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Impact-producing

# Quantifying extreme sea level frequency changes and the emergence of tidal inundation in Australia.

**Ben S. Hague[1,2], Bradley F. Murphy[1], David A. Jones[1], Shayne McGregor[2], Ruth Reef [2], Andy J. Taylor[1]**

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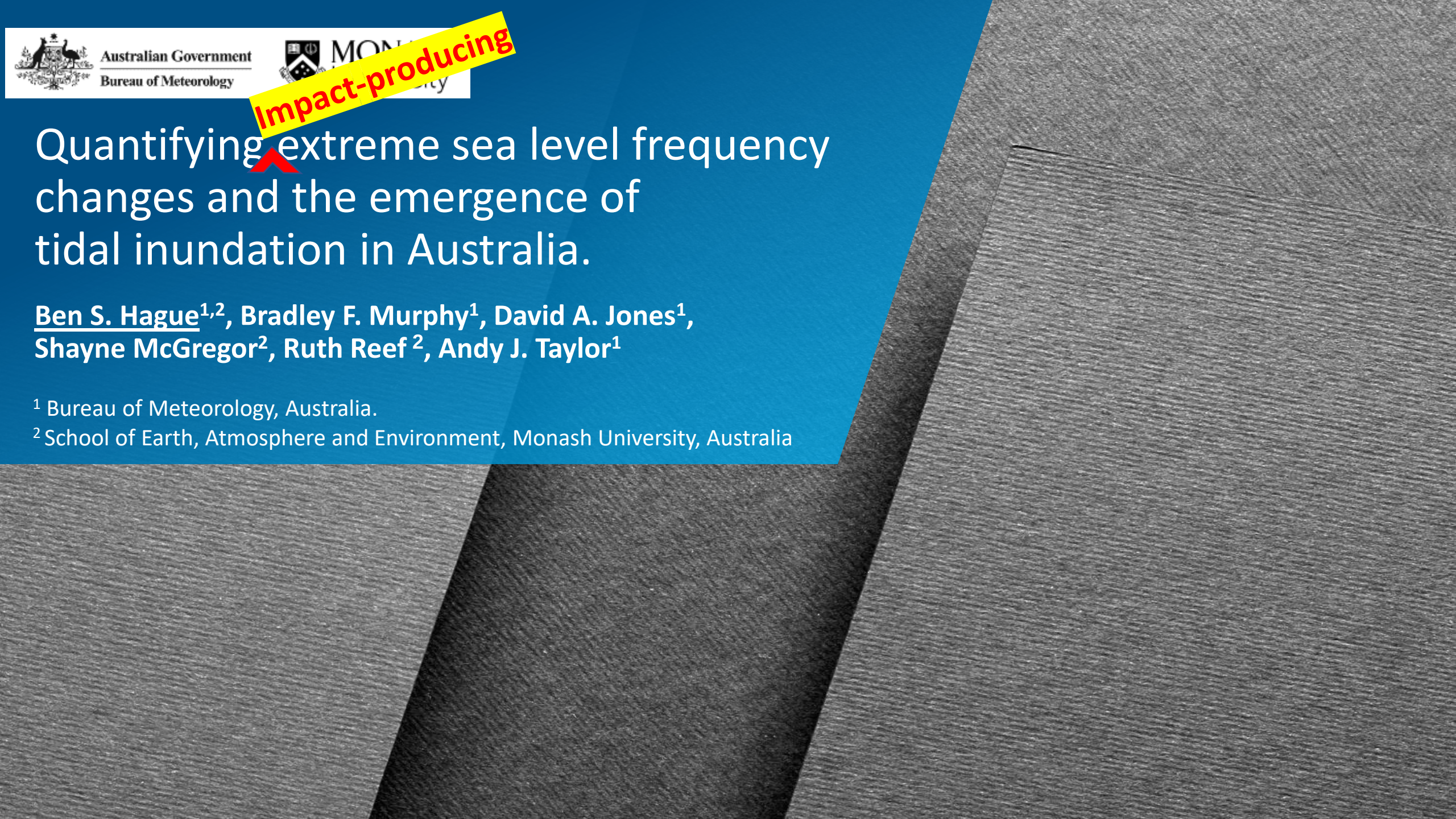
[2] School of Earth, Atmosphere and Environment, Monash University, Australia



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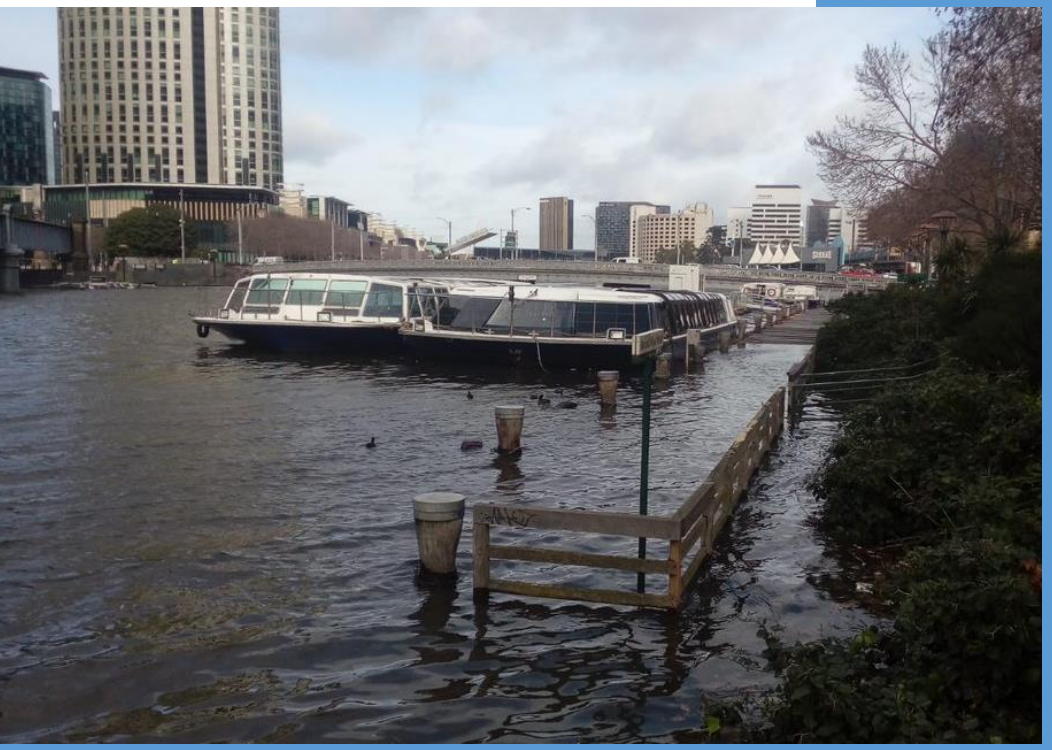


# Introduction

An impact-based approach to defining coastal inundation

Defining Tidal Inundation

Historical frequency of coastal inundation in Northern Australia

Sydney Case Study:

- Defining impact-based thresholds
- Historical frequency of tidal and coastal inundation
  - Future Projections

Photos: (Upper) Banana Alley Wharf, Melbourne, 9 August 2019, Ben Hague
(Lower) Windsor, QLD 21 Feb 2019, Harry Clark. Reproduced with permission

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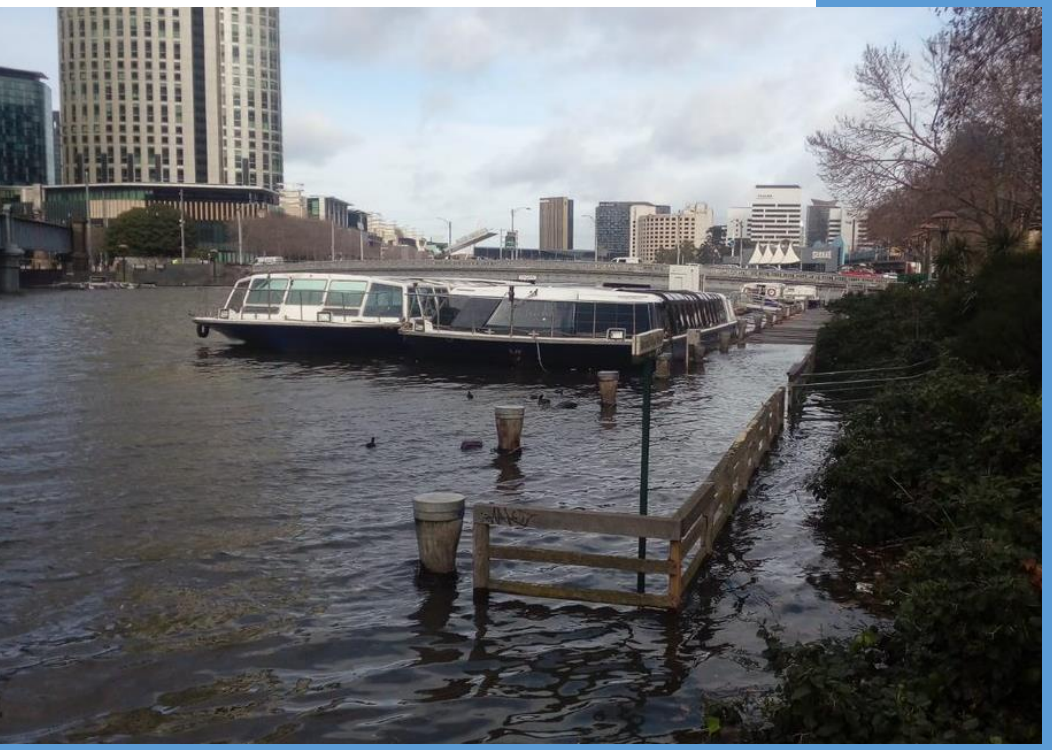


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# How do we measure coastal inundation?

Coastal inundation occurs when coastal water levels are sufficiently high to flood coastal assets.

Quantify by using **impact-based thresholds** as the water levels at which flooding of assets occurs.

Impact-based thresholds are derived by matching reports of coastal impacts to water levels recorded at a nearby (representative) tide gauge.

Photos: (Upper) Cocos Island. 25 July 2018, Alana-Jayne Moore .
(Lower) Lakes Entrance, Rodger Grayson 23 Nov 2018

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# What are impact-based thresholds

The impact-based threshold is a proxy for coastal inundation – **if you exceed the impact-based threshold then coastal inundation likely happens.**

-> Multiple (tiered) thresholds or a single 'lowest flood level' threshold for each location.

(Upper) Flooding due to storm surge coinciding with high tide in Birkenhead, SA, 9 May 2016. 891 ABC Adelaide (Audience submitted) - https://www.abc.net.au/news/2016-05-10/storm-conditions-ease-after-wild-night-across-sa/7399716
(Lower), South Arm Highway, Lauderdale, TAS 2 Jan 2014, Andrew Fisher (Witness King Tides - https://www.flickr.com/photos/witnesskingtides/11698117454/in/album-72157632212265998/).

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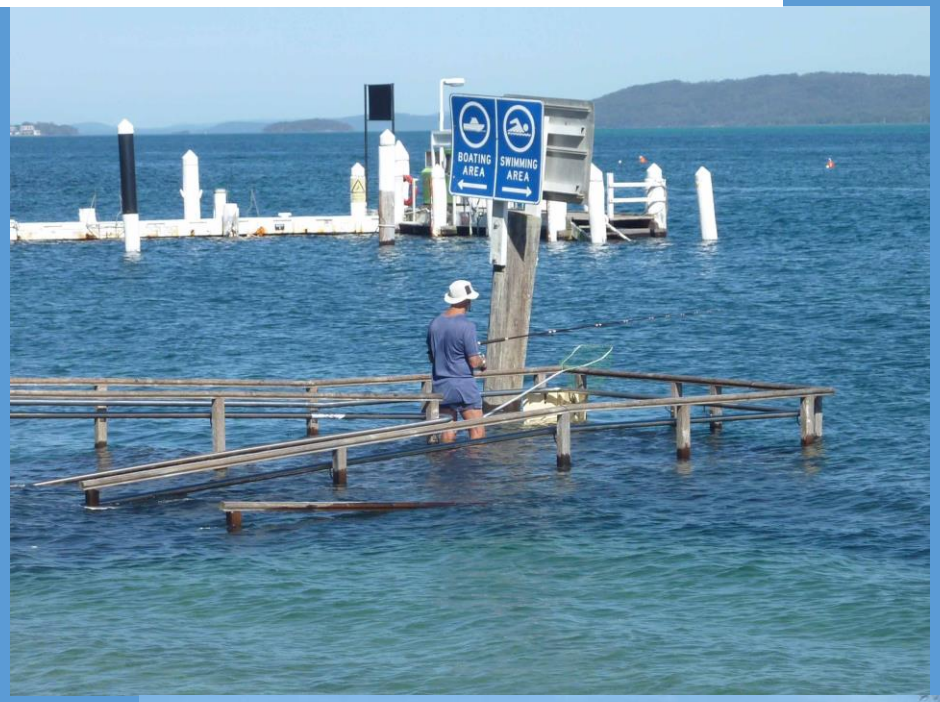



# Why Impact-Based Thresholds?

Update if get new reports or vulnerability changes.

Can account for spatial variability in:

- Tidal range
- Storm frequency (surge/residual climatology)
- Different exposure and risk due to planning offsets

Photo: (Upper) Nelson Bay 14/12/2012, Ian Shaw in Witness King Tides (2019): https://www.flickr.com/photos/witnesskingtides/8276817796/in/album-72157632264815668/
(Lower) Ballina, NSW, 3/1/2014, Garry Owers in Witness King Tides (2019)
https://www.flickr.com/photos/witnesskingtides/11786878775/in/album-72157632260968375/

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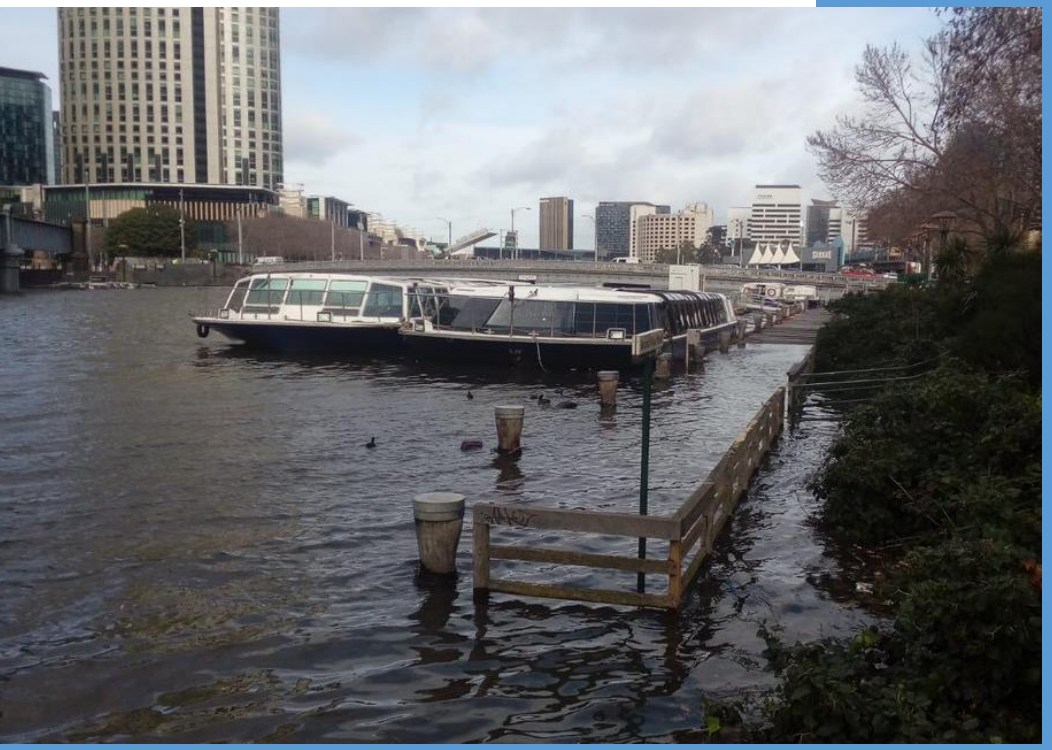


An impact-based approach to defining coastal inundation

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# What is tidal inundation?

Generally, coastal inundation where high tides are the predominant day-to-day contributor to total sea level.

We have used a quantitative definition: **when the (predicted) tide exceeds the impact-based threshold**.

Photo: (Upper) Tea Gardens, Central Coast, NSW, 4/1/2014 Stephen Palmer: https://www.flickr.com/photos/witnesskingtides/11787775036/in/album-72157632262482697/.
(Lower) Sydney Harbour 5 Dec 2017, Joe O'Brien in Maddox (2018)

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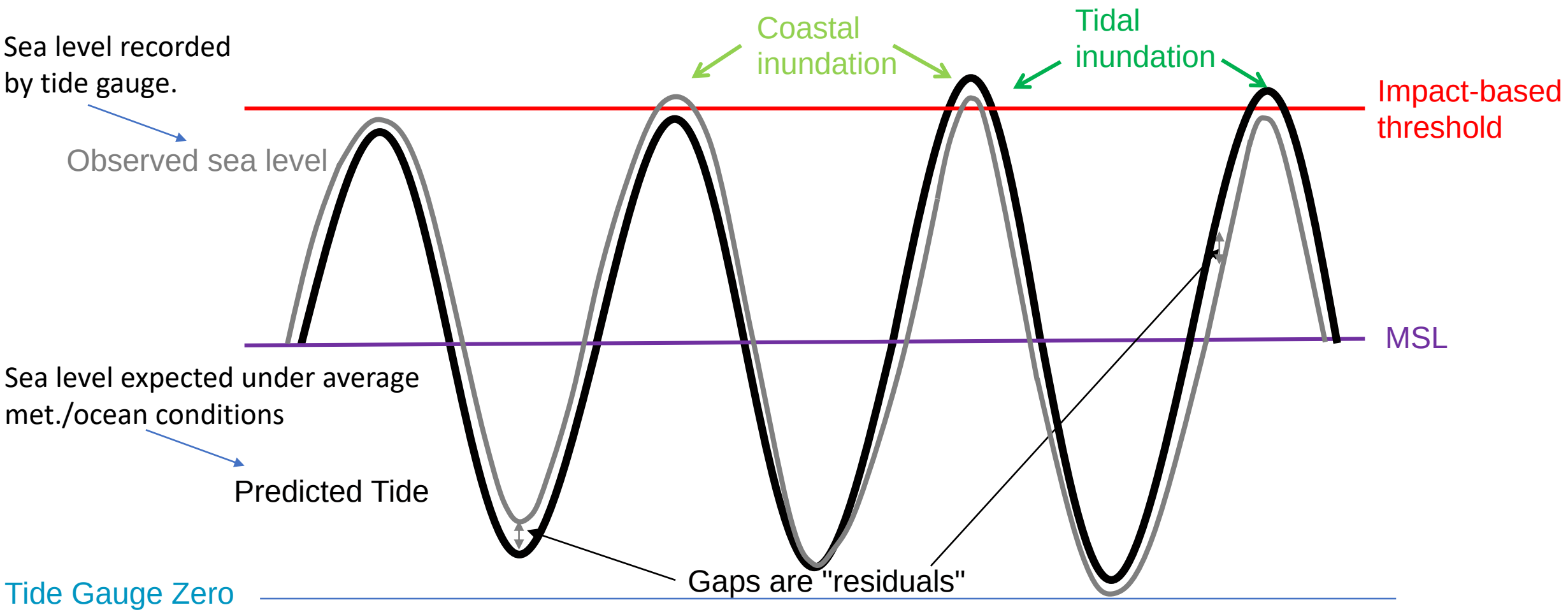
Tidal inundation = predicted tide exceeds impact-based threshold

Coastal inundation = observed sea level exceeds impact-based threshold




# A definition for tidal inundation

Diagrammatic representation of tidal and coastal inundation

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**Astronomical tide**
**(Moon-Sun-Earth system gravity & bathymetry)**

\+

**Local MSL Mean**
**(difference between mean sea level and tide gauge zero).**

\+

**MSL Change (Reconstruction/Projection/Trend)**
**(Dangendorf et al. 2019 / SROCC)**

\+

**Interannual variability**
**(e.g. La Nina)**

\+

**Storm Surge**
**(cold fronts/low/TC/CTWs)**

**= TOTAL SEA LEVEL**

**Prediction**
Calculated using Harmonic (Fourier) analysis on observation time series

\+

**Residual**
Calculated using tide gauge observation minus prediction

**= TOTAL SEA LEVEL**

# A definition for tidal inundation

Which physical components of total sea level are included in prediction?

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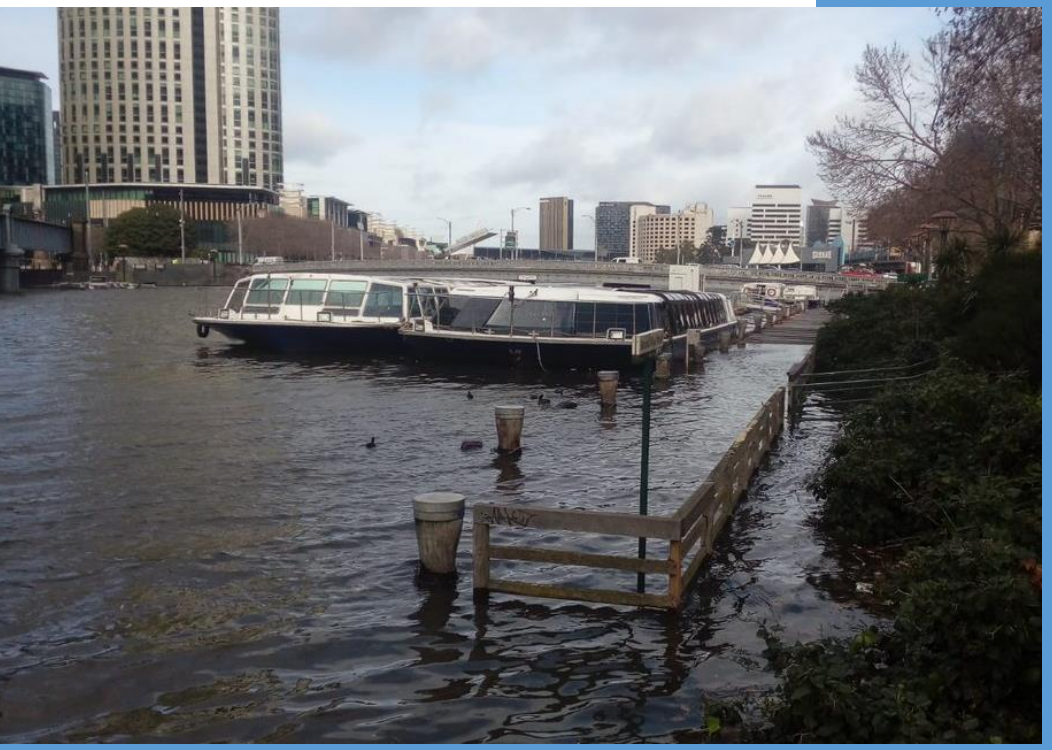


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Increased frequency of coastal inundation at all 21 locations where impact-based thresholds could be defined.

Brisbane has on average 22 inundation hours per year, increasing at a rate of 11 hours per decade.

The number of discrete events are increasing. This is a sign that the increasing frequency of coastal inundation is due to sea-level rise rather than increased storm severity.

Figures/Tables from Hague et al. (2019)

| Gauge Name | ANTT | HAT | IBT | Exceedance (hours above IBT) | | Events (number) | |
|---|---|---|---|---|---|---|---|
| | | | | Ann Ave | Trend (per decade) | Ann Ave | Trend (per decade) |
| Booby Island | 58230 | 4.3 | 4.20 | 21.44 | 11.24 | 4.65 | 0.58 |
| Bowen | 59320 | 3.7 | 3.67 | 2.74 | 0.08 | 0.7 | 0.00 |
| Brisbane | 59980 | 2.7 | 2.61 | 21.55 | 10.82 | 6.68 | 1.91 |
| Bundaberg | 59820 | 3.7 | 3.46 | 10.51 | 2.47 | 3.09 | 0.82 |
| Cairns | 59060 | 3.5 | 3.36 | 4.55 | 1.57 | 1.45 | 0.52 |
| Cape Ferguson | 59260 | 3.8 | 3.51 | 13.16 | 3.86 | 3.88 | 0.68 |
| Carnarvon | 62370 | 2.1 | - | | | | |
| Cocos Islands | 46280 | 1.6 | 1.6 | 48.33 | 35.97 | 5.65 | 3.02 |
| Darwin | 63230 | 8.1 | 7.89 | 2.03 | 0.84 | 1.19 | 0.52 |
| Gladstone | 59750 | 4.8 | 4.58 | 9.52 | 3.23 | 3.38 | 1.27 |
| Hay Point | 59511 | 7.1 | 6.81 | 6.92 | 2.56 | 2.76 | 0.85 |
| Ince Point | 58140 | 3.8 | 3.66 | 2.59 | 0.78 | 0.62 | 0.2 |
| Karumba | 63580 | 4.9 | 4.66 | 3.21 | 1.61 | 0.66 | 0.19 |
| Lucinda | 59200 | 4.0 | 3.76 | 9.81 | 3.13 | 2.77 | 0.92 |
| Mackay | 59510 | 6.6 | 6.35 | 3.71 | 1.53 | 1.81 | 0.86 |
| Mooloolaba | 59950 | 2.2 | 2.06 | 24.27 | 7.12 | 6.14 | 0.86 |
| Mourilyan Harbour | 59140 | 3.5 | 3.49 | 1.04 | 0.35 | 0.38 | 0.15 |
| Onslow | 62470 | 3.1 | - | | | | |
| Port Alma | 59690 | 6.0 | - | | | | |
| Port Hedland | 62590 | 7.6 | 7.76 | 0.06 | 0.03 | 0.05 | 0.02 |
| Shute Harbour | 59410 | 4.3 | 4.25 | 3.2 | 0.75 | 1.38 | 0.49 |
| Townsville | 59250 | 4.1 | 3.99 | 3.39 | 0.98 | 1.28 | 0.20 |
| Urangan | 59850 | 4.3 | 4.12 | 6.96 | 2.01 | 3.15 | 0.75 |
| Weipa | 63620 | 3.4 | 3.57 | 1.77 | 1.3 | 0.42 | 0.23 |

# Historical Trends in Northern Australia

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Increased frequency of coastal inundation at all 21 locations where impact-based thresholds could be defined.

Brisbane has on average 22 inundation hours per year, increasing at a rate of 11 hours per decade.

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|---|---|---|---|---|---|---|---|
| | | | | Ann Ave | Trend (per decade) | Ann Ave | Trend (per decade) |
| Booby Island | 58230 | 4.3 | 4.20 | 21.44 | 11.24 | 5.42 | 1.62 |
| Bowen | 59320 | 3.7 | 3.67 | 2.74 | 0.08 | 2.03 | -0.18 |
| Brisbane | 59980 | 2.7 | 2.61 | 21.55 | 10.82 | 3.77 | 0.32 |
| Bundaberg | 59820 | 3.7 | 3.46 | 10.51 | 2.47 | 3.22 | -0.25 |
| Cairns | 59060 | 3.5 | 3.36 | 4.55 | 1.57 | 2 | 0.36 |
| Cape Ferguson | 59260 | 3.8 | 3.51 | 13.16 | 3.86 | 3.96 | -0.19 |
| Carnarvon | 62370 | 2.1 | - | | | | |
| Cocos Islands | 46280 | 1.6 | 1.6 | 48.33 | 35.97 | 8.14 | 2.14 |
| Darwin | 63230 | 8.1 | 7.89 | 2.03 | 0.84 | 1 | 0.35 |
| Gladstone | 59750 | 4.8 | 4.58 | 9.52 | 3.23 | 2.74 | -0.11 |
| Hay Point | 59511 | 7.1 | 6.81 | 6.92 | 2.56 | 2.11 | 0.17 |
| Ince Point | 58140 | 3.8 | 3.66 | 2.59 | 0.78 | 1.95 | -0.05 |
| Karumba | 63580 | 4.9 | 4.66 | 3.21 | 1.61 | 2.11 | 0.59 |
| Lucinda | 59200 | 4.0 | 3.76 | 9.81 | 3.13 | 3.19 | 0.32 |
| Mackay | 59510 | 6.6 | 6.35 | 3.71 | 1.53 | 1.72 | 0.14 |
| Mooloolaba | 59950 | 2.2 | 2.06 | 24.27 | 7.12 | 4.19 | 0.35 |
| Mourilyan Harbour | 59140 | 3.5 | 3.49 | 1.04 | 0.35 | 0.91 | 0.22 |
| Onslow | 62470 | 3.1 | - | | | | |
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| Shute Harbour | 59410 | 4.3 | 4.25 | 3.2 | 0.75 | 1.73 | 0.12 |
| Townsville | 59250 | 4.1 | 3.99 | 3.39 | 0.98 | 1.81 | 0.30 |
| Urangan | 59850 | 4.3 | 4.12 | 6.96 | 2.01 | 1.99 | -0.30 |
| Weipa | 63620 | 3.4 | 3.57 | 1.77 | 1.3 | 1.65 | 1.09 |

# Historical Trends in Northern Australia

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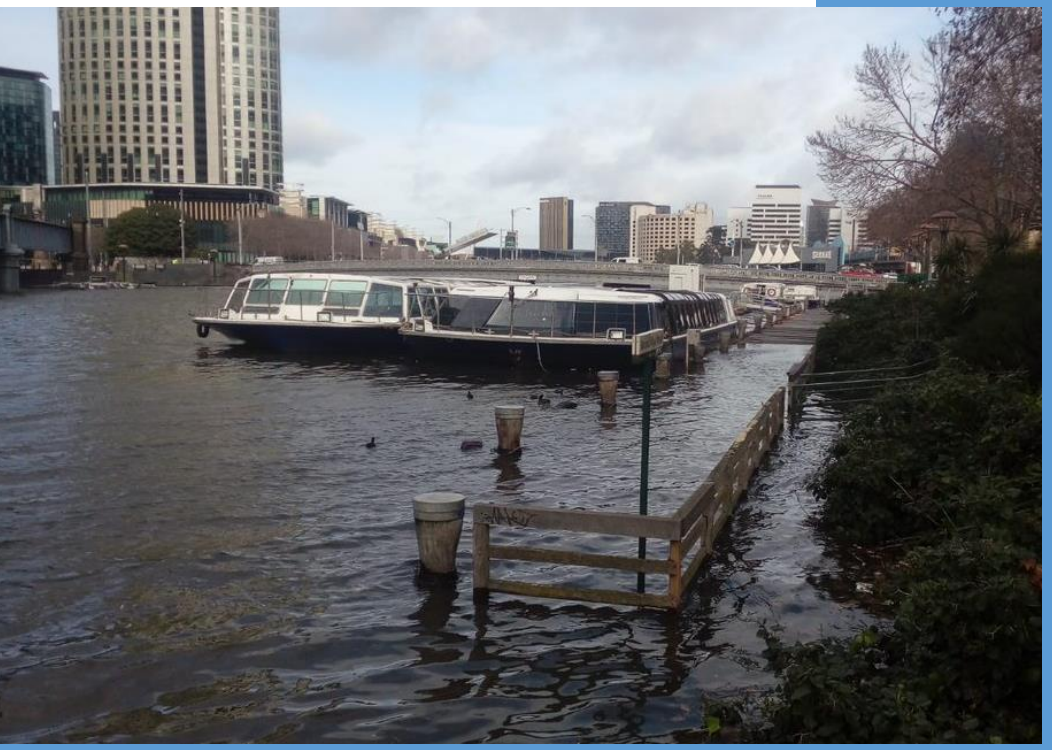


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Photos: (Upper) Banana Alley Wharf, Melbourne, 9 August 2019, Ben Hague
(Lower) Windsor, QLD 21 Feb 2019, Harry Clark. Reproduced with permission

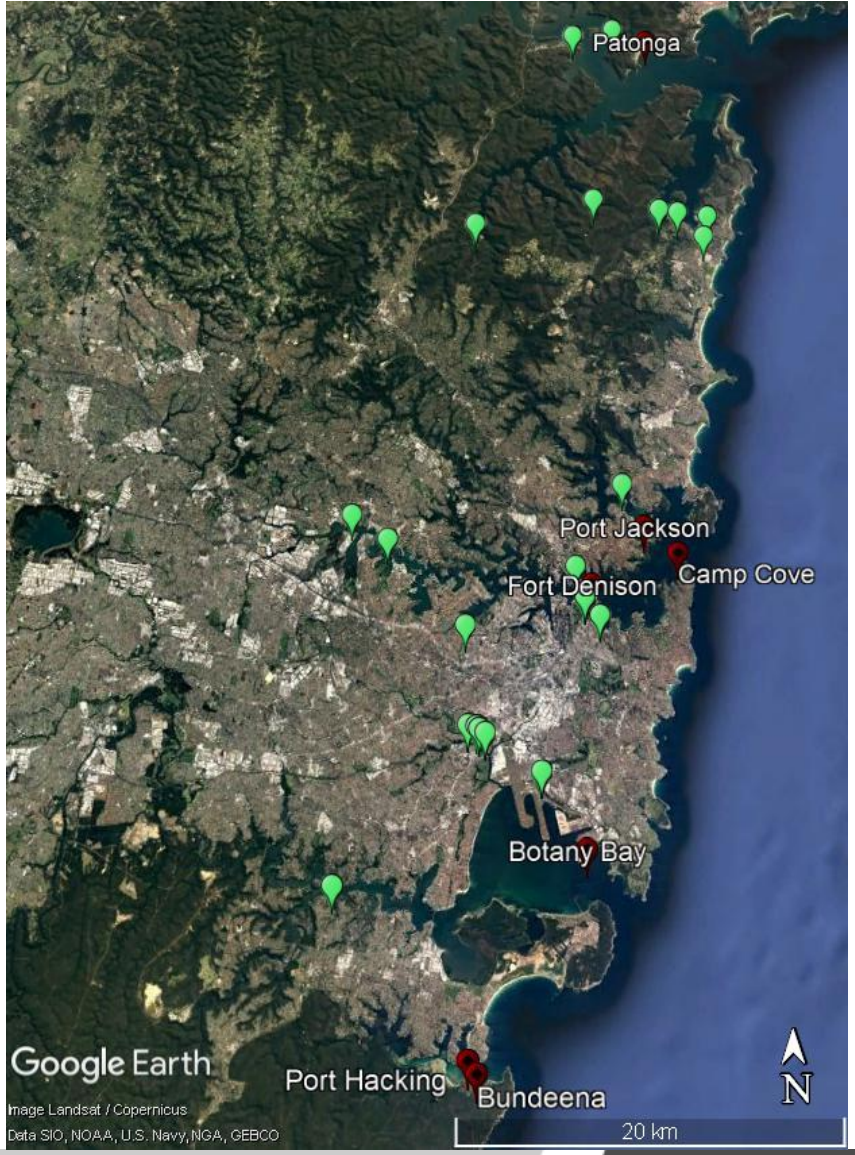
7 Tide Gauges, 5 still operational.

Longest record Fort Denison, 1914 – ongoing

All highly correlated comparing hourly data (R > 0.95 for daily max/mean/min, R > 0.90 for monthly max/mean).

Conforms to expectation based on estuary types (drowned river valley) (Hanslow et al. 2019).

Fort Denison tide gauge used to define impact-based threshold.




# Sydney data sources for defining impact-based thresholds

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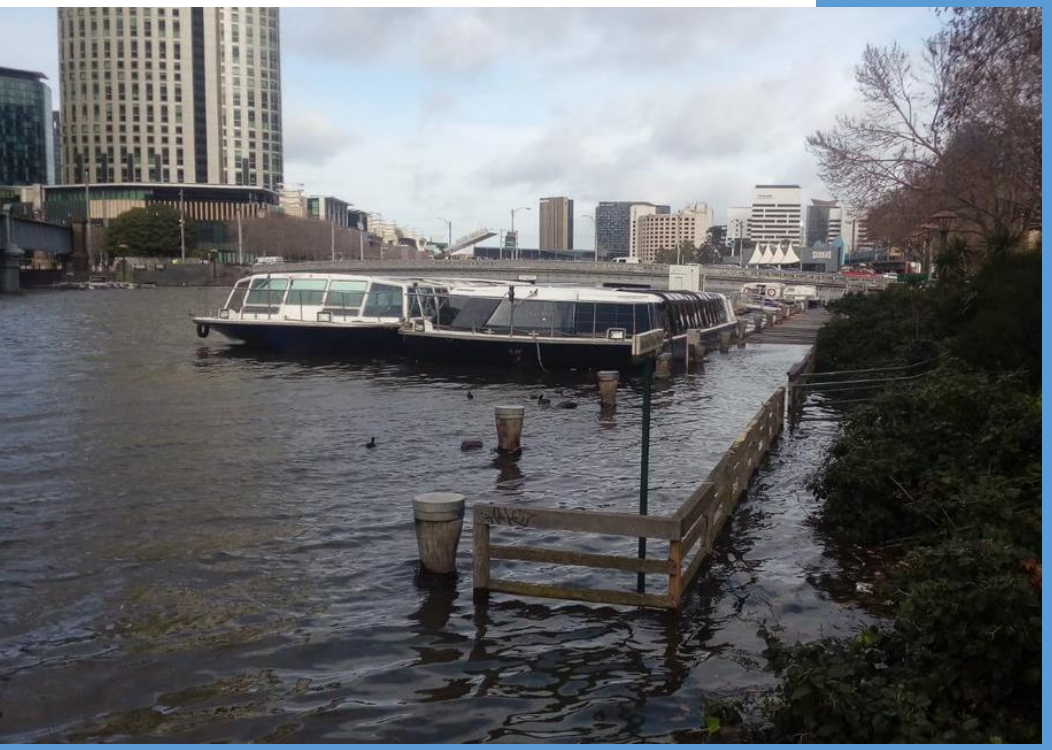


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Top: Zuster in Witness King Tides (2019), Bottom: Henley in Witness King Tides (2019)

13/12/2012 – 1.87m

14/12/2012 – 1.96m


# Inundation Reports - Tempe

12/1/2009 – 1.96m

Image: Mitchell in DECCW (2009)


# Inundation Reports - Putney

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14/12/2012
– 1.96m

Images: Collier in Witness King Tides (2019)


# Inundation Reports – Royal Botanic Gardens

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14/12/2012 – 1.96m

Image: Yates in Witness King Tides (2019)


# Inundation Reports - Mosman

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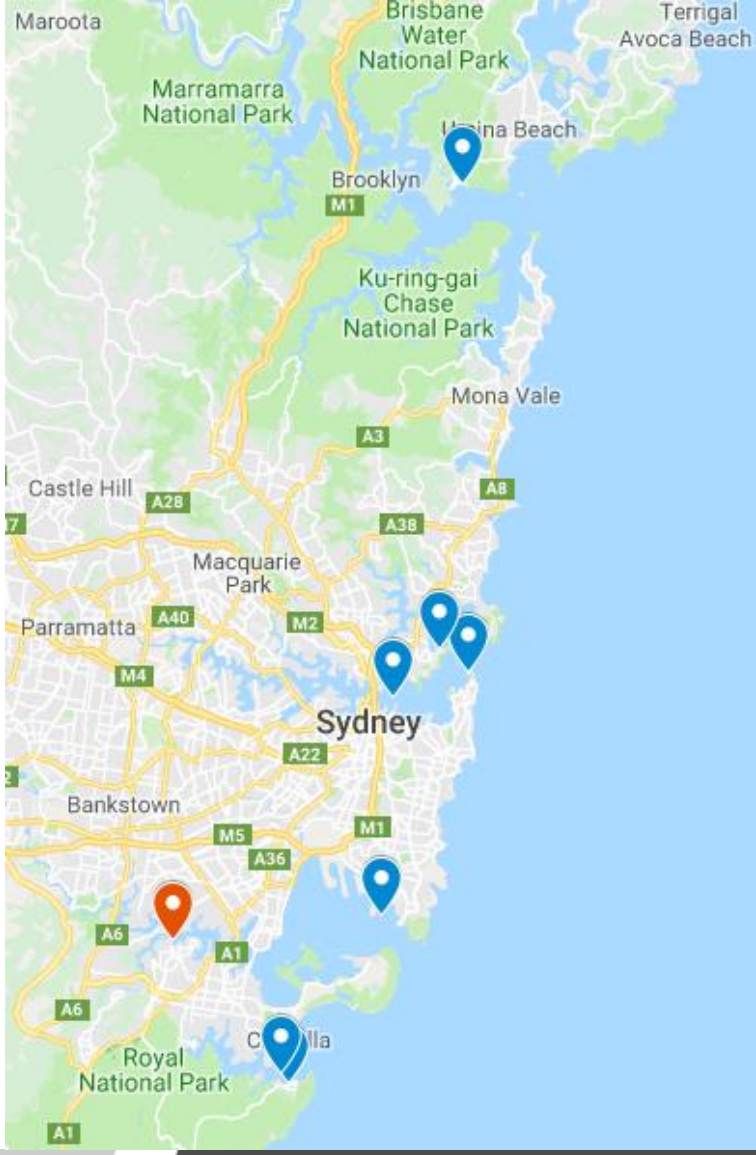
12/1/2013 – 2.07m

Image: Hanlon in Witness King Tides (2019)




# Inundation Reports - Como

Top: Fitzhenry in Maddox (2018) (MHL2618)

7/12/2017 – 2.07m

Bottom: O'Brien in DECCW (2009).

15/12/2008 – 2.12m


# Inundation Reports - Botany

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**Royal Botanic Garden** @RBGSydney · 13 Jan 2017

Yurong gate along the seawall, is closed due to a **King Tide**. Please take care near the water. bit.ly/2jJAHo7

13/1/2017 – 2.15m

Image: Twitter @RBGSydney


# Inundation Reports – Royal Botanic Gardens

3/1/2014 – 2.15m

Image: Laker in Witness King Tides (2019)


# Inundation Reports - Pittwater

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Image: Jacobs (2014) (MHL2292)


# Inundation Reports – Mona Vale

3/1/2014 – 2.15m

Image: Arnold in Witness King Tides (2019)


# Inundation Reports – Brooklyn

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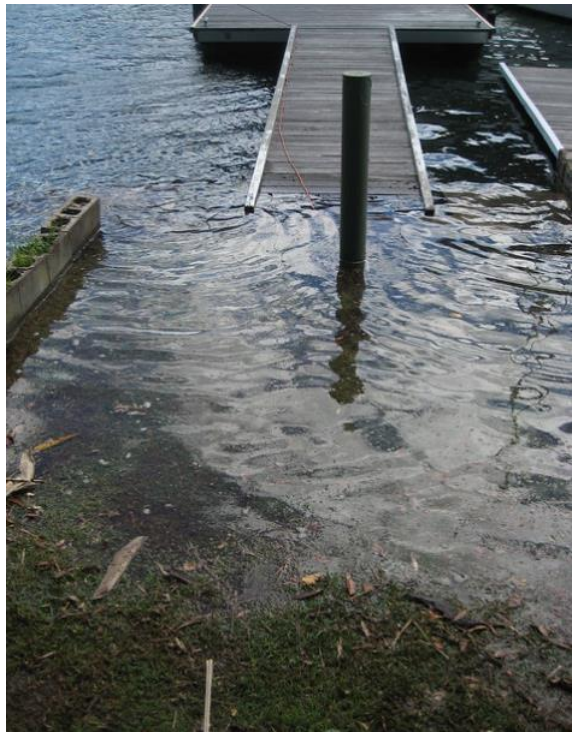

Images: Richmond in Witness King Tides (2019)

14/12/2008 – 2.16m


# Inundation Reports – Browns Bay

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Top: Campbell in Maddox (2018) (MHL2618)

Bottom: Frankel in Witness King Tides (2019).




# Inundation Reports – Bobbin Head

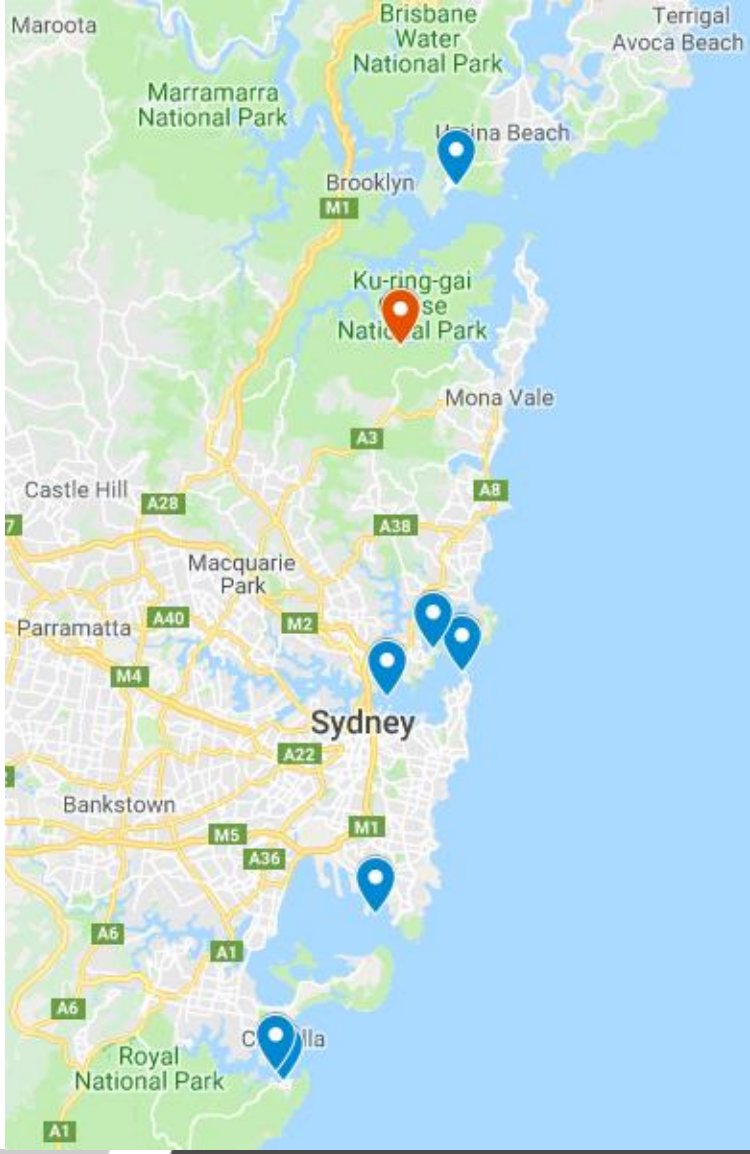

14/6/2014 – 2.19m

Image: Goad in Witness King Tides (2019)


# Inundation Reports - Kirribilli


2/01/2014 – 2.20m

Image: McNamara in Witness King Tides (2019)




# Inundation Reports – Akuna Bay

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2/01/2014 – 2.20m

Image: Hill in Witness King Tides (2019)


# Inundation Reports – Little Wobby Beach

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Images: Richmond in Witness King Tides (2019)

2/1/2014 – 2.20m


# Inundation Reports – Browns Bay

2-3/1/2014 – 2.20m (event max)

Image: Jacobs (2014) (MHL2292)


# Inundation Reports - Bayview

2/01/2014 – 2.20m

Image: Thompson in Witness King Tides (2019)


# Inundation Reports - Meadowbank

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Images:
Morgon in
Witness King
Tides (2019)

2/01/2014 – 2.20m


# Inundation Reports – Elizabeth Bay

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**Royal Botanic Garden** @RBGSydney · 5 Dec 2017

You may have seen last night's Supermoon, but did you know that this can cause a **#kingtide**? The higher than normal water levels have caused some flooding near Fleet Steps today, so please be careful if you're in this area today until flooding subsides. #RBGSydney

5/12/2017 – 2.23m

Image: Twitter @RBGSydney


# Inundation Reports – Royal Botanic Gardens

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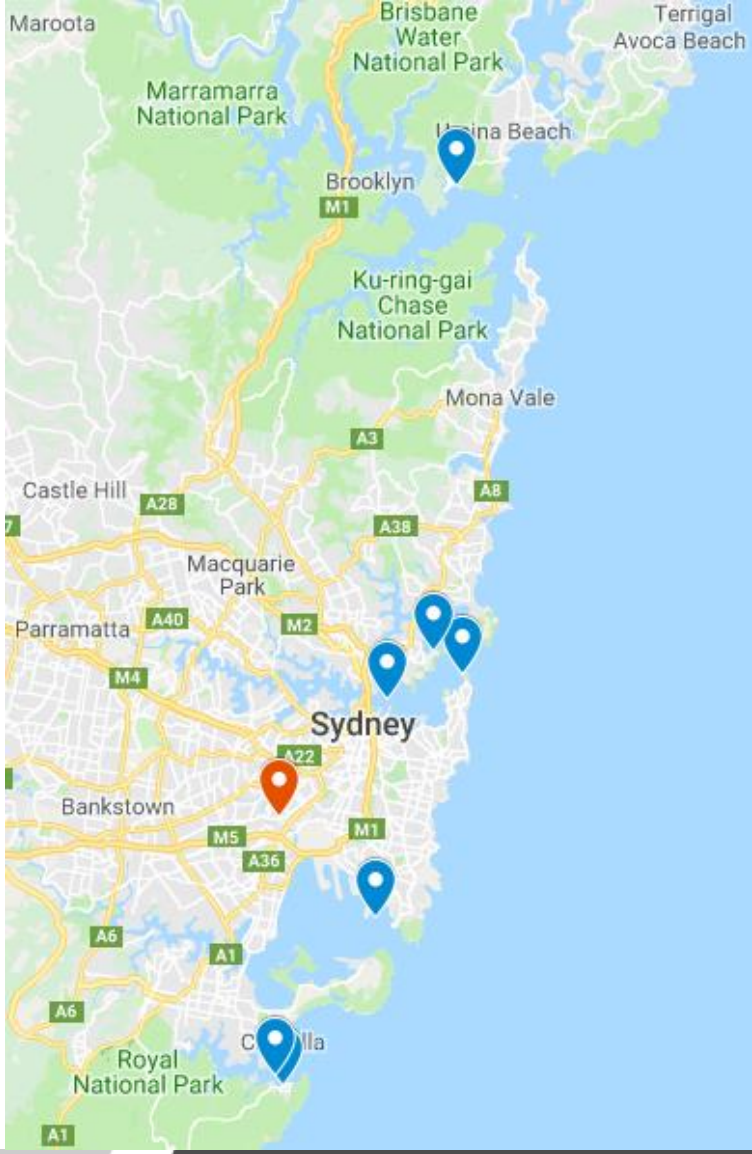
3/1/2018 – 2.26m

Images from:
https://www.youtube.com/watch?v=oUJ3TSTZmeY




3/1/2018 – 2.26m

# Inundation Reports - Earlwood

Image from:
https://www.youtube.com/watch?v=oUJ3TSTZmeY

3/1/2018 – 2.26m


# Inundation Reports - Earlwood

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3/1/2018 – 2.26m

Image from:
https://www.youtube.com/watch?v=oUJ3TSTZmeY


# Inundation Reports - Tempe

6/12/2017 – 2.27m

Image: O'Brien in Maddox (2018) (MHL2618)


# Inundation Reports – Royal Botanic Gardens

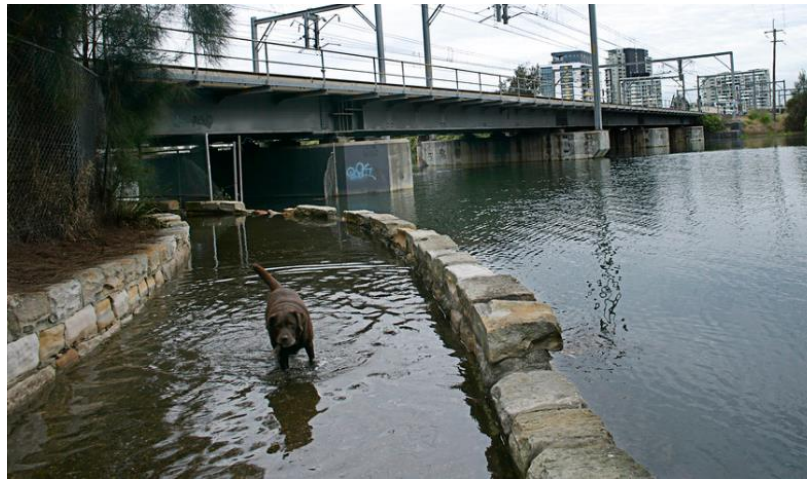

6/12/2017 – 2.27m (event max)

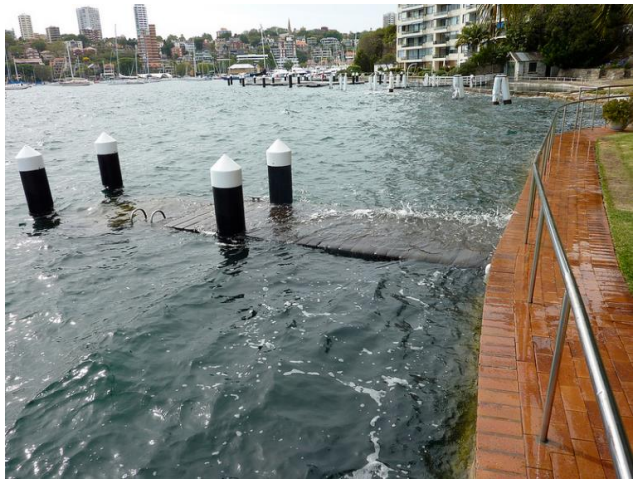
Images: Witness King Tides (2019)

# Inundation Reports - Haberfield

Photos: (Top Left) Cooks River Bike Path, Tempe, Sydney, 14/12/2012. Hanley in Witness King Tides (2019) - https://www.flickr.com/photos/witnesskingtides/8446371390/in/album-72157632237306616/
(Top Right) Elizabeth Point Jetty, Elizabeth Bay, Sydney, 14/12/2012. Barnes in Witness King Tides (2019) - https://www.flickr.com/photos/witnesskingtides/8271898832
(Lower) Farm Cove, Royal Botanic Gardens, Sydney, 14/12/2012, Collier in Witness King Tides (2019) - https://www.flickr.com/photos/witnesskingtides/8368074205/in/album-72157632237306616/

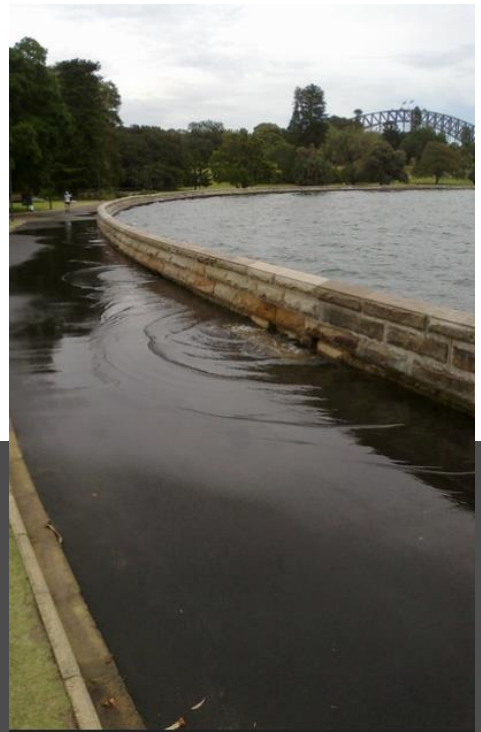
Nuisance flooding: 1.96m





Regional threshold means impacts may vary from place to place but generally:

Nuisance = bike paths, walking paths, jetties



# Sydney impact-based thresholds for 3 different flood levels

'Nuisance'

Photos: (Top Left) Botany, Sydney, 7/12/2017, Fitzhenry in Maddox (2018)
(Top Right) Brooklyn, NSW, 3/1/2014, Arnold in Witness King Tides (2019) - https://www.flickr.com/photos/witnesskingtides/12228586964/in/album-72157632262482697/
(Lower) Brooklyn NSW, 2/1/2014, Julian in Witness King Tides (2019)
https://www.flickr.com/photos/witnesskingtides/11787522556/in/album-72157632237306616/

Nuisance flooding: 1.96m

Minor flooding: 2.06m

Regional threshold means impacts may vary from place to place but generally:

Nuisance = bike paths, walking paths, jetties

Minor = nuisance impacts + residential streets, car parks, parklands

# Sydney impact-based thresholds for 3 different flood levels

'Minor'

Photos: (Top Left) Earlwood, Sydney, 3/1/2018, Werrong Lane, https://www.youtube.com/watch?v=oUJ3TSTZmeY
(Top Right) Flooding of a café at Elizabeth Bay, Sydney, 2/1/2014, Tim Morgan in Witness King Tides (2019) - https://www.flickr.com/photos/witnesskingtides/11700065064/in/album-72157632237306616/
(Lower) Haberfield, Sydney, 6/12/2017, Witness King Tides (2019) - https://www.flickr.com/photos/witnesskingtides/27089890829/

Nuisance flooding: 1.96m

Minor flooding: 2.06m

Moderate flooding: 2.26m

Regional threshold means impacts may vary from place to place but generally:

Nuisance = bike paths, walking paths, jetties

Minor = nuisance impacts + residential streets, car parks, parklands

Moderate flooding = minor impacts + major roads, homes/businesses.

# Sydney impact-based thresholds for 3 different flood levels

'Moderate'

Australian Government
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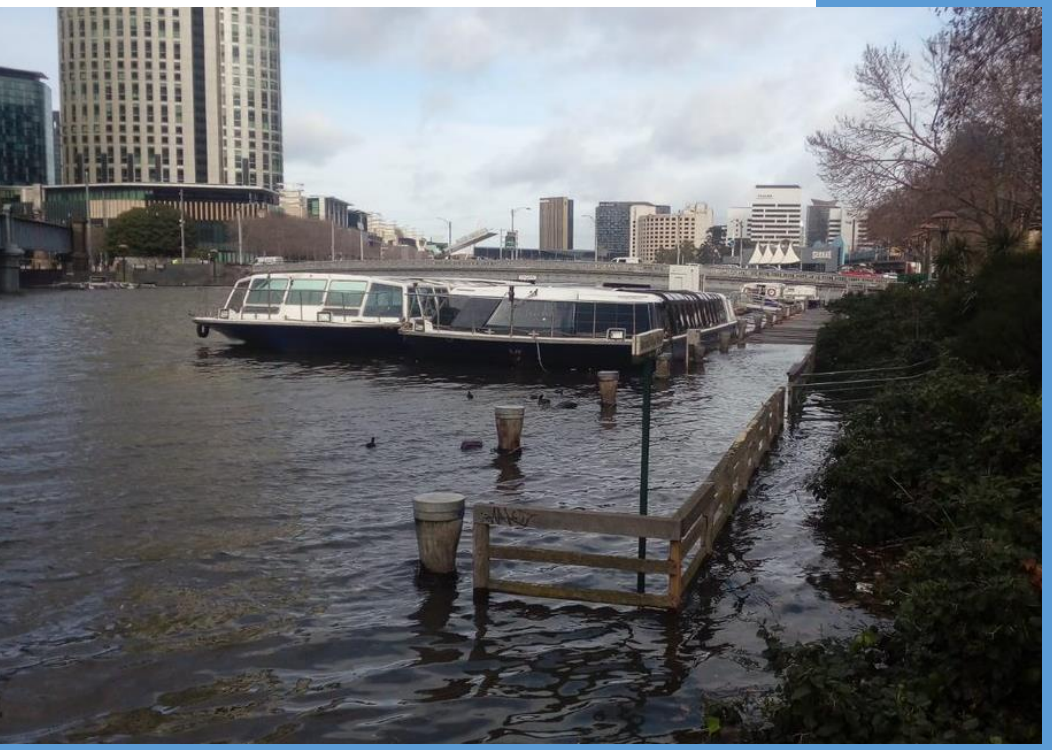
MONASH University




An impact-based approach to defining coastal inundation

Defining Tidal Inundation

Historical frequency of coastal inundation in Northern Australia

Sydney Case Study:

- Defining impact-based thresholds
- Historical frequency of tidal and coastal inundation
  - Future Projections

Photos: (Upper) Banana Alley Wharf, Melbourne, 9 August 2019, Ben Hague
(Lower) Windsor, QLD 21 Feb 2019, Harry Clark. Reproduced with permission

Australian Government
Bureau of Meteorology

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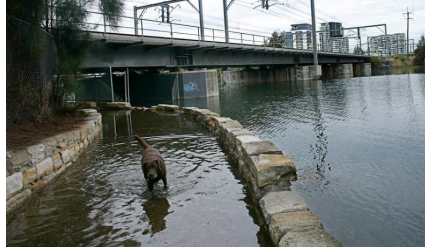
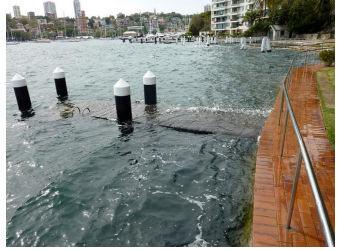
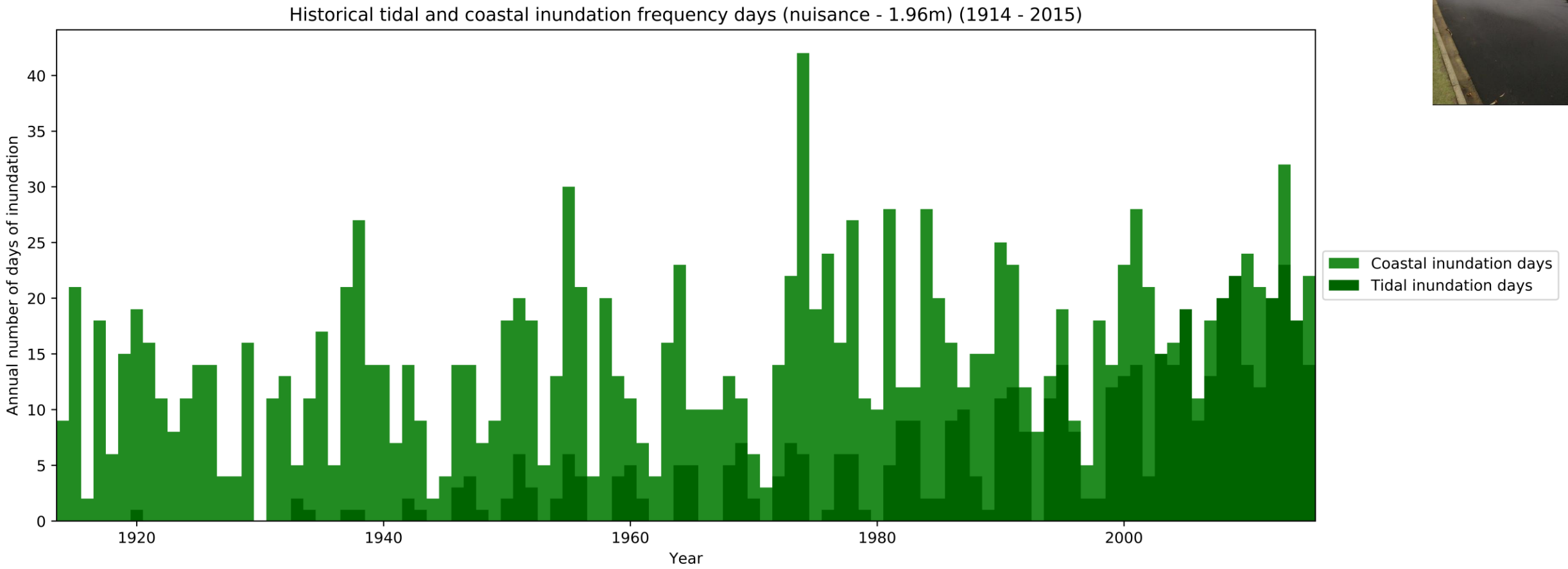




Coastal inundation: 19.05 days (97-15 mean), 170% increase since 14-32
Tidal inundation: 13.68 days (97-15 mean), 260-fold increase since 14-32




# Historical Frequencies of Coastal and Tidal Inundation

'Nuisance'

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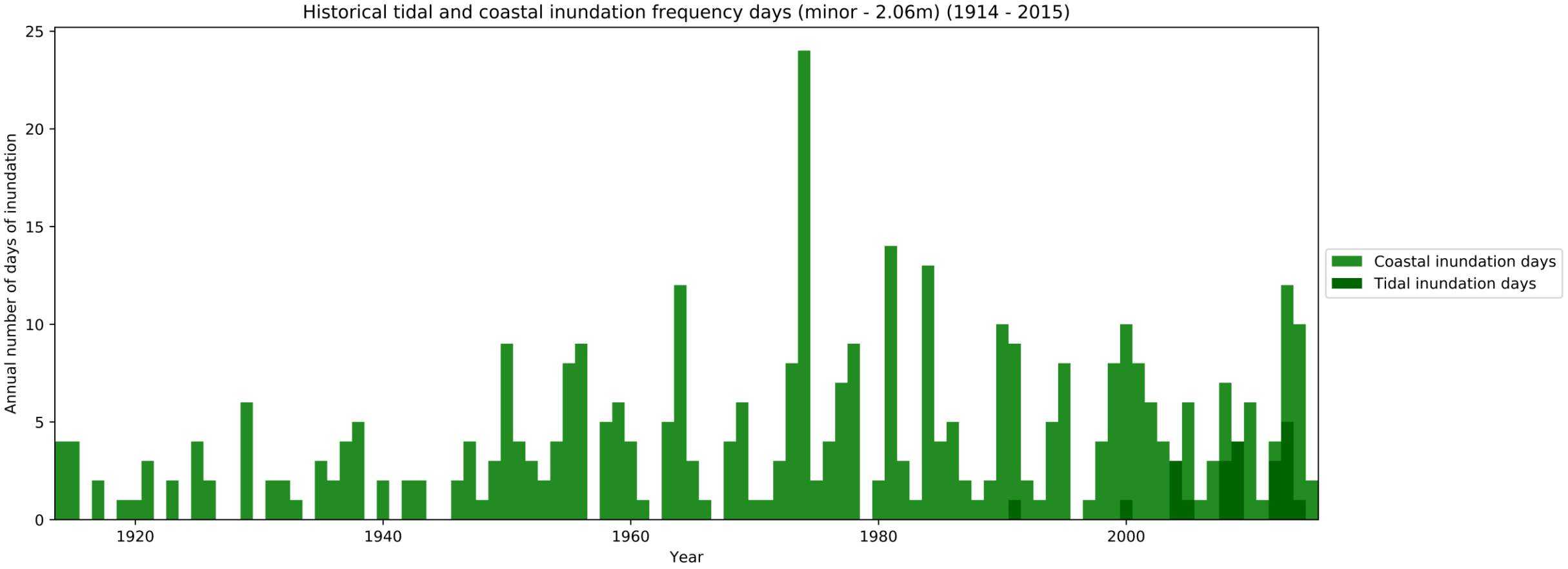
Coastal inundation: 5.16 days (97-15 mean), 300% increase since 14-32.
Tidal inundation emerged in 1991.






# Historical Frequencies of Coastal and Tidal Inundation

'Minor'

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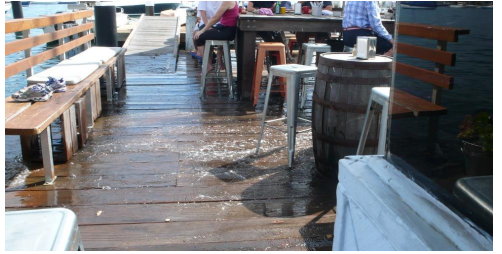
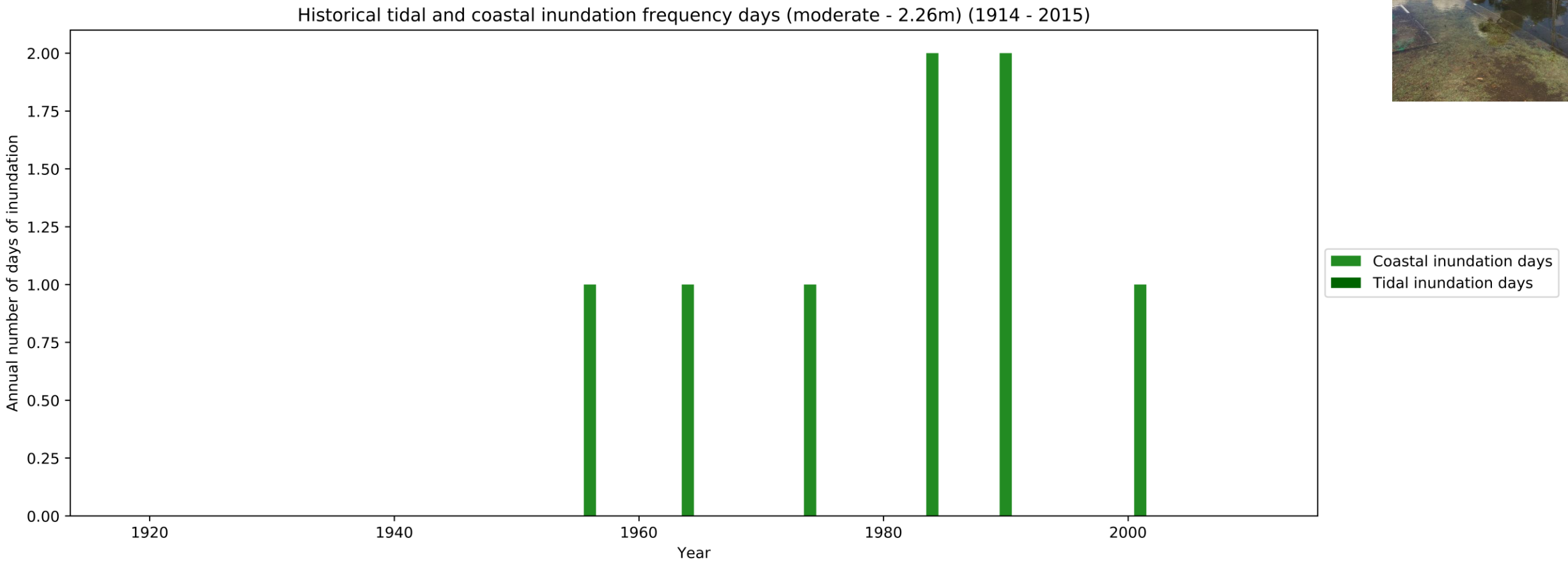
Coastal inundation: 11 days 1914-2018, 6 of those since 1990.
No tidal inundation






# Historical Frequencies of Coastal and Tidal Inundation

'Moderate'

Australian Government
Bureau of Meteorology

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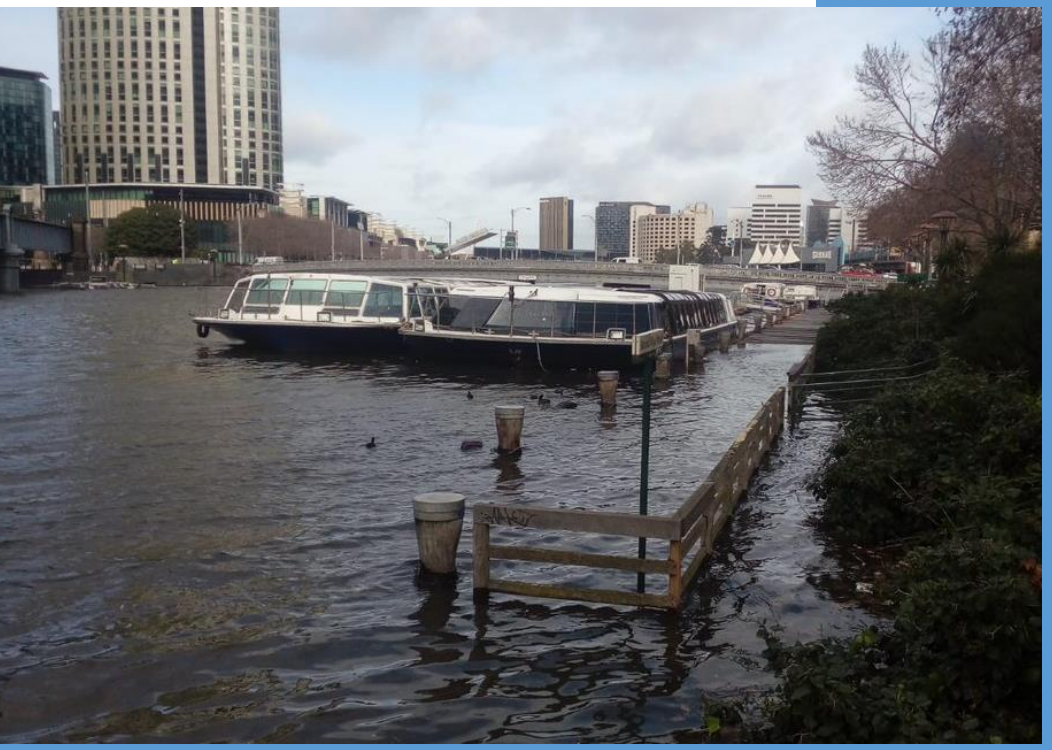


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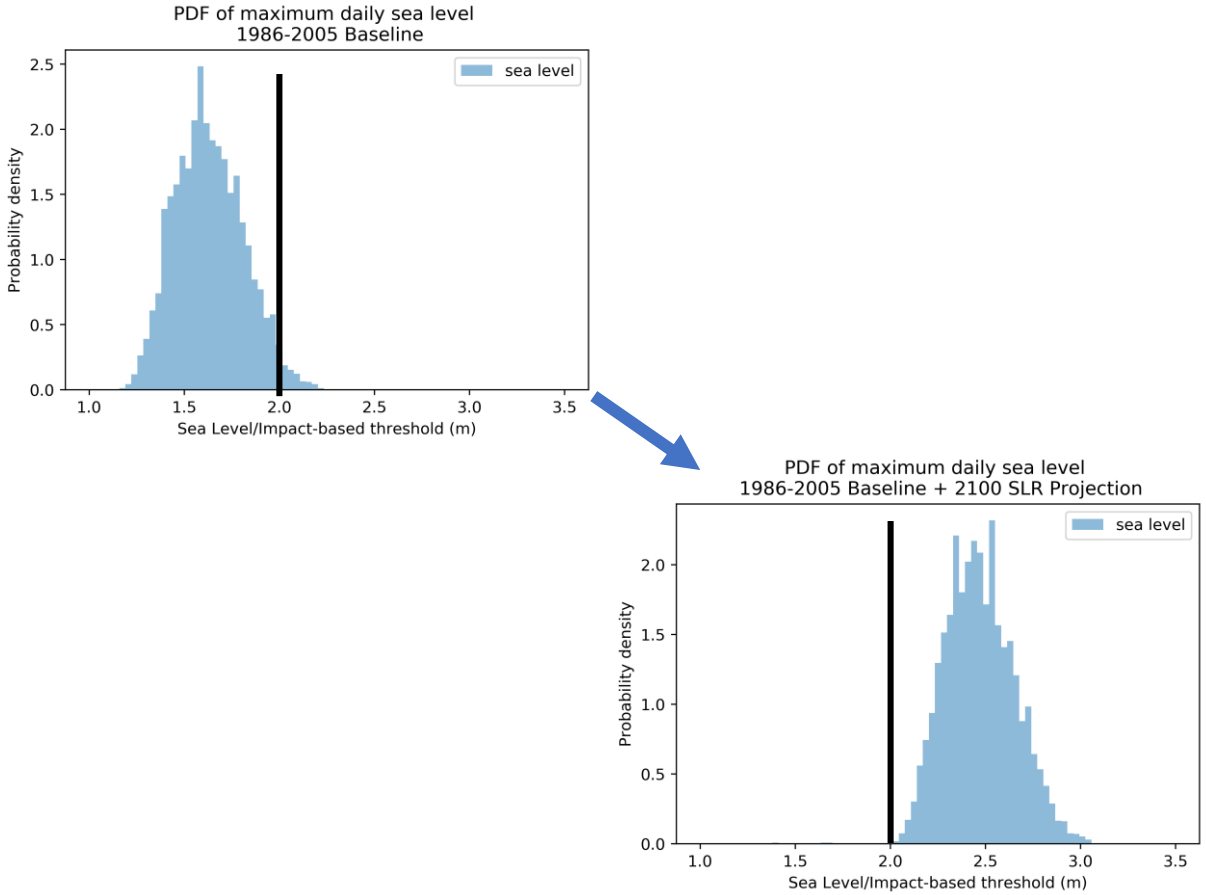
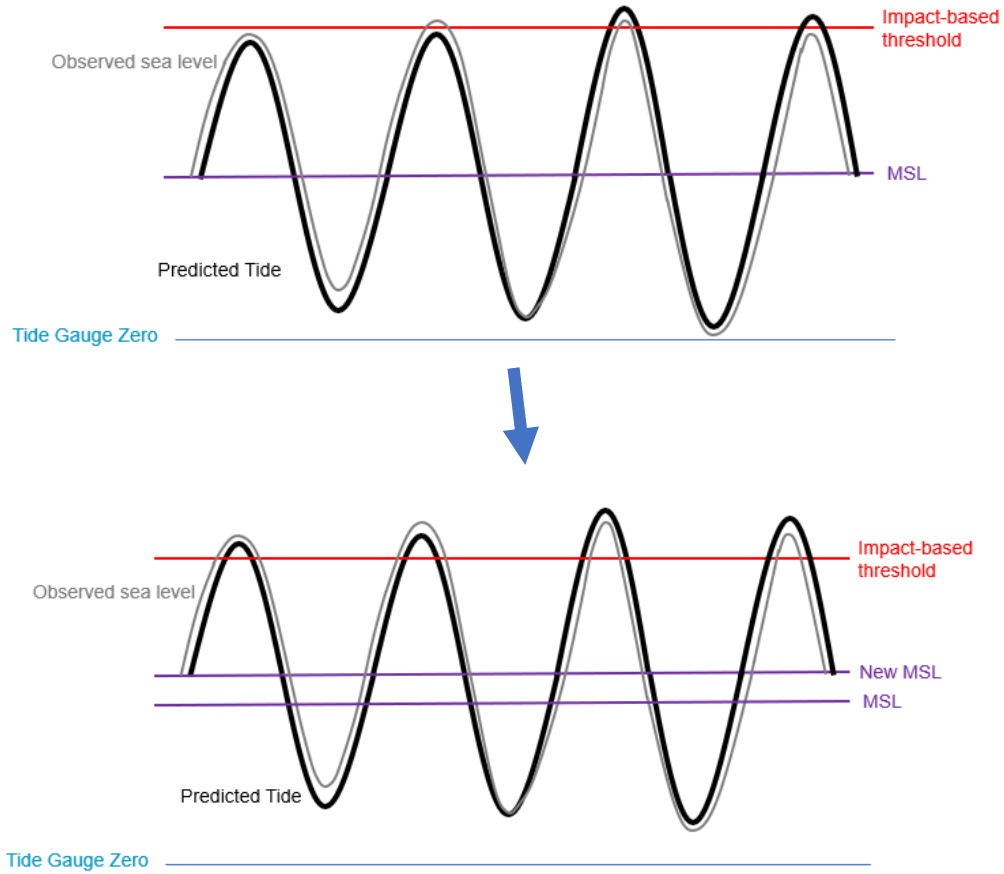
Coastal Inundation: Shift the probability distribution of total sea level by an increment of MSL rise projection




Tidal Inundation: Derive the tide predictions (i.e. tide tables) and add on an increment of MSL rise




# Future Frequencies of Coastal and Tidal Inundation

## How do we derive these?

Projections from IPCC (2019) Special Report on the Oceans and Cryosphere in a Changing Climate.

Australian Government
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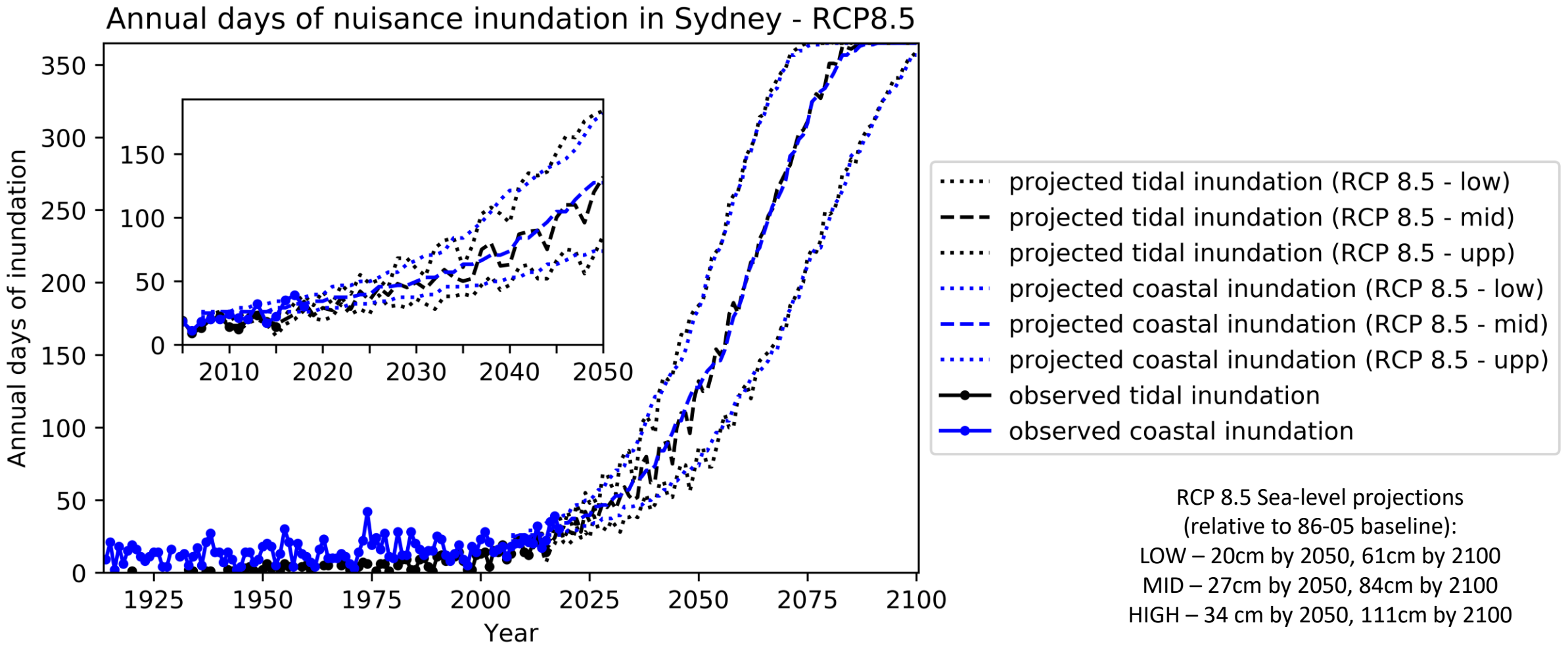


RCP 8.5 Sea-level projections
(relative to 86-05 baseline):
LOW – 20cm by 2050, 61cm by 2100
MID – 27cm by 2050, 84cm by 2100
HIGH – 34 cm by 2050, 111cm by 2100

# Future Frequencies of Coastal and Tidal Inundation

'Nuisance'

Projections from IPCC (2019) Special Report on the Oceans and Cryosphere in a Changing Climate.

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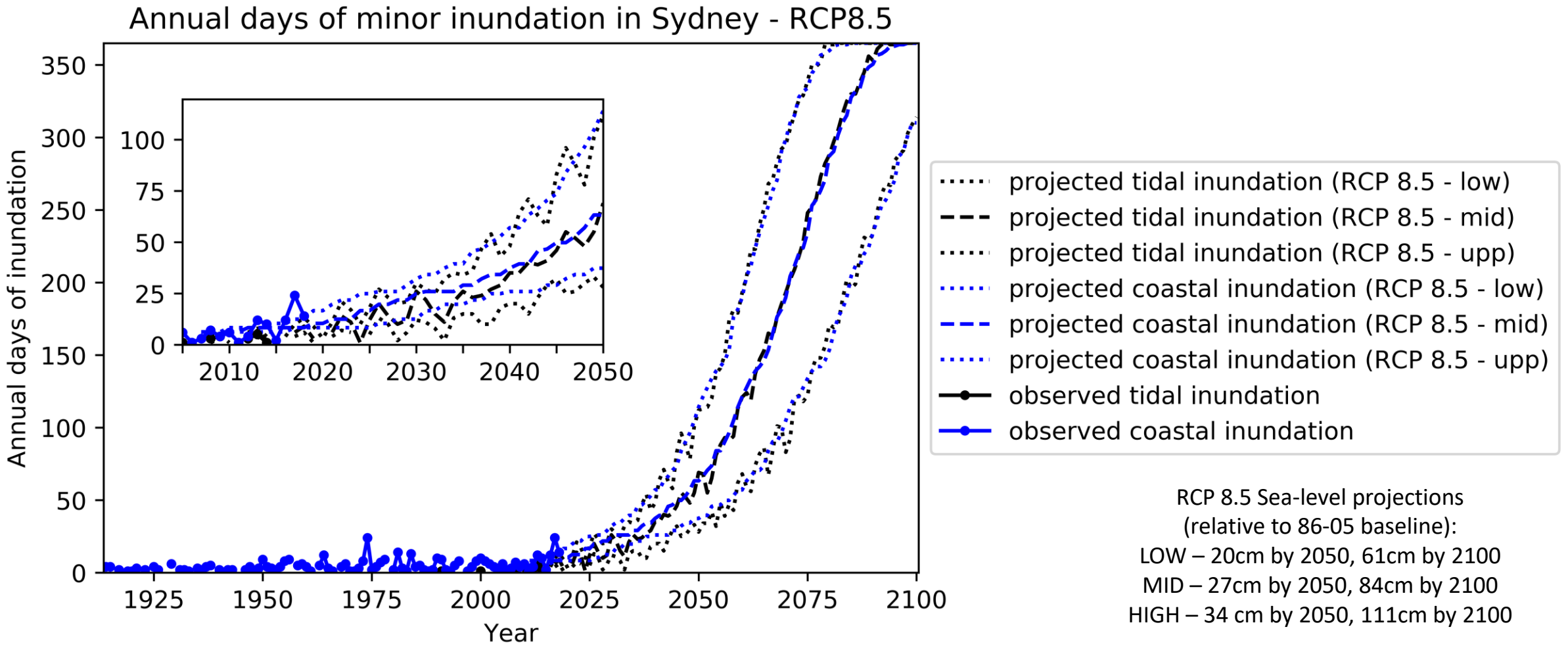


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# Future Frequencies of Coastal and Tidal Inundation

'Minor'

Projections from IPCC (2019) Special Report on the Oceans and Cryosphere in a Changing Climate.

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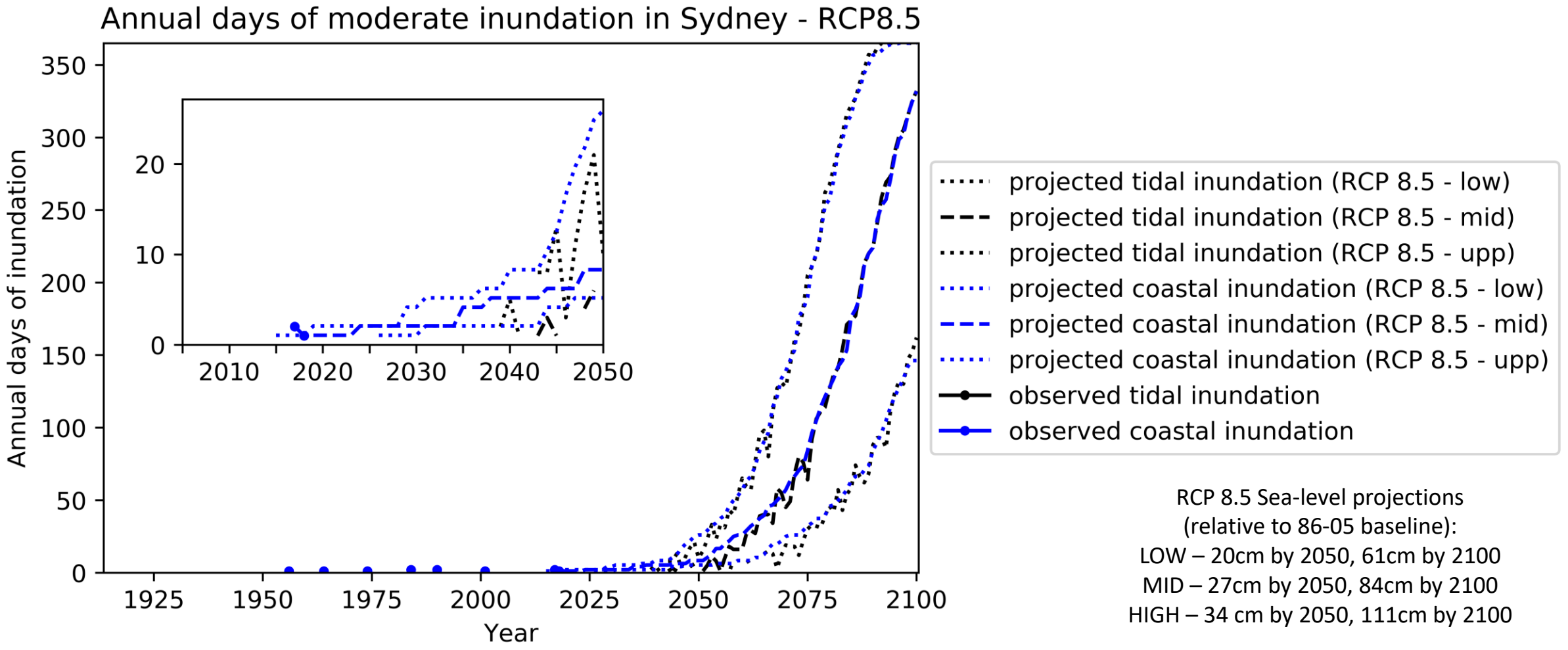
Convergence of tidal and coastal inundation frequency curves means that storm surge climatology is irrelevant to future flood frequencies, even for moderate flooding.




RCP 8.5 Sea-level projections
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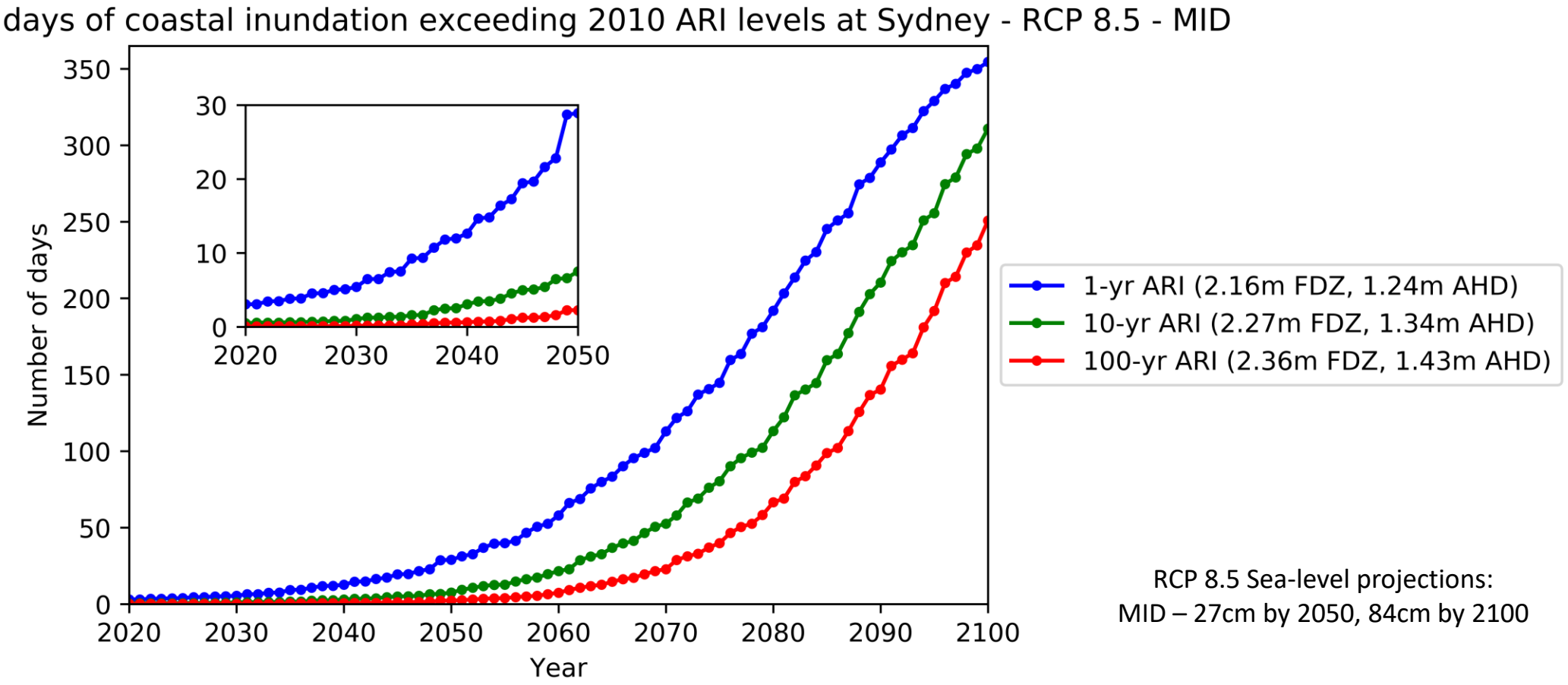
# Future Frequencies of Coastal and Tidal Inundation

'Moderate'

Projections from IPCC (2019) Special Report on the Oceans and Cryosphere in a Changing Climate.




RCP 8.5 Sea-level projections:
MID – 27cm by 2050, 84cm by 2100

# Future Frequencies of Modern-day Extremes

## Changing ARIs

Projections from SROCC (IPCC 2019).
ARIs from DECCW (2010)

Australian Government
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# Summary

The frequency of coastal inundation in northern Australia has increased over the last 50 years.

Minor flooding expected to occur daily under RCP8.5 scenario by 2100.

Impact-based thresholds can be used to define levels of coastal inundation impacts

Tidal inundation is becoming the leading cause of impact-producing extreme sea level events

Modern-day 1-in-100 year event expected to occur approx. 250 days per year by 2100.

Photo: Harry Clark.
Windsor, QLD. 3 January 2018

Australian Government
Bureau of Meteorology

MONASH University

# Thank you… Questions?

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