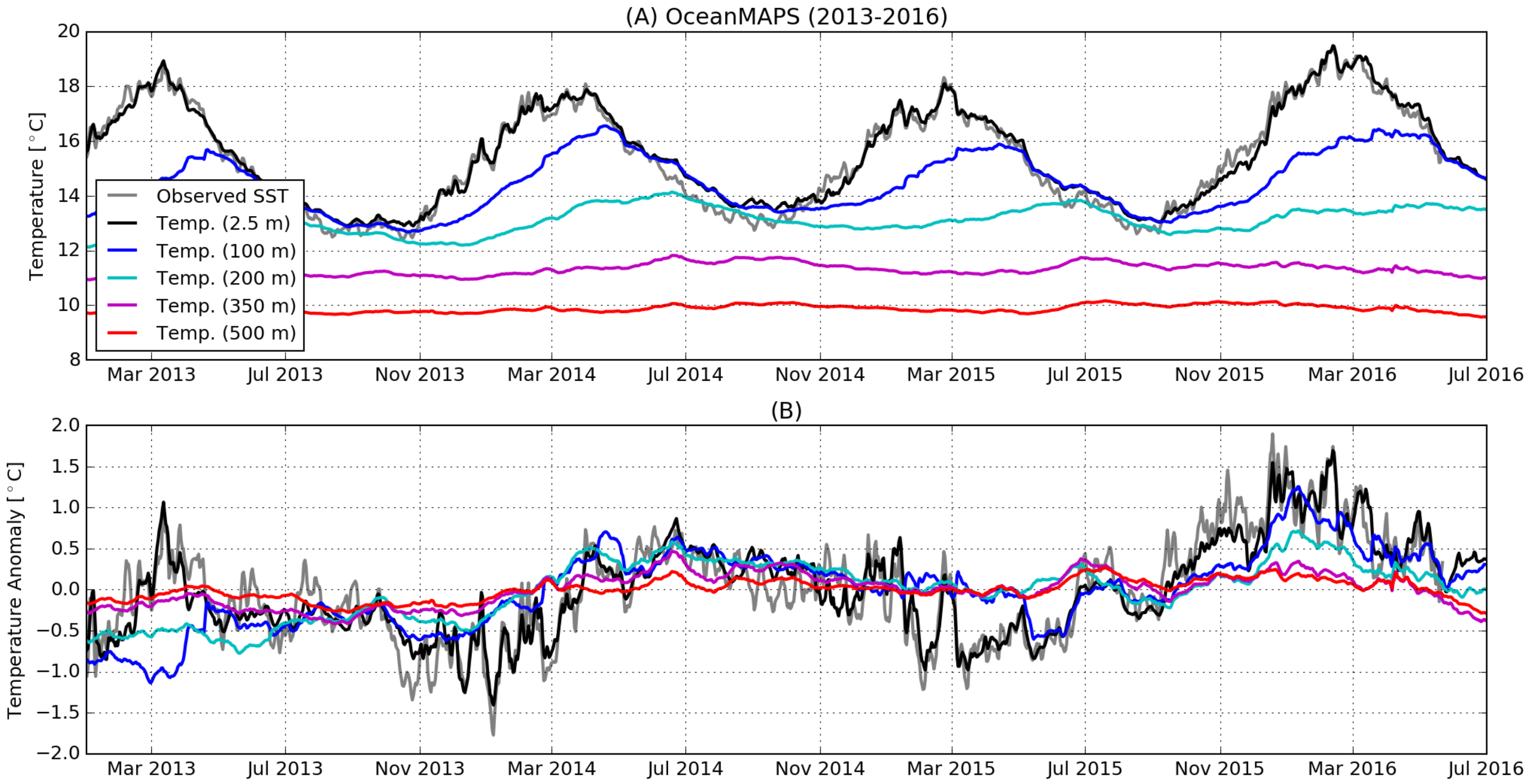
Air-sea heat flux

Includes: Horizontal and vertical diffusion, vertical advection

  - *Depth: H* = 100 m
  - *Area: A* = “SEAus box”
  - *Temperature* (T) and *velocities* (u_H) from OceanMAPS
  - *Surface heat flux* (Q) from NCEP CFSv2 reanalysis

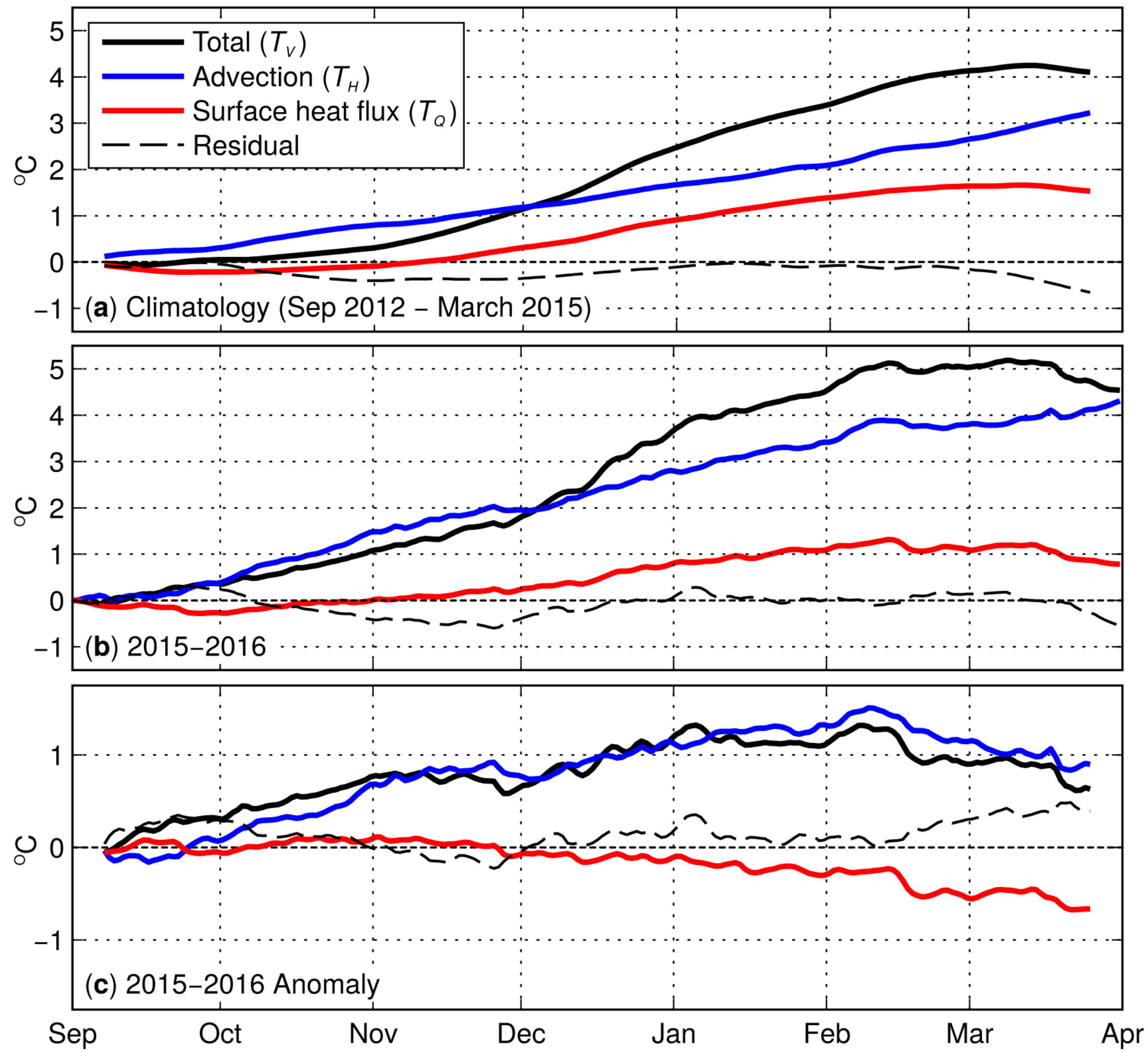
Physical drivers

- **How well does OceanMAPS get the temperature?**
- Good agreement at surface → we can trust OceanMAPS
- Warming evident down to 100-200 m → H = 100 m



Physical drivers

- **Temperature budget**
- Volume averaged temperature (T_V) since Sep 1st of:
  - 2012/13, 2013/14, 2014/15, 2015/16
- Consider:
  - Temperature avection (T_H)
  - Air-sea heat flux (T_Q)
- **Climatology:** by mid-February T_H contributes ~60% of the warming while T_Q contributes ~40%
- **2015-2016:** by mid-February T_H contributes ~80% of the warming while T_Q contributes ~20%
- Marine heatwave primarily driven by **anomalous temperature advection**



Role of climate change

- <u>**Event Attribution study**</u> following
  - Lewis & Karoly (*GRL*, 2013) on Australia's “angry summer” of 2013
  - King et al. (*ERL*, 2015) on Central England temps. of 2014
- **Calculation:** *Fraction of Attributable Risk (FAR)*:

$$\mathrm{FAR} = 1 - \frac{P_{\mathrm{histNat}}}{P_{\mathrm{hist}}}$$

where P_X is the probability of an the event larger/longer than the event in question based on the modelled climate *X*.

- **Informs:** change in likelihood of occurrence of an event like the one in question due to anthropogenic influence (*hist*) as opposed to a naturally-forced world (*histNat*)
- **Data:** Look at *SEAus* MHWs in CMIP5 *historical*, *historicalNat* and *RCP8.5* runs

Role of climate change

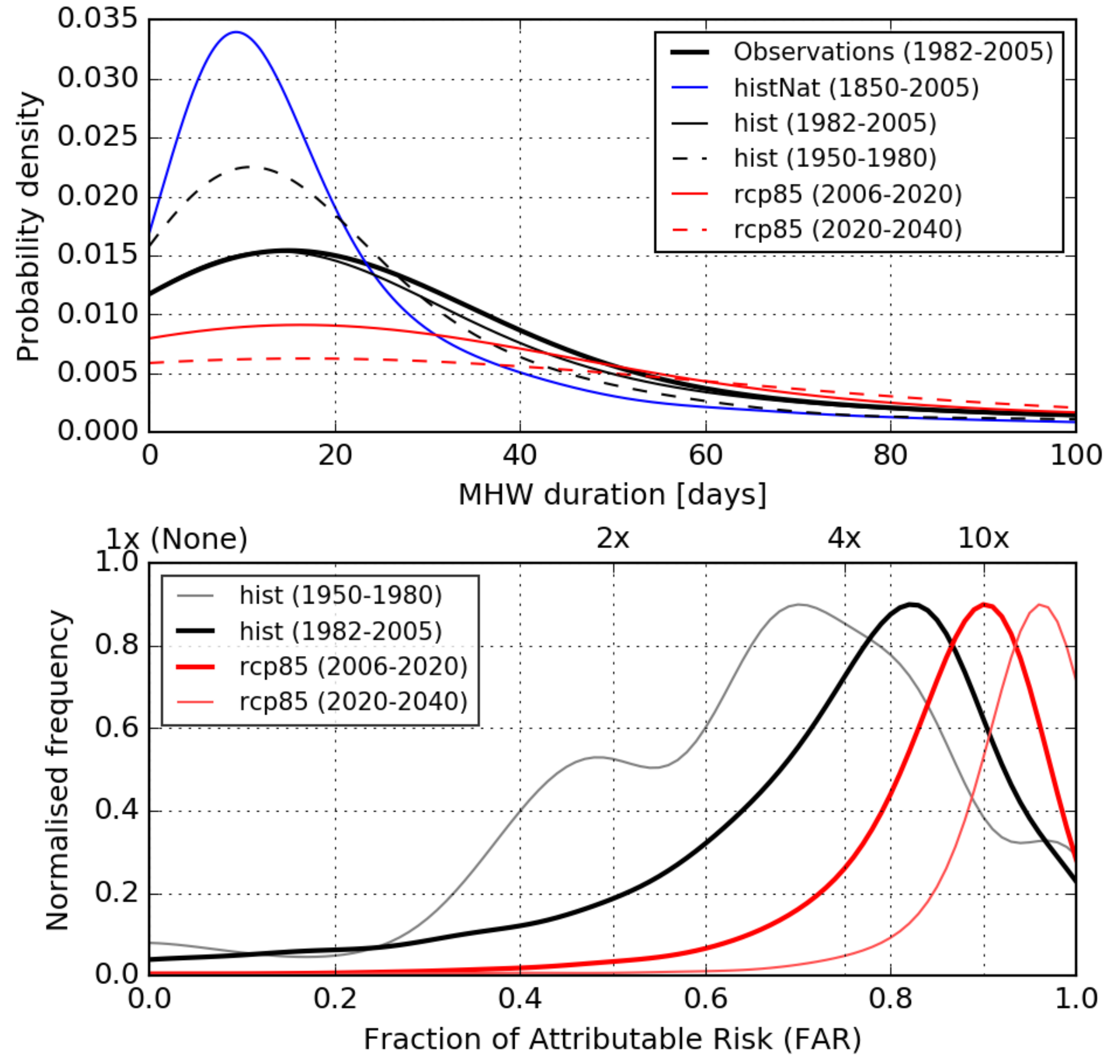
- Need *daily* SSTs, limits the number of available models:

Model	Historical	HistoricalNat	RCP8.5	Bias correction
ACCESS1.3	3	3	1	1.32
CanESM2	1	3	5	1.10
CSIRO Mk3.6.0	10	10	10	1.42
CNRM-CM5	1	5	5	0.80
HadGEM2-ES	4	4	4	0.96
IPSL-CM5A-LR	6	3	4	0.98
IPSL-CM5A-MR	3	3	1	0.91
Total	**28**	**31**	**30**	

- Did a **bias correction** rather than a model selection (so few models):
- **Decompose SST** time series as follows: $T_t = a + bt + T_t^{\mathrm{S}} + T_t'$
- **Isolate** *linear trend* ($a+bt$) and *seasonal cycle* ($T^S{}_t$) by regression, compare variance of non-seasonal variability (T'_t) between observations and model historical runs as a *ratio*
- **Bias correct**: *Scale variance of each model run* based on the calculated bias ratio, then add it back to the linear and seasonal component

Role of climate change

- **<u>Attribution statement</u>** made separately around 2nd-largest (intensity) and 2nd-longest (duration) event *(1911-1940 base period)*:
  - 3.1 °C
  - 377 days
- **<u>Duration</u>**: An event of this duration was
  - **4x as likely** in 1982-2005 (hist simulations) compared to the “natural world” (historicalNat 1850-2005 simulations) *[95% CI: 0.5-53x]*
  - **9x as likely** by 2006-2020 (RCP8.5 simulations) *[95% CI: 2-22x]*



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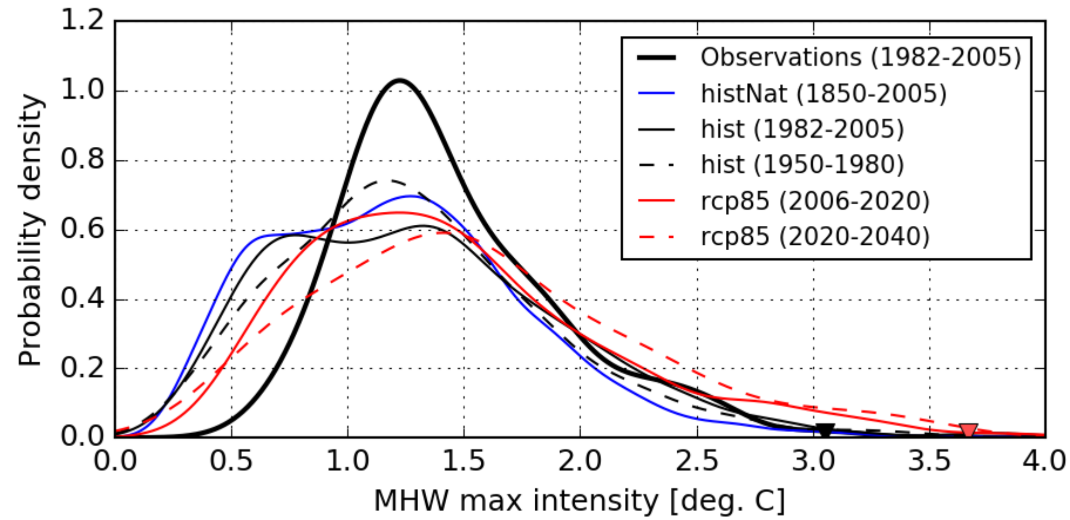
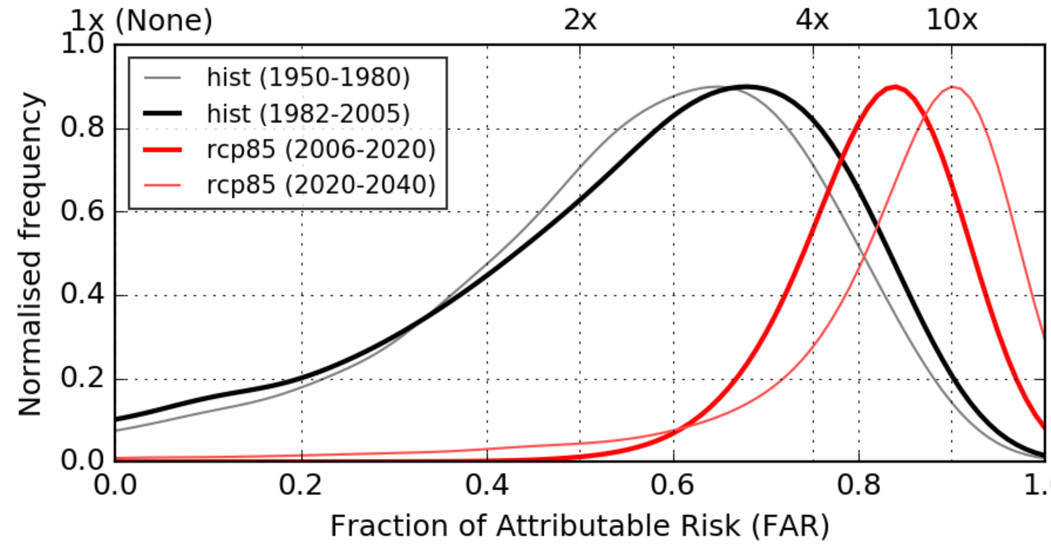
  - **6x as likely** by 2006-2020 *[95% CI: 3-13x]*
- → Virtually certain (>99%) that anthropogenic climate change increased the likelihood of an event of this duration or intensity by 2005-2020





Ecological Impacts

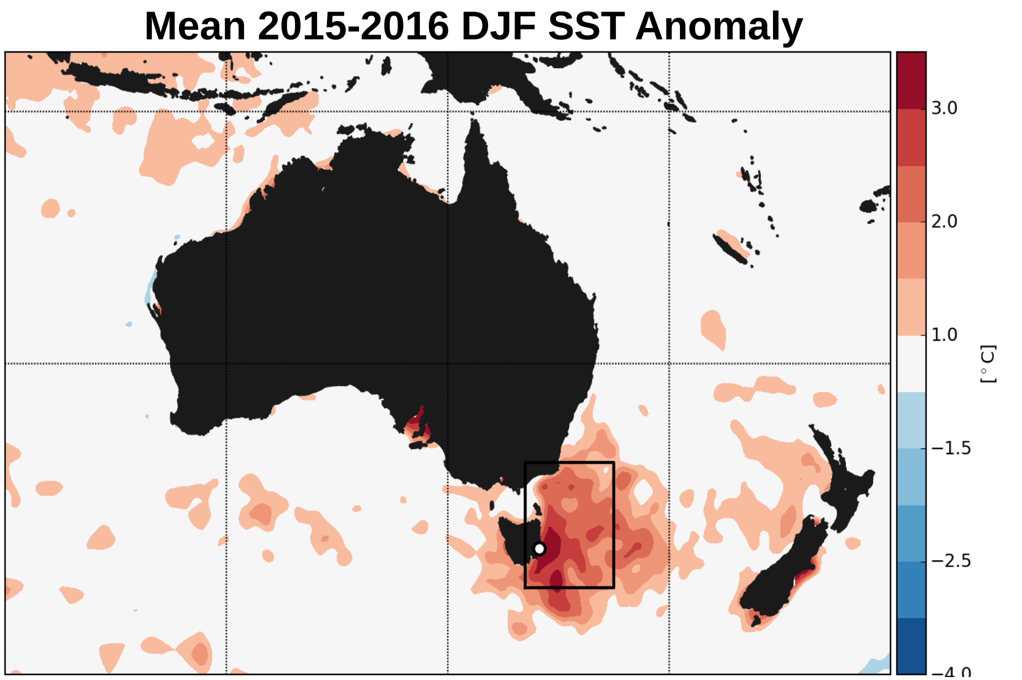
- **Pacific Oyster Mortality Syndrome (POMS)**
  - Absent in March 2015 but present from mid-Dec 2015,
  - Linked with anomalously warm waters (NSW, France)
- **Blacklip abalone**
  - 5% mortality rate, normally ~zero
  - Mortality recorded throughout heatwave across most of east coast
- **Atlantic Salmon**
  - Reduced aquaculture performance
- **Out of-range fish**
  - More than normal sightings of:
    - Yellowtail kingfish, Snapper, Dusky morwong, Mahi mahi, Blue moki, Moonlighter fish

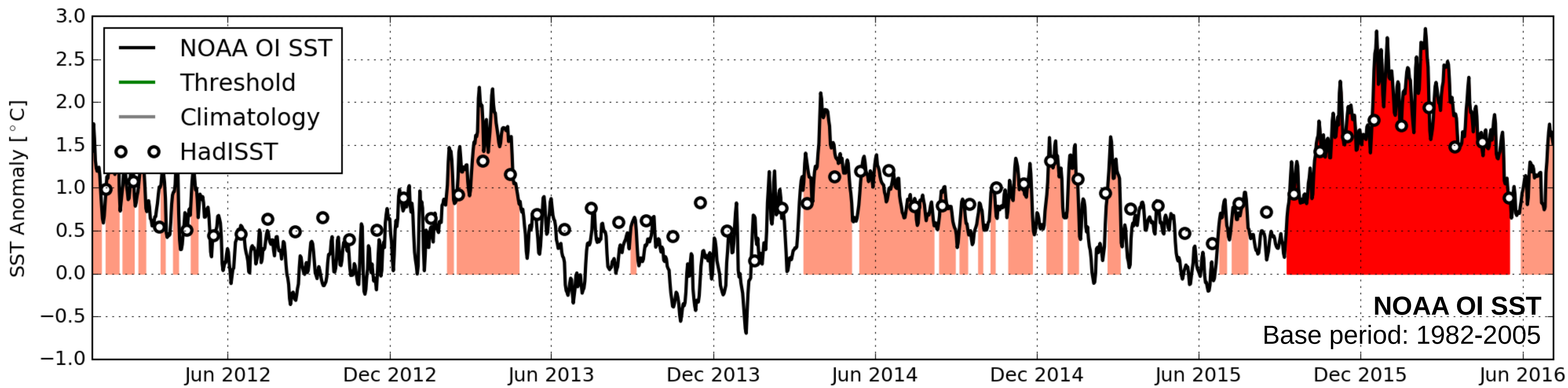
- Despite the **MHW intensity and duration**, recorded impacts have been **moderate**,
  - esp. in comparison to the 2011 WA event

Conclusions

1. The **2015/16 Tasman Sea MHW** was the **longest** and **most intense** ever recorded in this region
2. **Driven** by anomalous temperature advection (an **EAC Extension event**)
3. **Anthropogenic climate change** significantly **raised the likelihood** of such an event

Oliver, Benthuysen, Bindoff, Hobday, Holbrook, Mundy and Perkins-Kirkpatrick, *Nat Comms* (under review)





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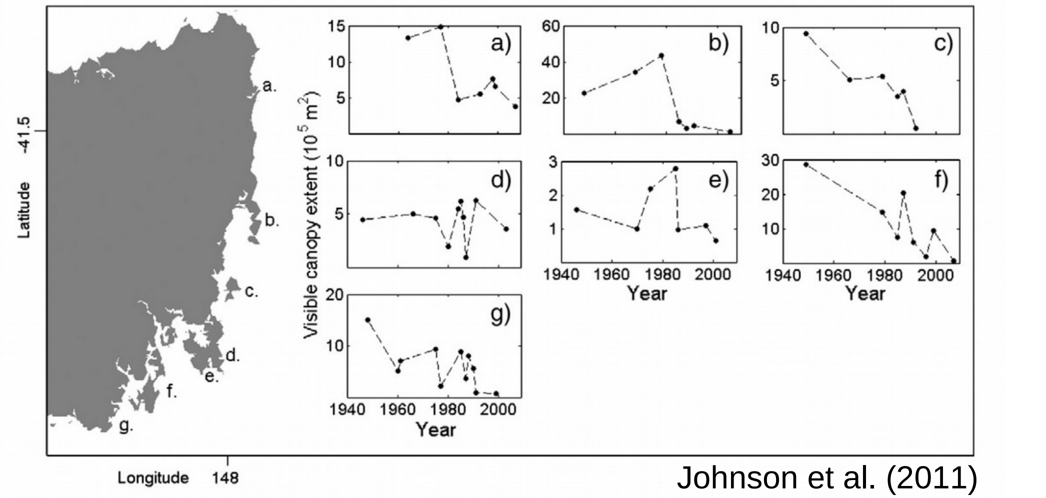

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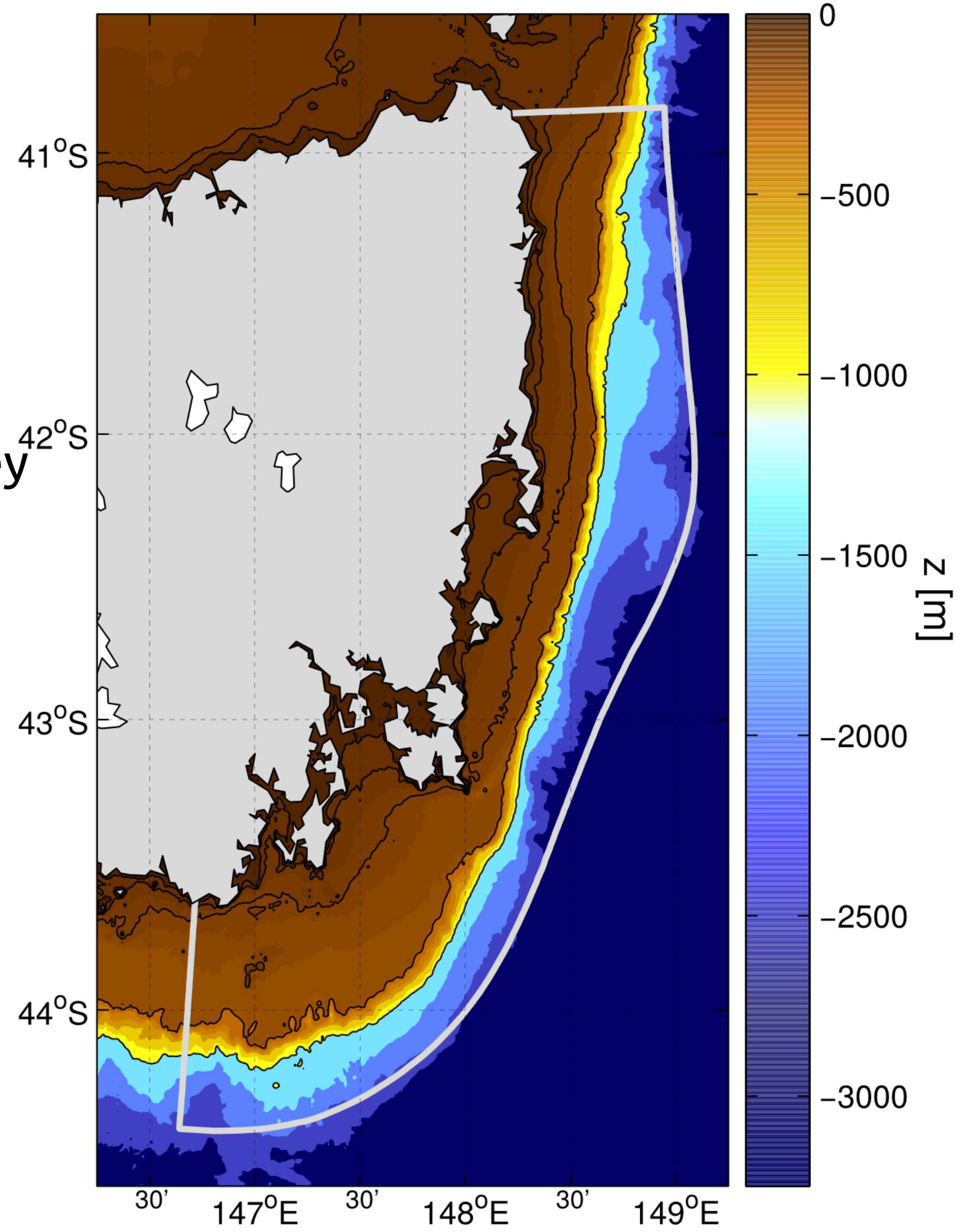
- Domain: South Cape to ~Eddystone Point and seaward out to shelf break
- Bathymetry: Australian Geological Survey Organisation (AGSO) 2002 + SETAS
- Resolution: ~1.9 km resolution
- 43 *z*-levels in the vertical
- Surface forcing: NCEP CFSR, CFSv2
  Boundary forcing: BRAN, OceanMAPS
  Time period: 1993-2015, daily output
- Publication: Oliver et al. (*CSR*, 2016)



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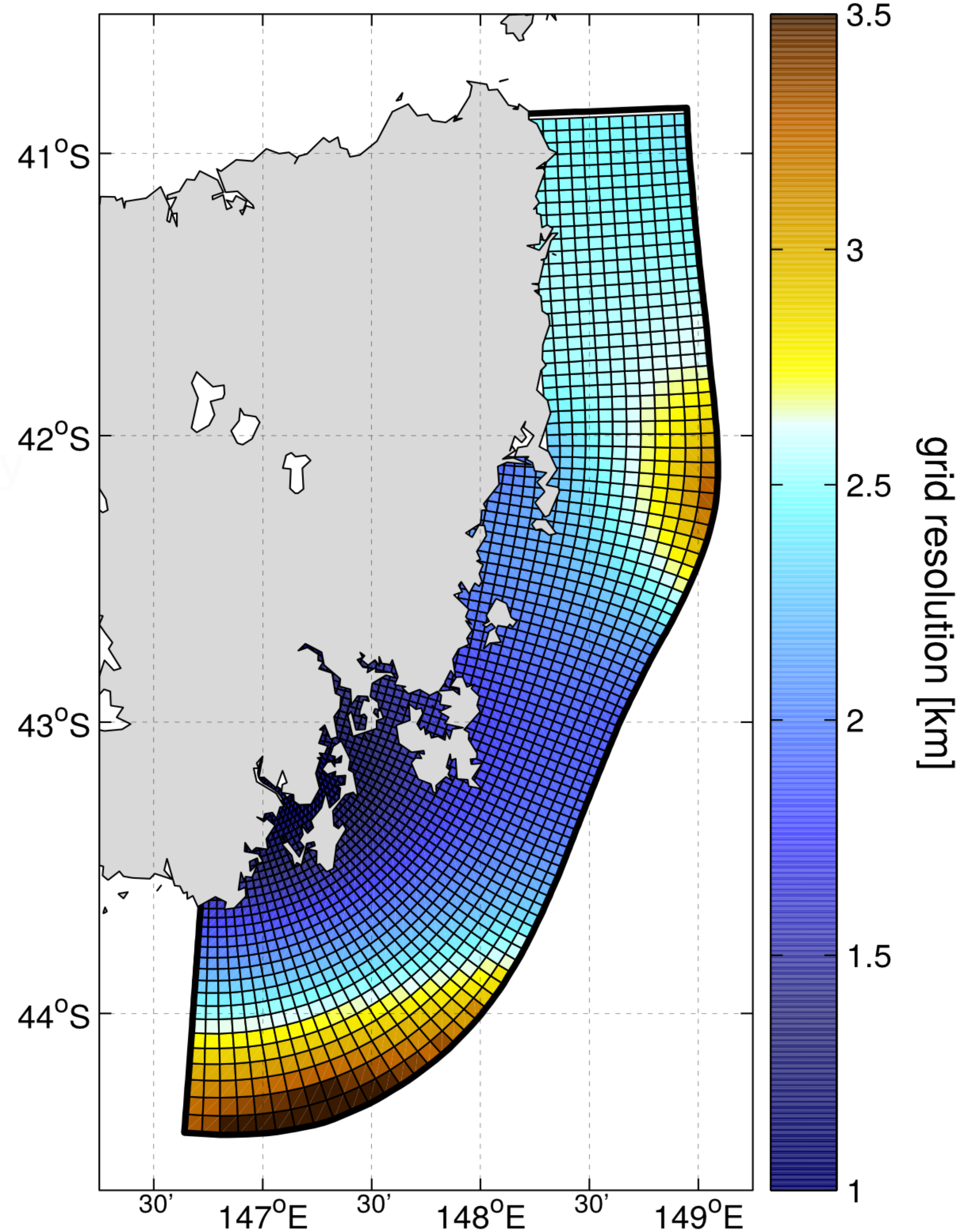

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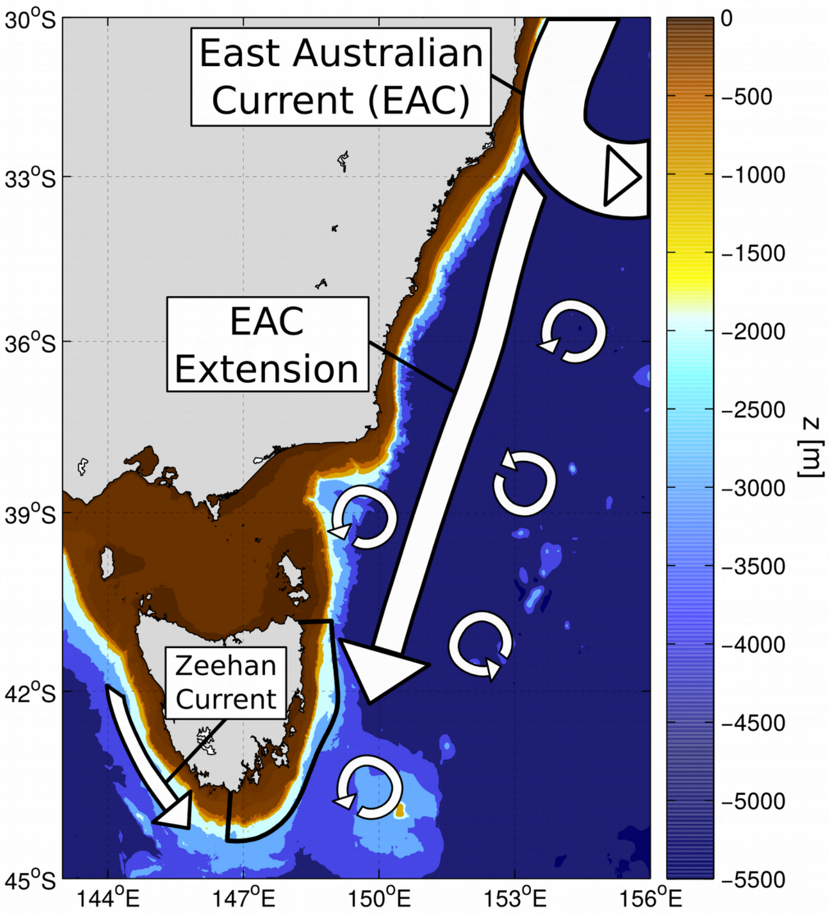
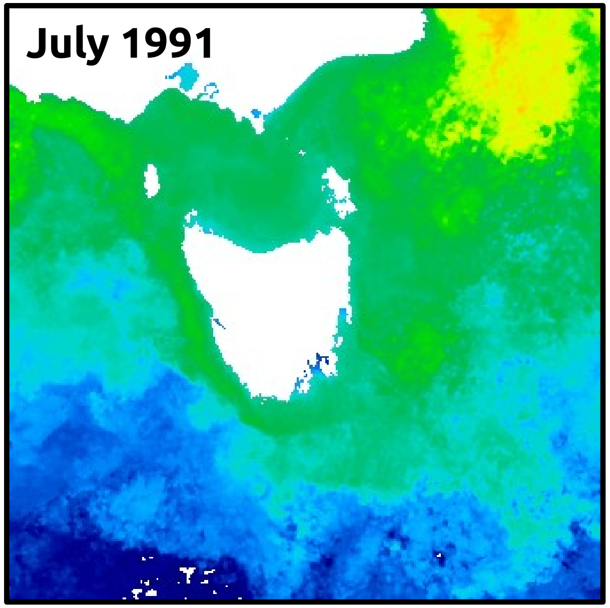
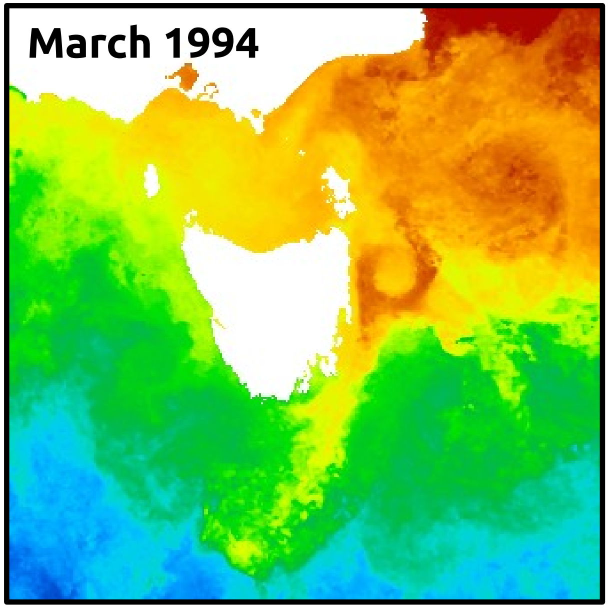
- **East Australian Current (EAC)**, a quasi-steady western boundary current, separates from the coast ~33^{O}S.
- The **EAC Extension** continues southward transport as far as Tasmania, but as an unsteady, eddy-rich “current”
- The **Zeehan Current (ZC)**, part of a current system extending all the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



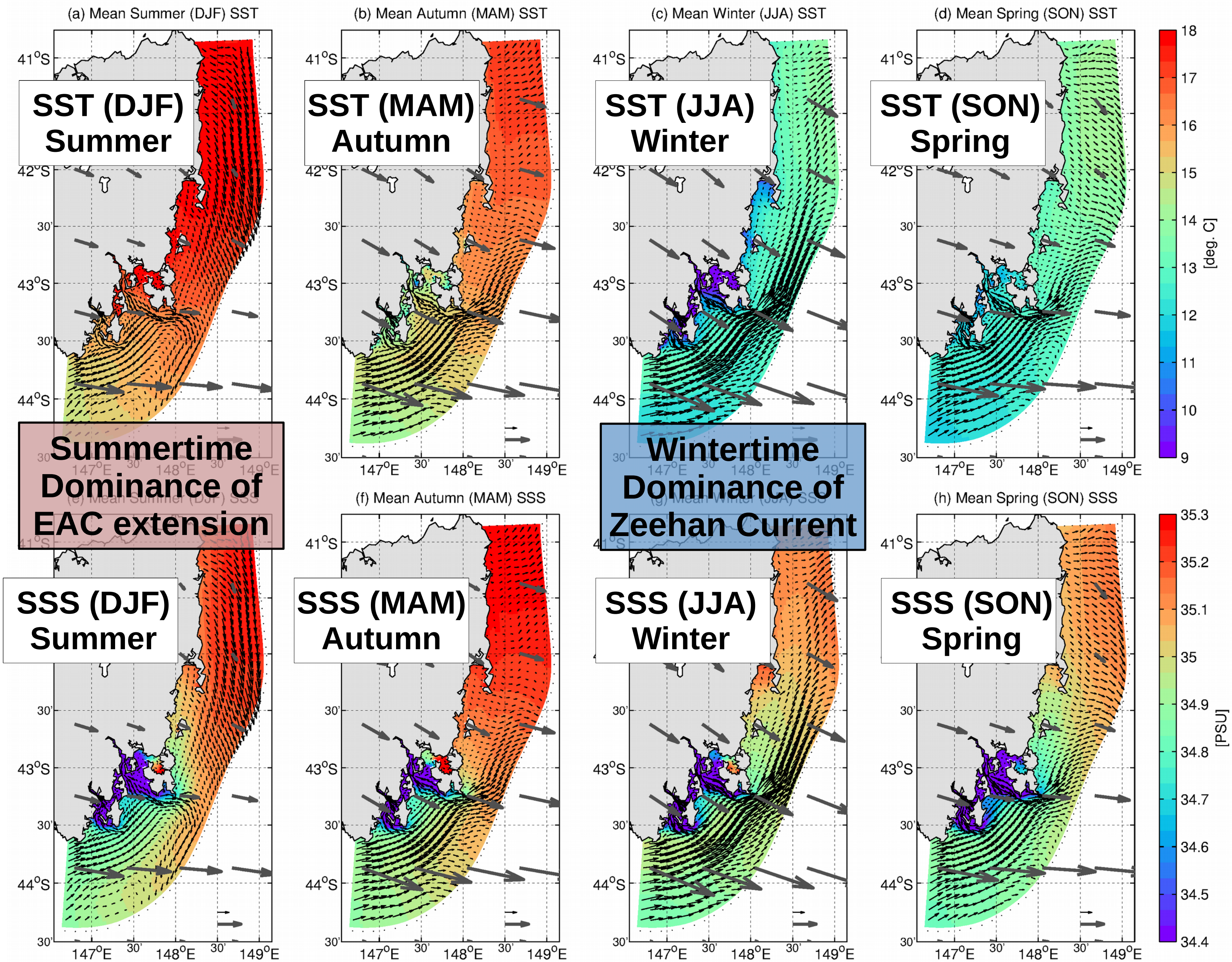




http://www.marine.csiro.au/~lband/yacht_races/yyzeecur.html

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

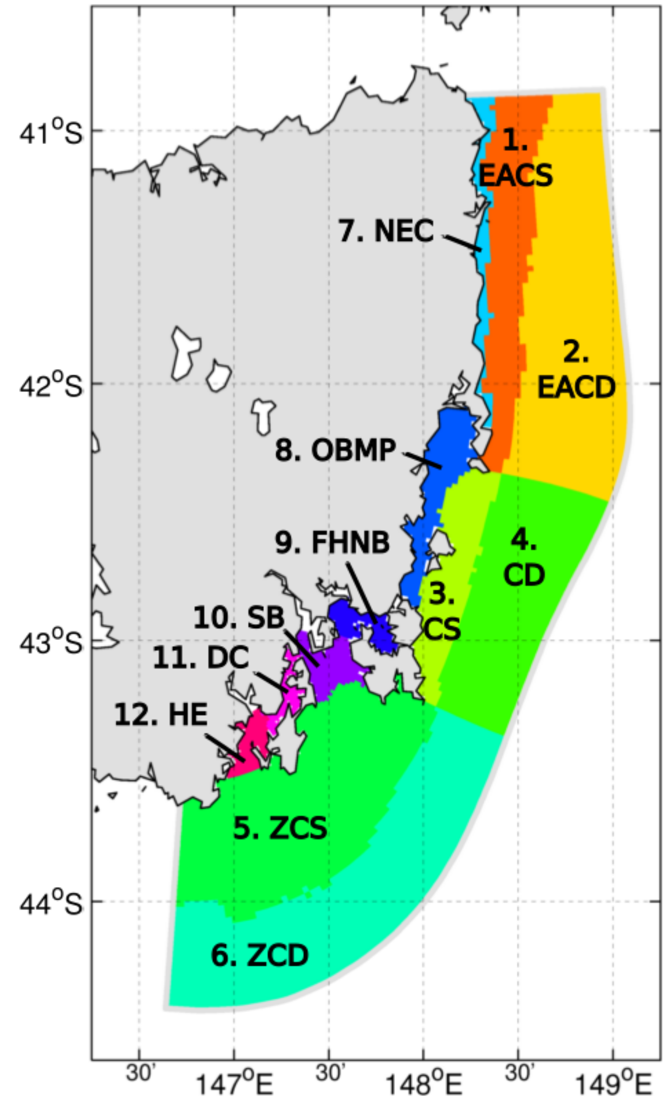
Surface Climatology



Oliver, Herzfeld and Holbrook (*Cont. Shelf. Res.*, 2016)

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

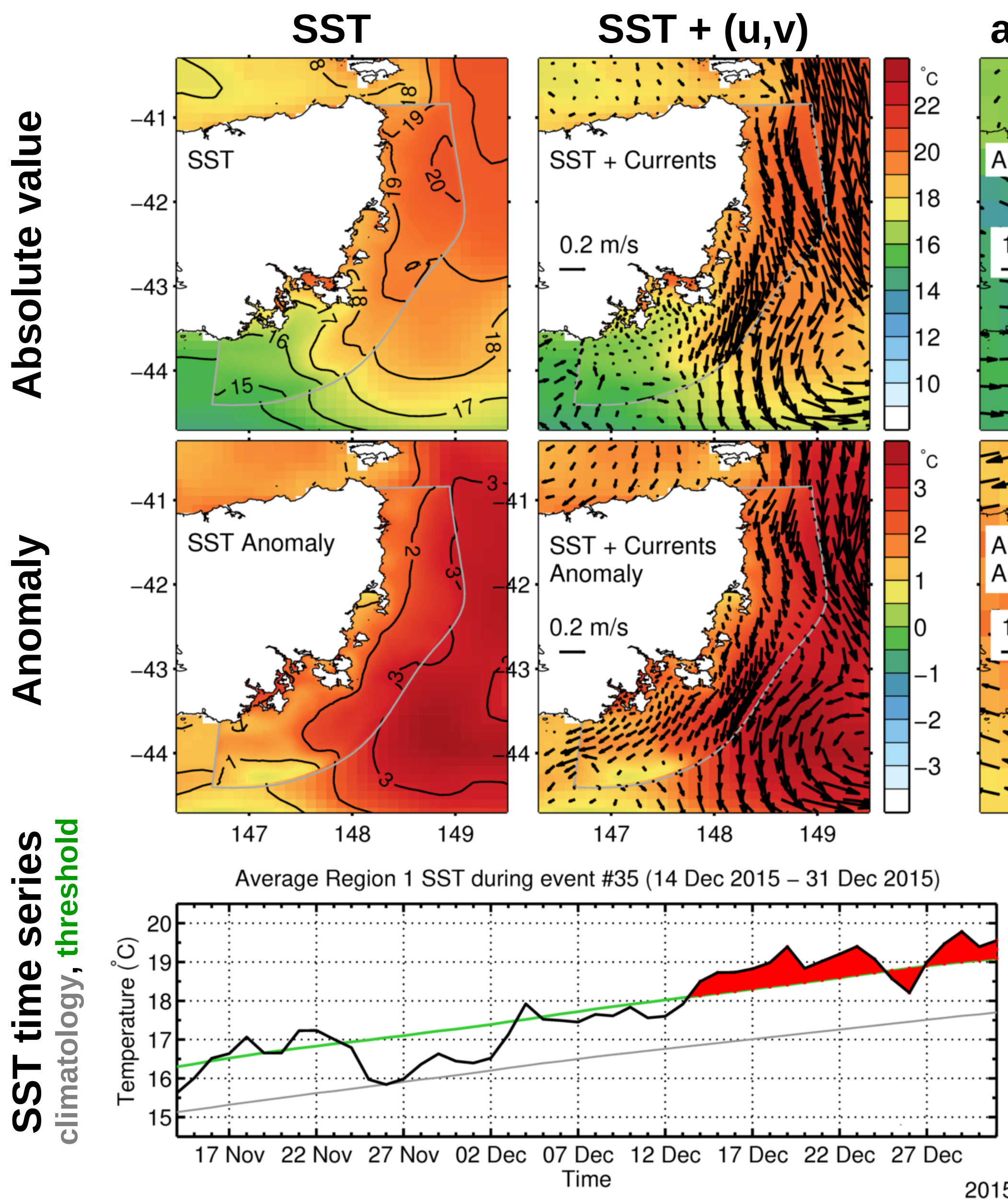


LEGEND

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 35 (of 35) in Region 1 (EACS = EAC Shelf)**
- Also calculate regional SST, currents, air temp., wind averaged over event duration

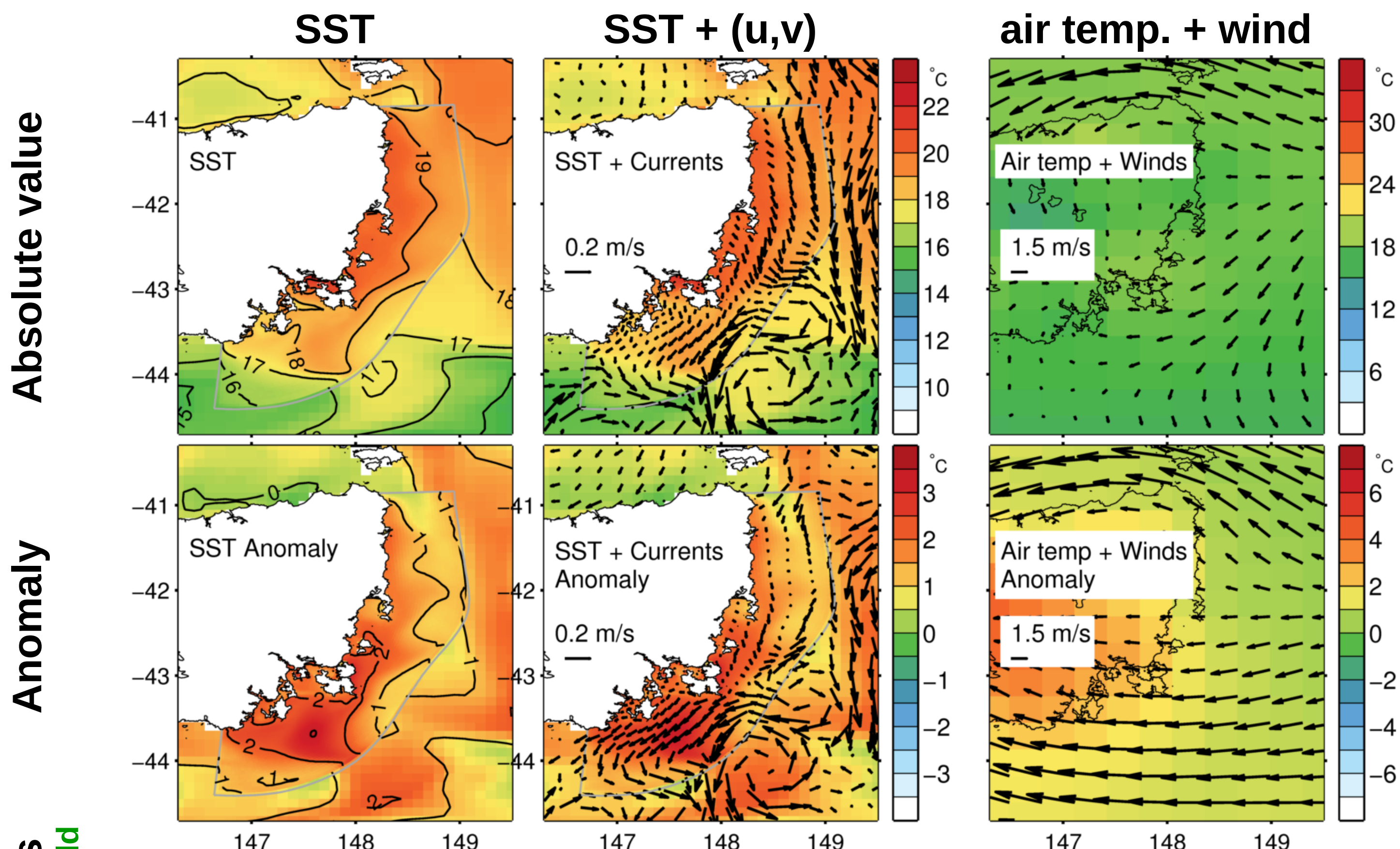


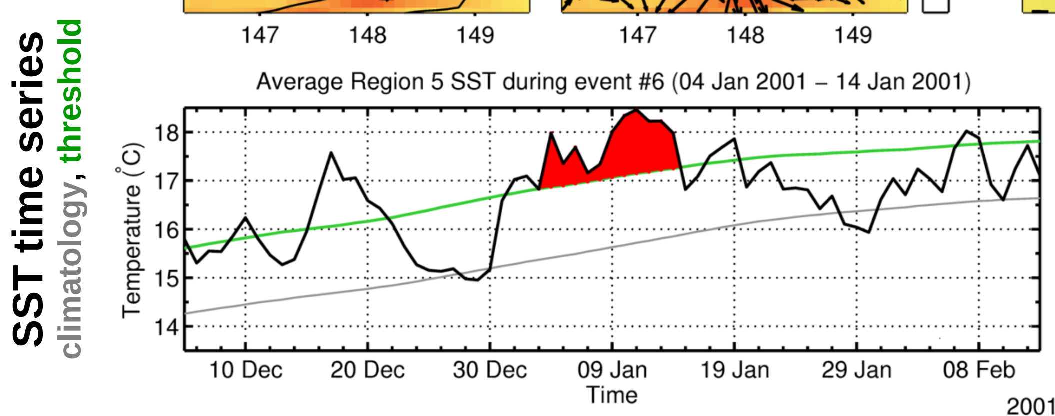
Total number of events: 35	Rank
Duration: 18 days	7/14
Max. intens.: 2.3 °C	3/35
Mean intens. : 1.8 °C	4/34
Cum. intens. : 32 °C·days	5/35
Onset rate: 0.2 °C/day	15/35
Decl. rate: 0.04 °C/day	30/35
Depth: 270 m	1/16

Event properties and rank

Individual events

- **Event 6 (of 37) in Region 5 (ZCS, roughly the "Bruny Island bioregion")**
- Also calculate regional SST, currents, air temp., wind averaged over event duration



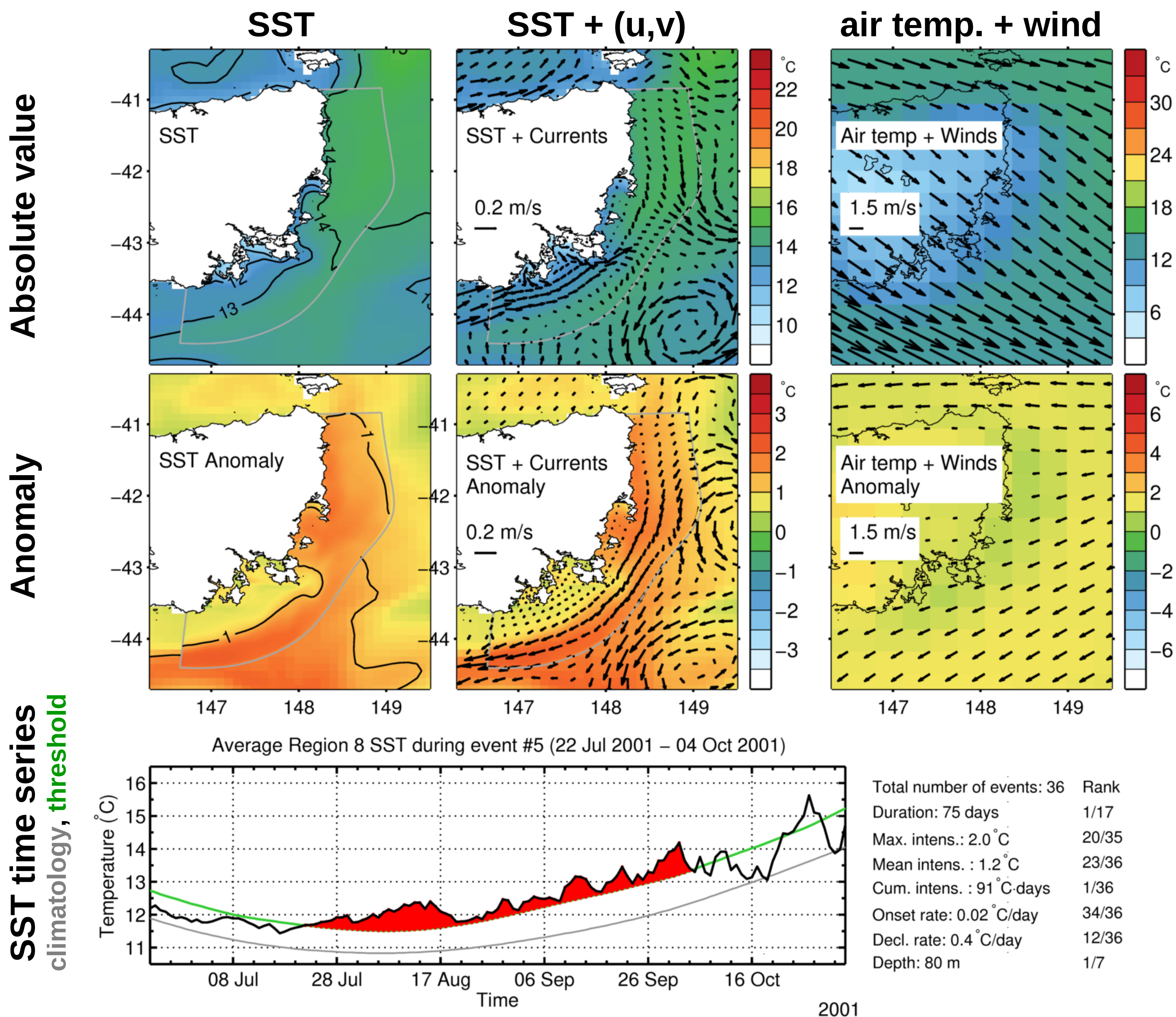


Event properties and rank

	Rank
Total number of events: 37	
Duration: 11 days	11/17
Max. intens.: 2.7 °C	2/37
Mean intens. : 2.3 °C	1/37
Cum. intens. : 25 °C·days	9/37
Onset rate: 0.1 °C/day	30/37
Decl. rate: 0.4 °C/day	14/37
Depth: 12 m	12/15

Individual events

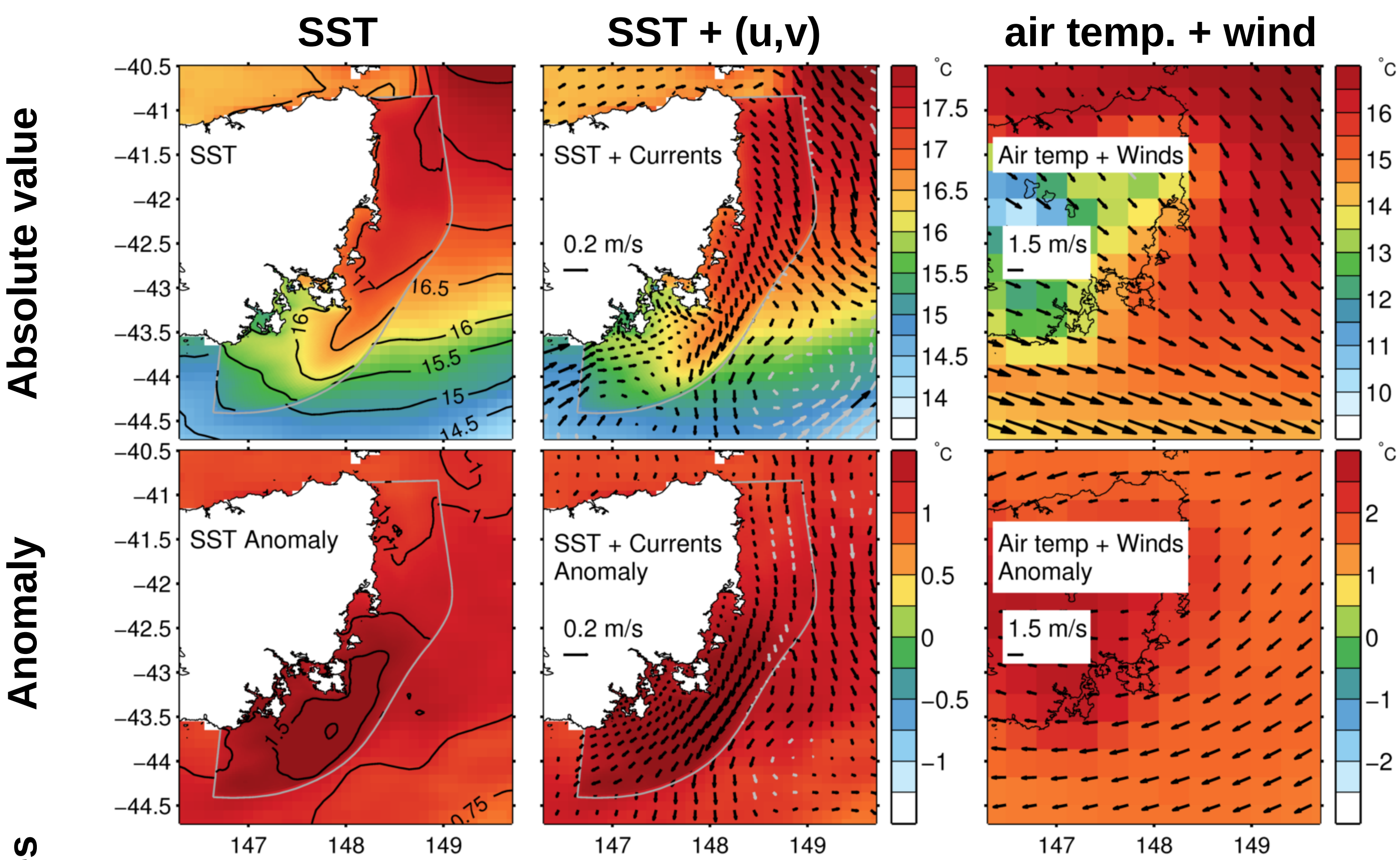
- **Event 5 (of 36) in Region 8 (Oyster Bay – Mercury Passage)**
- Also calculate regional SST, currents, air temp., wind averaged over event duration

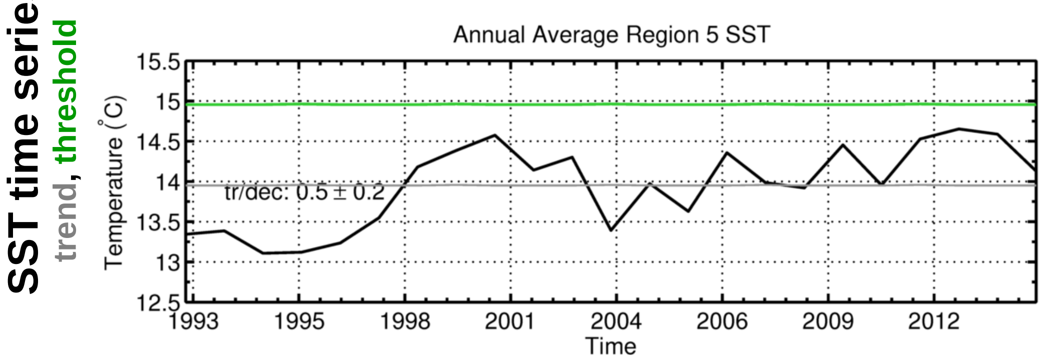


Event properties and rank

Average MHW conditions

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





Property (units)	Trend (decade^{-1})
Frequency (# events)	1.0 ± 1.0
Duration (days)	15.5 ± 12.5
Max. intens. (°C)	−0.21 ± 0.35
Mean intens. (°C)	−0.24 ± 0.25
Cum. intens. (°C·days)	16.0 ± 13.5
Depth (m)	111.2 ± 72.6

Property trends

Average MHW conditions

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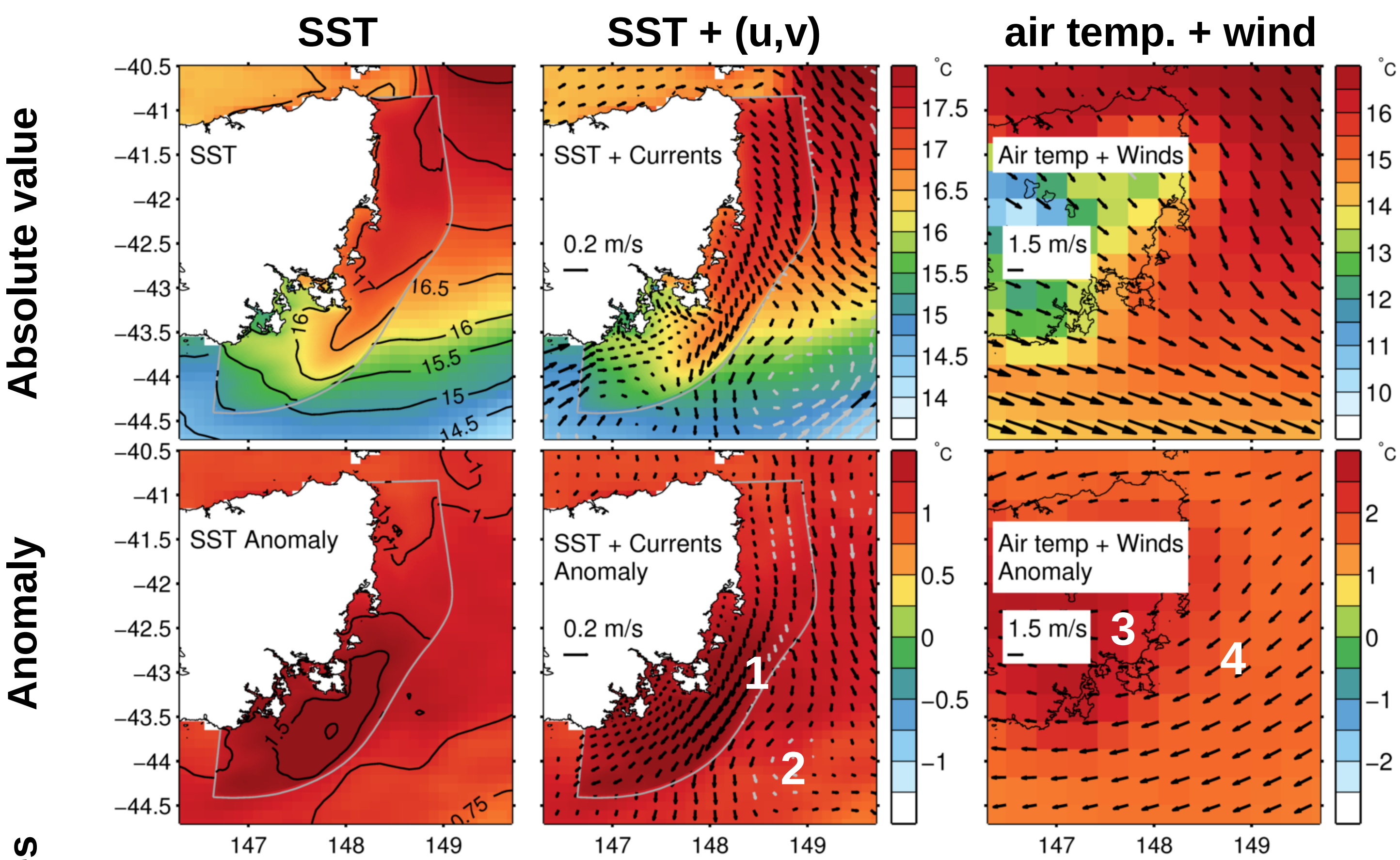

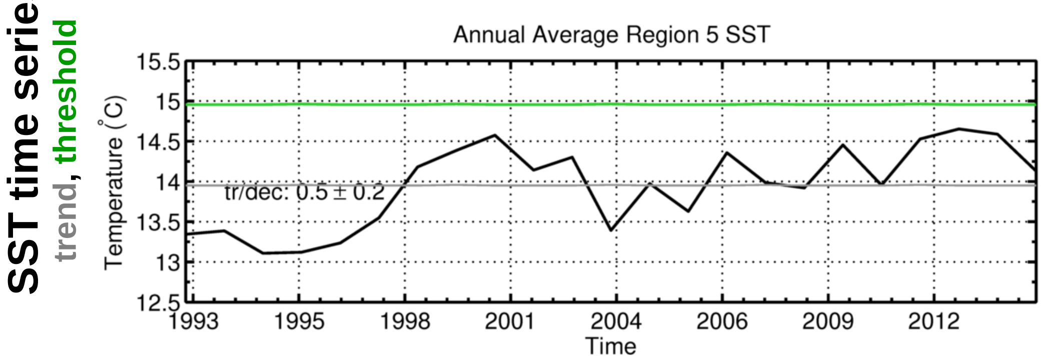

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Property trends

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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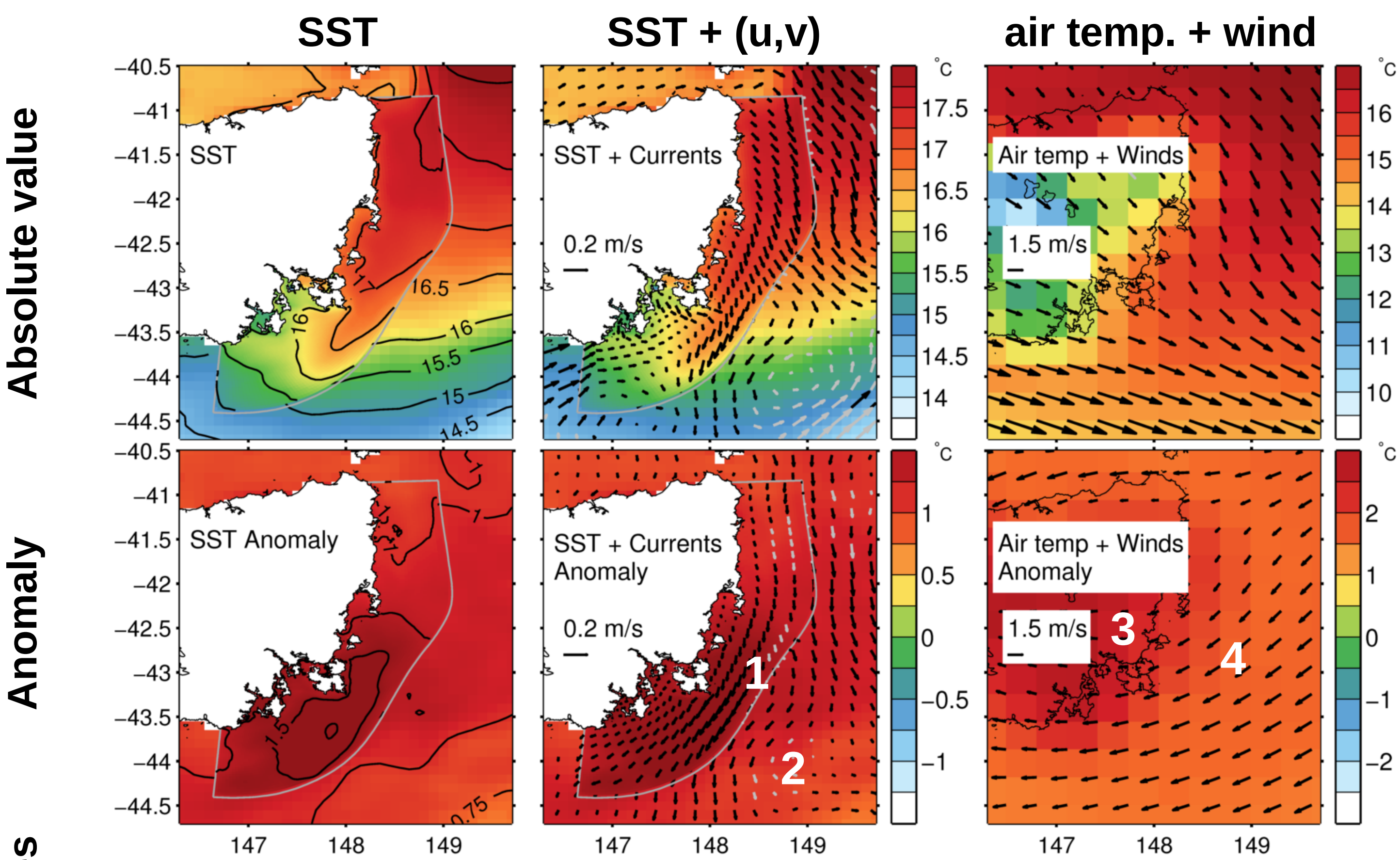

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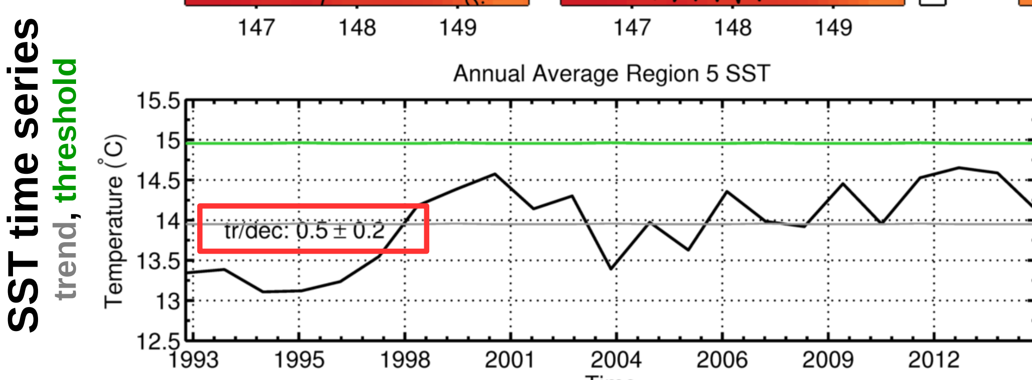

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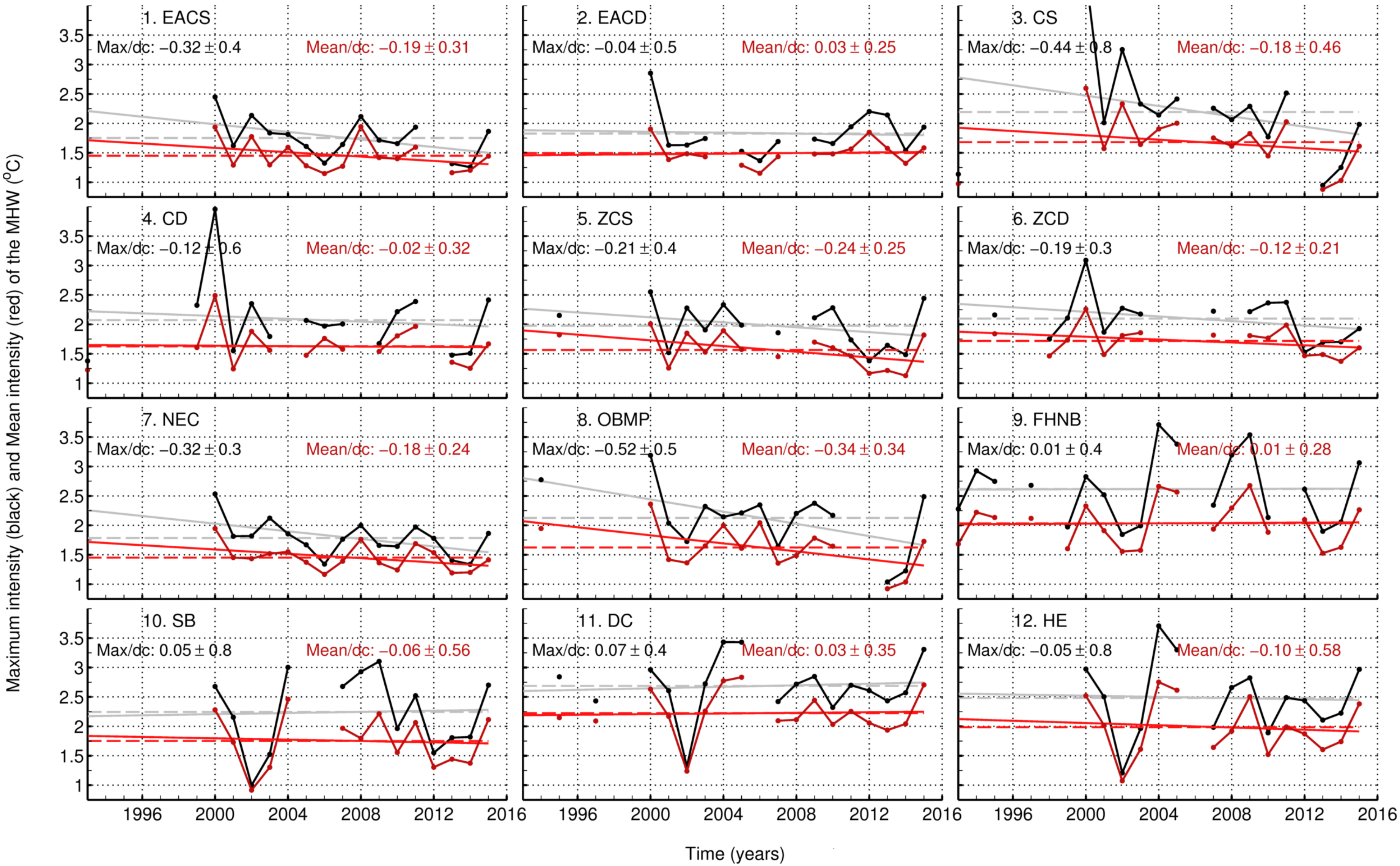
Property trends

Significant linear trends in <u>SST</u>, <u>MHW duration</u>, <u>Cum. Intensity</u>, <u>Depth</u>

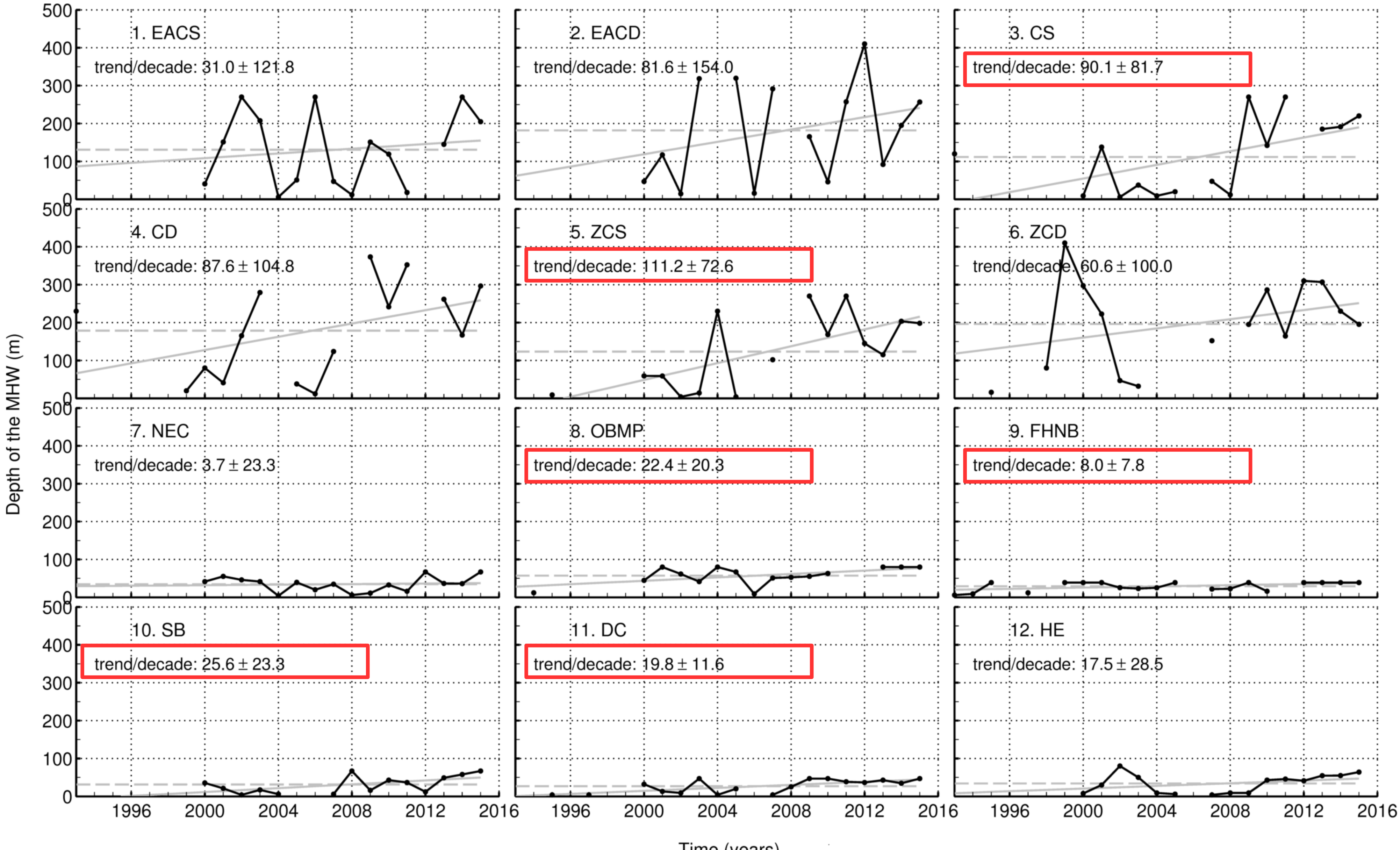
Annual Timeseries

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



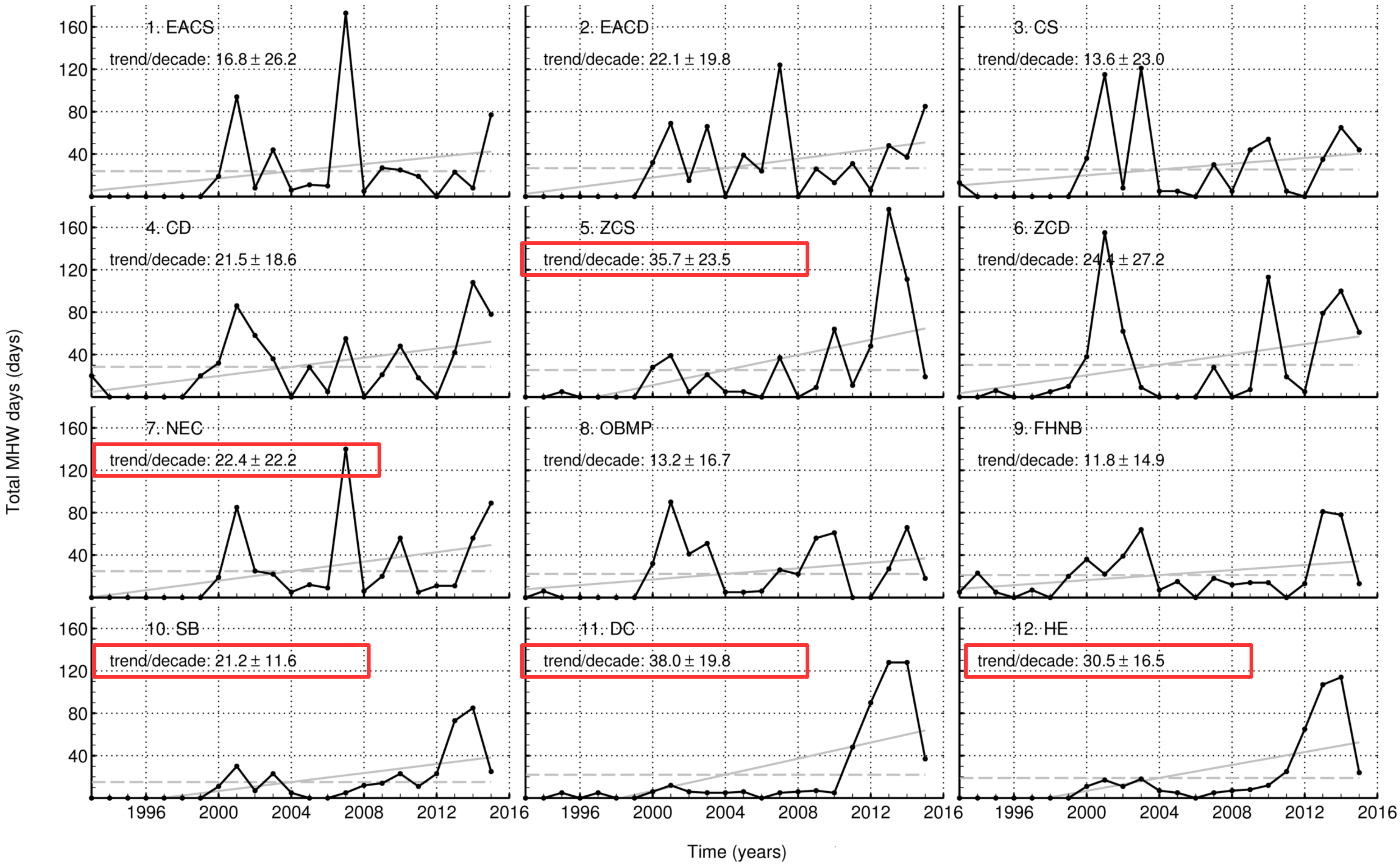
Annual Timeseries

- Annual time series' of **maximum depth** of MHWs
- Significant trends in half of the regions



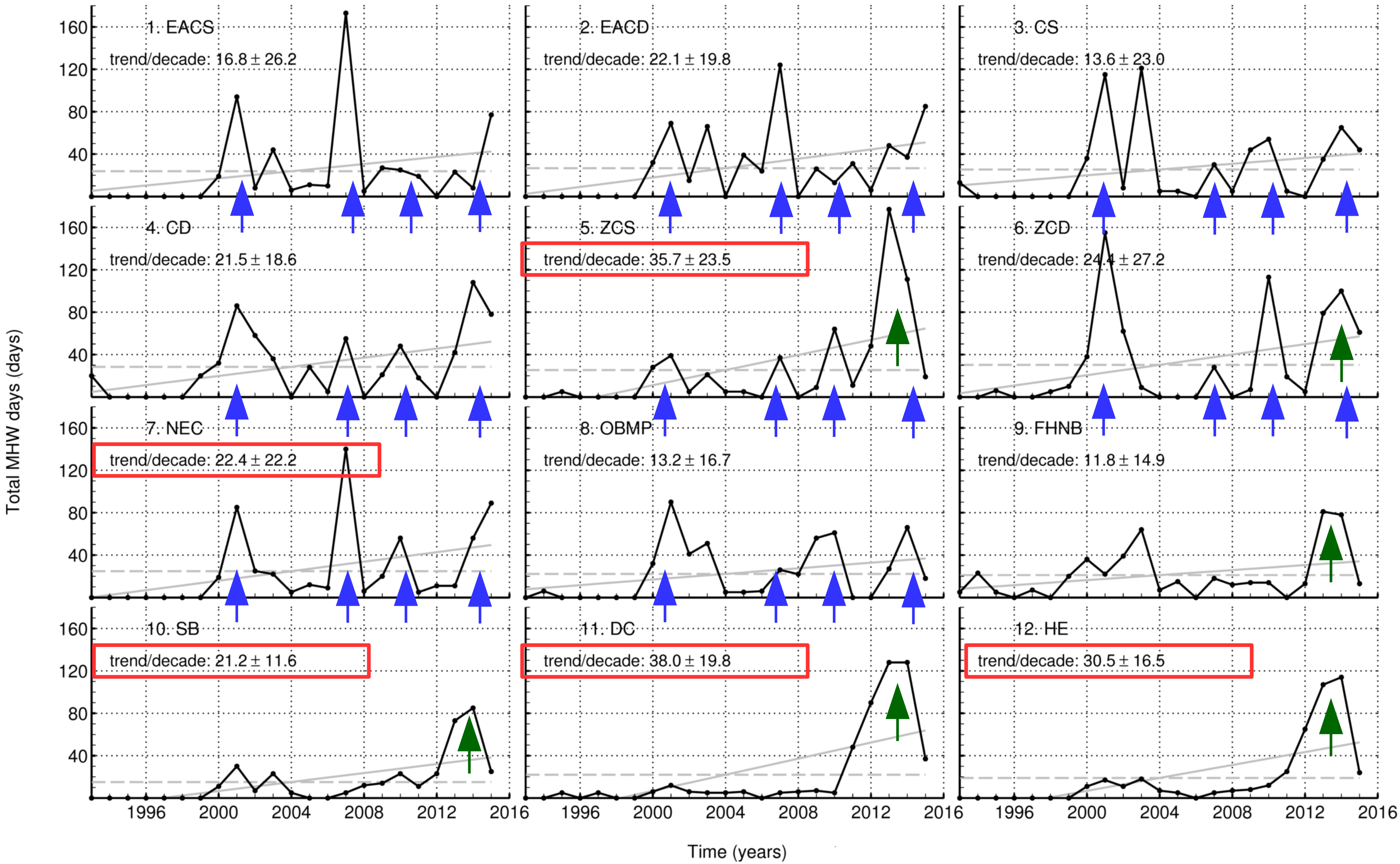
Annual Timeseries

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



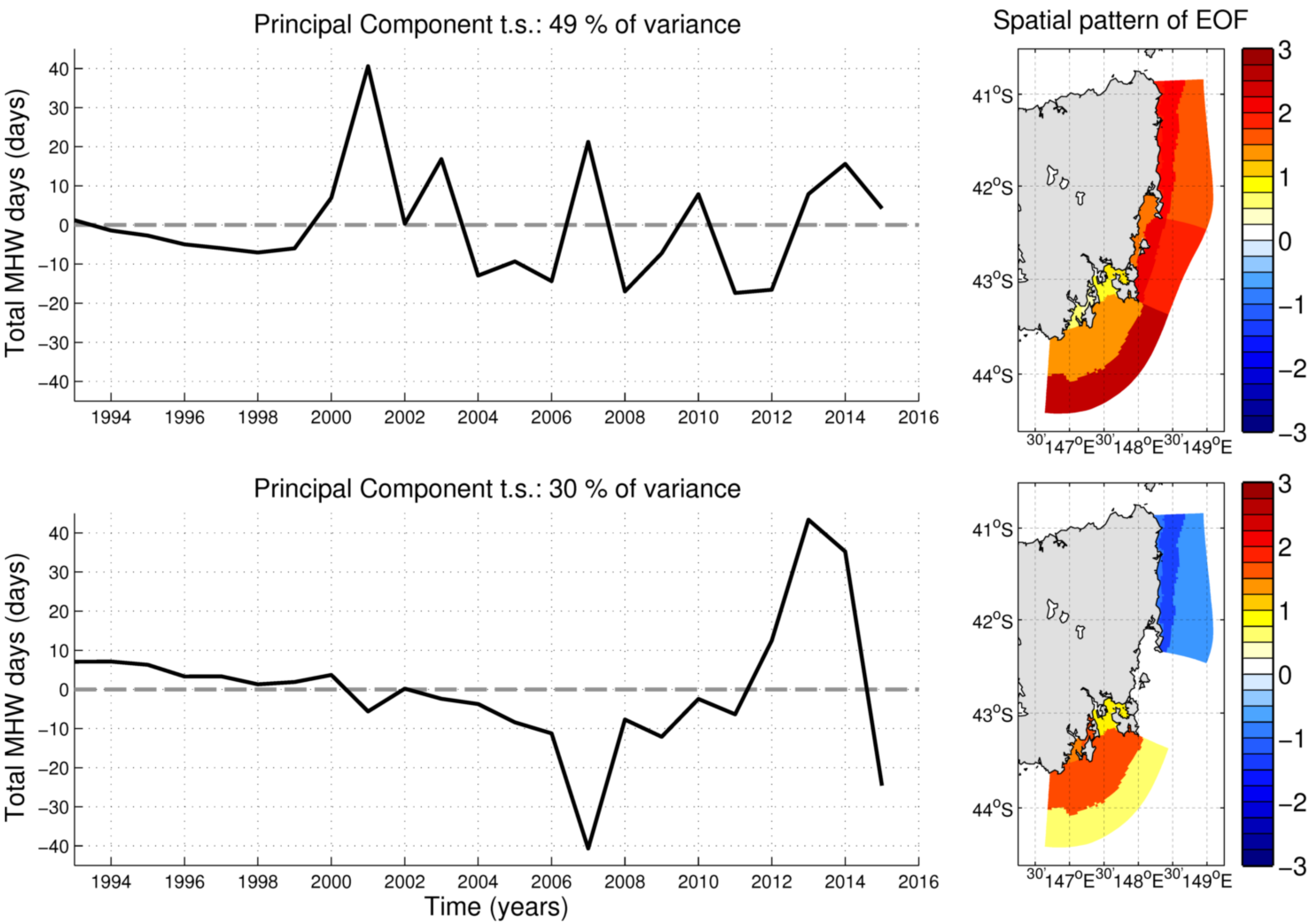
Annual Timeseries

- Annual time series of **Total MHW days** i.e. "the count of MHW days in each year"
- **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 most regions excl. SE nearshore
  - **Mode 2:** Lower frequency mode (~*decadal*) picks up 2004-2011 low and 2012-2014 high for nearshore southeastern Tasmania & opposite for northern regions



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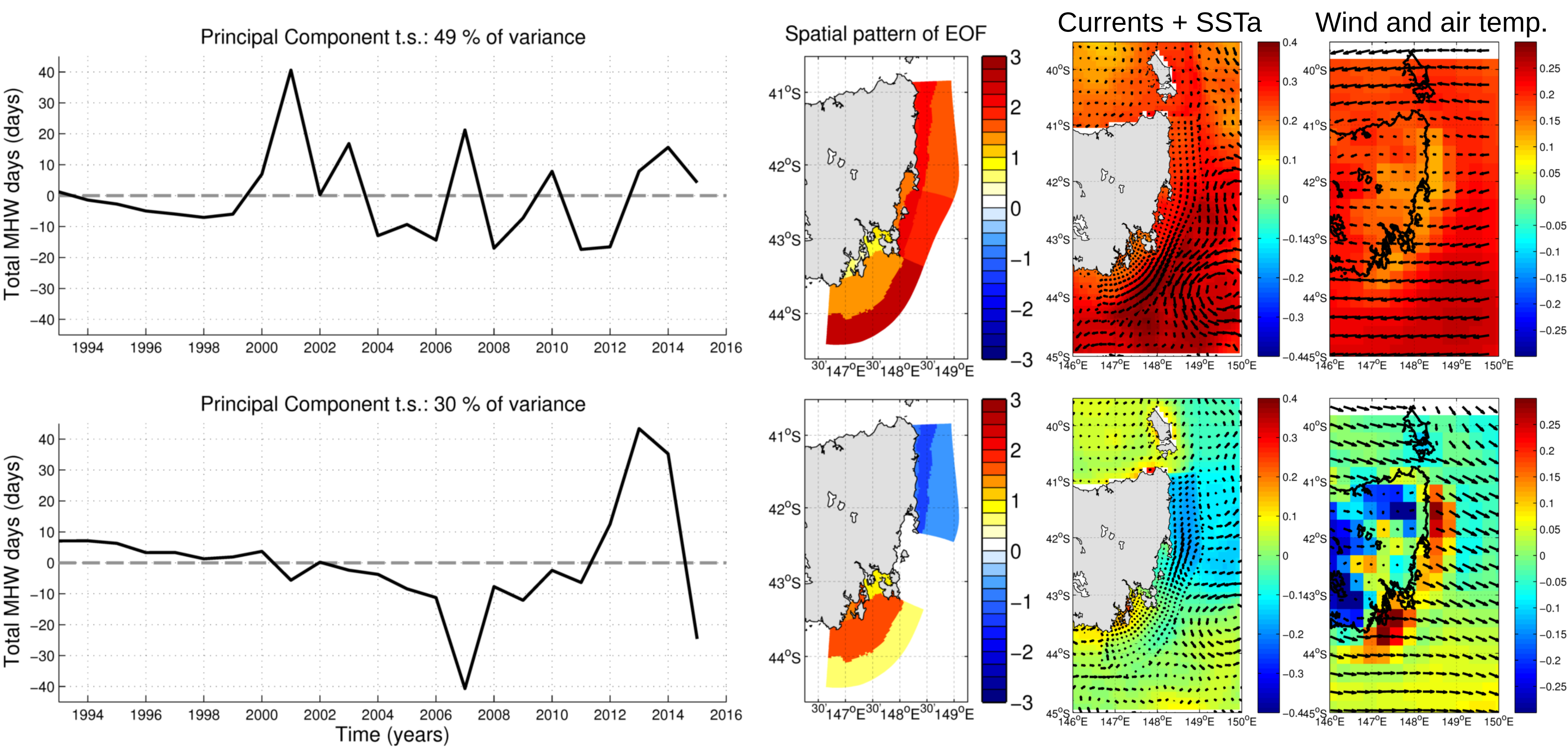
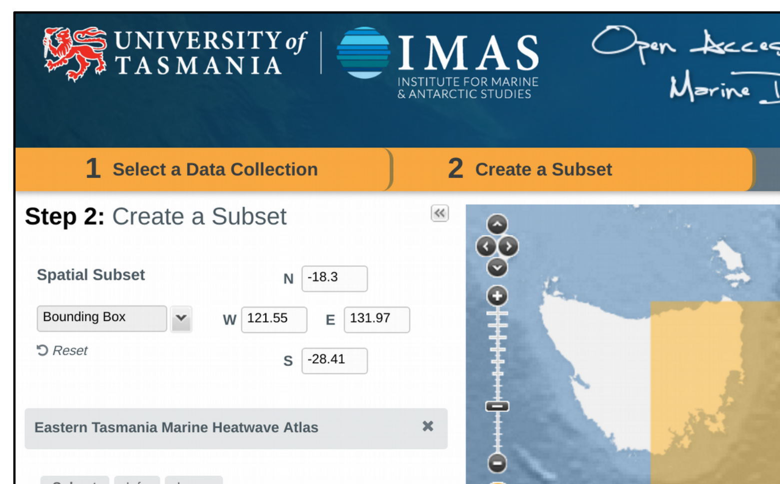


Summary

- **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, deeper but not more intense*
- **Modes of variability** indicate two modes with different time scales (interannual, decadal), with Mode 1 picking up the EAC signal
- Looking into Self **Organising Maps** to detect MHW "typologies"
- **Data**: IMAS Data Portal (data.imas.utas.edu.au):
  - "Eastern Tasmania Marine Heatwave Atlas"[1]
  - Complete 1993-2015 ETAS data files[2]

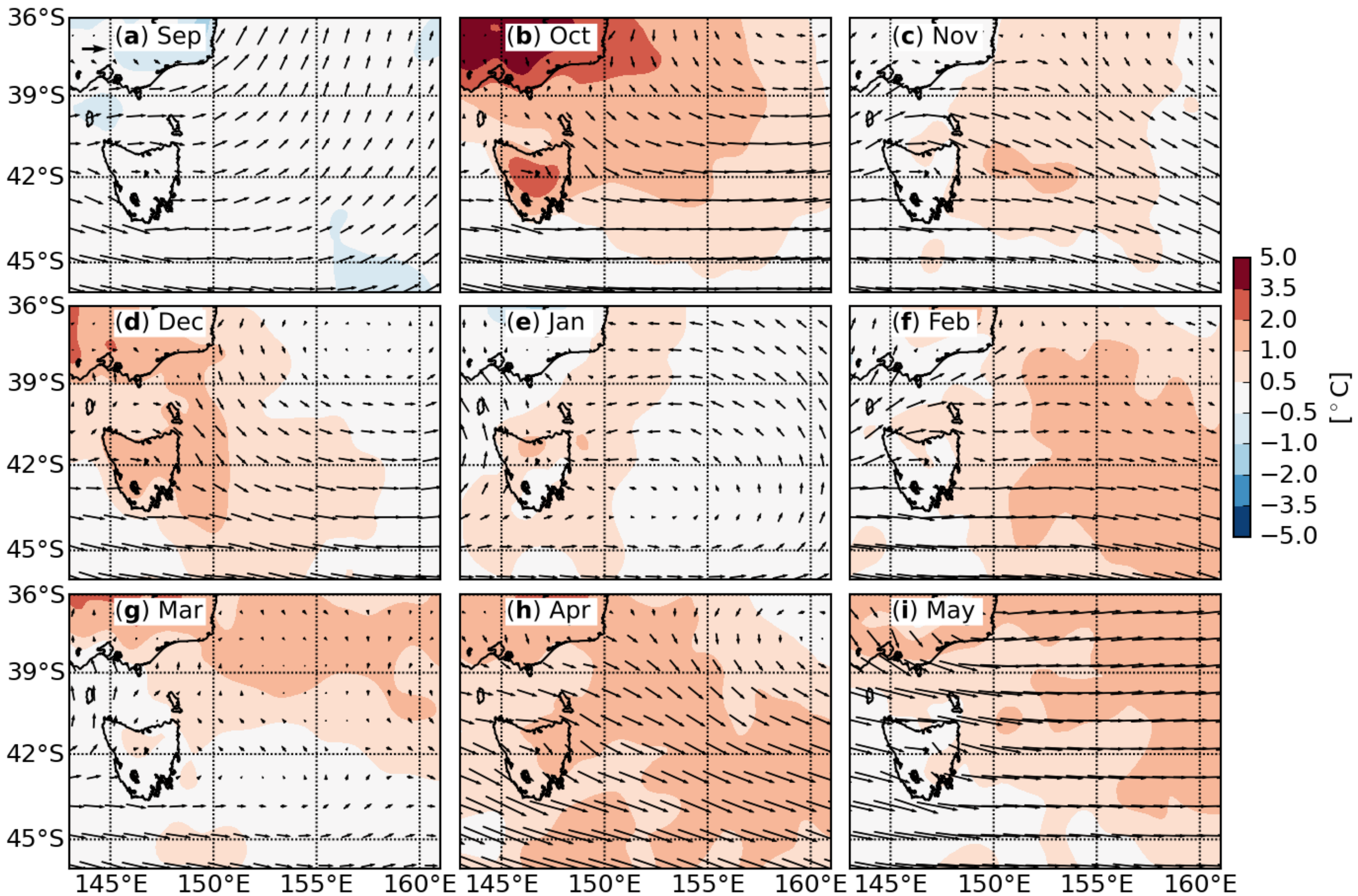


[1] http://data.imas.utas.edu.au/portal/search?uuid=20188863-0af6-4032-98f8-def671cdaa58
[2] http://thredds.imas.utas.edu.au/thredds/catalog/IMAS/catalog.html


Farewell Tassie
Dalhousie University
2017-?
IMAS/UTAS
2012-2017

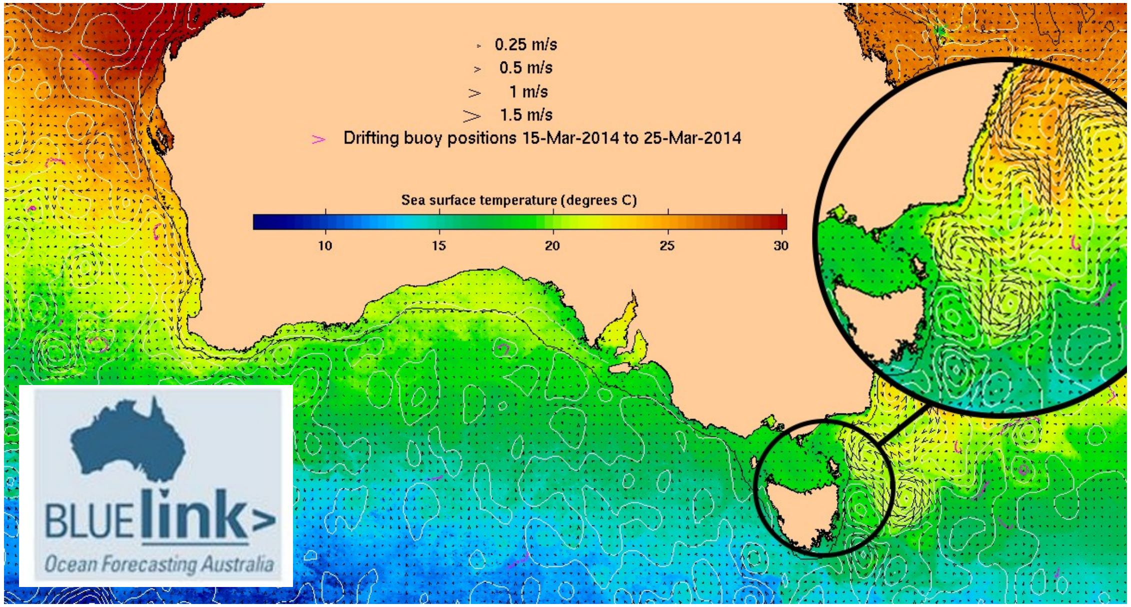
Evolution of the event

Monthly SAT and 10 m wind anomalies (NCEP CFSv2)

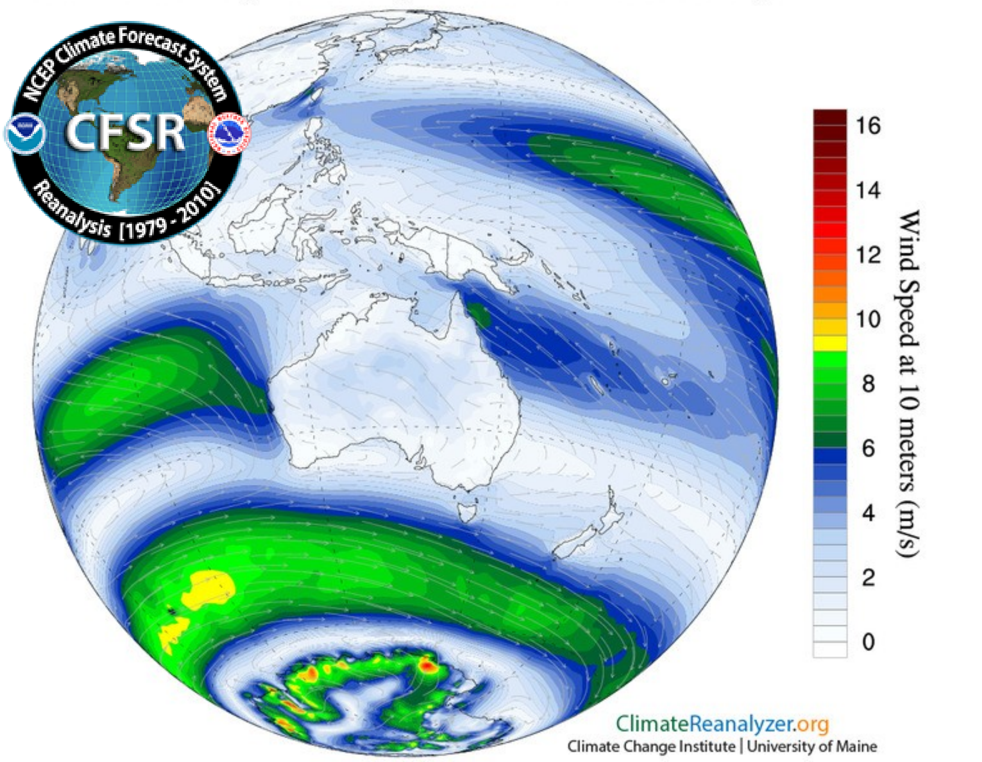


Forcing

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



Climate Forecast System Reanalysis Annual 1979-2013 Average



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

BRAN = Bluelink ReANalysis
OceanMAPS = Bluelink Ocean Modelling, Analysis, and Prediction System
CFSR = Climate Forecast System Reanalysis
CFSv2 = Climate Forecast System version 2 (operational forecast system)