Numerical Modelling of Thermodynamic Drivers in a Coral Reef Atoll

Introduction

- Coral reefs support more than 25% of all marine life, however current future temperature projections indicate a likely 90% decrease in live coral on reefs by 2050.
- Temperature variability occurs at smaller scales than most datasets provide, and most current management tools rely on low-resolution remote sensing, failing to capture local processes.
- There is a need to understand fine-scale processes on reefs under future temperature conditions
- The present study aimed to:
  1. Assess relative roles of different forcing (e.g. tides, waves) in controlling reef-scale temperatures;
  2. Characterize the spatial and temporal patterns of temperature variability; and,
  3. Investigate how temperature varies under past and future marine heatwave conditions.

Fig. 1 *(left) Healthy coral (right) Bleached coral.*

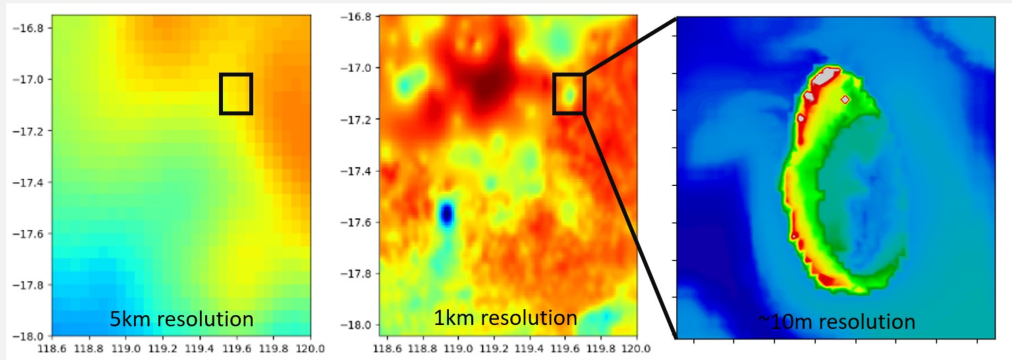

Fig. 2 *(left) 5km resolution SST (middle) 1km resolution SST (right) Numerical model.*

Methods

- Rowley Shoals, Western Australia, has avoided mass bleaching seen elsewhere; extensive temperature observations collected in-situ at Mermaid Reef during 2017-2018.
- Coral reef atoll located ~300 km offshore in waters ~400 metres deep.
- Mean tidal range ~2.3 m, reef flat exposed at low tide; and mean significant wave heights ~0.9 m.

- Delft3D-FM thermo-hydrodynamic coupled wave-flow model developed.
- Flexible mesh grid 500 m (offshore) to 25 m (on reef) resolution.
- Tidal and wave boundary conditions using TPXO 8.0 (astronomical tides) and CAWCR (WW3), validated using current and pressure sensors .
- SST boundary conditions from GHRSST and meteorological forcing from ERA5 to include solar radiation, air temperature, humidity, cloud cover, and wind.
- Output data classified by reef zone: reef flat (>-4m, within atoll), lagoon (<-4m, within atoll), fore reef (<-4m & >-30m, outside atoll), or offshore (<-30m, outside atoll).

- Past heatwave sea surface conditions based on data products from NOAA Coral Reef Watch, which indicated highest thermal stress on record for Rowley Shoals during April 2016; and ERA5 dataset.
- Future heatwave and meteorological conditions based on Earth System Model outputs.
- Custom degree-heating-week (DHW) product developed from 2015 to 2050 using SST from control dataset (no carbon emissions) and RCP8.5 scenario to develop daily climatology, mean monthly maximum (MMM), and coral bleaching hotspot (HS):

$$HS = SST_{RCP8.5} - MMM_{control}$$

$$DHW_i = \sum_{j=i-83}^{i} \left(\frac{HS_j}{7}\right) \quad where\ HS_j \geq 1$$

- Highest DHW value occurred in 2044.

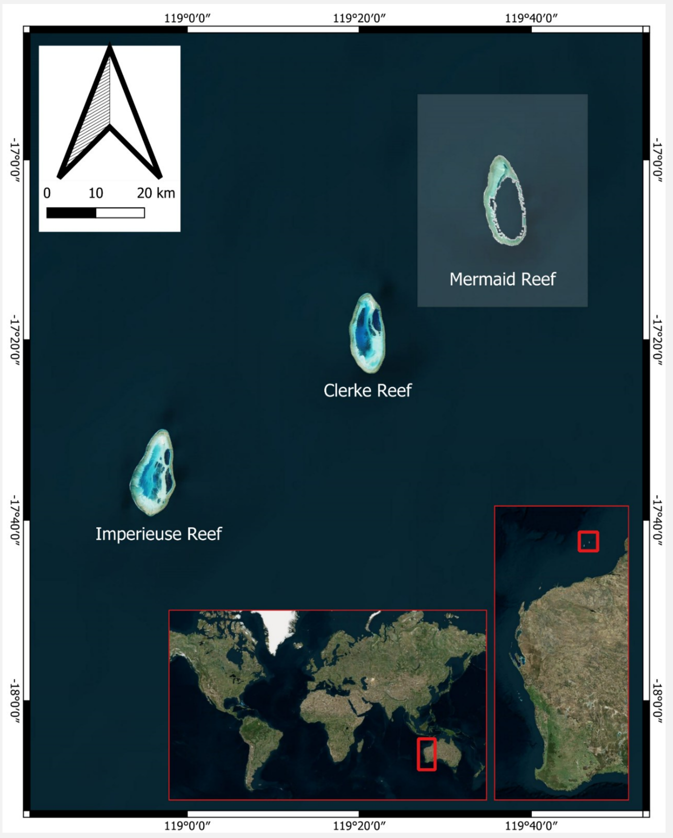

Fig. 3 *Study site.*

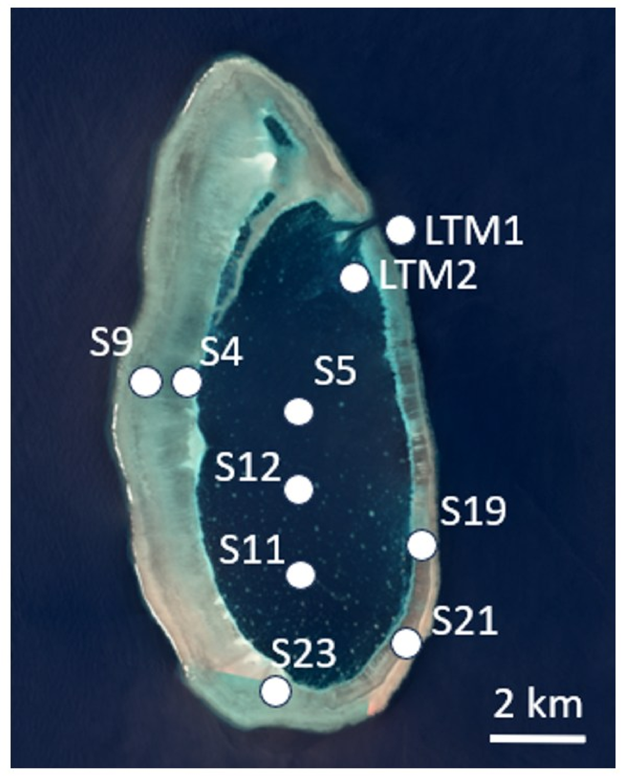

Fig. 4 *In-situ observation sites.*

Results

- Temperatures were stable in offshore and lagoon areas, while the reef flat exhibited significant diurnal changes with the western reef flat experiencing more extreme temperatures than the eastern side.
- Key drivers of temperature fluctuations at the reef included relative humidity, solar radiation, wind and tides. Clouds and waves were relatively less important.

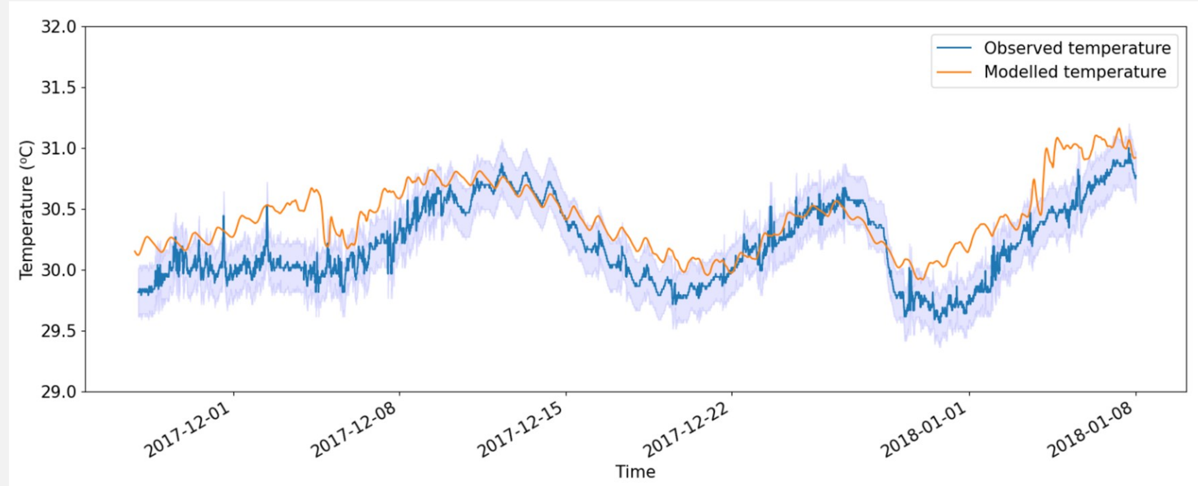

Fig. 5 *Observed and modelled temperatures at lagoon (site 5).*

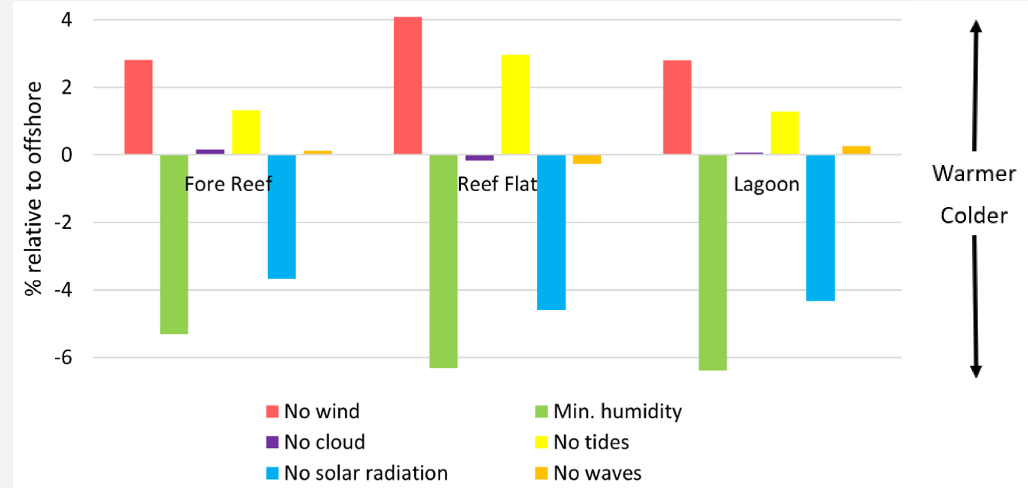

Fig. 6 *Relative contribution of forcings to on-reef temperatures.*

- During the April 2016 marine heatwave, offshore areas experienced significant heat stress, reaching 25°C-weeks, in excess of the coral threshold for death (8°C-weeks). Diurnal fluctuations cooled the reef, and the lagoon stabilized temperatures.
- The model for January 2044 indicated all reef zone temperatures were elevated compared to 2017-2018. The reef flat experienced spatially-averaged temperatures up to 34.7°C.
- Daily spatially-averaged temperatures were more than 1°C higher in the 2044 model compared to the 2016 model.

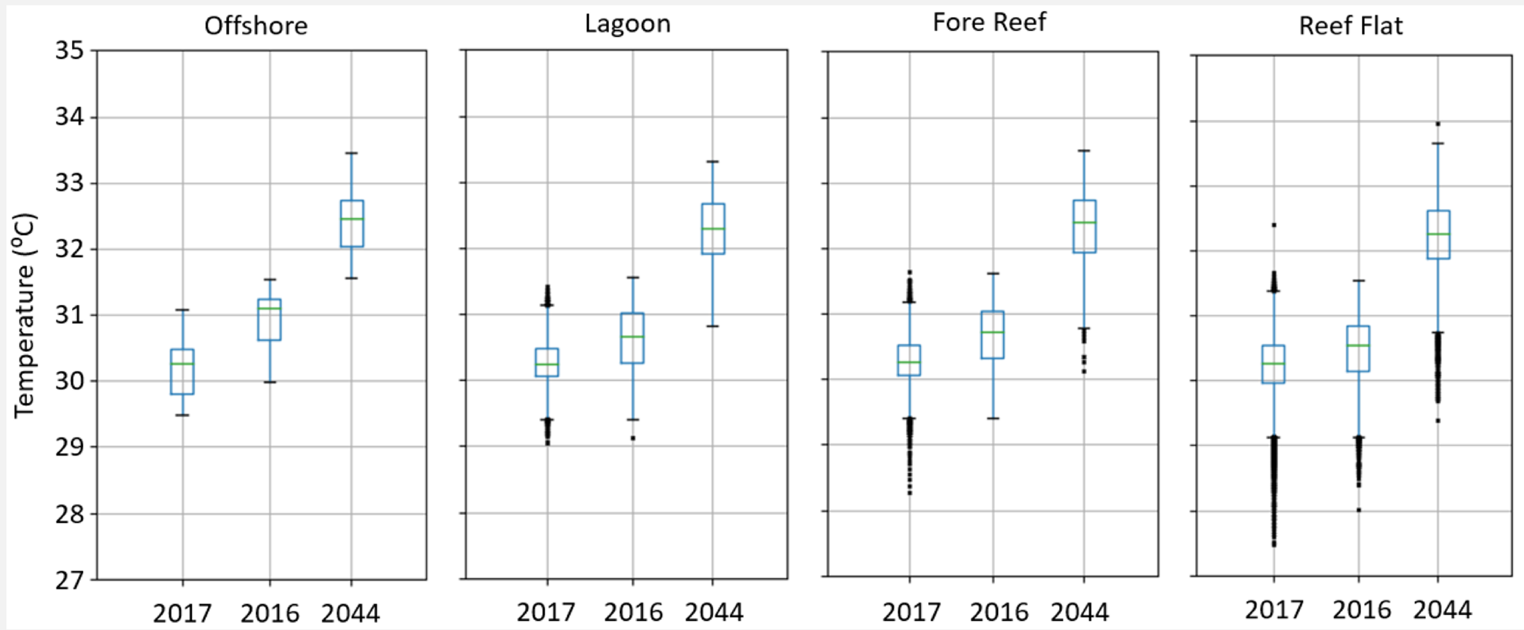

Fig. 7 *Daily spatially-averaged temperatures across model timeframes and reef zones.*

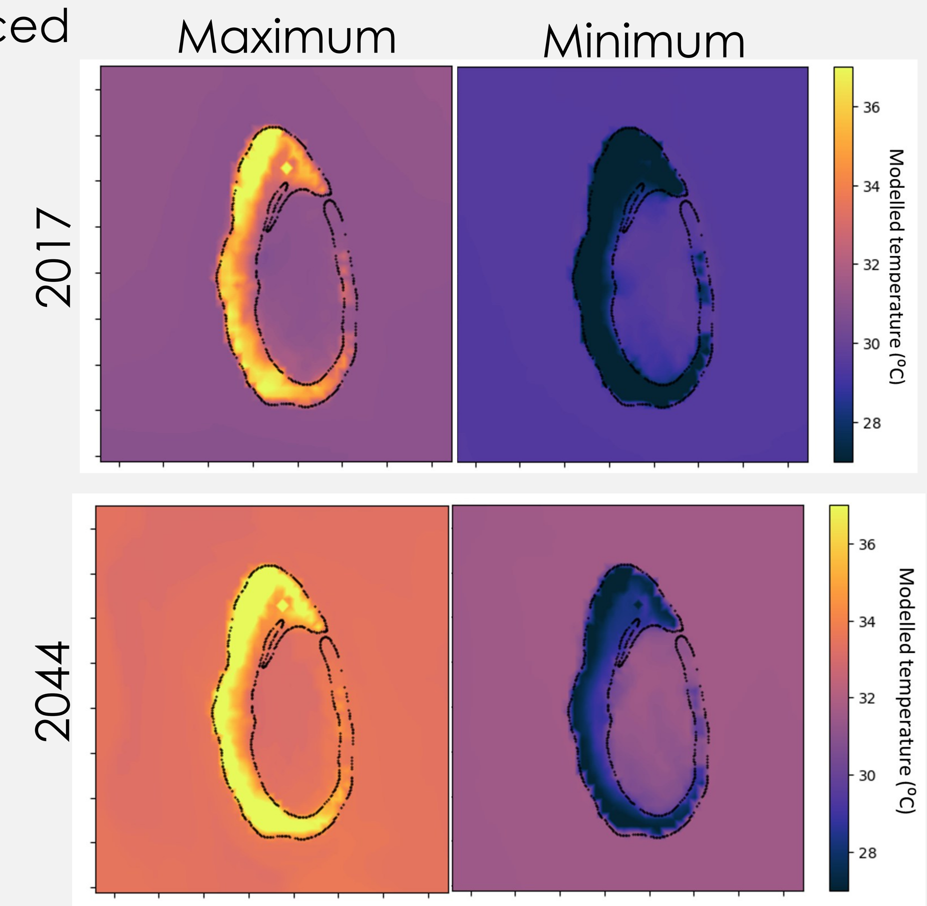

Fig. 8 *Temperature extremes across model timeframes.*

Discussion and Conclusion

- In-situ SSTs were highest in 2008, while satellite SSTs were highest in 2016. This highlights limitations of relying on satellite-only products for coral reef management.
- During neap tides, peak solar radiation and low tides were in phase, leading to extreme temperature fluctuations on the western reef flat. During spring tides, the eastern reef flat became exposed to similar extremes.
- The model showed limitations in capturing complex heat exchanges like upwelling and downwelling associated with wave action.
- Numerical modeling has practical applications in monitoring heat stress on coral reefs.
- Comparisons of past and projected future heatwaves suggest that future conditions will surpass past heat stress levels.

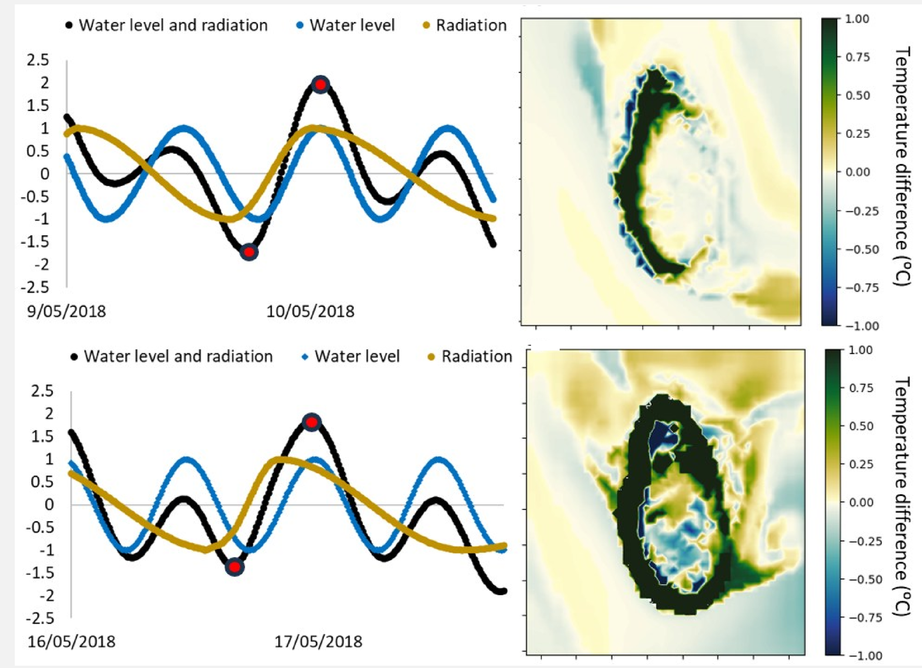

Fig. 9 *Phasing of radiation and water levels during neap (upper) and spring (lower) tide.*