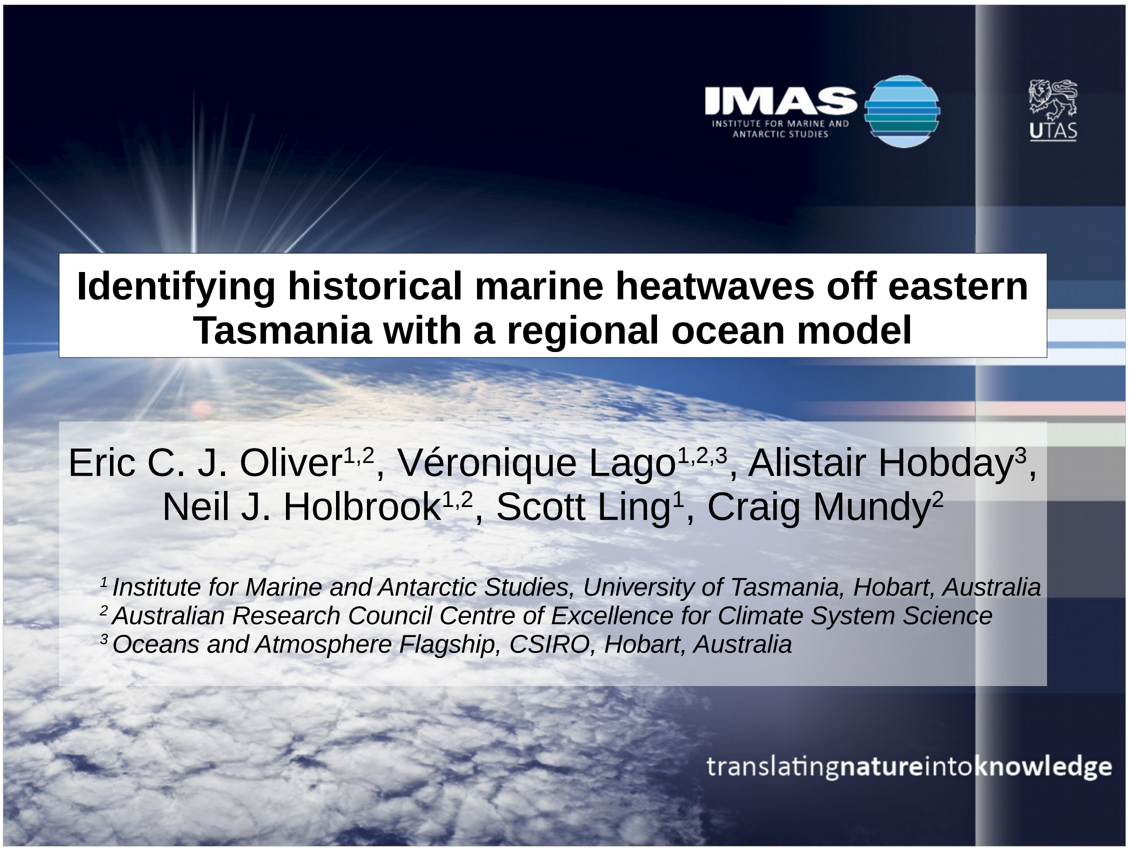


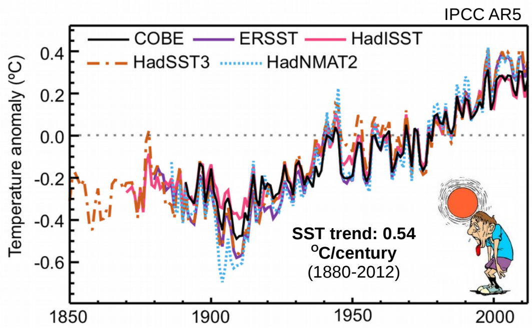
This work was funded by a UTAS Research Enhancement Granting Scheme and supported through the ARC Centre of Excellence for Climate System Science, the work was undertaken at IMAS/UTAS primarily in the first half of 2016.

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

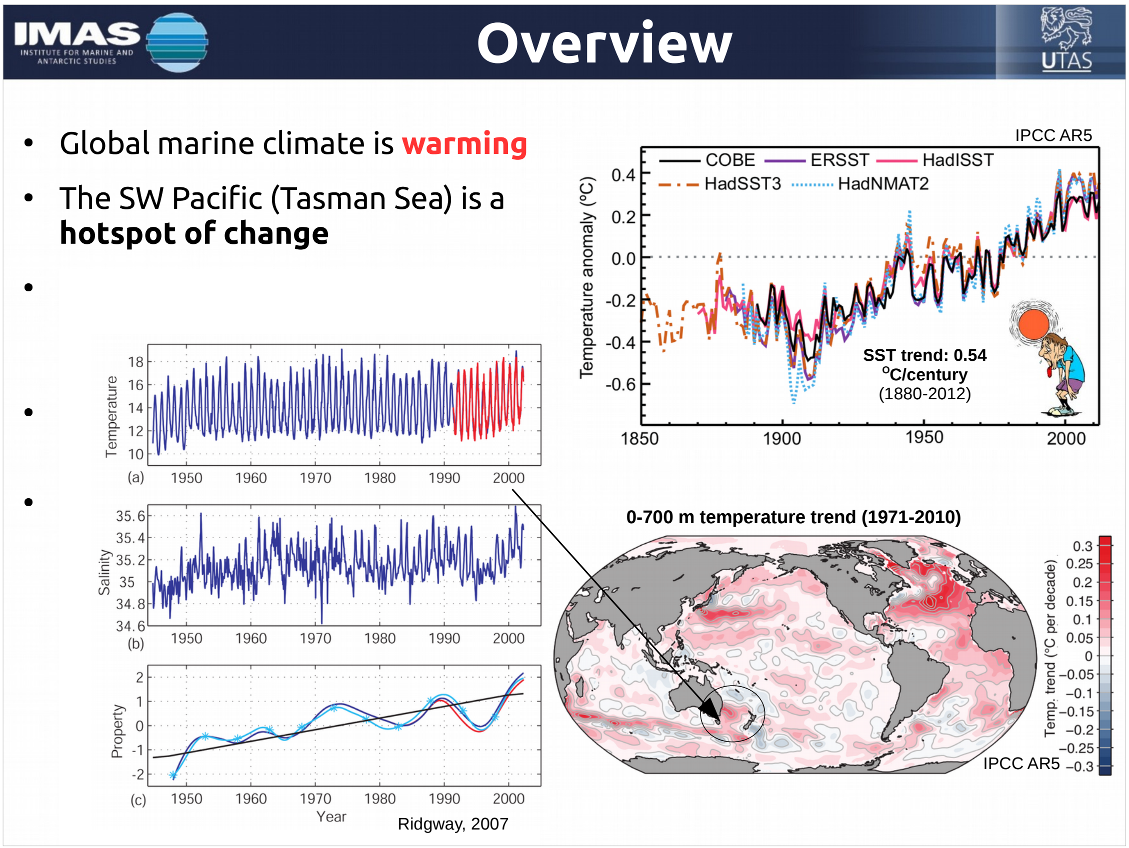
Eric was originally intending to present this talk but is not here because his little baby girl Coral decided to be born quite a bit earlier than expected, so he’s off work caring for the little one and her mom.

Overview

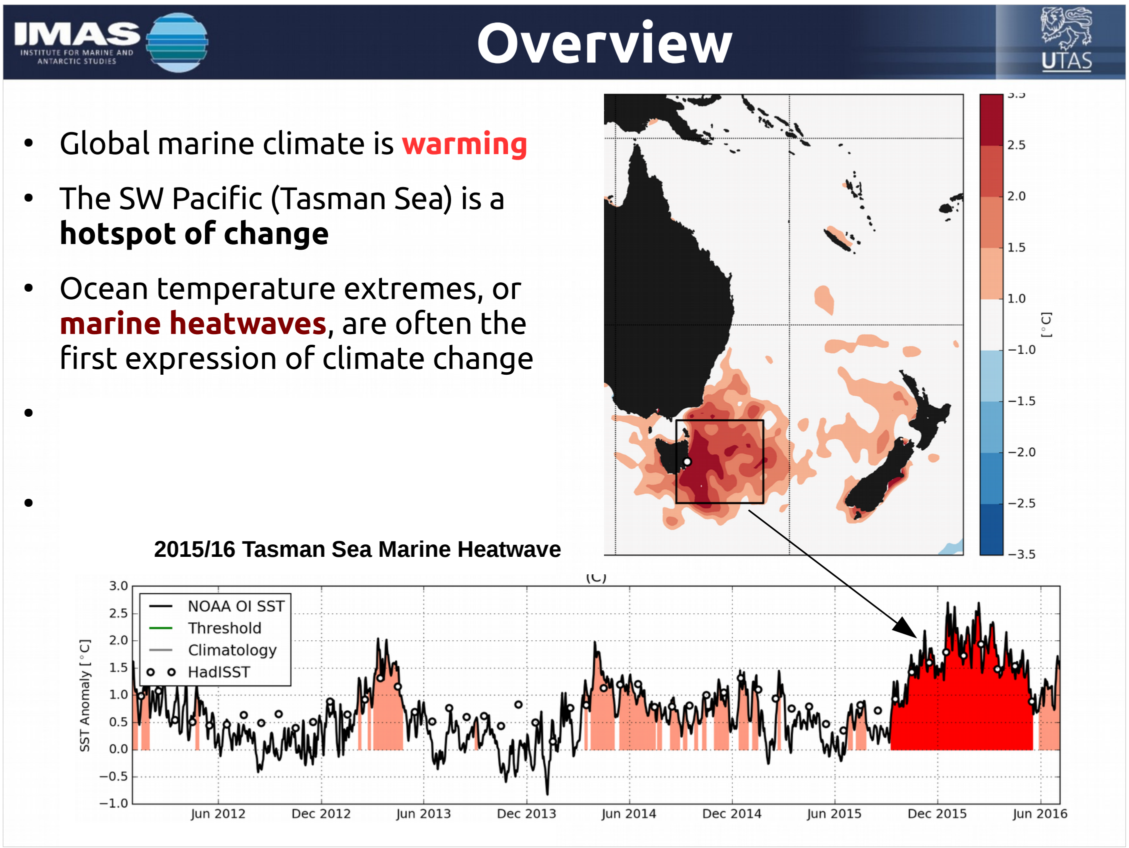
- Global marine climate is **warming**
- The SW Pacific (Tasman Sea) is a **hotspot of change**
- Ocean temperature extremes, or **marine heatwaves**, are often the first expression of climate change
- Impacts on **marine ecology** are already being felt
- Regional ocean modelling can help us understand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



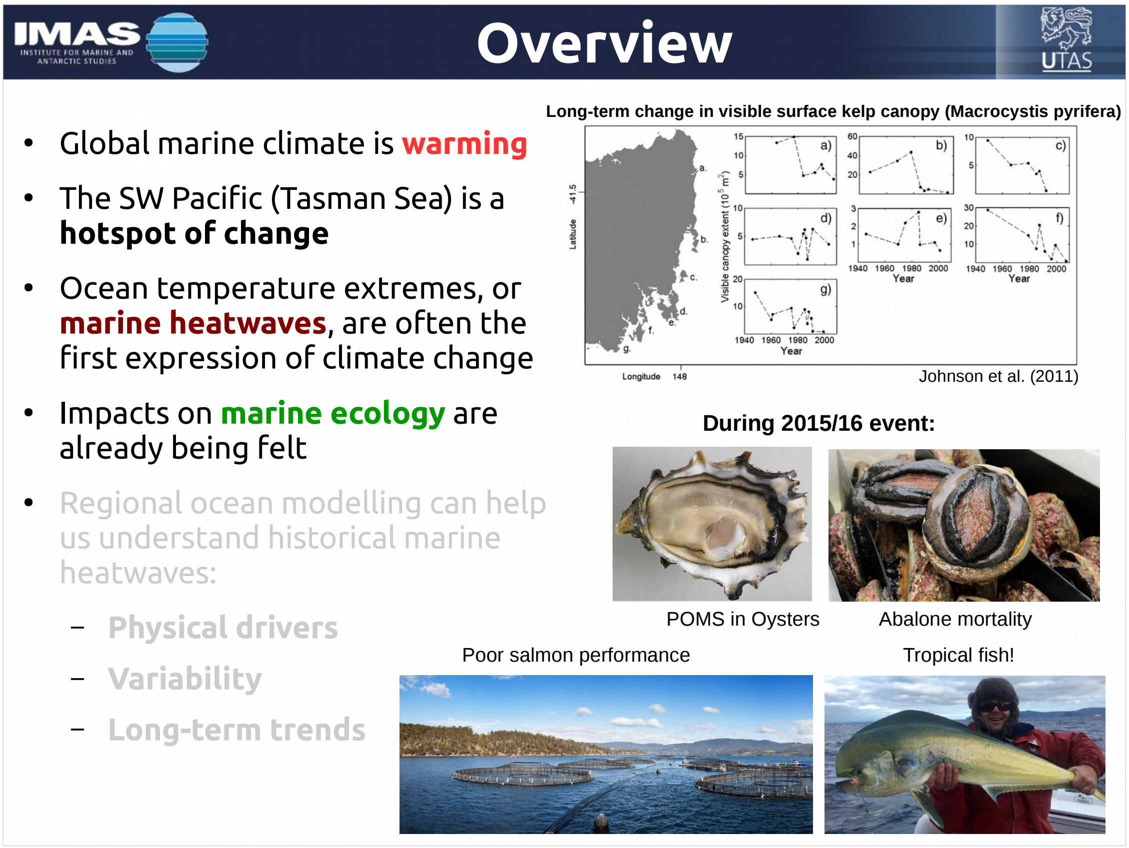
- Global marine climate is warming significantly
- Global SST increasing at a rate of 0.6°C/century, but this trend is non-homogeneous in space



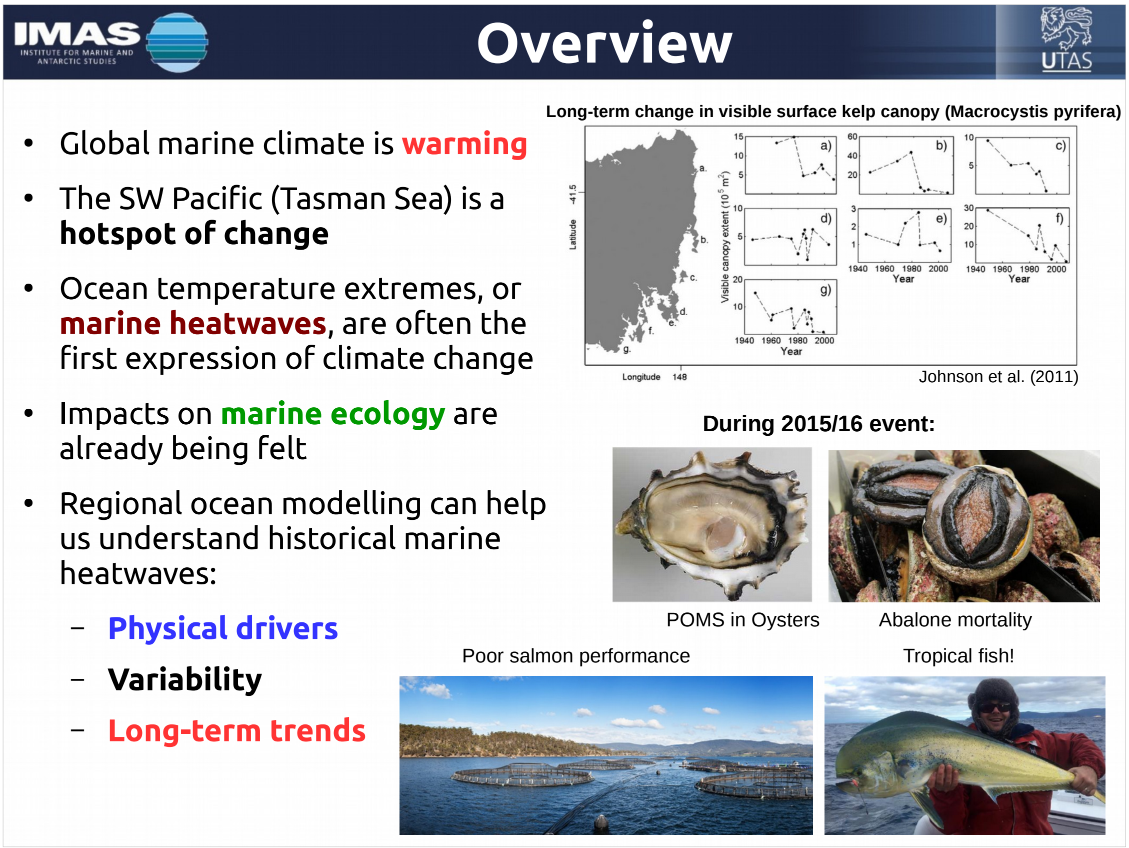
- The Southwest Pacific (Tasman Sea) is a hotspot of change including changes to upper ocean temperature, first shown by Holbrook and Bindoff (1997) and explored further by Ridgway (2007)
- The upper ocean heat in the Tasman Sea is increasing at nearly 4 times the global average rate! [Holbrook and Bindoff, 1997]
- Ridgway (2007) showed that locally, the influence East Australian Current appears to be increasing along the East coast of Tasmania bringing with it warm and salty (and nutrient-poor) water



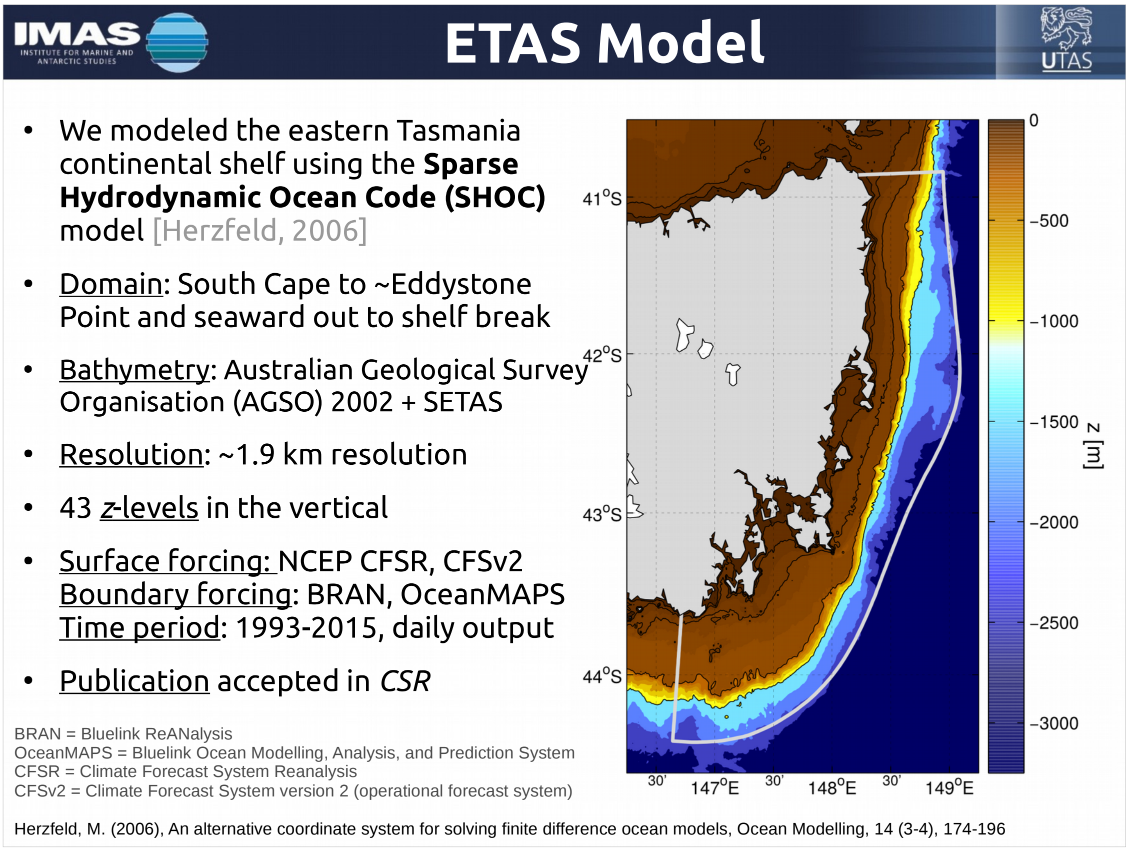
- The coupling of overall background warming with increases in southward flows due to the EAC Extension makes the Tasman Sea particularly at risk to marine climate change
- One of the first expressions of warming are temperature extremes, i.e., marine heatwaves
- One example is the massive Tasman Sea marine heatwave that occurred during the summer of 2015/16
- Temperature anomalies over 2^{O}C extended over a contiguous blob over 7 times the size of Tasmania and persisted for several months



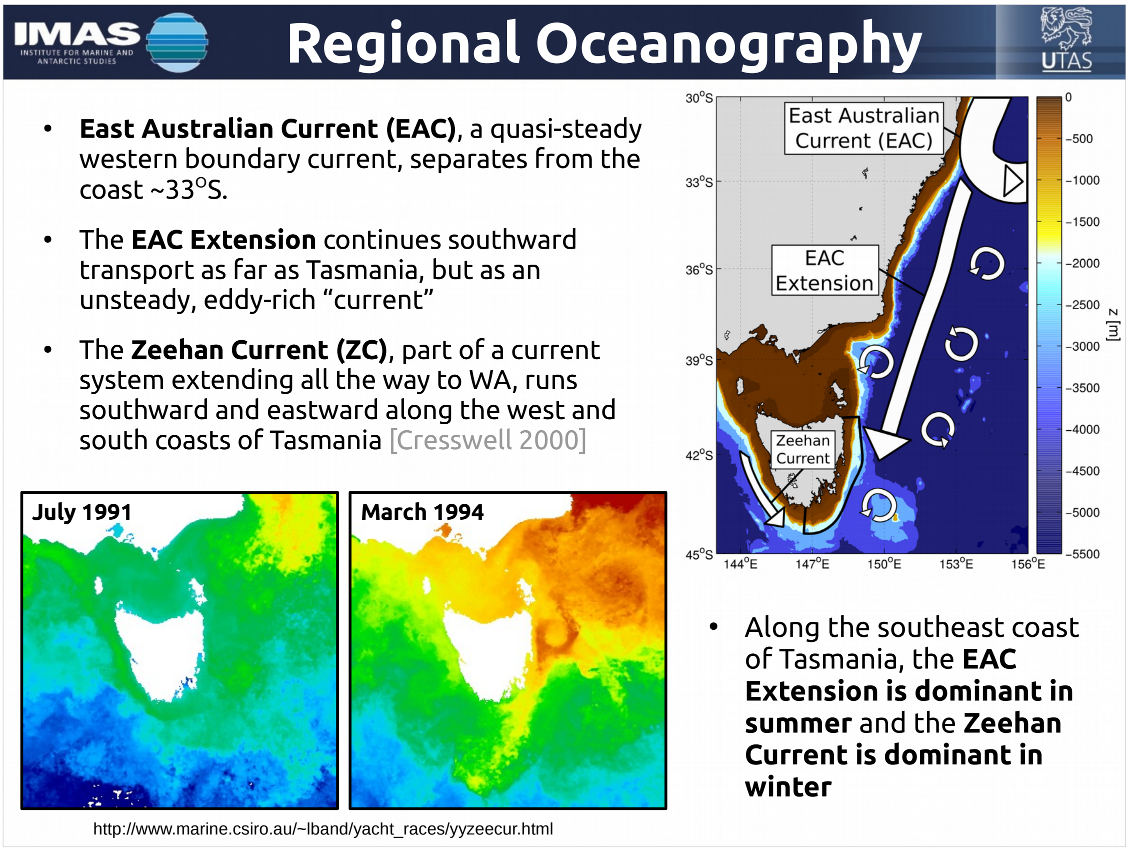
- Impacts on marine ecology due to warming are already being felt
- One long-term example includes the loss of kelp forests and increase of spiny sea urchins along the East coast of Tasmania e.g. work by IMAS's Craig Johnson and Scott Ling
- For example, Johnson et al. (2011) documented shifts in species ranges off eastern Tasmania and linked it to shifts in the regional oceanography.
- During the 2015/16 Tasman Sea MHW there were a number of impacts including Pacific Oyster Mortality Syndrome (POMS), mortality in abalone, poor salmon aquaculture performance, and intrusions of rarely seen tropical fish
- Extreme events can lead to "ratchet-like" ecosystem change events, where the event pushes the system over a "tipping point"



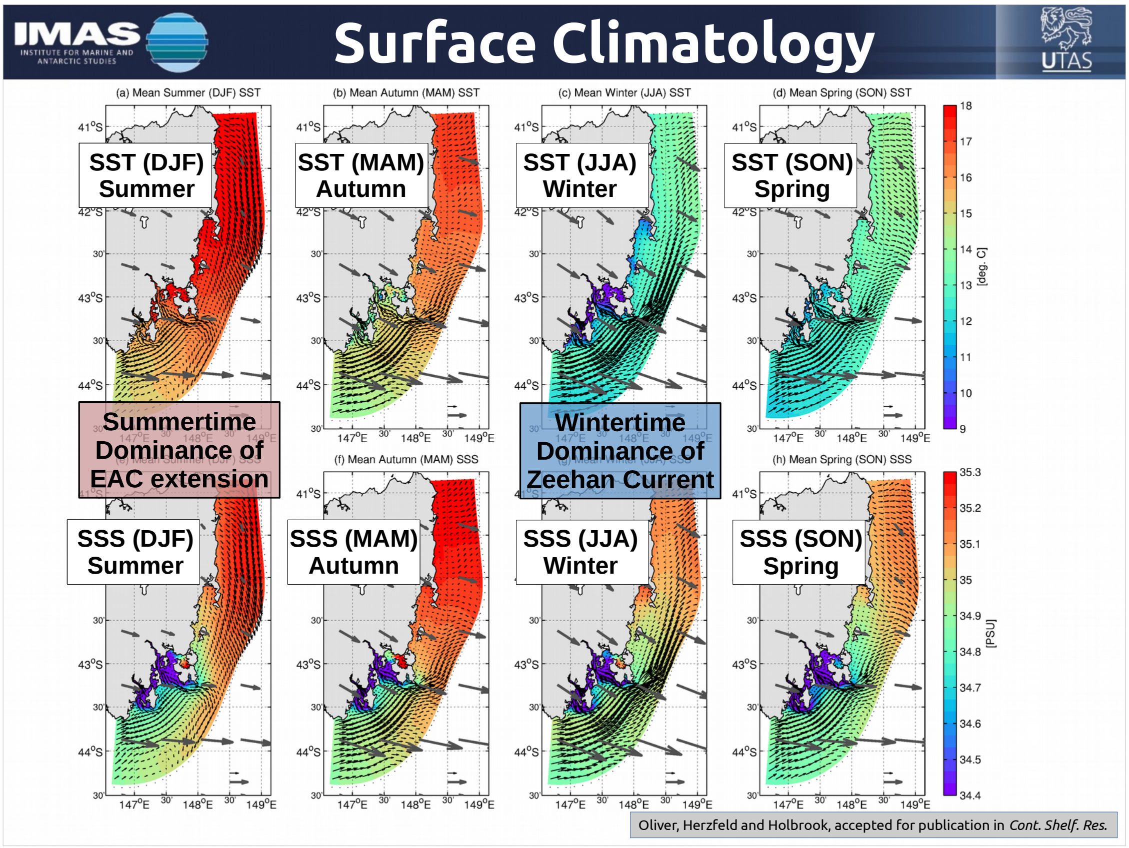
- Therefore there is a need to understand the marine heatwaves off eastern Tasmania in the historical record
- i.e.
  - What are their physical drivers?
  - What sort of year-to-year variability is there?
  - Are there any long-term trends (climate change)?
- Given the limited observations available over the shelf, we turn to numerical ocean modelling to aid us in answering the above questions



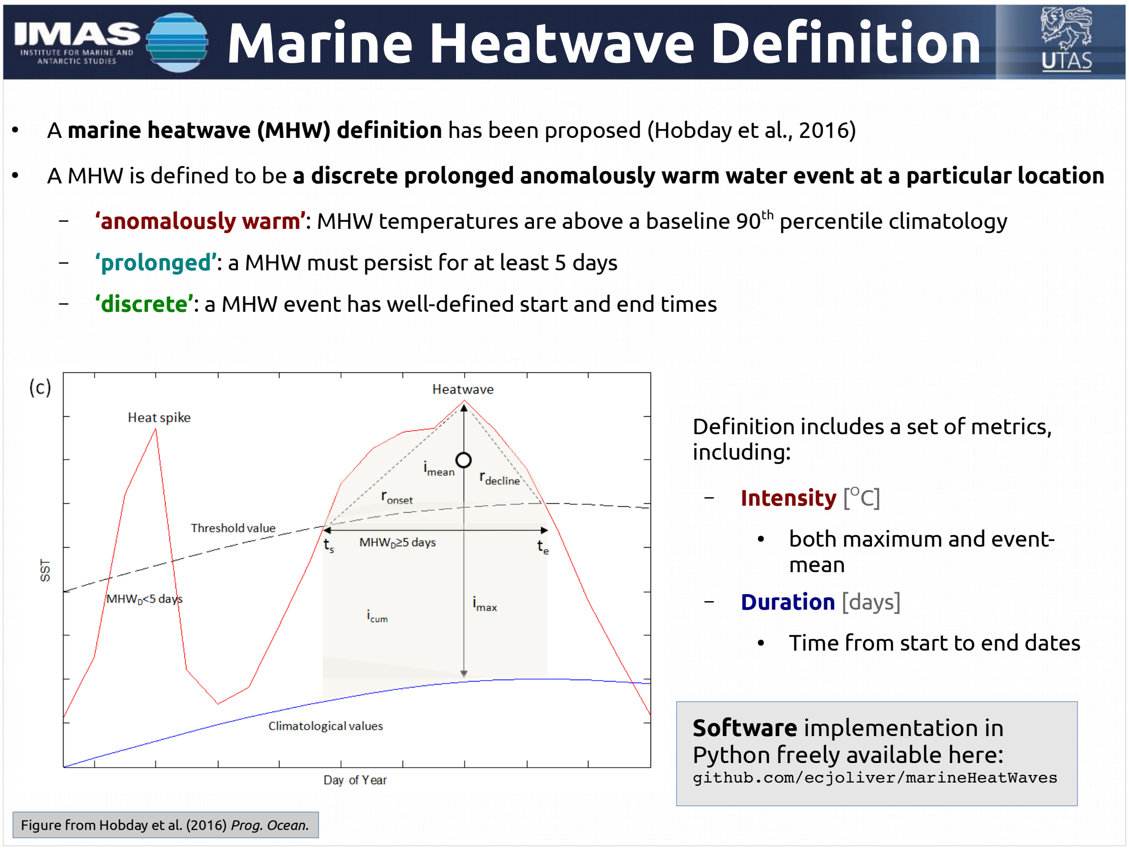
- We model the eastern Tasmania continental shelf using the **Sparse Hydrodynamic Ocean Code (SHOC)** [Herzfeld, 2006], a numerical ocean model well-suited to complex curvilinear grids with a large proportion of “dry cells”. The model is called **ETAS** and a publication has been accepted in Contintental Shelf Research
- Domain: South Cape in the south to approx. Eddystone Point in the northeast and seaward out to just off the shelf break (~2500 m)
- Bathymetry: Australian Geological Survey Organistaion (AGSO) 2002 (0.01^{O}x0.01^{O}), augmented by SETAS bathymetry in southern portion
- Resolution: 200 x 120 grid cells, ~1.9 km resolution
- 43 *z*-levels in the vertical
- Boundary forcing includes NCEP Climate Forecast System (CFS) Reanalysis and Version 2 at the surface, and Blulink Reanalysis and OceanMAPS at the lateral boundaries.
- Model provides daily output over 1993-2015
- Note: model has been run with rivers, without tidal forcing



- Just as a refresher here is the seasonal circulation off southeastern Australia
- The quasi-steady East Australian Current (EAC) flows south along the coast of Australia bringing warm and salty water down from the north.
- The EAC tends to separate from the coast around 33^{O}S and south of that it there is a continuation of it known as the EAC Extension, which is unsteady and rich in mesoscale eddies.
- The Zeehan Current (ZC) is the termination of a series of currents along southern and western Australia and flows along the western, southern and southeastern coasts of Tasmania.
- Both the EAC Extension and ZC influence eastern Tasmania, with the EAC Extension being dominant in summer and the ZC dominant in winter



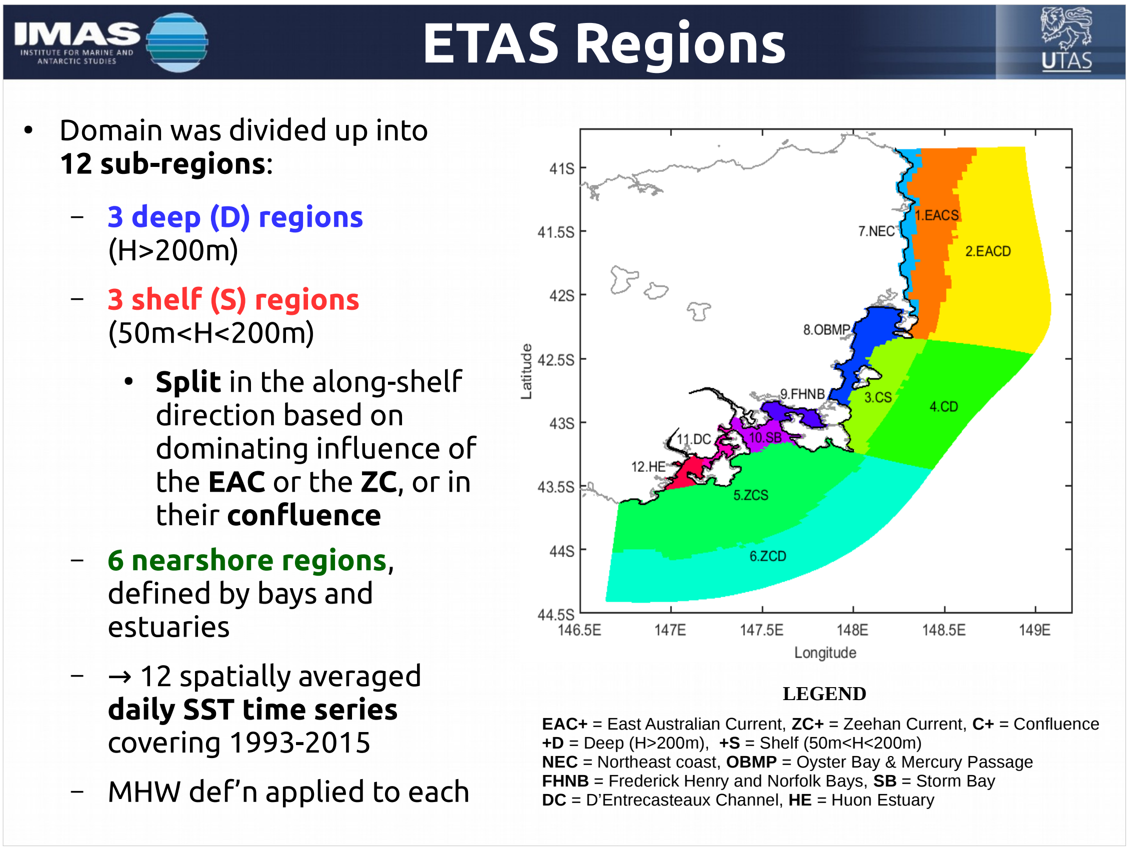
- The surface climatology of ETAS reflects this seasonal circulation
- Summer (DJF) show the dominance of the southward EAC Extension over the northern 2/3 of the domain
- Winter (JJA) shows the dominance of the northward ZC over nearly the entire domain
- Autumn (MAM) and Spring (SON) are seasons of transition between the dominance of the two currents



Here we use the Hobday et al. (2016) MHW definition whereby a MHW is defined relative to a baseline climatology. A period of 30 years is recommended but we only have 23 years so we use the full period to define the climatology (blue line). The climatology seasonally varying, using all data within an 11-day window centred on the day of year from which the climatological mean and threshold are calculated. A MHW is defined as when SST (red line) exceeds the 90th percentile threshold (also seasonally varying, dashed line) for at least 5 days. A percentile threshold is used rather than an absolute value above the climatological value as the magnitude of variability across a range of timescales varies considerably by region.

Once events are defined they can then be characterised using a hierarchy of metrics including

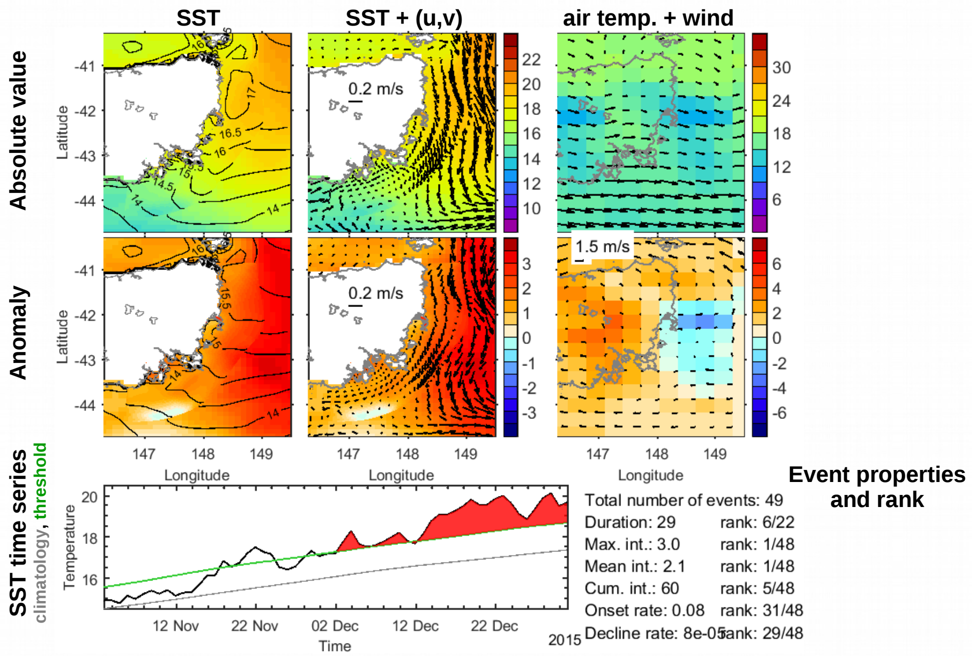
- Duration, which is the time from the start date to the end date of the event (days)
- Intensity (max or mean), which is the average SST anomaly over the duration of the event (deg. C). Referenced relative to the climatological mean.
- Frequency, which is the count of events in a year



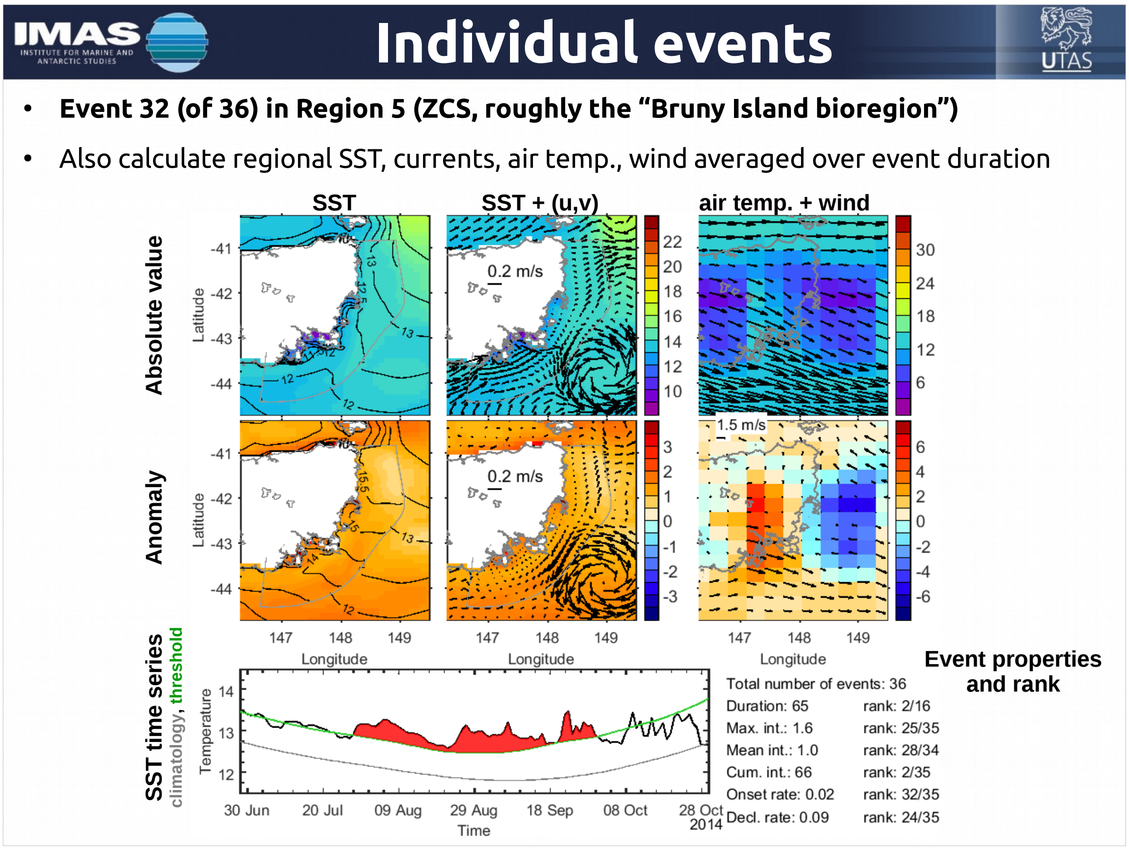
- The domain defined by the ETAS model has been divided into 12 regions. Boundaries between regions were defined by bathymetry, geography, and oceanography. Waters deeper than 200 m were termed ``deep (D)", those between approximately 50 m and 200 m were termed ``shelf (S)", and those in shallower water had more descriptive names derived from local geography. The ``shelf" and ``deep" zones were dominated by either the East Australia Current (EAC) in the north, the Zeehan Current (ZC) in the southwest, or their confluence (C) in between. These zones were thus divided into six regions according to if they were EAC-dominated, ZC-dominated, or in the confluence and were either deep (D) or shelf (S), and named accordingly: EACD, EACS, CD, CS, ZCD, ZCS. The coastal zone is divided into six regions defined by their geography with appropriate names: north-east coast (NEC), Oyster Bay-Mercury Passage (OBMP), Frederick Henry and Norfolk Bays (FHNB), Storm Bay (SB), D'Entrecasteaux Channel (DC) and Huon Estuary (HE). The rivers and upper reaches of the Derwent and Huon estuaries were excluded from the 12 defined regions.
- SST from ETAS was spatially averaged in each of these regions to generate a set 12 regional daily SST time series covering 1993-2015
- The marine heatwave definition was then applied to each SST time series to detect all the events for each region

Individual events

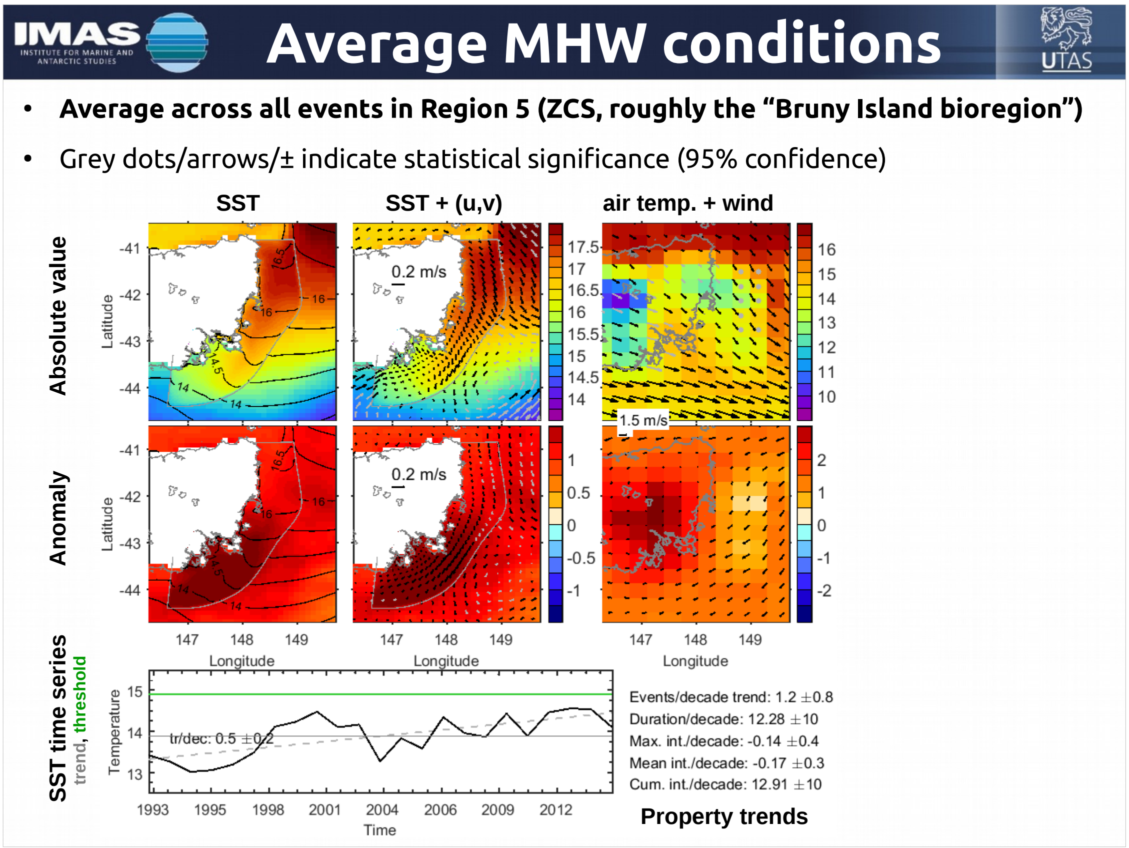
- **Event 49 (of 49) in Region 2 (EACD, region with strongest EAC influence)**
- Also calculate regional SST, currents, air temp., wind averaged over event duration



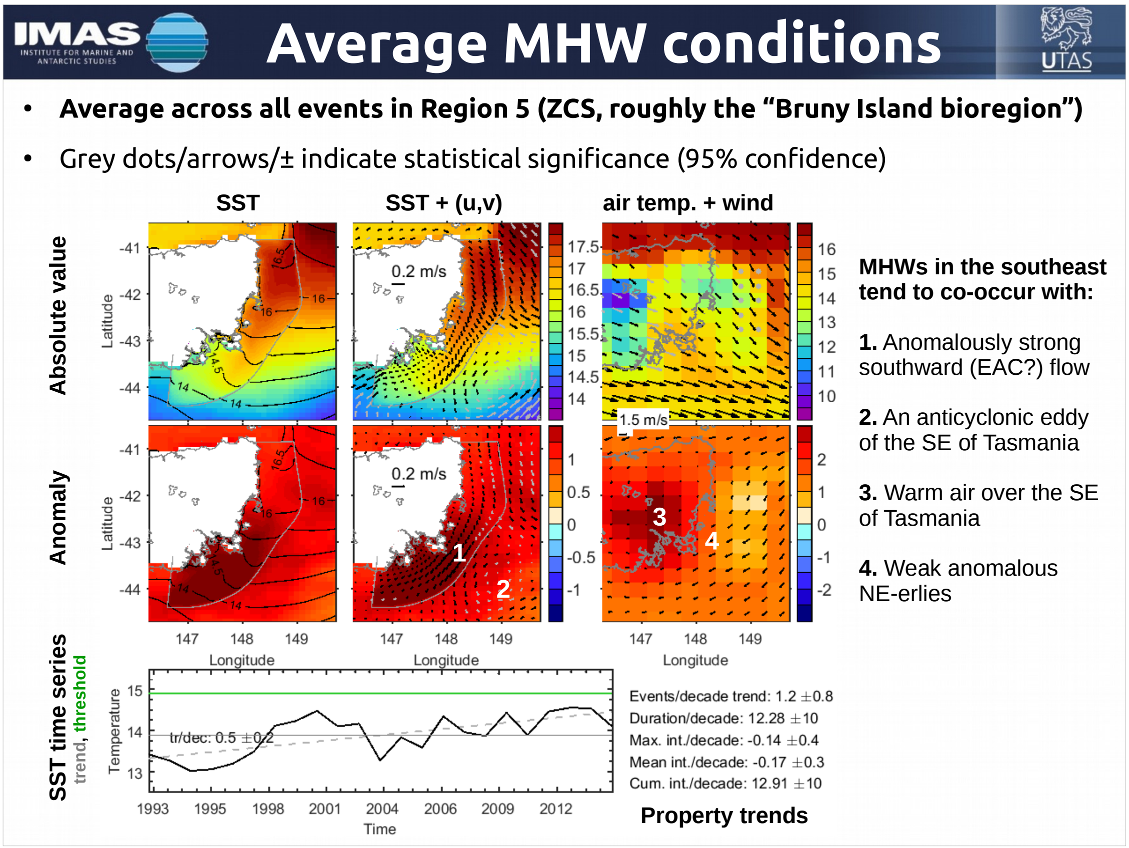
- This is an example of the marine heatwave information available for each event in each region. This example is event #49 from Region 2 (of a total of 49 events). Region 2 is the "EAC Deep" region, so the region most influenced by the EAC
- The bottom panel shows the time series of SST with the event highlighted in red above the threshold (green line). This event was in fact the 2015/16 Tasman Sea MHW. In this case the event lasted up to the end of the record (31 Dec 2015) and so for ETAS it "ends" then, but we know it continued well into 2016 but we have no model data for that period.
- Next to the time series are the event properties including their rank out of all events. This event lasted 20 days with a maximum intensity of 3^{O}C and a mean intensity of 2.1^{O}C.
- The six panels above show the SST, surface currents, air temperature and surface winds averaged over the duration of the event, both as their absolute values (top row) and their anomalies relative to seasonal climatology (middle row). For the ocean variables we used ETAS inside the domain and BRAN outside the domain.
- We can see the northeastern portion of the ETAS domain (roughly the location of the EACD region) was anomalously warm at this time. This warming also co-occurred with strong southward EAC flow and also a dipole of air temperature anomalies between land and sea.



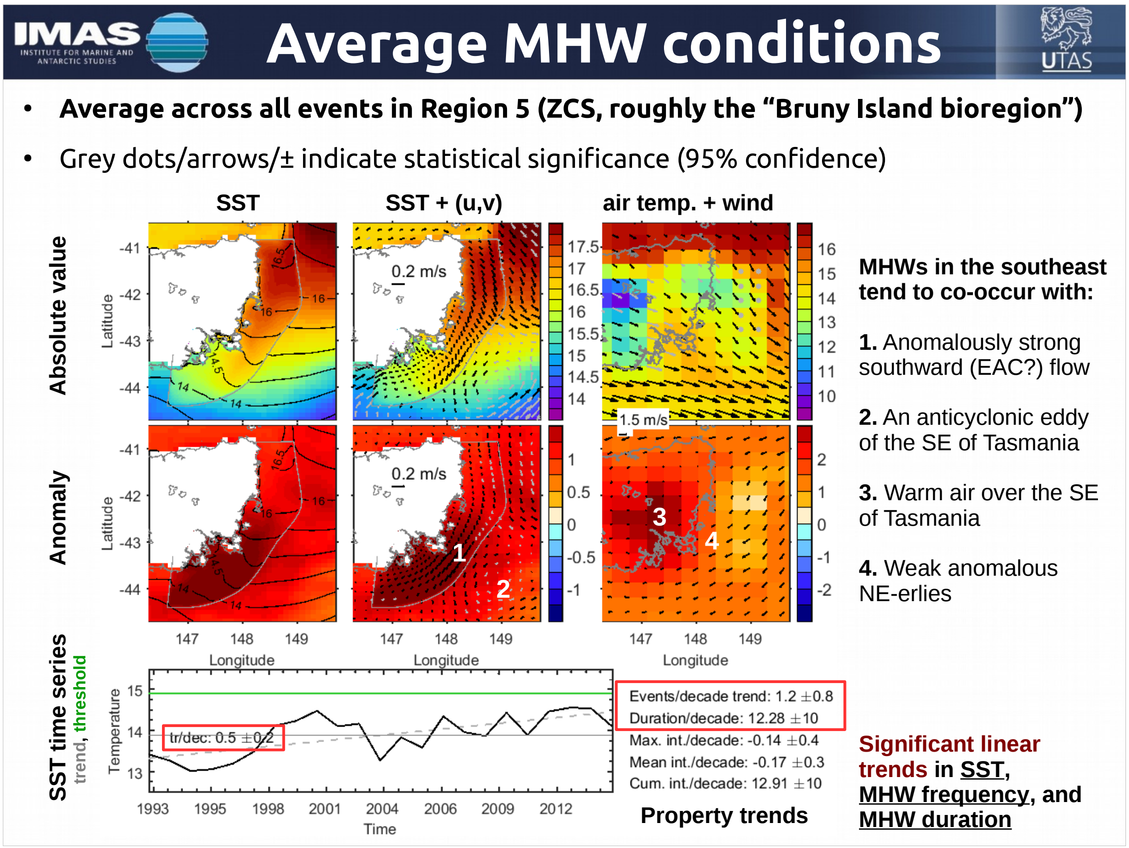
- This next example is event #32 from Region 5 (of a total of 36 events). Region 5 is the "ZC Shelf" region, which is roughly coterminous with the Bruny Island bioregion.
- In the lower panel we we can see that this event actually occurred in the winter of 2014, showing us how the MHW definition can be used to detect not only summer heatwaves but also winter warm spells.
- This event lasted a whopping 65 days with a maximum intensity of 1.6^{O}C and a mean intensity of 1^{O}C. So it was a long, low-intensity winter event – effectively a relatively warm winter.
- The warming was not restricted to the ZCS region but in fact extended over most of the ETAS domain. Interestingly, during the event there was an anticyclonic eddy sitting of southeastern Tasmania. This eddy impinged onto the shelf and cause anomalies southward flow (and likely temperature advection) over the southeastern portion of the shelf.
- Again, we see a dipole of air temperature anomalies between land and sea. This is seems to be a common occurrence during MHWs but we have yet to understand how, why and even if it might drive the occurrence of MWHs.



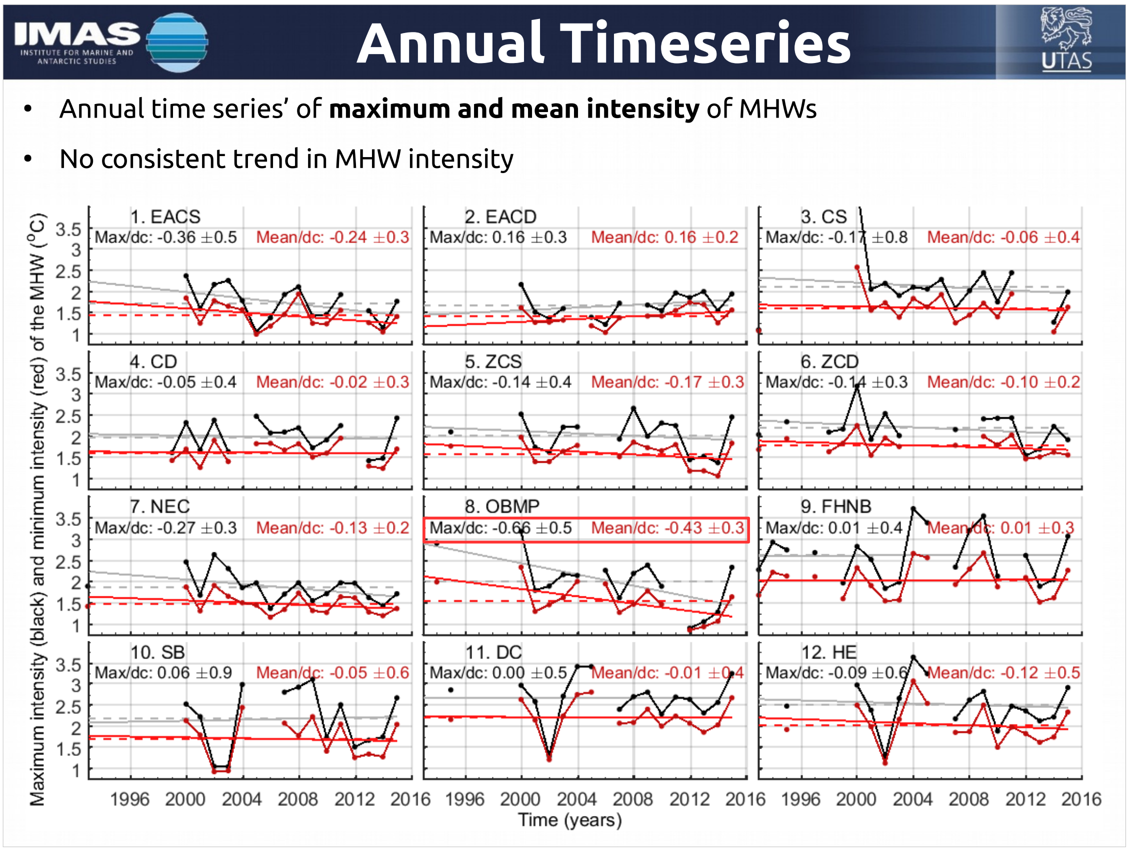
- We have also averaged the ocean and atmosphere conditions across all events in each region. This allows us to see if there are any conditions that are consistent across many events, leading us to make generalisation about possible MHW drivers. Here we see the average conditions for the ZCS region in the southeast.
- Statistical significance of the all-event average was calculated using a 2-sample t-test, and regions of non-significance are indicated by grey dots/arrows.



- Clearly the southeast is anomalously warm across all events.
- However, we can also see a number of other features
  1) There is anomalous southward flow along the shelf, possibly indicating a role of the EAC Extension
  2) There is an anticyclonic eddy sitting off the southeast, however much of it is not statistically significant indicating that it likely does not play a role in the occurrence of all events
  3) and 4) We also see in the atmosphere anomalously warm air over Tasmania and anomalous (but weak) northeasterly winds.



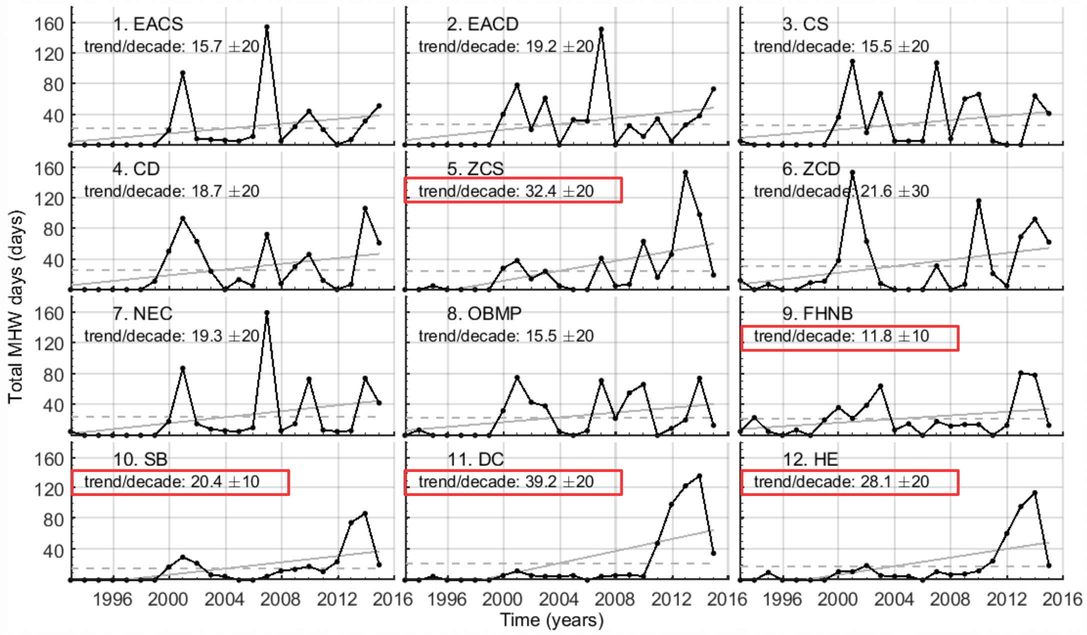
- We can also look at the annual time series of all-event means, and see how each MHW property varies with time including trends.
- In this case there is a statistically significant linear increase in SST as well as the frequency and duration of events.



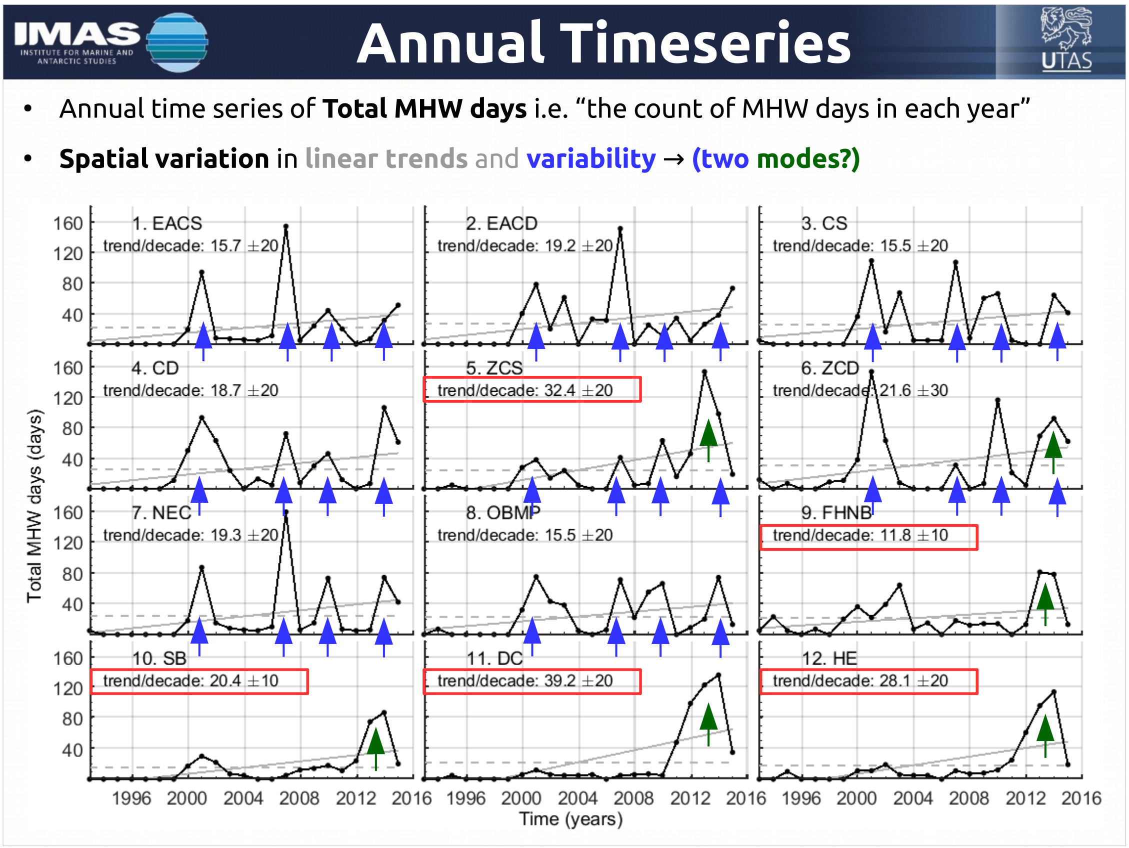
- Here we see the annual time series of MHW intensity, including linear trends, for all 12 regions. While there is a lot of interannual variability we see no significant trends in intensity (except a decrease in Oyster Bay-Mercury Passage, OBMP).
- This lack of increase in intensity is surprising considering the long-term warming we know is occurring here.

Annual Timeseries

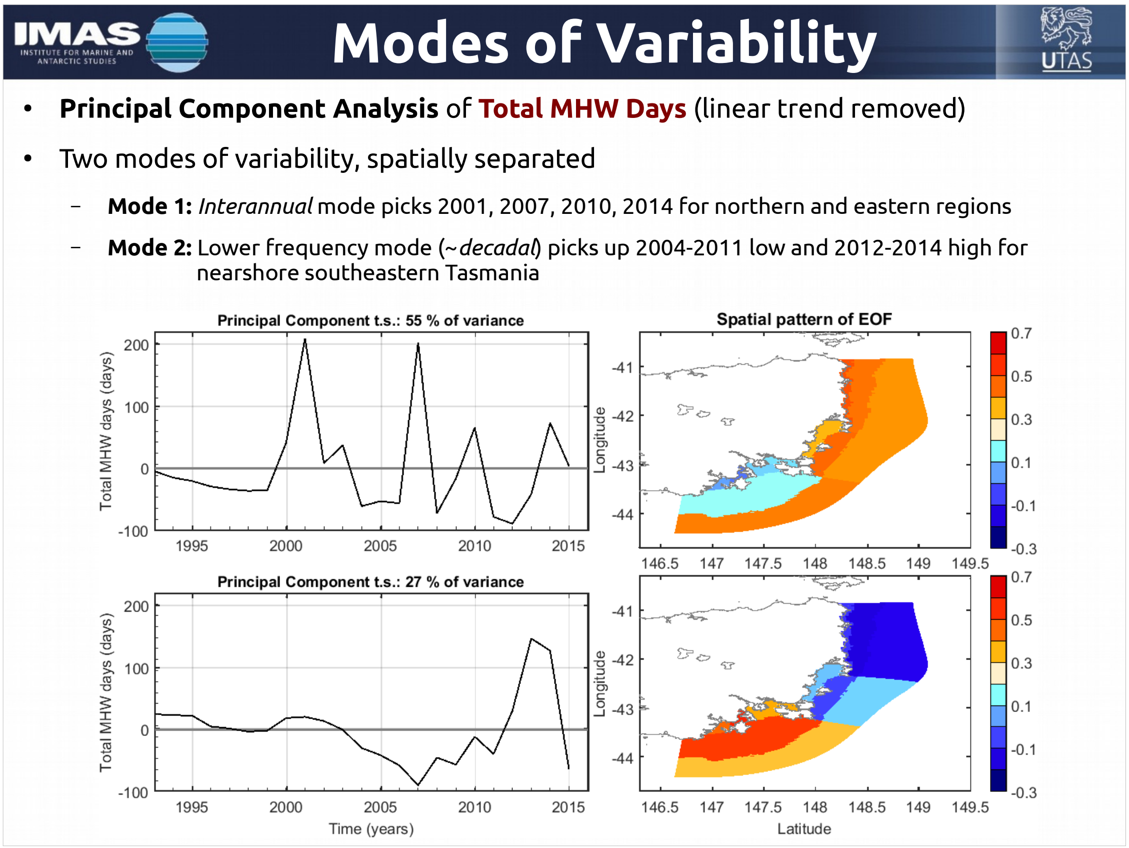
- Annual time series of **Total MHW days** i.e. "the count of MHW days in each year"
- **Spatial variation** in **linear trends**



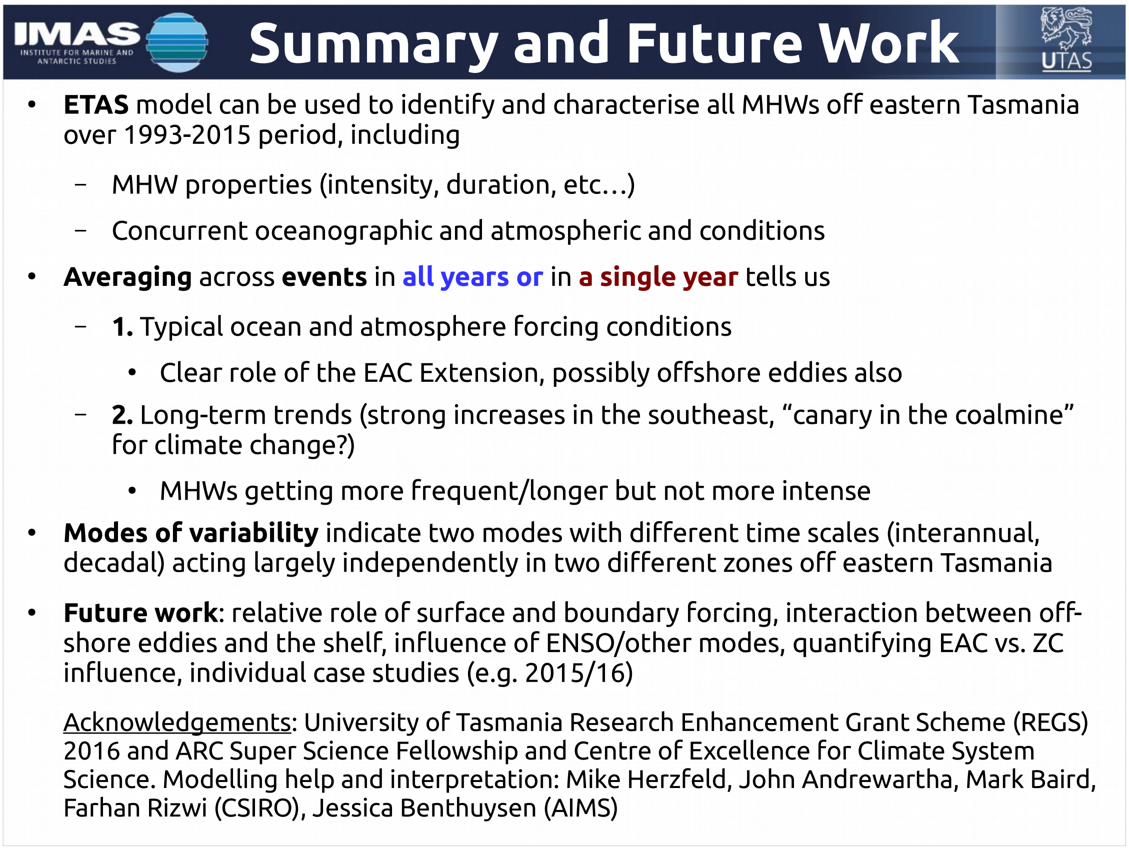
- However if we look at other metrics we can see evidence of long term changes
- Here we are plotting the "Total MHW days" which is the count of MHW days in each year. Equivalently it is the sum of the duration of all events in a year and is a good measure of the total time spent per year in extremely warm conditions.
- We see significant linear increases in the southeast regions including ZCS and nearby nearshore regions including Storm Bay (SB), Frederick Henry and Norfolk Bays (FHNB), D'Entrecasteaux Channel (DC), and the Huon Estuary (HE).
- We see positive but not statistically significant trends in the central or northern regions.



- There is also significant year-to-year variation. In addition, this variability is not identical across all stations. By eye we can see variability shared across the central and northern regions (blue arrows) and variability shared across the southern regions (green arrows).
- Is this an indication of two separate modes of variability?



- To test this we performed a Principal Component Analysis (AKA an EOF Analysis) on these 12 time series of total MHW days.
- First the linear trend was removed, since we are interested in the variability about the long-term change.
- The analysis indicated that the first two modes account for a significant portion of the variability and they explain the two patterns seen previously in the time series themselves
- The first mode explains 55% of the variability, and is mostly loaded to the central and northern regions (also the offshore region in the southeast). This mode is interannual in variability and picks up the peak years of 2001, 2007, 2010, 2014
- The second mode explain 27% of the variability, and is mostly loaded to the southeastern regions. This mode is approximately decadal in variability and picks up the low years of 2004-2011 and the high years of 2012-2014



- In conclusion, the ETAS model can be used to identify and characterise all MHWs off eastern Tasmania over 1993-2015 period. This has allowed us catalogue the properties of all events in 12 sub-regions of the shelf and their concurrent oceanographic and atmospheric and conditions.
- Further, by averaging across events in all years we can examine what the typical ocean and atmosphere forcing conditions are. We see clear roles of the EAC Extension and possibly offshore eddies also, which has implications for the predictability of these MHWs.
- Averaging across individual years allows us to examine long-term trends, indicating strong increases in the southeast. Is the “canary in the coal-mine” for climate change? Since this region is on the fore-front of an EAC Extension edging further south? In addition, MHWs appear to be getting more frequent and longer but not more intense, at odds with our intuition regarding climate change.
- The annual time series has allowed us to identify modes of variability, indicating two modes with different time scales (interannual, decadal) acting largely independently in two different zones off eastern Tasmania.
- Future work includes examining the relative role of surface and boundary forcing, the interaction between off-shore eddies and the shelf, influence of ENSO/other modes, quantifying EAC vs. ZC influence, and individual case studies (e.g. 2015/16 MHW)