Physical drivers of reefs in the Kimberley

KIMBERLEY MARINE RESEARCH PROGRAM NODE

PROJECT 2.2.1/3 – RYAN LOWE, RENEE GRUBER, JIM FALTER, GRAHAM SYMONDS
Wave- versus tide-dominated reefs

- Historical focus on the hydrodynamics of wave-dominated reefs (examples: southern GBR, Ningaloo, Pacific islands)

- “Tide-dominated reefs” = where the tidal range > incident wave height (examples: NW Australia, northern GBR)
Global distributions of tide-dominated reefs

- ~30% of the world’s reefs are tide-dominated
- Tend to be poorly studied regions, e.g. northern Australia, east Africa, southeast Asia, Central/South America, etc.
- Reefs typically ~1 m below MSL (Falter et al. 2013) -> tidal elevation often falls below these reefs
- Fundamentally different dynamics (circulation, heat budgets, etc.) than wave-dominated reefs

\[(\text{Lowe and Falter 2015, Ann. Rev. Marine Science})\]
Macrotidal reefs in the Kimberley

- Macrotidal Kimberley region (~10 m semi-diurnal tides)
- Largest tidal range of any tropical region worldwide
- Numerous coastal reef systems but largely unexplored

Tallon Island
Montgomery Reef
Talbot Bay
Outline

• How do tides interact with the reefs to drive water level and current variability?
• How do the tidal and solar cycles interact to drive temperature variability (and extremes)?
• How are these physical processes likely to change in the future?
Tidal interactions with reefs

- Case study of Tallon Island (*Jalan*)
Hydrodynamic field experiments

- Acoustic Doppler velocimeters / current profilers (PUV)
- Tide gauges (P)
Water level variability (hydraulic ‘ponding’ in reefs)

- Large tidal asymmetries on the reef
- ‘Tidal truncation’: ~2 hr flood vs ~10 hr ebb duration
- ~0.5 m water always remains on the reef (reduced exchange with the ocean)

(Lowe et al., J. Geophysical Research, 2015)
Importance of reef morphology and bottom roughness on keeping reefs submerged

- Model functionally explains how water drains off a reef depending on its bottom roughness, morphology and tidal conditions
- Keeps reefs from drying out → BUT, dramatically increases reef residence times

Effect of bottom friction ($C_d$)

\[ \frac{h_r(t)}{h_{r,0}} \]

\( C_d = 0.05 \)
\( C_d = 0.15 \)
\( C_d = 0.3 \)
\( C_d = 0.5 \)

(Lowe et al., J. Geophysical Research, 2015)
Implications for tide-dominated reefs (benefits and drawbacks for reef communities)

‘Residence time’ of reef waters is enhanced...

- **BENEFIT**: Reefs avoid aerial exposure despite offshore tidal level extremes
- **DRAWBACK**: Reduced ocean exchange and extended low tide drives water quality extremes (temperature, oxygen, pH, etc.)

Up to 8 °C diurnal temperature range
Assessing how tides regulate temperature variability within reefs

- A large array of thermistors (64 total) and hydrodynamic instruments were deployed throughout the reef.
- ~2 week study coinciding with detailed hydrodynamic observations
- Air-sea heat fluxes over the reef surface measured with weather station mounted on a scaffolding
Extreme diurnal temperature variability
Tidal modulation of reef temperature variability

(Lowe et al. 2016, Science Advances)
Interactions between tidal and solar cycles

• Semi-diurnal (lunar M2) tide with 12.4 hr period causes low tide to advance by ~50 min each day
• Extreme temperatures when solar noon occurs at low tide
• Results in a 14.8 day cycle in daily temperature extremes

(Lowe et al. 2016, Science Advances)
Importance of mean sea level (MSL) and tidal range

- Lower MSL relative to tidal range leads to larger temperature changes by the:
  1) Shallower average water column
  2) Extended duration of low tide
Role of mean sea level on temperature extremes

- Reefs with tidal truncation experience much greater temperature variability (extends low tide duration)
- For reefs with, $\frac{h_{\text{MSL}}}{\eta_{\text{tide}}} \leq 1$ a SLR can substantially alter temperatures (~50-80% reduction in many cases)
What are the implications of such a changing temperature regime?

- Results indicate that SLR would:
  - Reduce diurnal temperature extremes (max temperatures) by >2-3°C for many tide-dominated reef habitats
  - Daily average temps would not be affected with semi-diurnal tides

The scenario...

- What are the biological implications for such a changing thermal regime?
  - The same chronic stress from sustained global warming?
  - BUT, comparable max temperatures (acute stress)?
Summary and conclusions

• New model framework was developed to predict tide-dominated reef hydrodynamics - > functional dependency on morphology, tidal conditions and bottom roughness characteristics

• Can explain how productive reef ecosystems can be present high above low tide elevation of these reefs

• Tide and solar cycles interact on these reefs to control diurnal temperature variability

• Can explain temperature beating (~14.8 day cycle) and why tidally truncated reefs experience extreme temperature variations

• Reefs near or less than $h_0/\eta_{\text{tide}} \leq 1$ will experience substantial reductions in diurnal temperature extremes with SLR
Acknowledgments

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• Additional field assistance provided by Mike Cuttler and Nick Mortimer

Relevant references


Tidal asymmetries and ‘truncation’ in shallow tide-dominated reefs

A few analogous examples ...

Lady Eliot Island, GBR

One Tree Island, GBR

(McCabe et al. 2010)

(Ludington 1979)
Investigating the response of reef temperature extremes to sea level rise (SLR)

- Consider six Indo-Pacific reefs with accurate reef bathymetry surveys, tidal and temperature data
- Assume rapid relative SLR: rates (6-10 mm year\(^{-1}\)) much greater than typical reef accretion rates (also further slowed by climate change)

Table 1. Projected temperature changes due to sea level rise for sample tidally forced reefs globally. Labels refer to sites plotted in Fig. 5. Tidal amplitudes (\(R_{\text{tide}}\)) represent average values (that is, intermediate between spring and neap). \(F_{\text{tide}}\) denotes the tidal flow factor (see text for details). Diurnal temperature range changes (%\(\Delta T\), change) are relative to present conditions with a mean sea level (MSL) of 0 m. Present temperature ranges (\(\Delta T\)) are drawn from literature values and projected for different mean sea level rise scenarios (+0.7 m and +1.5 m) using the model NA, not available.

<table>
<thead>
<tr>
<th>Label</th>
<th>Site</th>
<th>(\Delta T_{\text{tide}})</th>
<th>(\Delta T_{\text{tide, present}})</th>
<th>(\Delta T_{\text{tide, +0.7 m}})</th>
<th>(\Delta T_{\text{tide, +1.5 m}})</th>
<th>References</th>
</tr>
</thead>
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<tr>
<td>A</td>
<td>Tallon Island, Kimberley, northwestern Australia</td>
<td>3.0</td>
<td>0.13</td>
<td>0.07</td>
<td>0.13</td>
<td>2.5–6.5°C</td>
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<tr>
<td>B</td>
<td>Wanniher Island, Torres Strait</td>
<td>1.2</td>
<td>0.46</td>
<td>0.03</td>
<td>0.46</td>
<td>1.5–3.0°C</td>
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<tr>
<td>C</td>
<td>Cocos (Keeling) Islands, eastern Indian Ocean</td>
<td>0.6</td>
<td>0.48</td>
<td>0.06</td>
<td>0.48</td>
<td>NA</td>
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<tr>
<td>D</td>
<td>Lady Elliot, Great Barrier Reef</td>
<td>0.8</td>
<td>0.42</td>
<td>0.03</td>
<td>0.42</td>
<td>0.5–1.2°C</td>
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<tr>
<td>—</td>
<td>Ofu, American Samoa</td>
<td>0.5</td>
<td>0.15</td>
<td>0.01</td>
<td>0.15</td>
<td>1.5–3.0°C</td>
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<td>0.16</td>
<td>0.01</td>
<td>0.16</td>
<td>NA</td>
</tr>
</tbody>
</table>

(Lowe et al. 2016, Science Advances)
Predicting tidally-driven temperature variability (reef heat budgets)

- A reef heat budget model (conservation of thermal energy and tidally-driven flows)
- For details see Lowe et al. (2016), *Science Advances* ...

- Model validation from the Kimberley (above) and other reefs (e.g. Lady Elliot, McCabe et al. 2009)