Navigating Coastal Inundation in Rarotonga, Cook Islands: Probabilistic Risk Mapping and Forecasting

UNEP CIS-PAC 5 project

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Pacific Community (SPC), Fiji

Santander, September 2025


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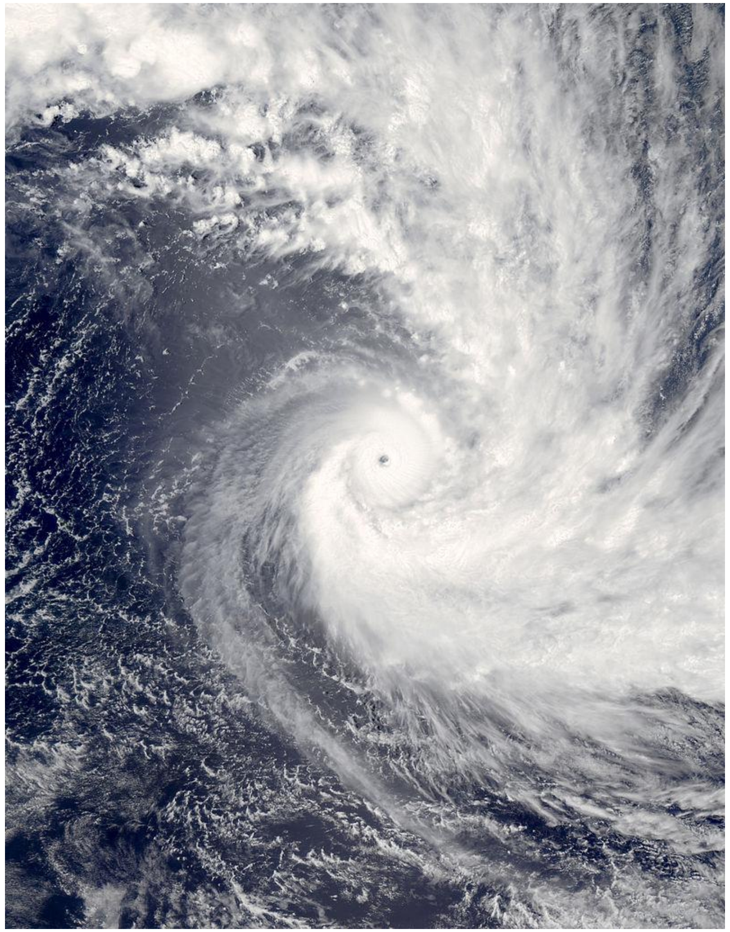
Coastal Inundation in the Cook Islands

Severe TC Meena, Feb 2005



https://www.youtube.com/watch?v=M6S-IfdS6eU&ab_channel=geoffmackley

Coastal Inundation in the Cook Islands

July 2022 Swell

- Waves: + 4.5 m and + 16 s
- Damage to hotels, homes and businesses
- Washed out coastal defenses, left huge boulders across the road

Source: https://x.com/MattBlacka/

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Goals

- Develop island scale **probabilistic inundation maps** that combine swells, tropical cyclones and SLR using state-of-the-art tools and methodologies.
- Establish an actionable **early warning system** to forecast coastal flooding up to 7 days in advance.
- Work closely with the Cook Islands Meteorological Service and Emergency Management Office to **co-design, build trust, and ensure long-term ownership**.






What dominates water levels?

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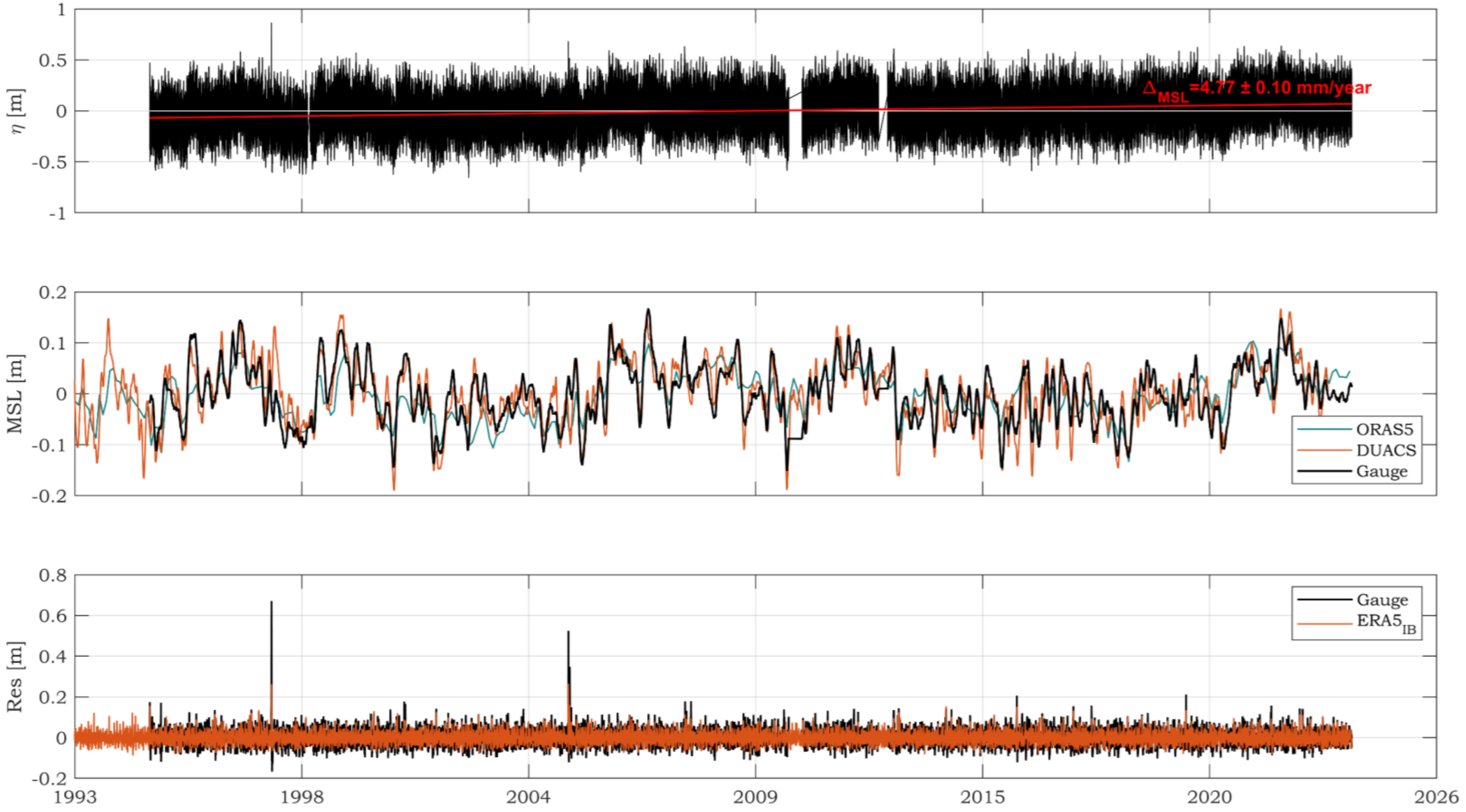
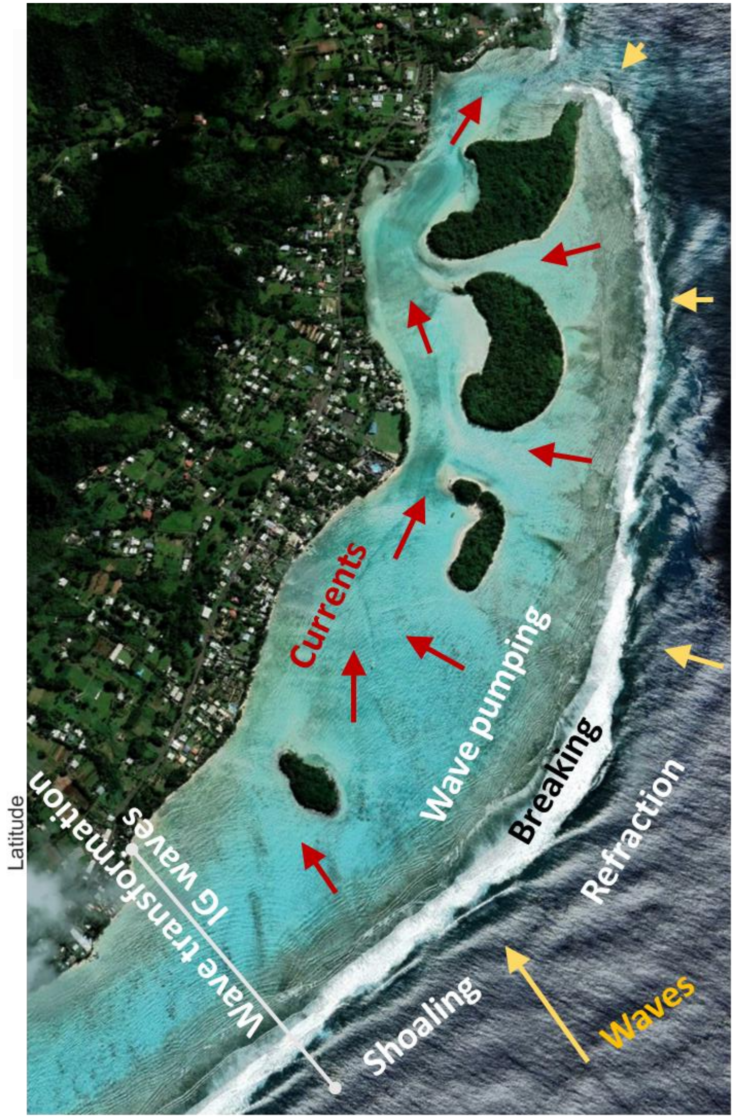
COSPPac

Australian Government
Bureau of Meteorology

Rarotonga tide gauge





Baseline data

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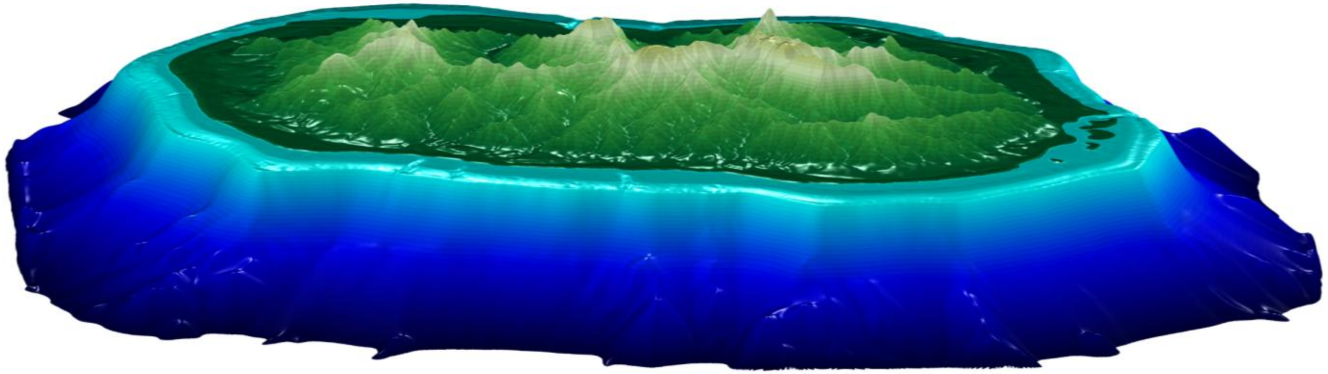
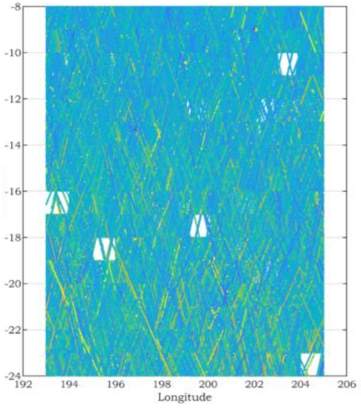
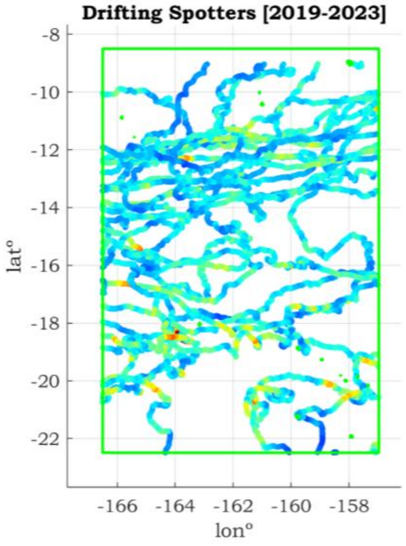
Seamless topobathy 5m = LiDAR + Multibeam + SRTM15



Altimeters

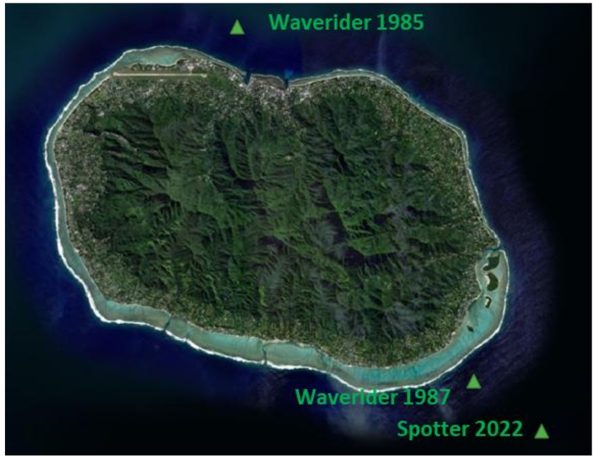




Oceanographic data

- Tide gauges
- Altimeters
- Fixed buoys
- Drifting buoys

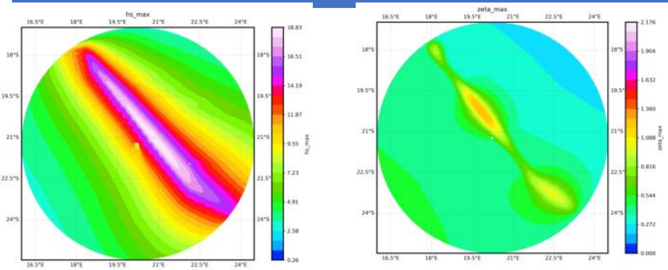
Fixed buoys



Coastal Inundation model chain

SWAN
Simulating WAves Nearshore

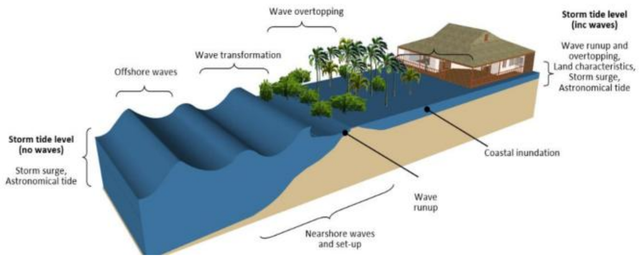
SWAN 2D
- Downscale waves to the island resolution
- TC waves



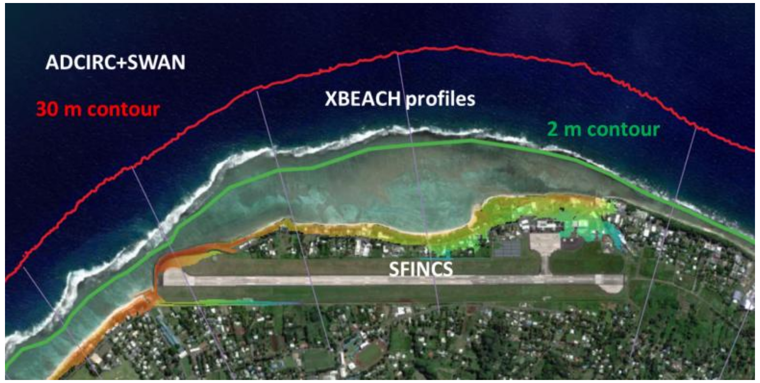
ADCIRC

ADCIRC 2D
- Tides
- TC storm surge

XBeach NH 1D
- Wave transformation processes
- IG waves and runup



SFINCS 2D
- Compound flooding



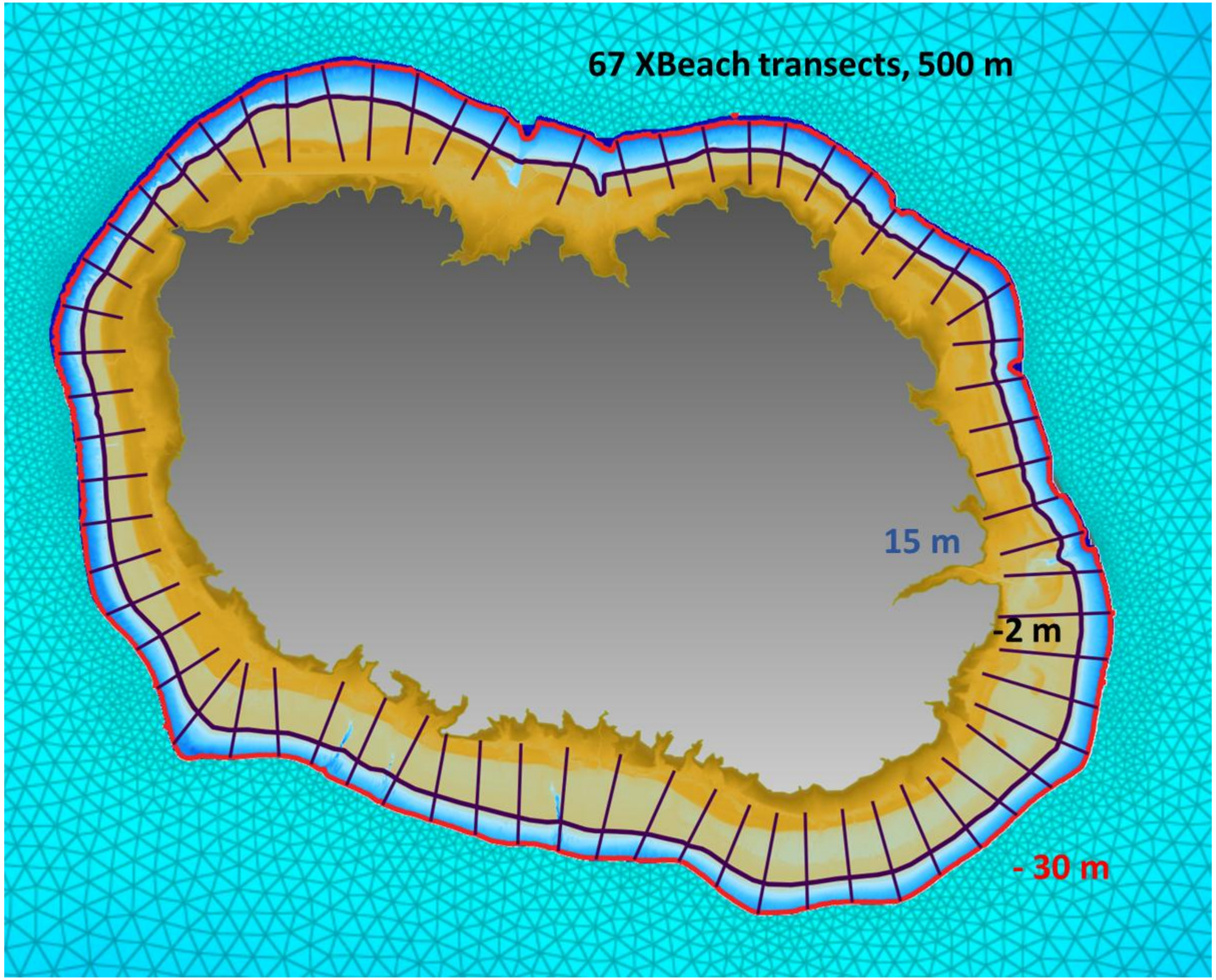
Coastal Inundation model chain

1) Extract wave parameters from hindcast [Hs,Tp,Dir,Dispr,Fspr], tide (TPXO9), SLA (ORAS5), and IB (ERA5)

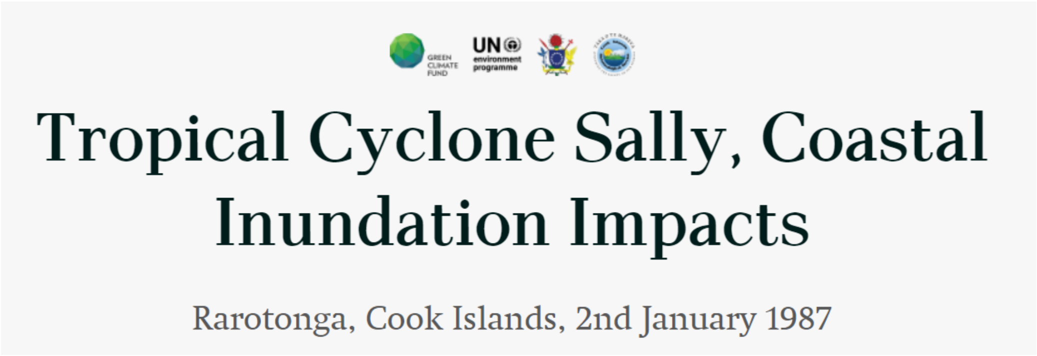
2) Run XBeach profiles

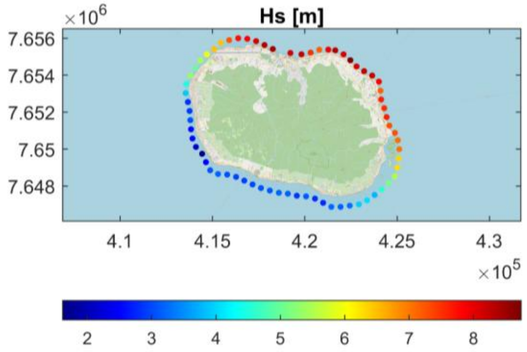
3) Extract free surface elevation time series at the intersection with the 2 m contour

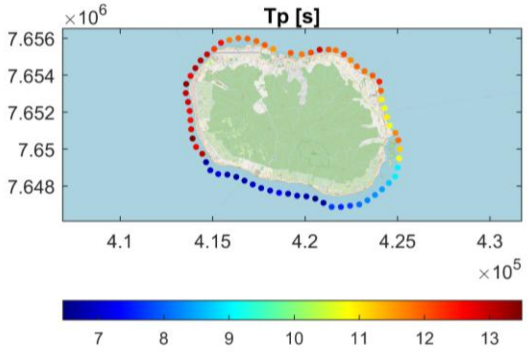
4) Run SFINCS

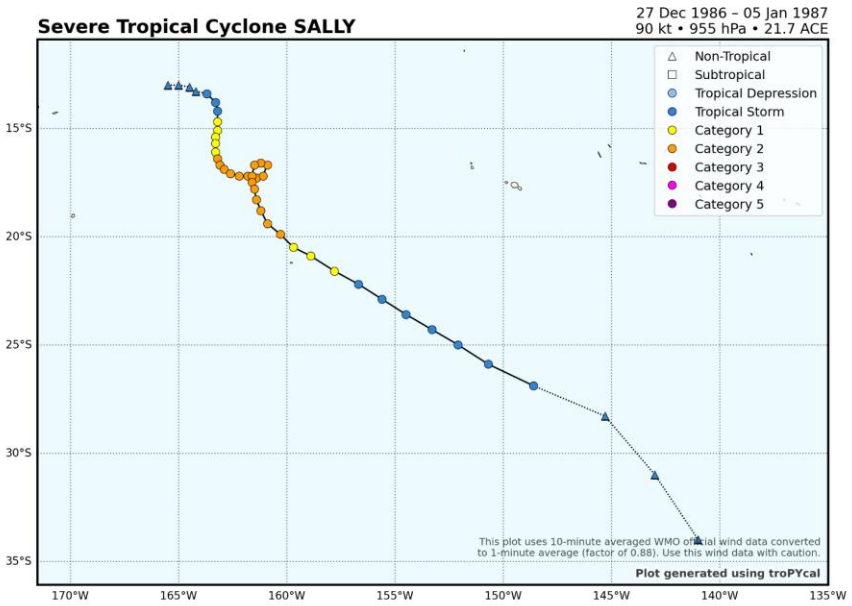


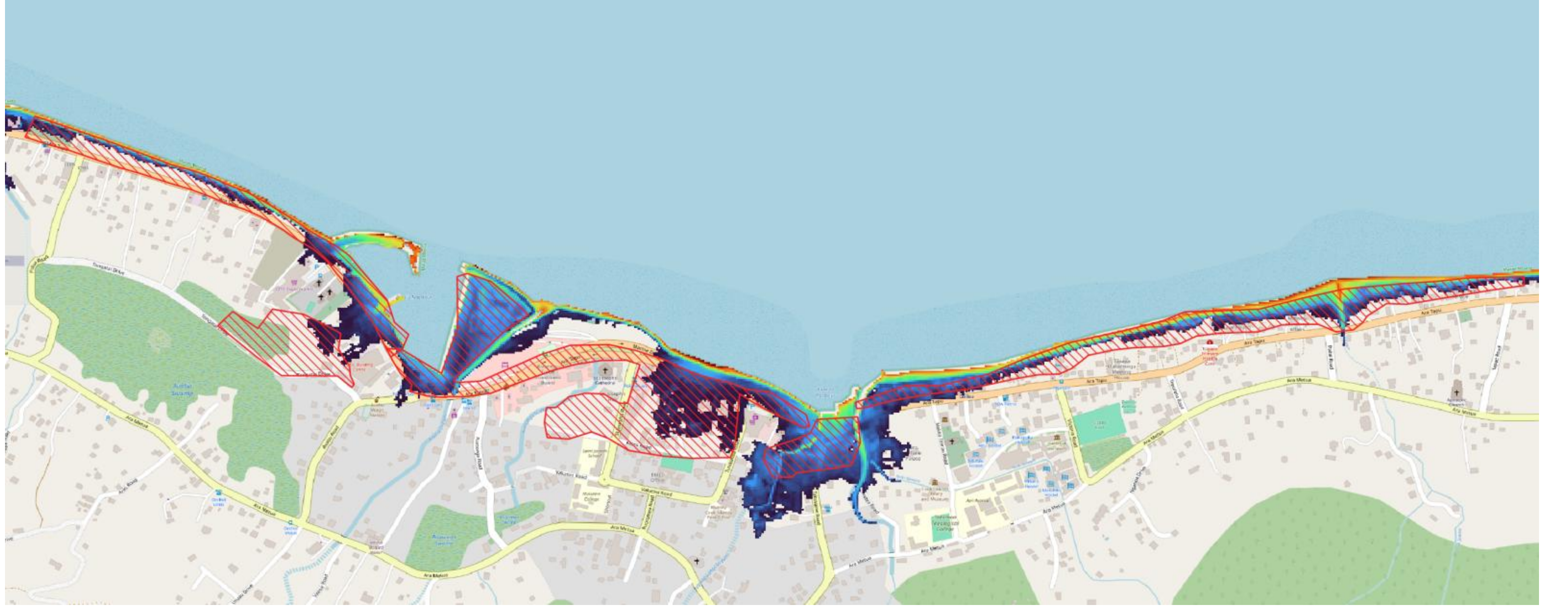
Coastal Inundation model chain



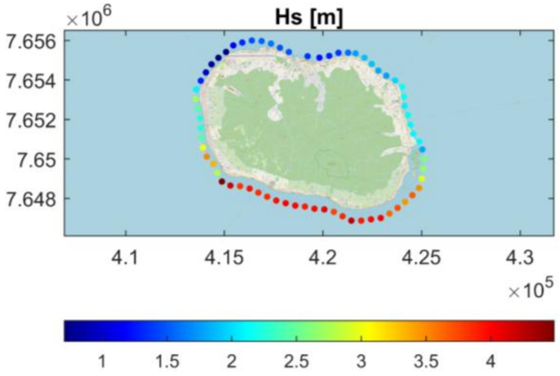


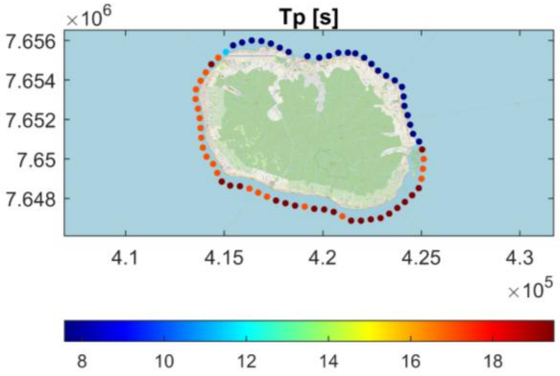


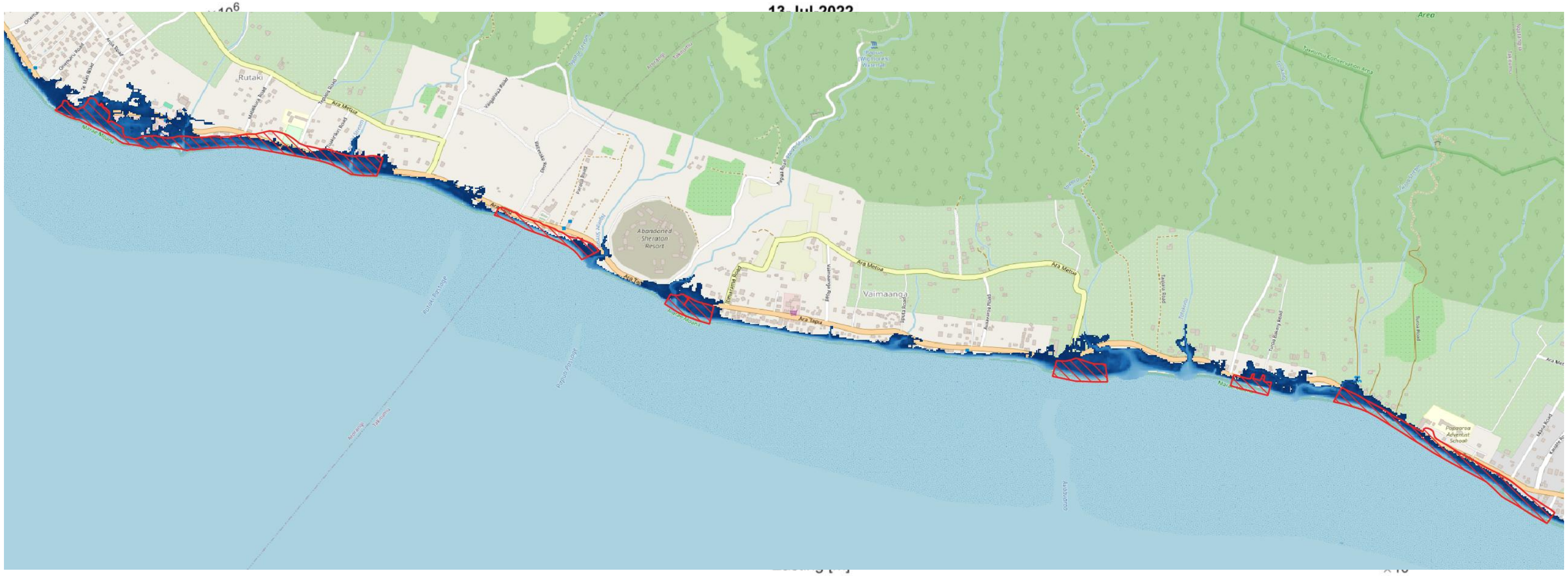




Coastal Inundation model chain



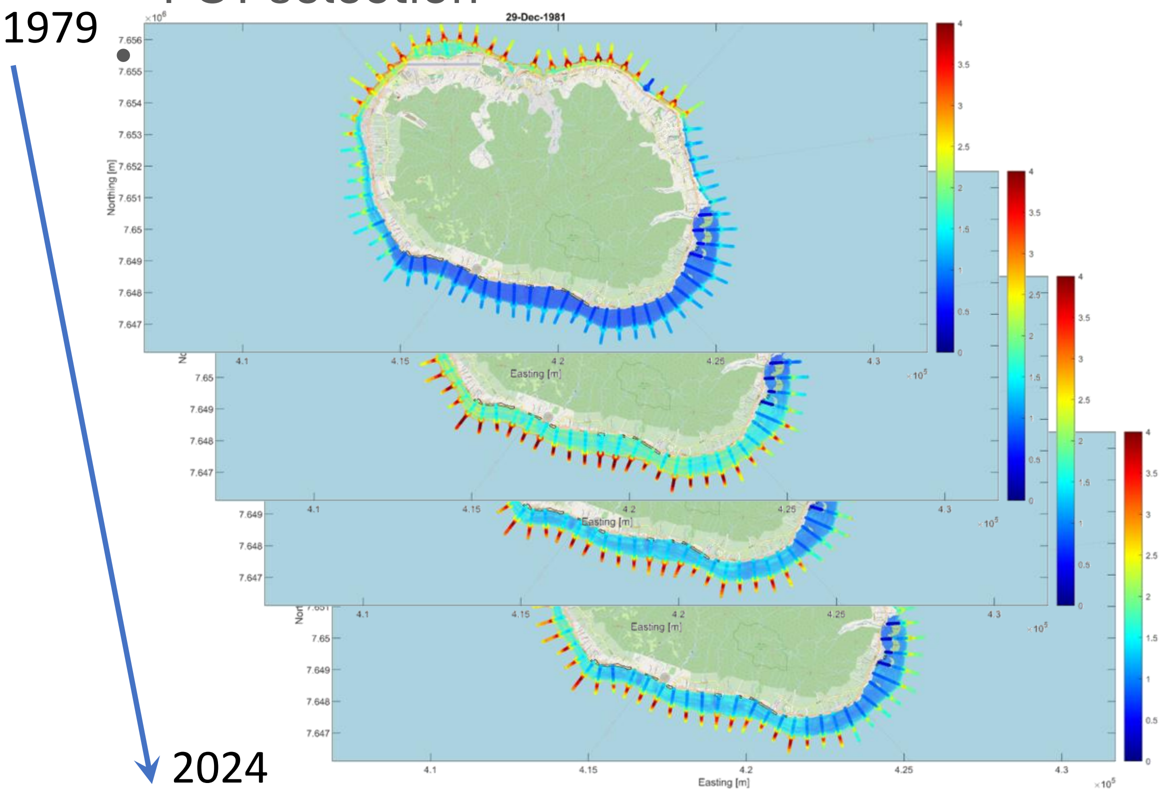




Probabilistic Hazard Assessment

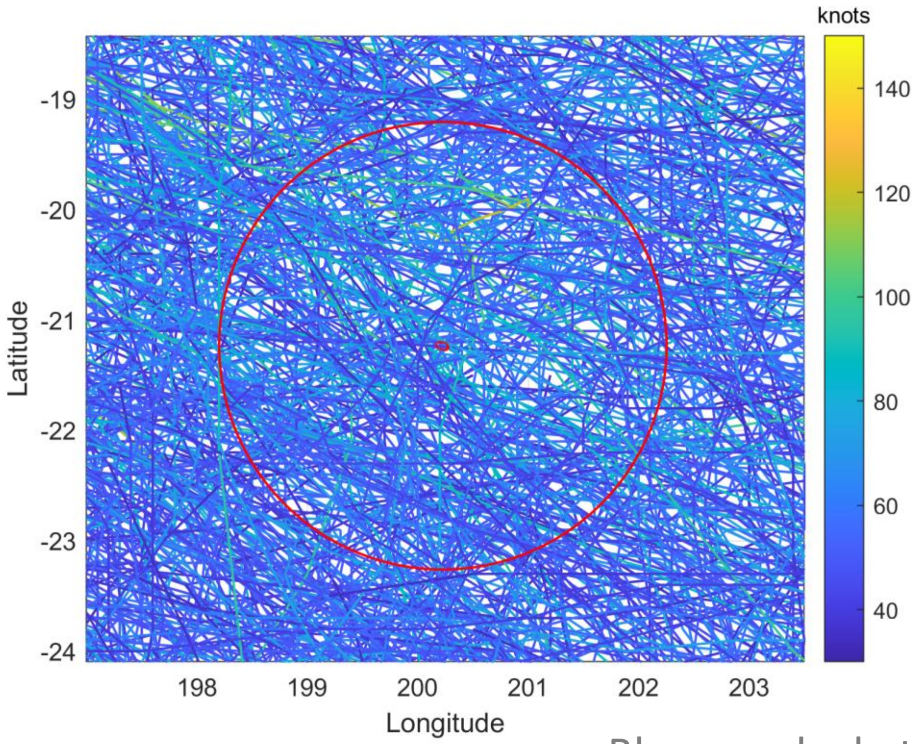
Swells

- Well represented in the high-res hindcast
- Remove near field TC related events
- POT selection



Tropical Cyclones

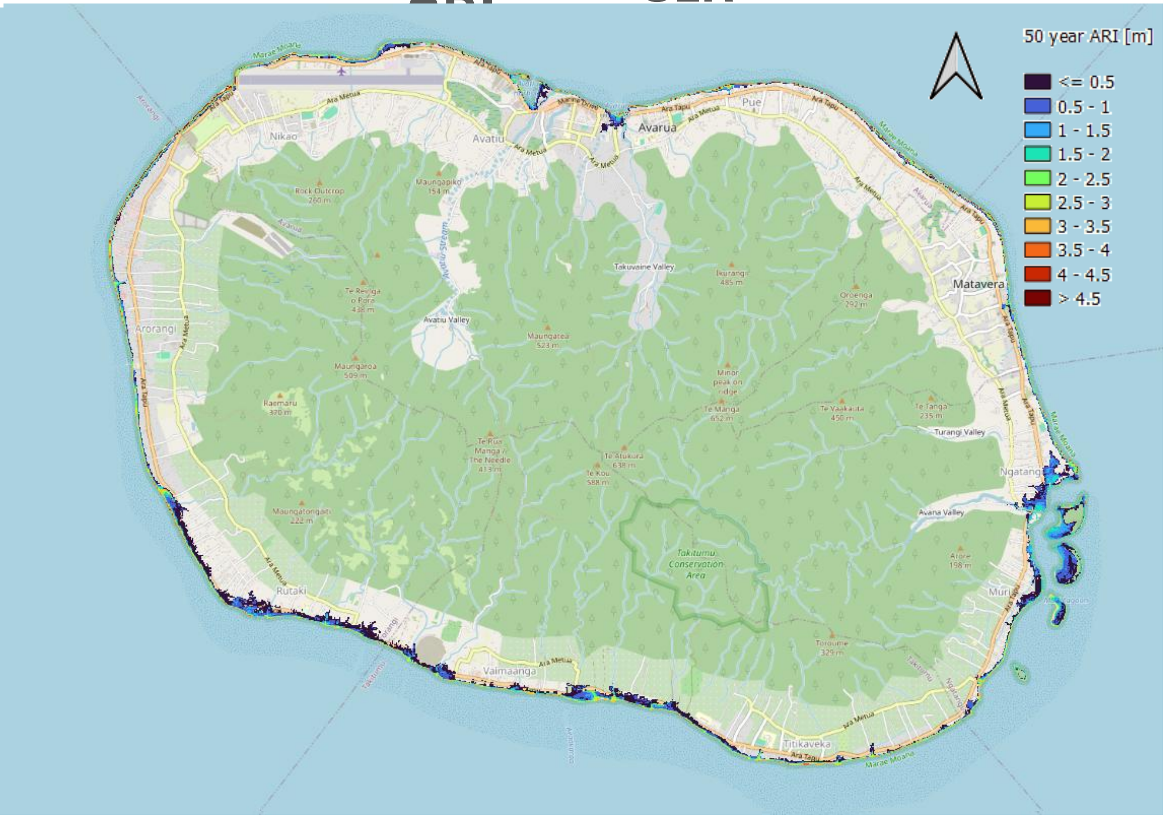
- Only 20 TCs from 1979 – 2023 less than 200 Km from Rarotonga, only two > Cat 2
- Stochastic simulation of TC tracks needed, ~ 370 TCs in 1000 years from STORM database
- ADCIRC+SWAN



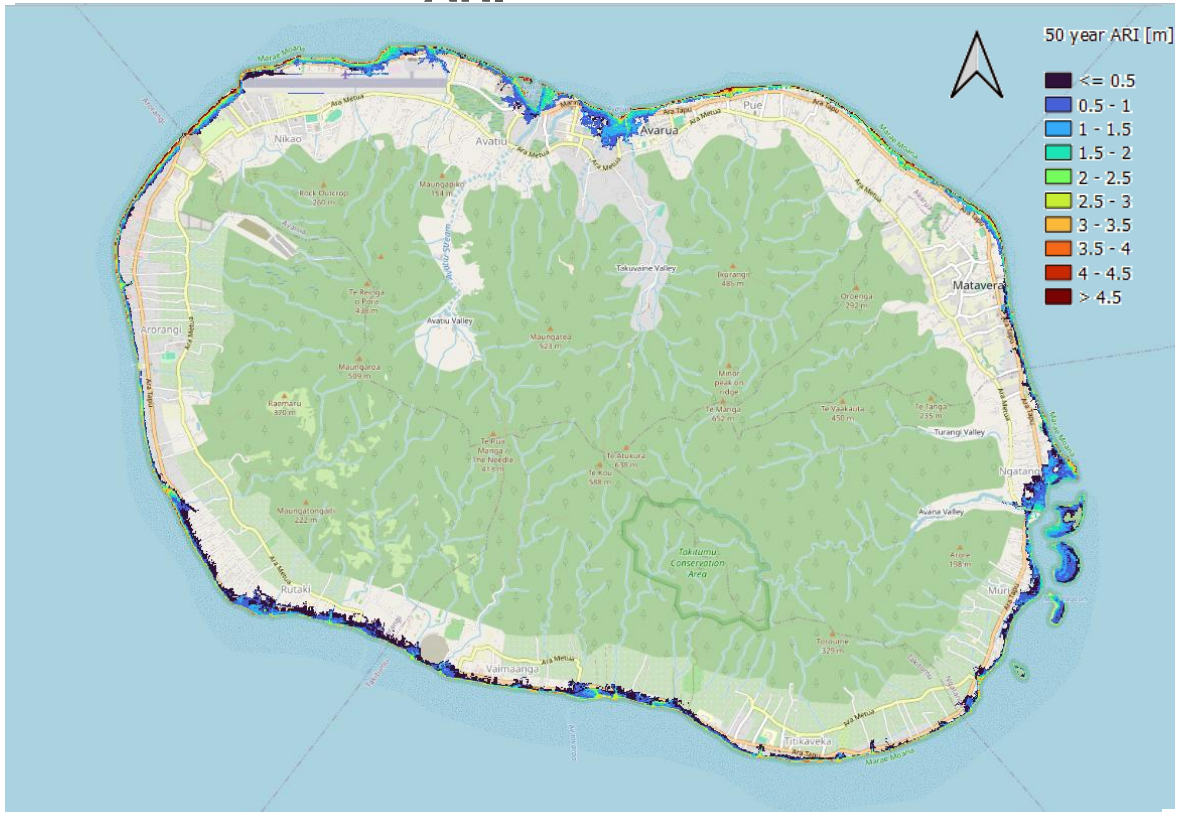
Bloemendaal et al., 2020

Hazard Maps

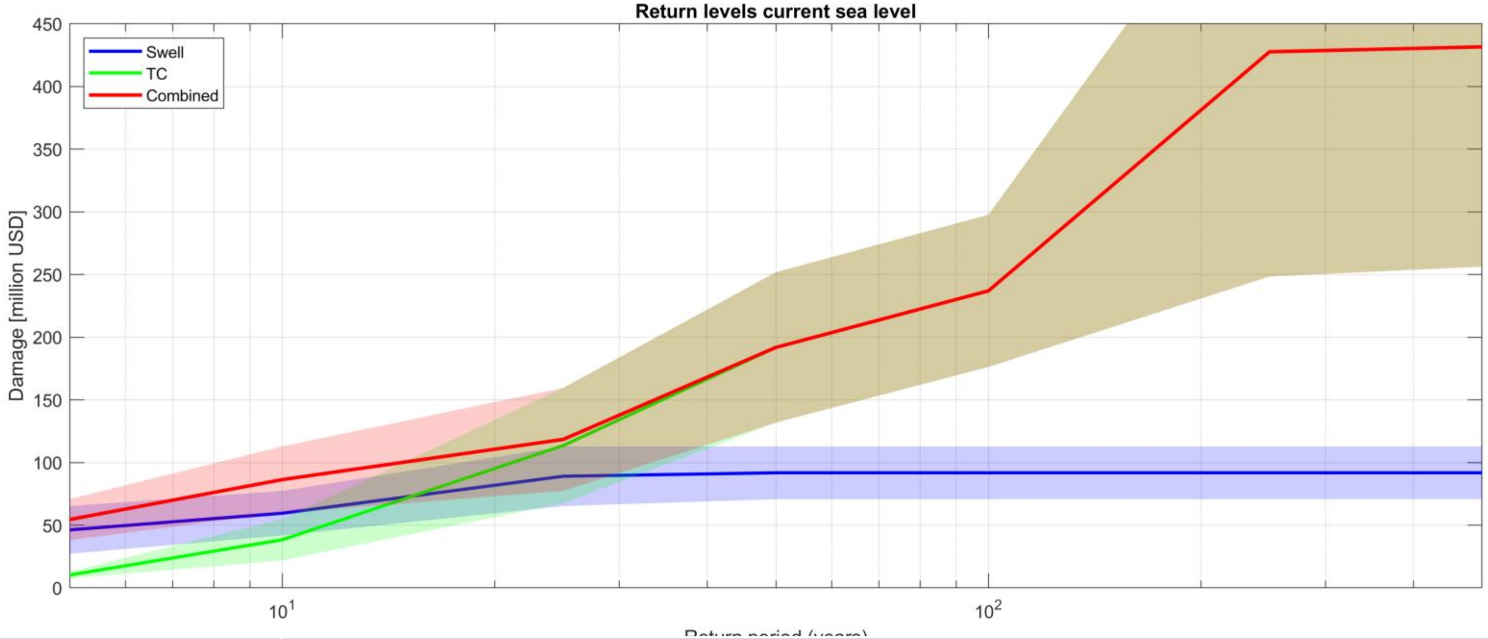
10 year ARI + 50 cm SLR



50 year ARI + 50 cm SLR

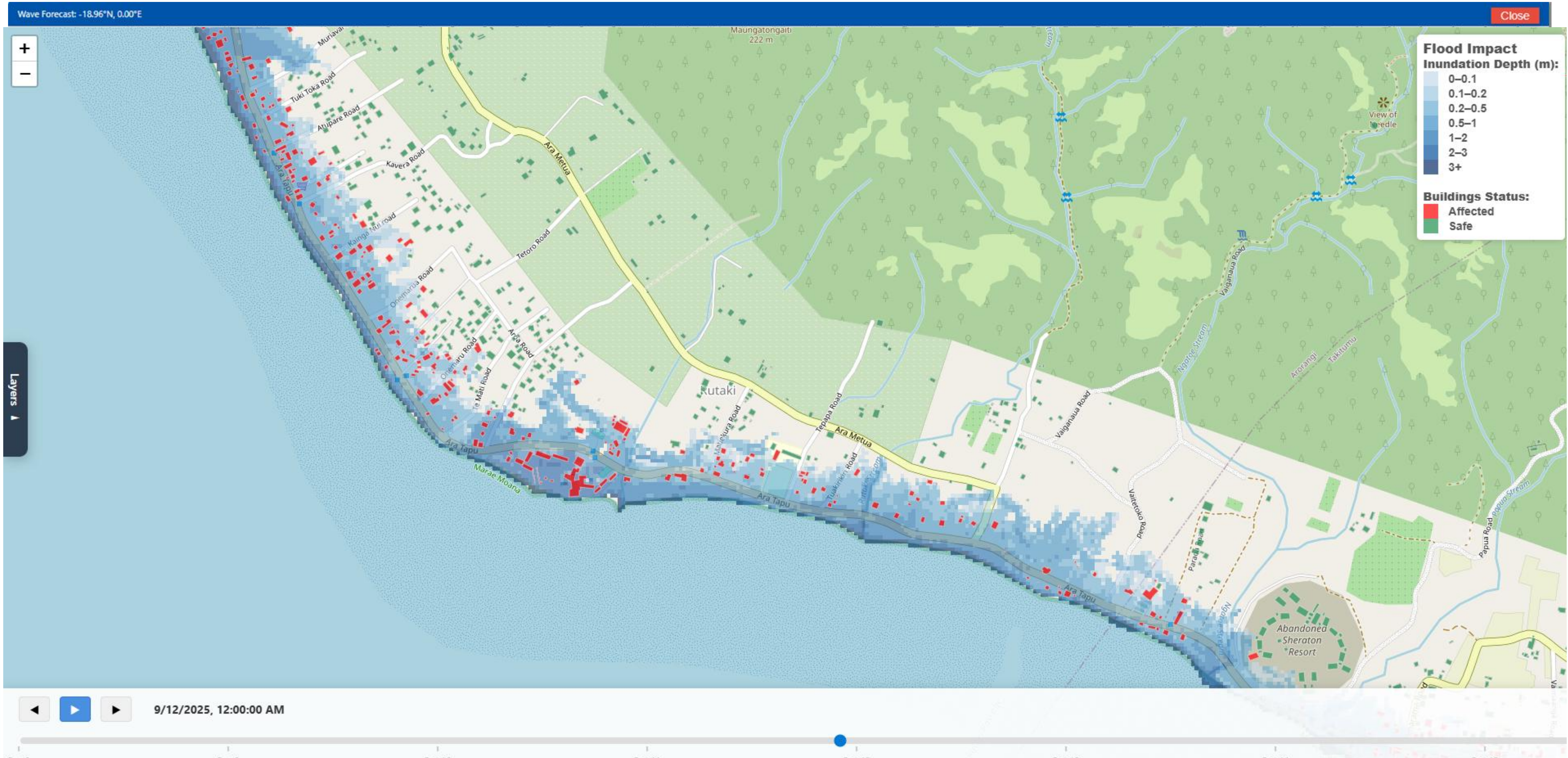


Probabilistic Risk Assessment



SLR [cm]	Expected Annual Damage [Million USD/year] PCRAFI 2025*		
	Swells	**TCs**	**Combined**
0	6.1	5.2	11.4 [9.1–13.8]
25	8.9	6.9	15.8 [12.6-19]
50	13.4	9.3	22.7 [18.2-27.13]
100	**30.8**	**17.1**	**47.9 [39.8-55.15]**

Towards Impact Based EWS



Takeaways

- Integrated multi-model approach to reproduce observed coastal inundation events in reef fronted islands
- Compromise between accuracy and computational cost, focused on the most dominant processes and time scales
- Modular and scalable to other Pacific islands
- Actionable Impact-based EWS, co-designed and owned by CIMS
- Project outcomes support long-term planning, disaster preparedness, and community resilience
- Weather Ready Pacific, UN EWS4all, UN OceanPredict…

Meitaki ma'ata!!!

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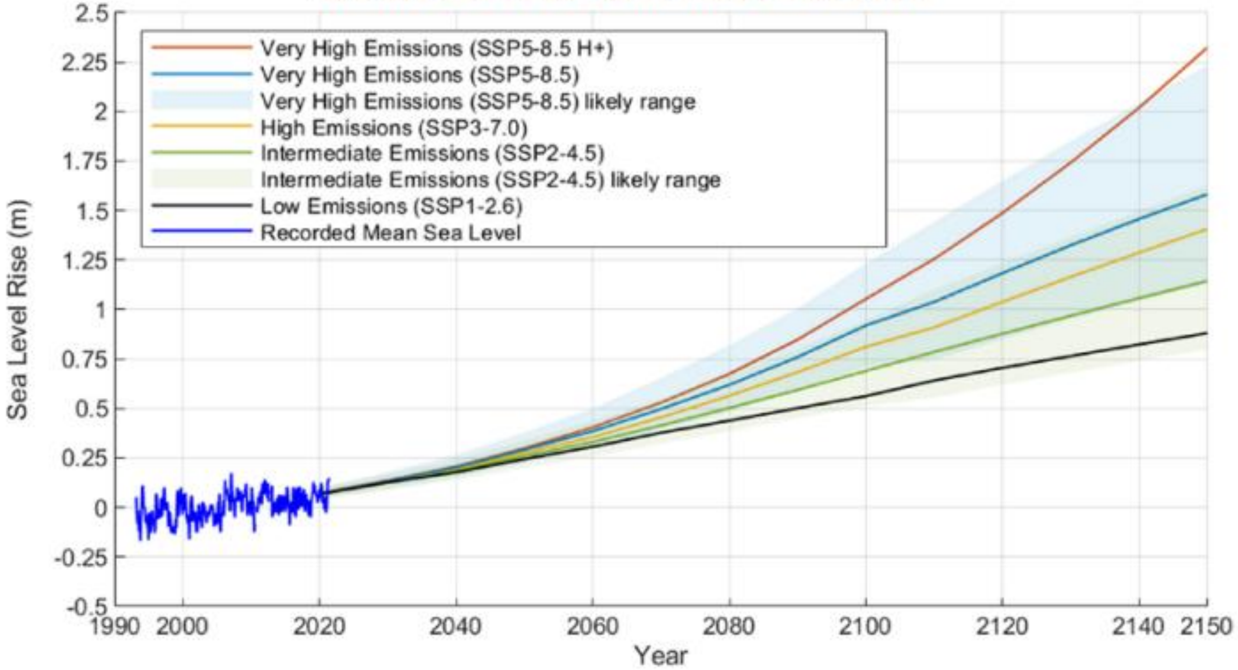
Figure 3.4: Sea Level Rise Projections to 2150 for the Cook Islands Relative to 1995–2014 Mean Sea Level



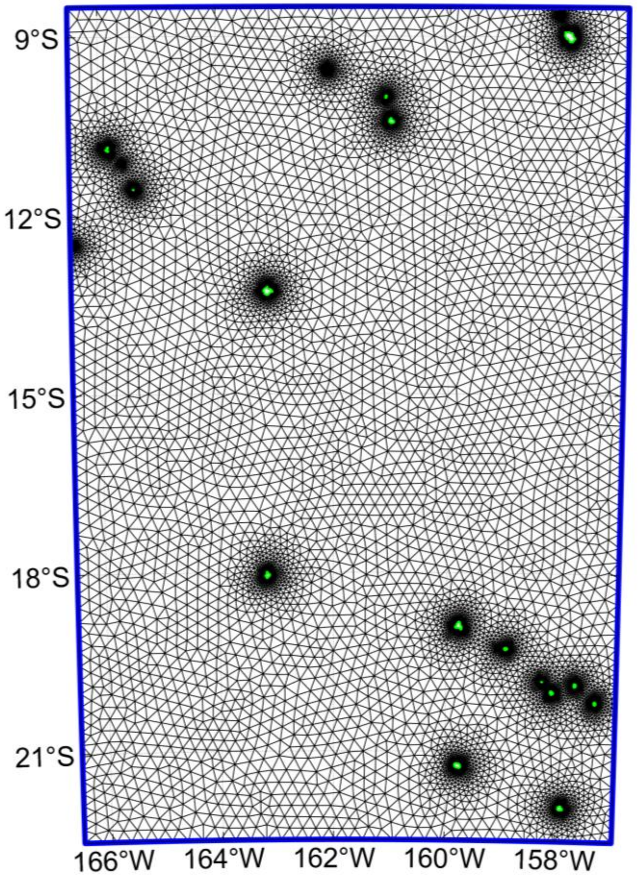
Notes:

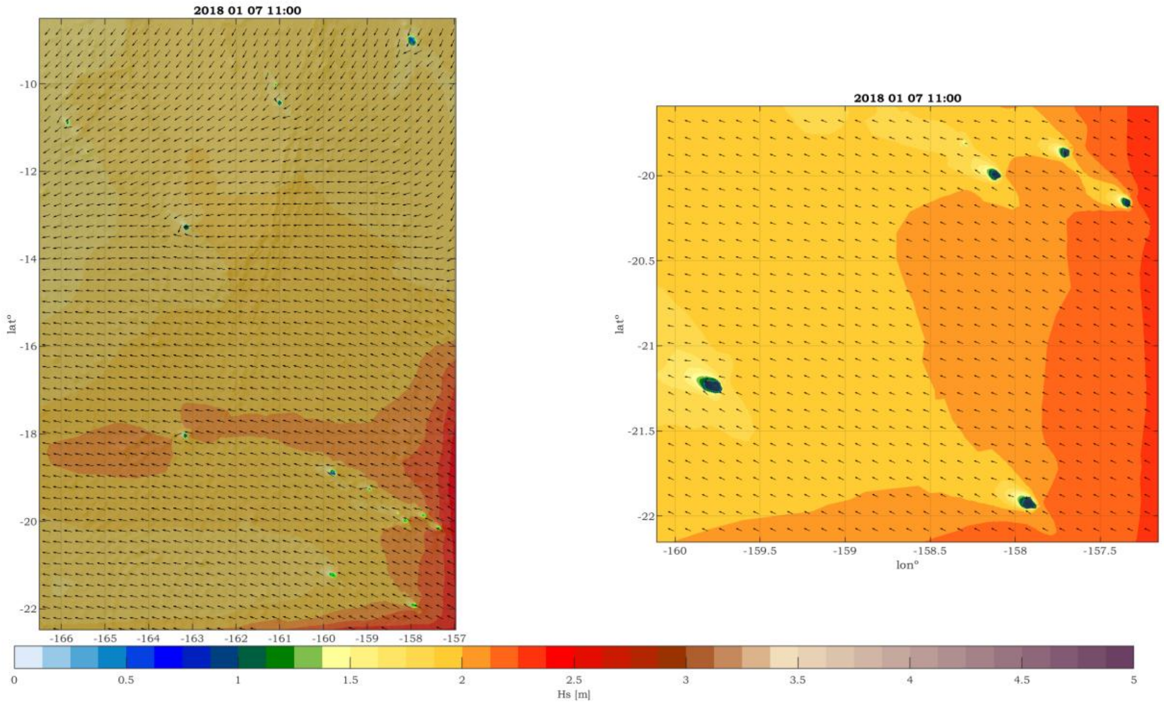
1. Shared Socioeconomic Pathway (SSP); H+ represents low confidence high consequence scenario.
2. Projections based on IPCC (2021), sourced from AR6 and interpolated to nearest decade and adjusted for the upper bound of the *most likely* vertical land movement as defined by Fox-Kemper et al. (2021).
3. Projections are given for the 50%ile of the CMIP6 model ensemble unless otherwise defined.

High-resolution Un-SWAN model

44820 nodes

...from 25 Km to 100 m...





Un-SWAN sensitivity analysis

Run ID	Configuration	Description
ERA5	ERA5	--
Default	Standard setup with SWAN default parameters	Standard Komen physics (GEN3)
$ST6_1$	GEN3 ST6 4.7E-7 6.6E-6 4.0 4.0 UP HWANG VECTAU U10PROXY 28.0 AGROW	Low-growth, Hwang wind input, vector τ, U10 proxy, wave age 28
$ST6_2$	GEN3 ST6 4.7E-7 6.6E-6 4.0 4.0 UP FAN VECTAU U10PROXY 28.0 AGROW	Same as above but FAN wind input
$ST6_3$	GEN3 ST6 2.8E-6 3.5E-5 4.0 4.0 UP HWANG VECTAU U10PROXY 32.0 AGROW	Moderate-growth, Hwang input, wave age 32
$ST6_4$	GEN3 ST6 2.8E-6 3.5E-5 4.0 4.0 UP HWANG VECTAU U10PROXY 32.0 DEBIAS 0.89 AGROW	Same as Run 4 but with 0.89 wind bias correction
$ST6_5$	GEN3 ST6 6.5E-6 8.5E-5 4.0 4.0 UP HWANG VECTAU U10PROXY 35.0 AGROW	High-growth, Hwang input, wave age 35
$ST6_6$	GEN3 ST6 4.7E-7 6.6E-6 U10P 28. AGROW	Simplified wind input, wave age 28
$ST6_7$	GEN3 ST6 2.8E-6 3.5E-5 U10P 32. AGROW	Simplified wind input, wave age 32
$ST6_8$	GEN3 ST6 5.7E-7 8.0E-6 4.0 4.0 UP HWANG U10PROXY 28.0 AGROW	Mid-growth, Hwang input, wave age 28
$ST6_9$	GEN3 ST6 5.7E-7 8.0E-6 4.0 4.0 UP AGROW	Mid-growth, unified input, wave age 28

Refs: Komen et al., 1984; Ardhuin et al., 2010; Hwang,2011; Rogers et al., 2012; Zieger et al., 2015

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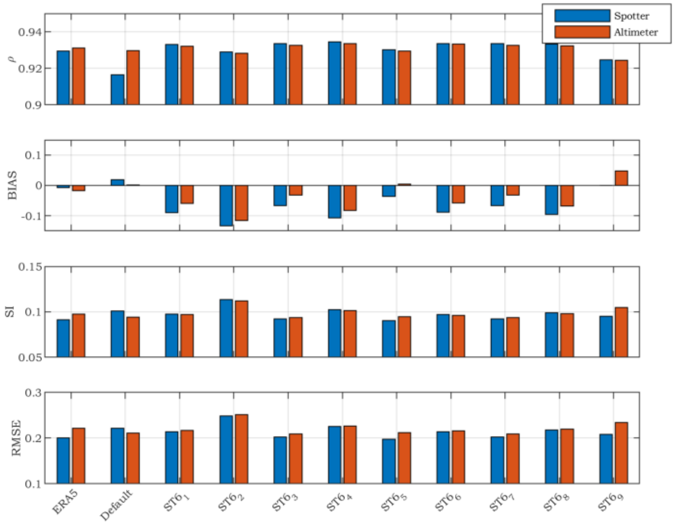
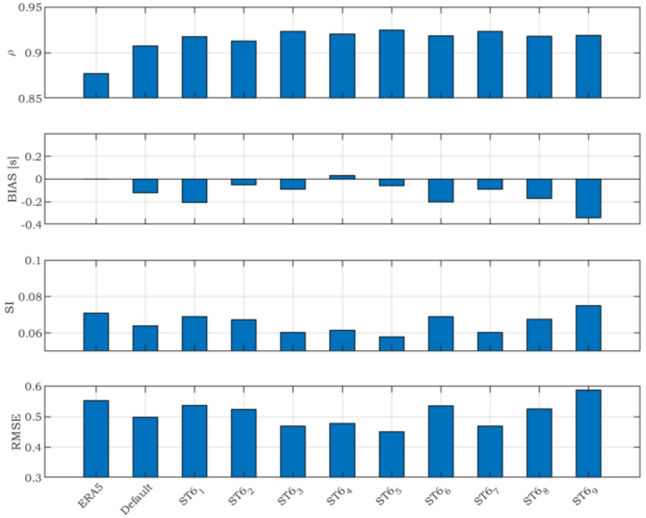
Un-SWAN sensitivity analysis

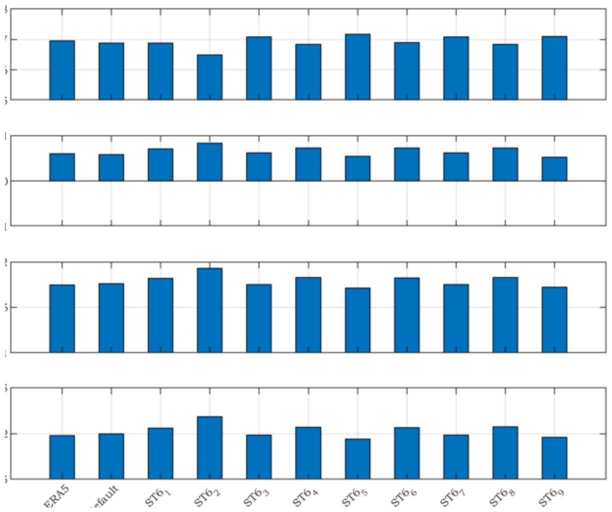
Hs



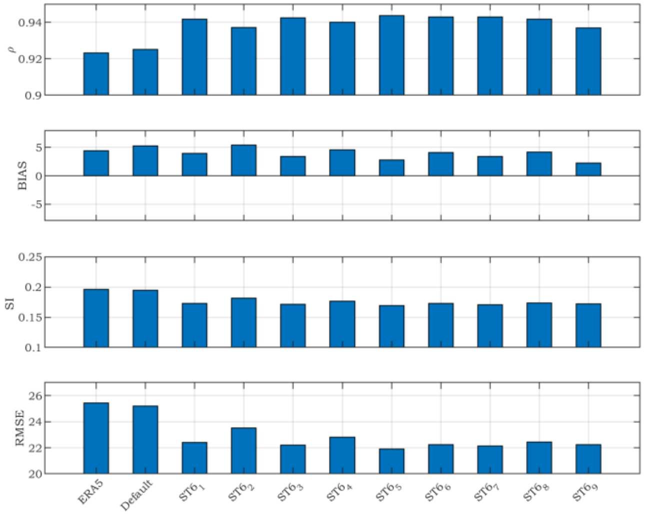
Tm 01



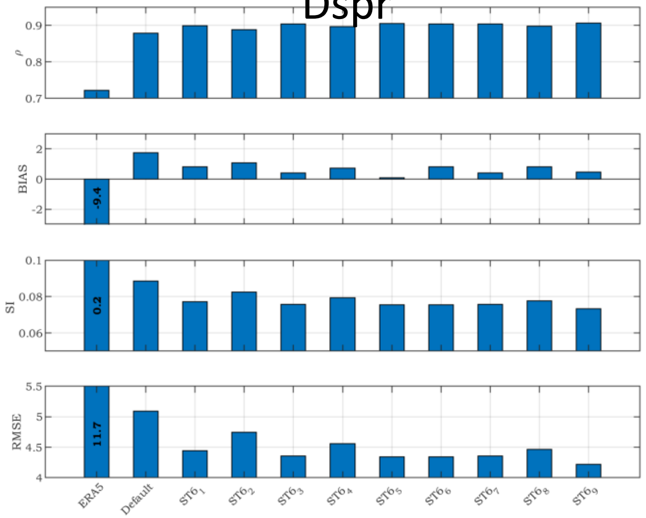
Tp

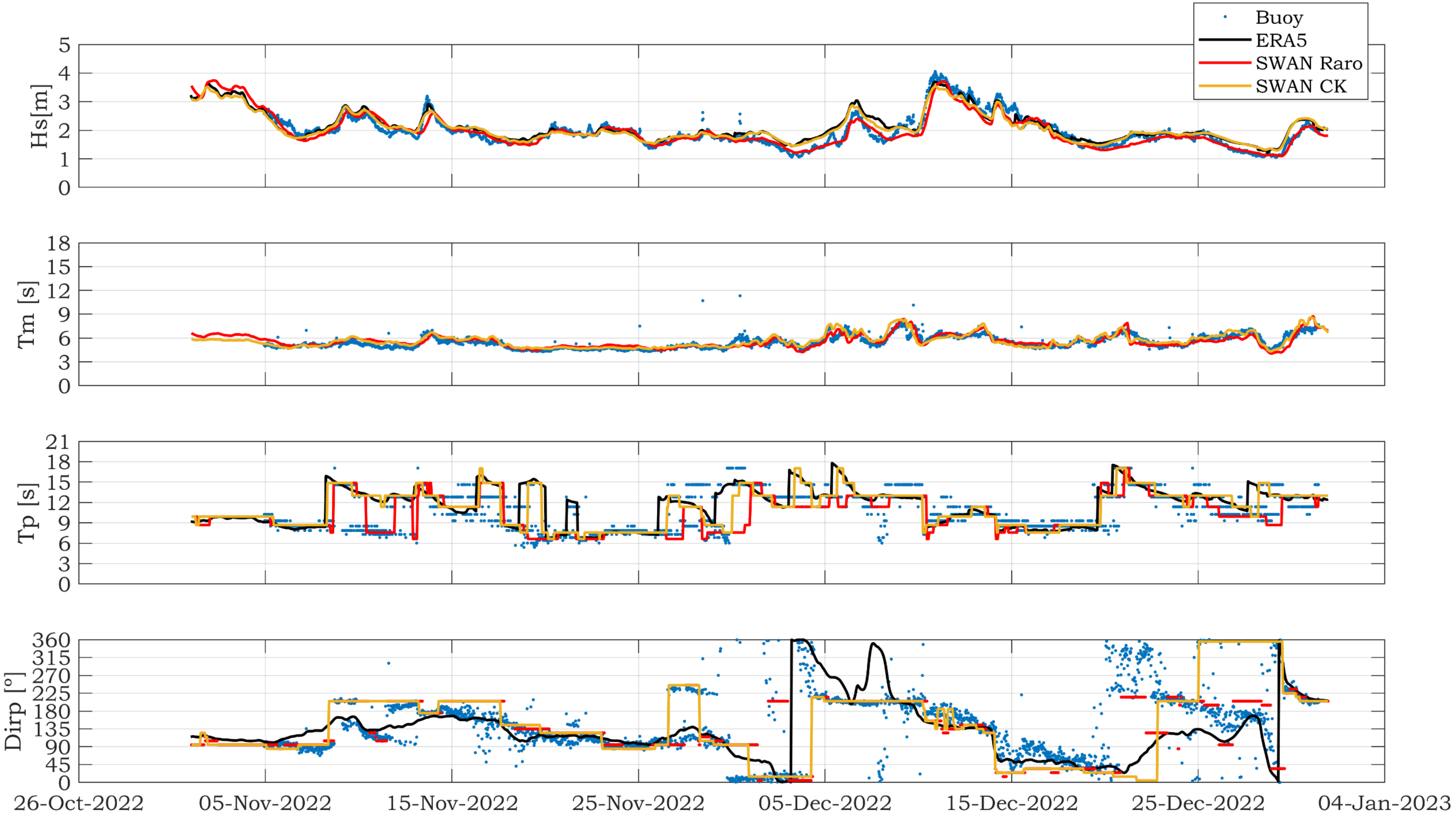


Dir

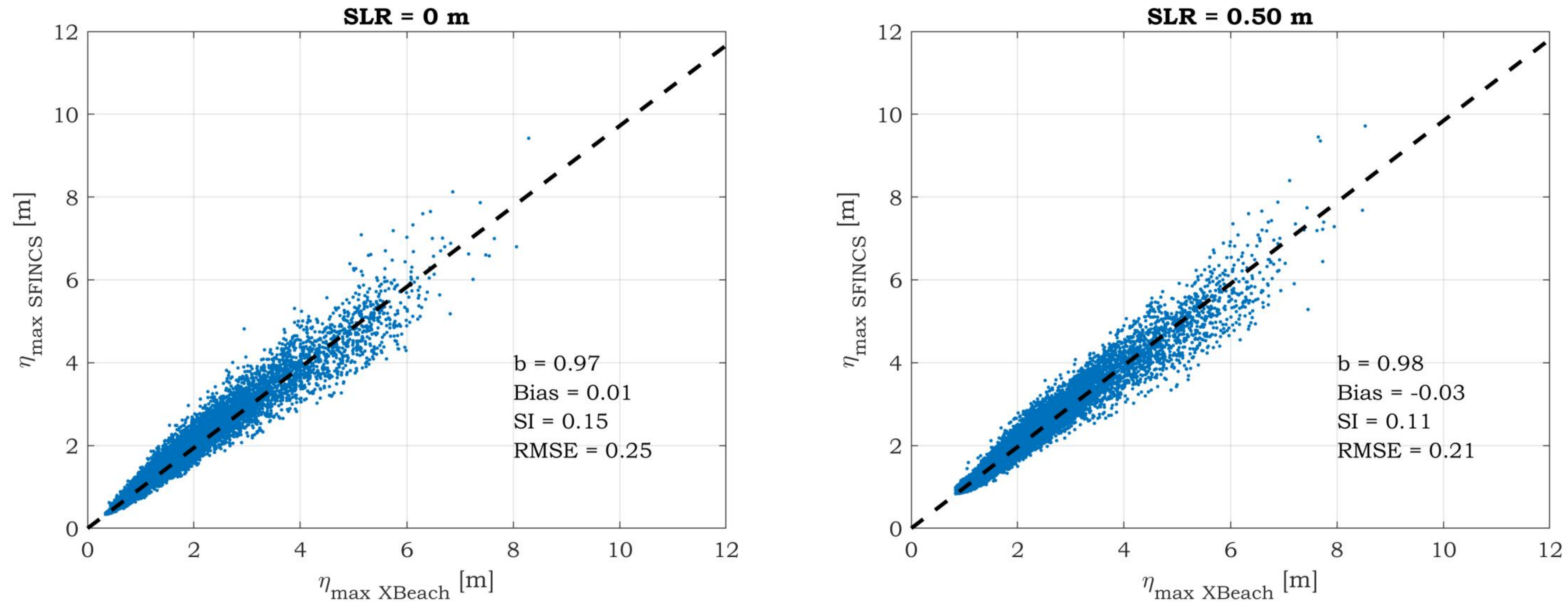


Dspr





Buoy
ERA5
SWAN Raro
SWAN CK
Hs[m]
Tm [s]
Tp [s]
Dirp [°]
26-Oct-2022
05-Nov-2022
15-Nov-2022
25-Nov-2022
05-Dec-2022
15-Dec-2022
25-Dec-2022
04-Jan-2023


SLR = 0 m
b = 0.97
Bias = 0.01
SI = 0.15
RMSE = 0.25
$\eta_{\text{max SFINCS}}$ [m]
$\eta_{\text{max XBeach}}$ [m]
SLR = 0.50 m
b = 0.98
Bias = -0.03
SI = 0.11
RMSE = 0.21
$\eta_{\text{max SFINCS}}$ [m]
$\eta_{\text{max XBeach}}$ [m]

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Wave Forecast: -18.96°N, 0.00°E

Close

UTC	Mon 8 02:00	Mon 8 05:00	Mon 8 08:00	Mon 8 11:00	Mon 8 14:00	Mon 8 17:00	Mon 8 20:00	Mon 8 23:00	Tue 9 02:00	Tue 9 05:00	Tue 9 08:00	Tue 9 11:00	Tue 9 14:00	Tue 9 17:00	Tue 9 20:00	Tue 9 23:00
Wave (m)	3.2	3.2	3.1	3.0	2.9	2.8	2.7	2.6	2.4	2.3	2.2	2.1	2.0	1.9	1.9	1.8
Wave period (s)	8.4	8.4	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
Wave direction (→)	←	←	←	←	←	←	←	←	←	←	←	←	←	←	←	←
Wave energy (kJ)	147	150	160	148	140	130	118	107	95	85	78	72	67	62	57	54
1.Swell (m)	0.4	0.4	0.5	0.6	0.7	0.8	0.8	2.5	2.4	2.2	2.1	2.1	1.9	1.8	1.8	1.7
1.Swell period (s)	10.3	13.8	14.0	13.8	13.6	13.5	13.2	9.1	9.1	9.1	9.1	9.1	9.2	9.2	9.2	9.2
1.Swell direction (→)	↗	↑	↑	↑	↑	↑	↑	←	←	←	←	←	←	←	←	←
2.Swell (m)	0.2	0.3	0.3	--	--	0.2	0.2	0.7	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.4
2.Swell period (s)	14.8	10.1	10.0	--	--	14.8	14.9	12.8	12.5	12.2	12.1	12.0	6.8	6.8	12.2	12.7
2.Swell dir (→)	↖	↗	↗	--	--	↗	↗	↑	↑	↑	↑	↑	↖	↖	↑	↗
Wind wave (m)	3.2	3.2	3.2	3.0	2.9	2.8	2.6	--	--	--	--	--	--	--	--	--
Wind wave per.(s)	8.7	8.9	9.2	9.2	9.2	9.2	9.1	--	--	--	--	--	--	--	--	--
Wind wave dir (→)	↖	↖	↖	↖	↖	↖	↖	--	--	--	--	--	--	--	--	--

UTC	Wed 10 02:00	Wed 10 05:00	Wed 10 08:00	Wed 10 11:00	Wed 10 14:00	Wed 10 17:00	Wed 10 20:00	Wed 10 23:00	Thu 11 02:00	Thu 11 05:00	Thu 11 08:00	Thu 11 11:00	Thu 11 14:00	Thu 11 17:00	Thu 11 20:00	Thu 11 23:00
Wave (m)	1.8	1.8	1.8	1.9	2.0	2.1	2.3	2.3	2.3	2.3	2.2	2.1	2.0	2.0	2.0	2.0
Wave period (s)	9.2	9.2	9.2	9.2	9.2	9.2	13.5	12.3	12.3	12.3	12.3	11.2	11.2	11.2	11.2	11.2
Wave direction (→)	←	←	←	←	←	↗	↗	↗	↑	↑	↑	↑	↑	↑	↑	↑
Wave energy (kJ)	52	52	54	57	62	71	121	119	119	113	105	89	82	78	79	81
1.Swell (m)	1.7	1.7	1.6	1.5	1.5	1.6	1.9	2.0	2.0	2.0	1.9	1.8	1.7	1.6	1.5	1.4
1.Swell period (s)	9.2	9.2	9.3	9.3	9.3	13.6	13.3	13.1	12.6	12.4	12.2	12.0	11.6	11.4	11.3	11.2
1.Swell direction (→)	←	←	←	←	←	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗
2.Swell (m)	0.5	0.7	0.8	0.9	1.3	1.4	1.4	1.3	1.3	1.2	1.2	1.2	1.3	1.3	--	0.4
2.Swell period (s)	11.9	11.6	11.4	11.0	14.3	9.3	9.3	9.3	9.3	9.4	9.5	9.9	10.3	10.8	--	11.3
2.Swell dir (→)	↗	↗	↗	↗	↗	←	←	←	←	←	←	←	←	←	--	↖
Wind wave (m)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.4	1.5
Wind wave per.(s)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10.8	10.4
Wind wave dir (→)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	↖	↖

UTC	Fri 12 02:00	Fri 12 05:00	Fri 12 08:00	Fri 12 11:00	Fri 12 14:00	Fri 12 17:00	Fri 12 20:00	Fri 12 23:00	Sat 13 02:00	Sat 13 05:00	Sat 13 08:00	Sat 13 11:00
Wave (m)	2.0	2.0	2.0	1.9	1.9	1.8	1.7	1.7	1.6	1.6	1.5	1.5
Wave period (s)	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
Wave direction (→)	↑	↑	↖	↖	↖	↖	↖	↑	↑	↗	↗	↗
Wave energy (kJ)	81	80	79	75	69	63	58	54	51	48	46	44
1.Swell (m)	1.3	1.3	1.3	1.2	1.1	1.1	1.0	1.0	1.0	1.3	1.0	1.0
1.Swell period (s)	11.2	11.3	11.5	10.5	11.6	11.5	11.4	11.3	11.3	10.1	11.2	11.2
1.Swell direction (→)	↗	↗	↗	↖	↗	↗	↗	↗	↗	↖	↗	↗
2.Swell (m)	--	--	--	1.2	--	--	--	--	0.5	1.0	--	--
2.Swell period (s)	--	--	--	11.7	--	--	--	--	10.7	11.2	--	--
2.Swell dir (→)	--	--	--	↗	--	--	--	--	↖	↗	--	--
Wind wave (m)	1.6	1.6	1.6	1.0	1.5	1.5	1.4	1.4	1.2	--	1.2	1.2
Wind wave per.(s)	10.8	10.8	10.8	5.2	10.4	10.3	10.3	10.2	10.0	--	10.1	10.0
Wind wave dir (→)	↖	↖	↖	↖	↖	↖	↖	↖	↖	--	↖	↖

Close

Coastal Risk Details - Rarotonga

Risk Level:	Moderate Risk
Max TWL:	3.29 m