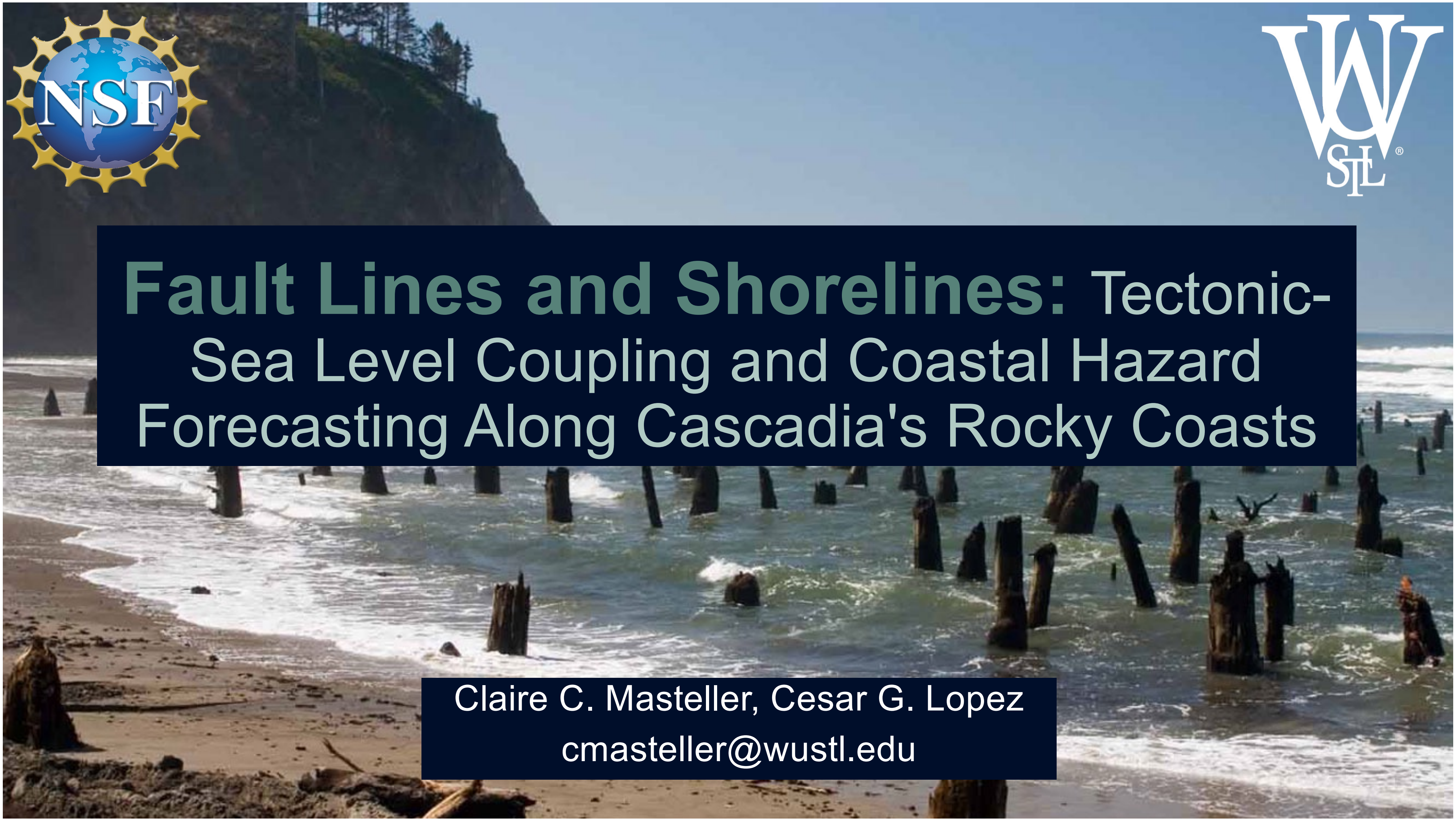

Fault Lines and Shorelines: Tectonic-Sea Level Coupling and Coastal Hazard Forecasting Along Cascadia's Rocky Coasts

Claire C. Masteller, Cesar G. Lopez
cmasteller@wustl.edu

Fault Lines and Shorelines: Tectonic-Sea Level Coupling and Coastal Hazard Forecasting Along Cascadia's Rocky Coasts

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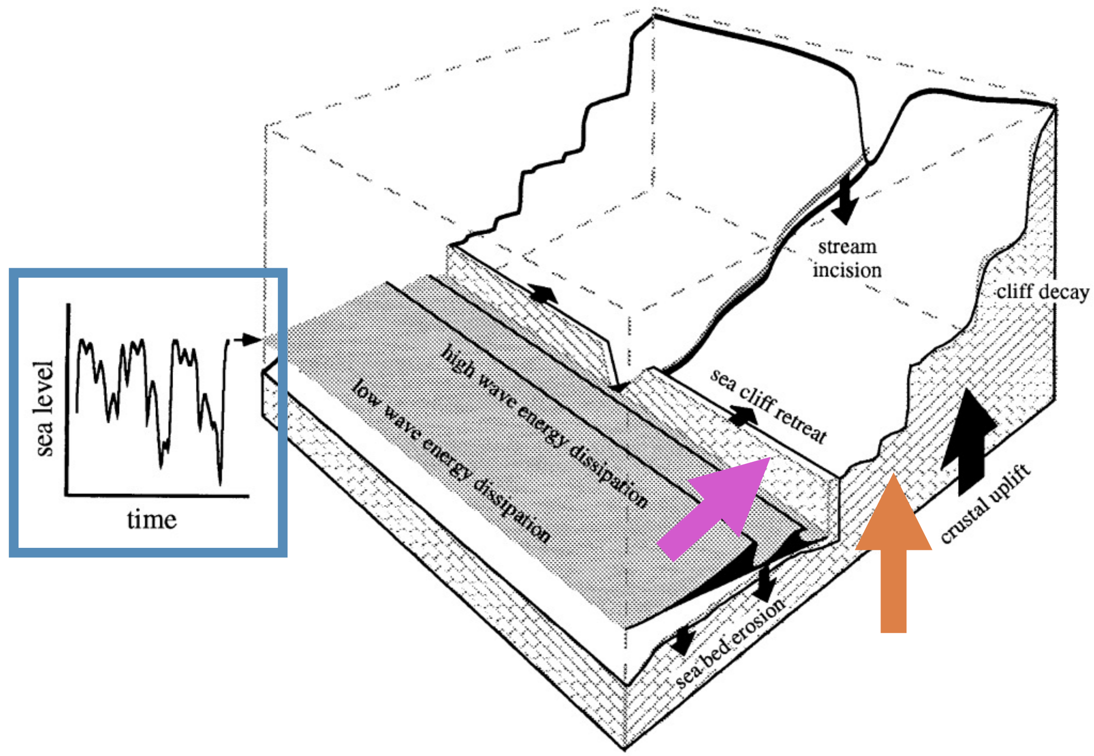
Rocky coasts are an expression of **tectonics**, **sea level**, and **wave action**

- **Vertical land motion** exposes fresh rock at the shoreline
- Power delivered by **broken and breaking waves** backwears the shoreline
- Sea level **shifts nearshore water depth** and locus of wave attack



Anderson, 1999

What is the role of the **earthquake cycle** in pacing rocky coast **erosion**?

- Decadal scale shoreline retreat rates scale inversely with interseismic uplift
- More rapid uplift buffers shoreline retreat, subsidence accelerates retreat

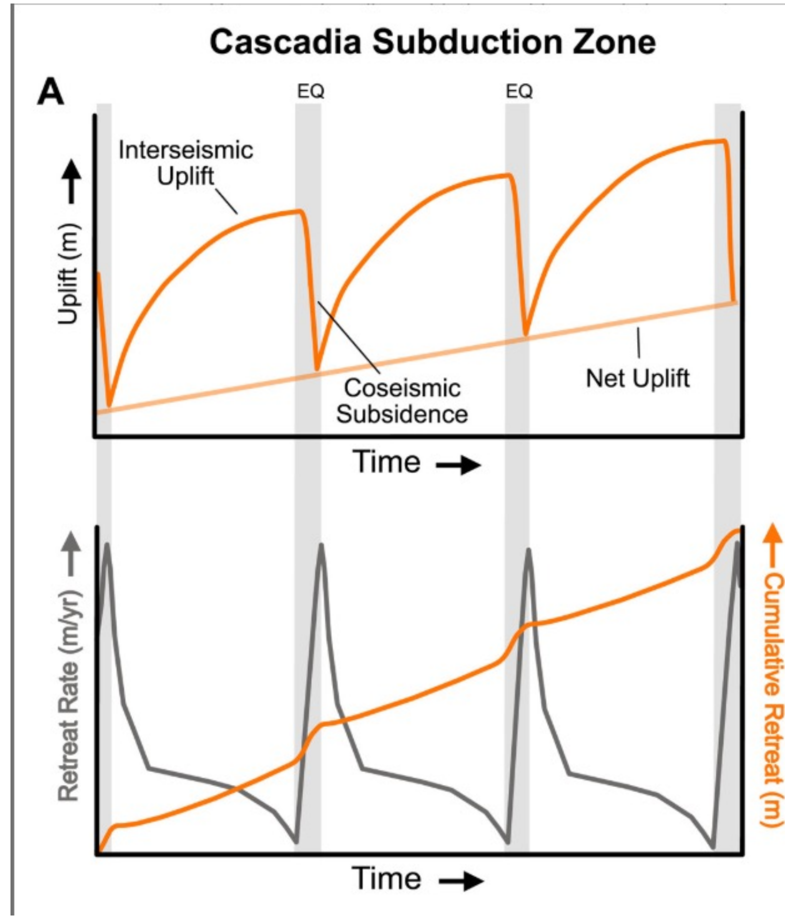
Lopez and Masteller, 2026

AGU Advances

Research Article | Open Access

Tectonics as a Regulator of Shoreline Retreat and Rocky Coast Evolution Across Timescales

Cesar G. Lopez, Claire C. Masteller



What is the role of the **earthquake cycle** in pacing rocky coast **erosion**?

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- More rapid uplift buffers shoreline retreat, subsidence accelerates retreat

How can we predict shifting coastal erosion hazards following the next Cascadia earthquake?

Lopez and Masteller, 2026

AGU Advances

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Tectonics as a Regulator of Shoreline Retreat and Rocky Coast Evolution Across Timescales

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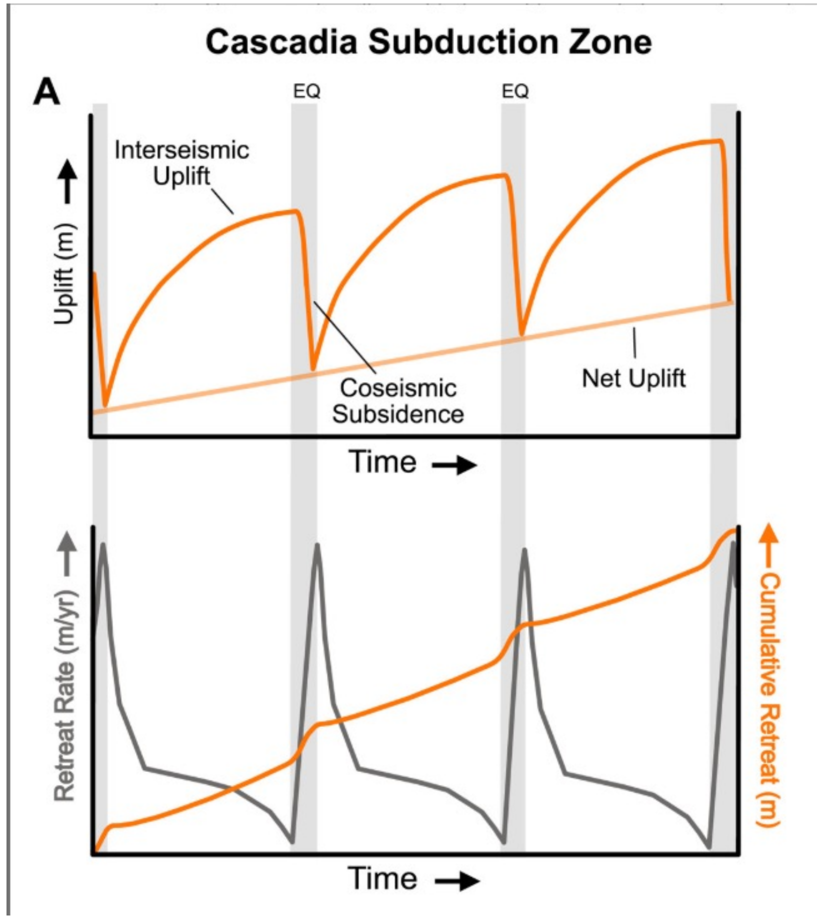
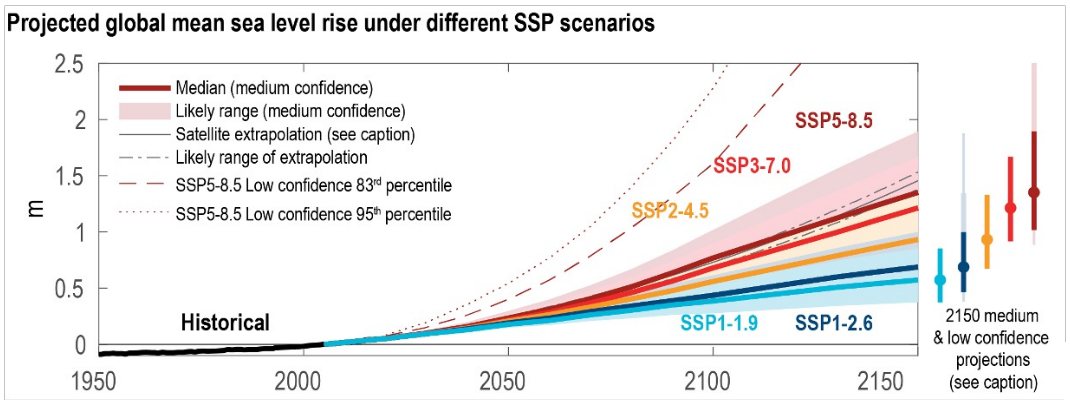
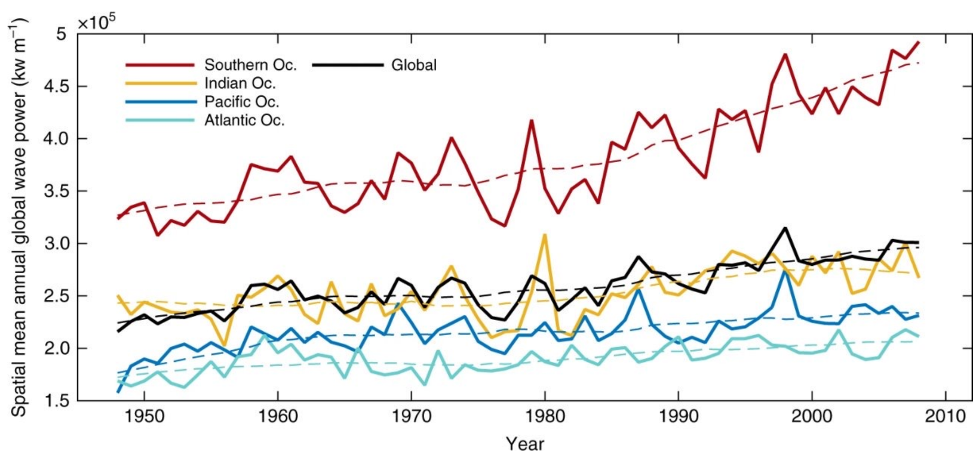


Rising sea level rise and intensifying wave climate as a shifting baseline





Article | Open access | Published: 18 November 2022

Sea-level rise will likely accelerate rock coast cliff retreat rates

Jennifer R. Shadrick, Dylan H. Rood, Martin D. Hurst, Matthew D. Piggott, Bethany G. Hebditch, Alexander J. Seal & Klaus M. Wilcken

Nature Communications **13**, Article number: 7005 (2022) | Cite this article

13k Accesses | **43** Citations | **367** Altmetric | Metrics

Matters Arising | Open access | Published: 21 December 2023

Sea-level rise may not uniformly accelerate cliff erosion rates

M. E. Dickson, H. Matsumoto, W. J. Stephenson, Z. M. Swirad, C. F. Thompson & A. P. Young

Nature Communications **14**, Article number: 8485 (2023) | Cite this article

3531 Accesses | **11** Citations | **5** Altmetric | Metrics

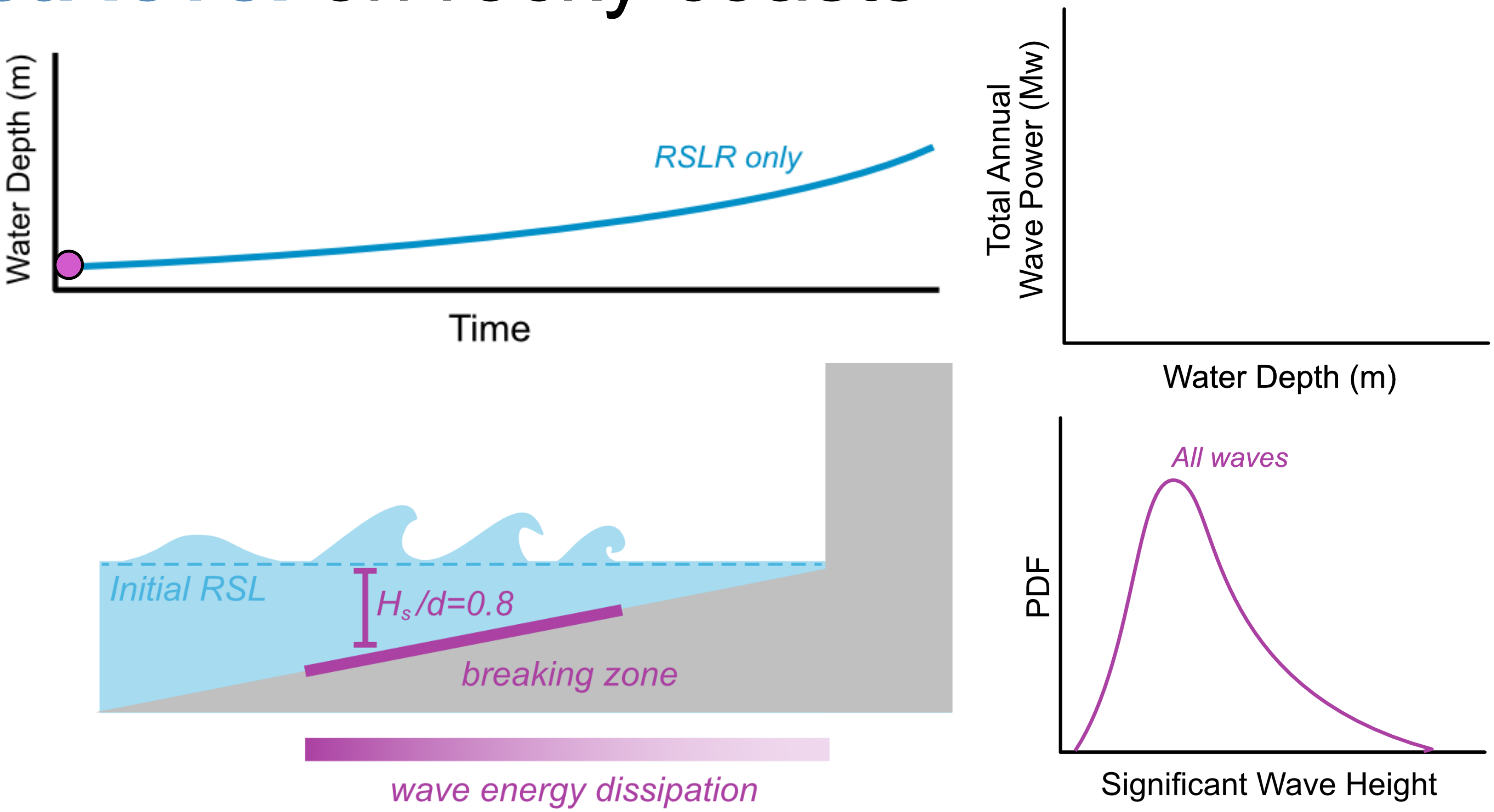
Matters Arising | Open access | Published: 21 December 2023

Reply to: Sea-level rise may not uniformly accelerate cliff erosion rates

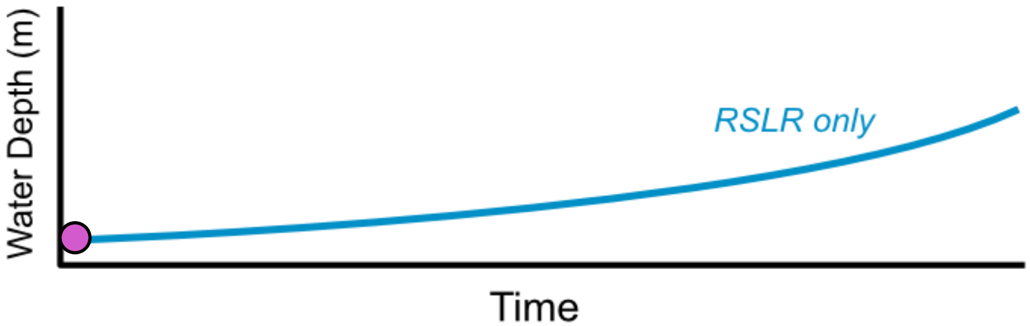
Jennifer R. Shadrick, Dylan H. Rood & Martin D. Hurst

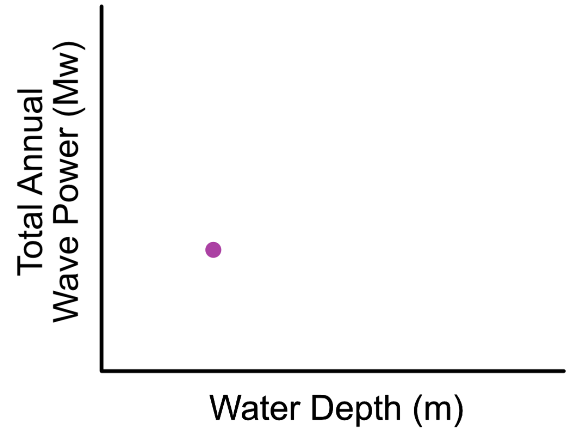
Nature Communications **14**, Article number: 8486 (2023) | Cite this article

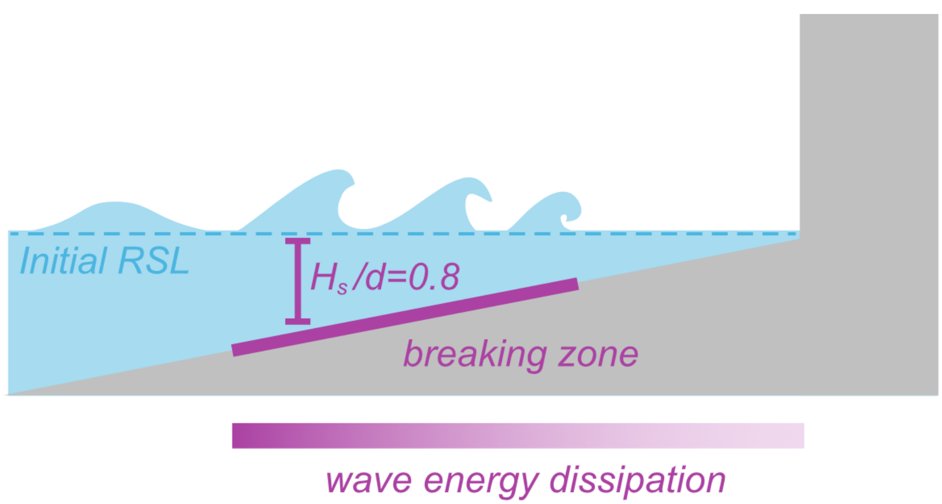
The trajectory of wave breaking with rising sea level on rocky coasts

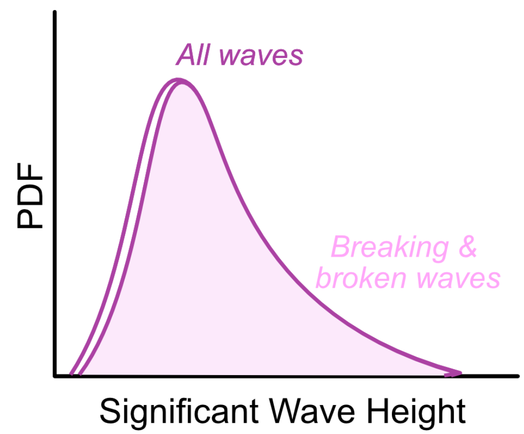


The trajectory of **wave breaking** with **rising sea level** on rocky coasts

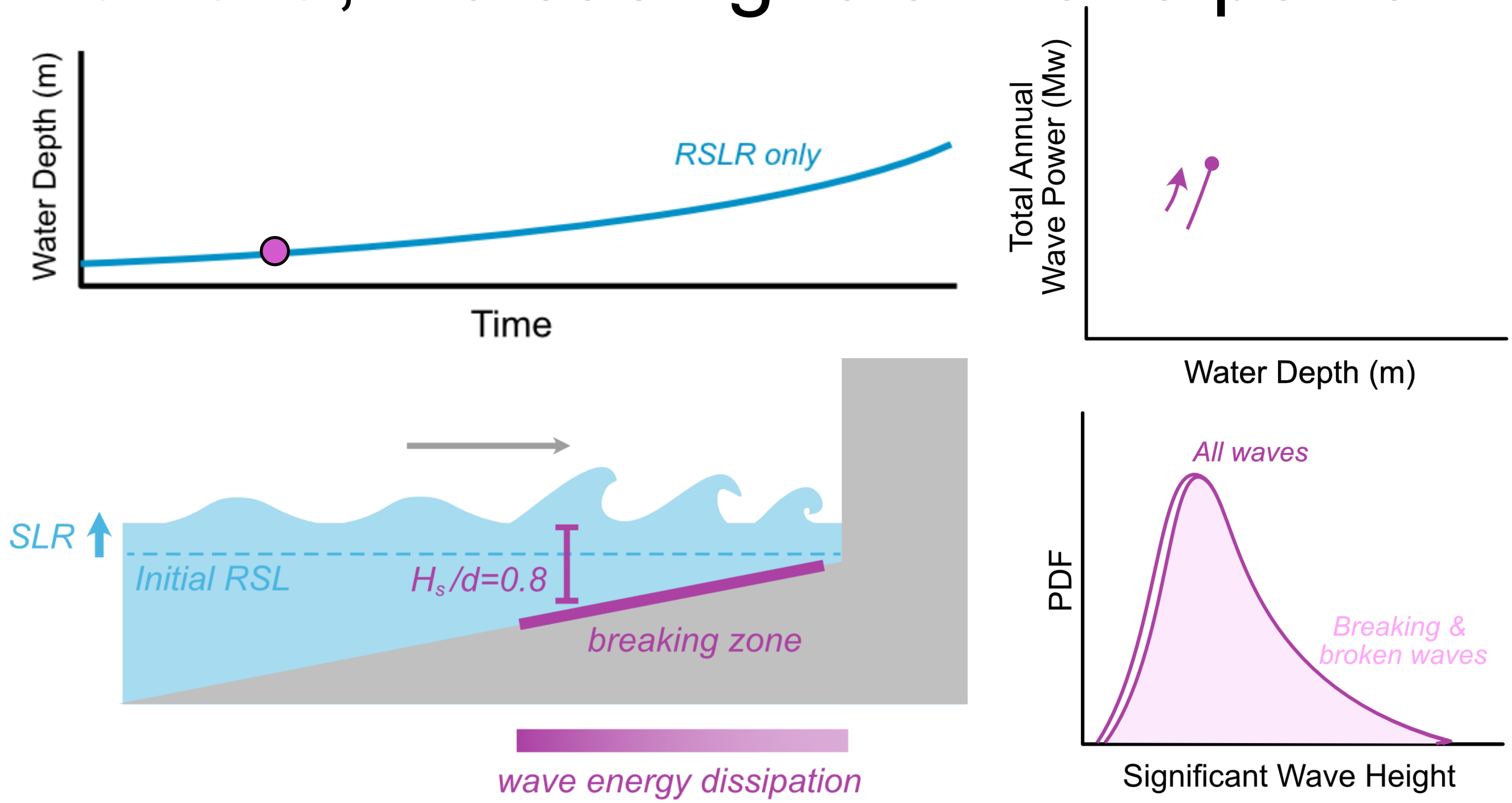




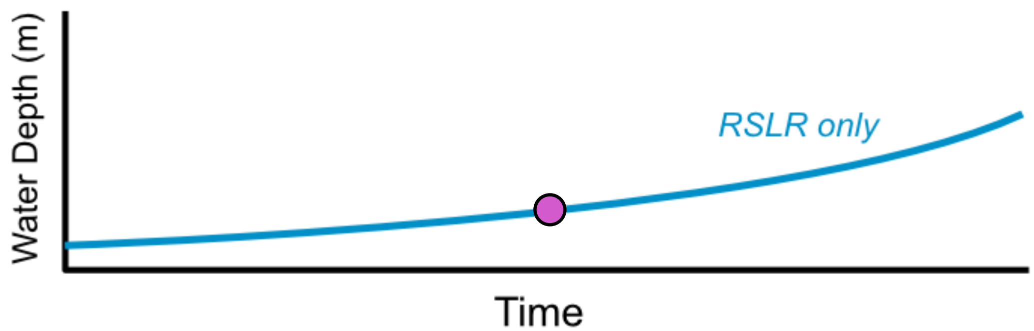


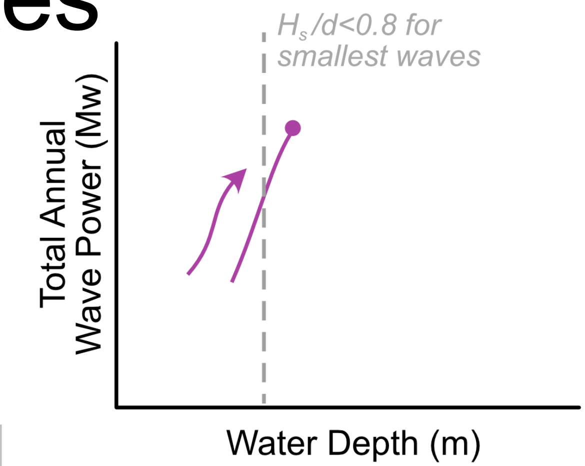


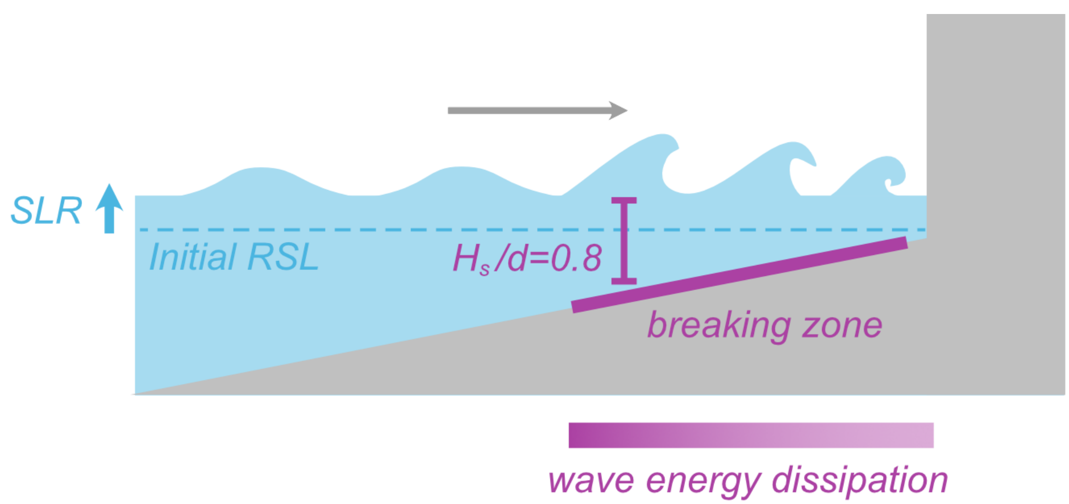
Rising water levels **shift wave breaking landward**, increasing total wave power

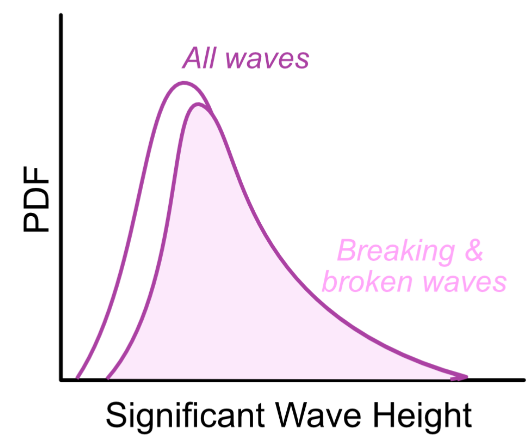


Small wave breaking **suppressed**, but landward shift still dominates

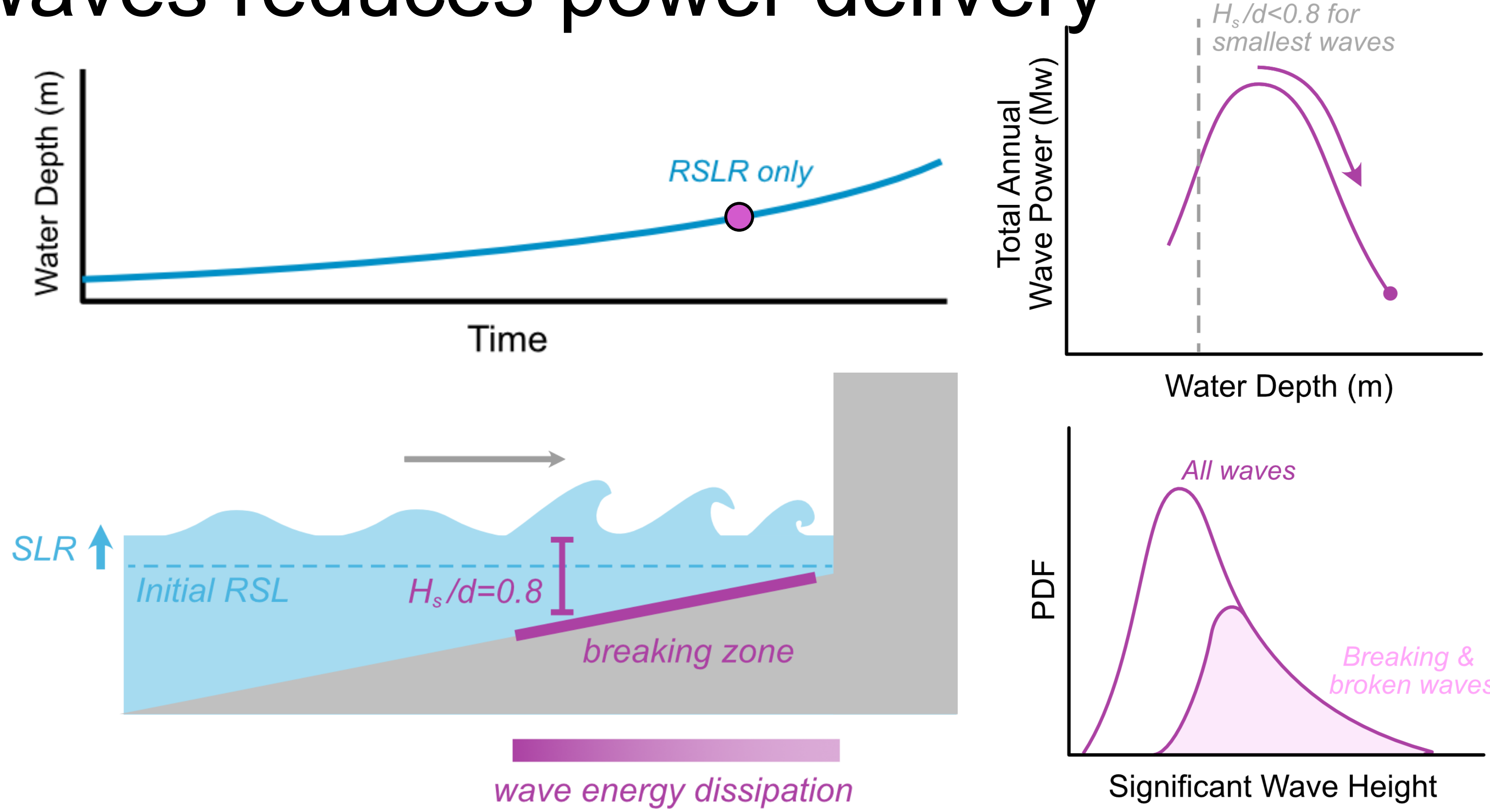




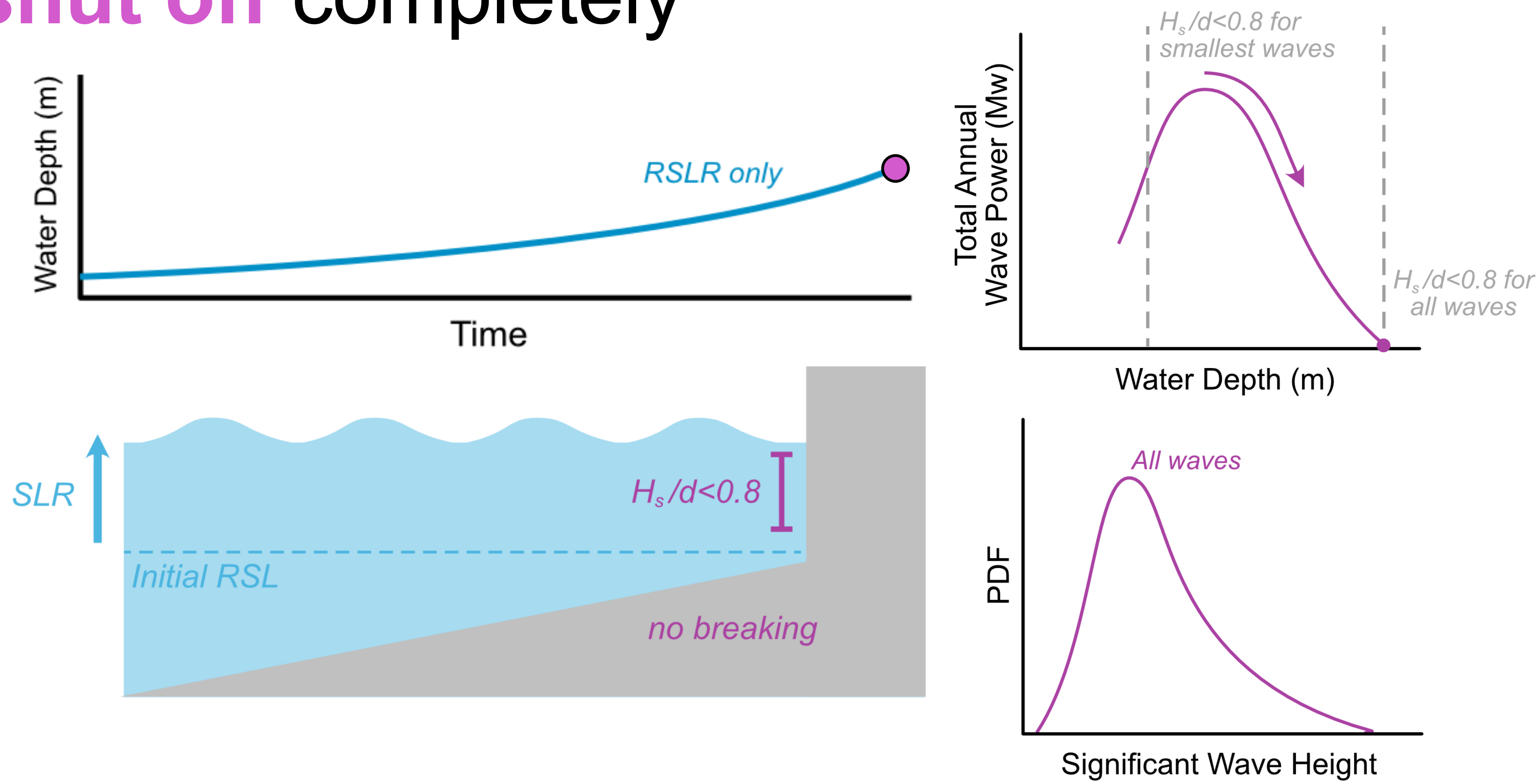




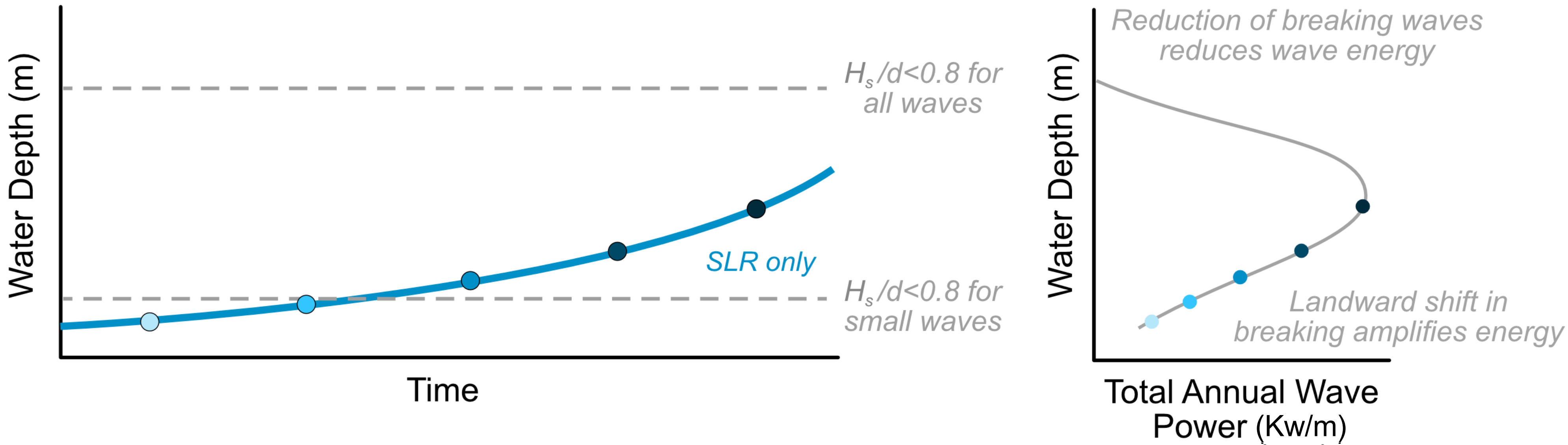
Landward shift **saturates**, loss of breaking waves reduces power delivery



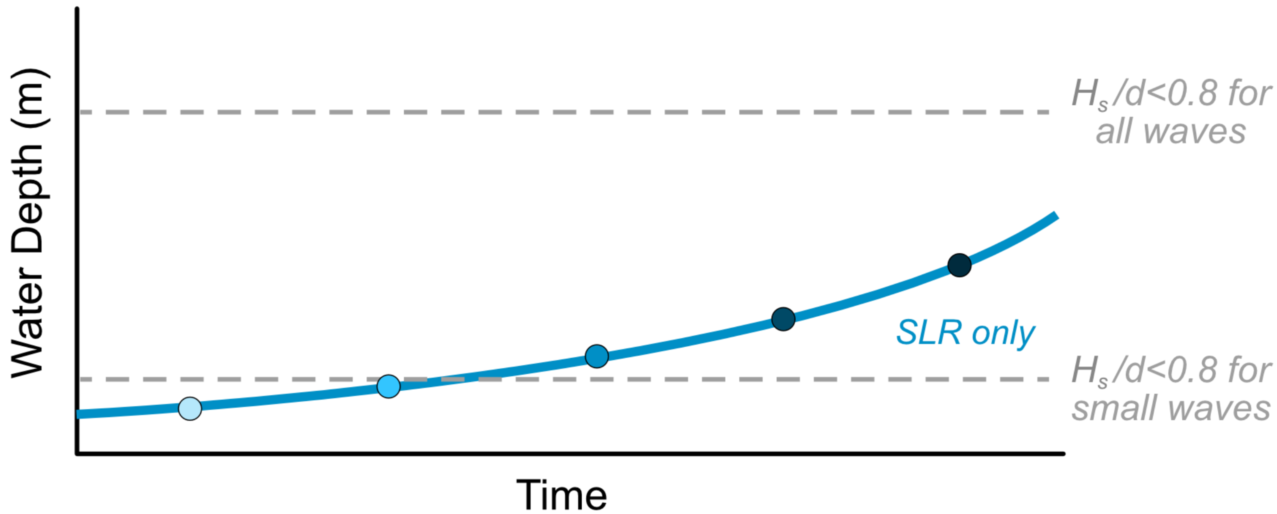
Shore platform is drowned, wave breaking **shut off** completely

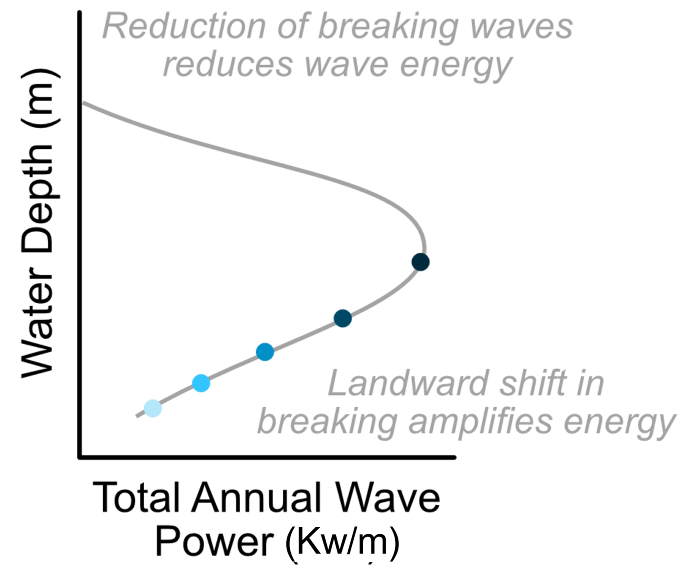


Wave power delivery follows a humped trajectory with rising water level



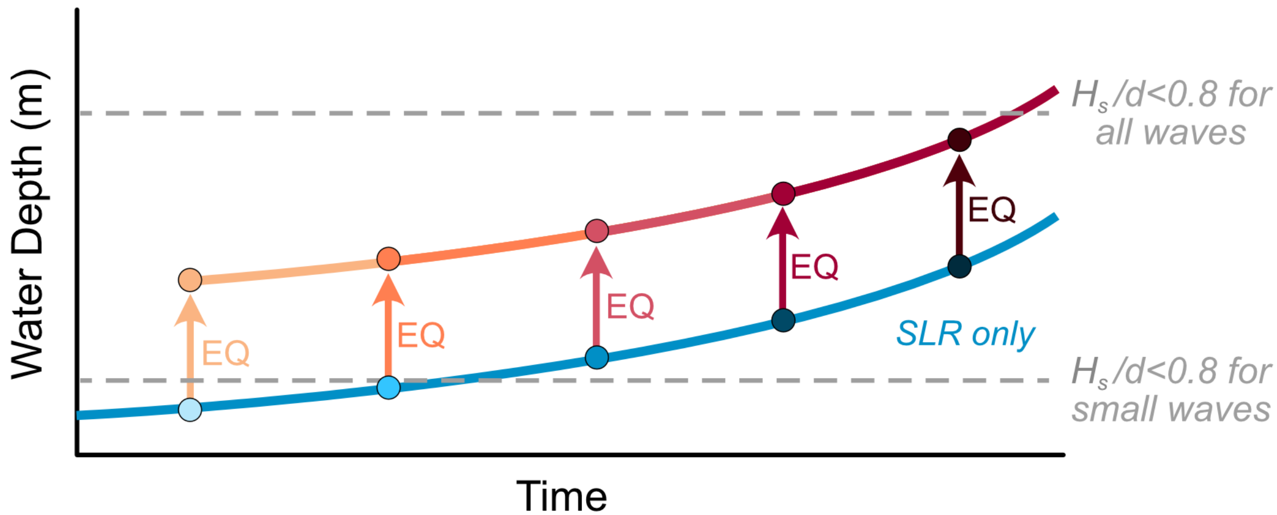
Wave power delivery follows a **humped trajectory** with rising **water level**

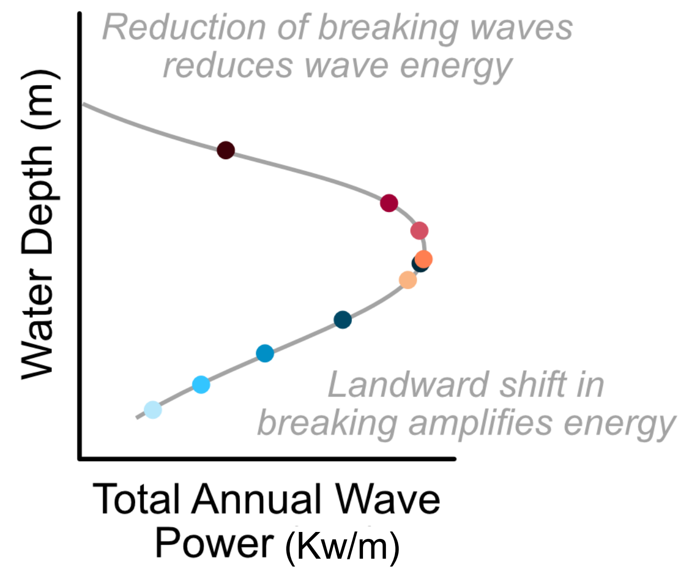




What happens when we add an **earthquake**?

Coseismic subsidence rapidly **shifts the trajectory** of wave power delivery

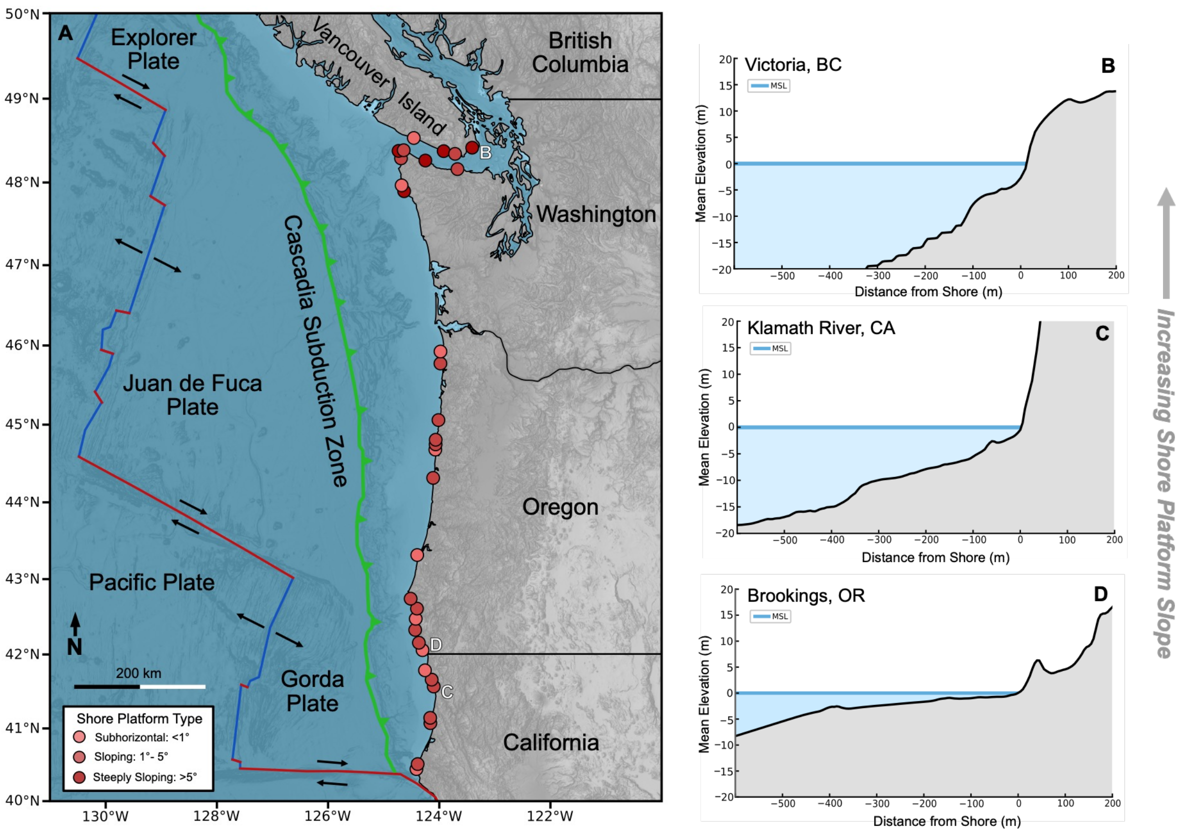




The degree of this trajectory shift is ***location specific*** – integrating offshore wave climate, timing and magnitude of coseismic subsidence, and shore platform morphology

Lopez and Masteller, *in prep*

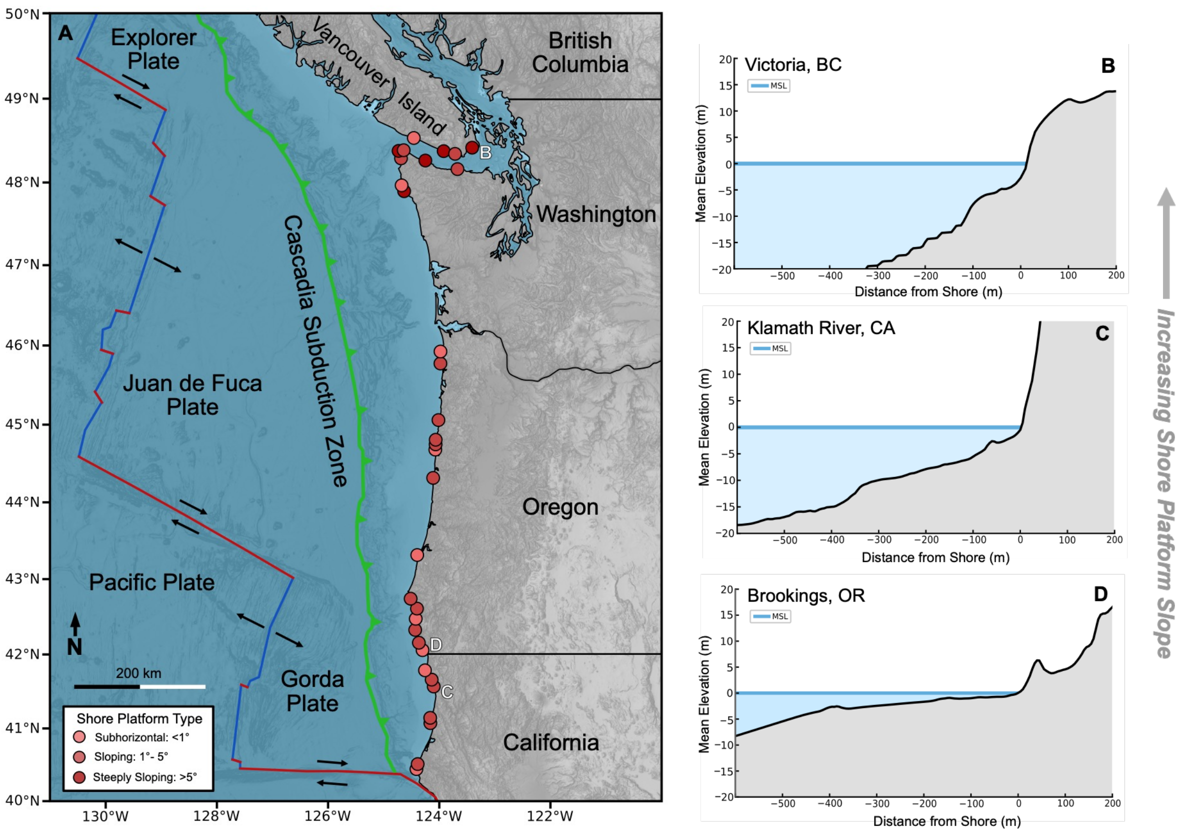
Modeling **EQ-driven shifts** in coastal wave power delivery across Cascadia



- **32 rocky coast study sites** across Washington, Oregon, and Northern California
- **Shore platform morphology** modulates RSLR effects and wave breaking
- **Steeper slopes concentrate wave breaking** near the shore and are less sensitive to water level changes than more gradual slopes

Lopez and Masteller, *in prep*

Modeling **EQ-driven shifts** in coastal wave power delivery across Cascadia

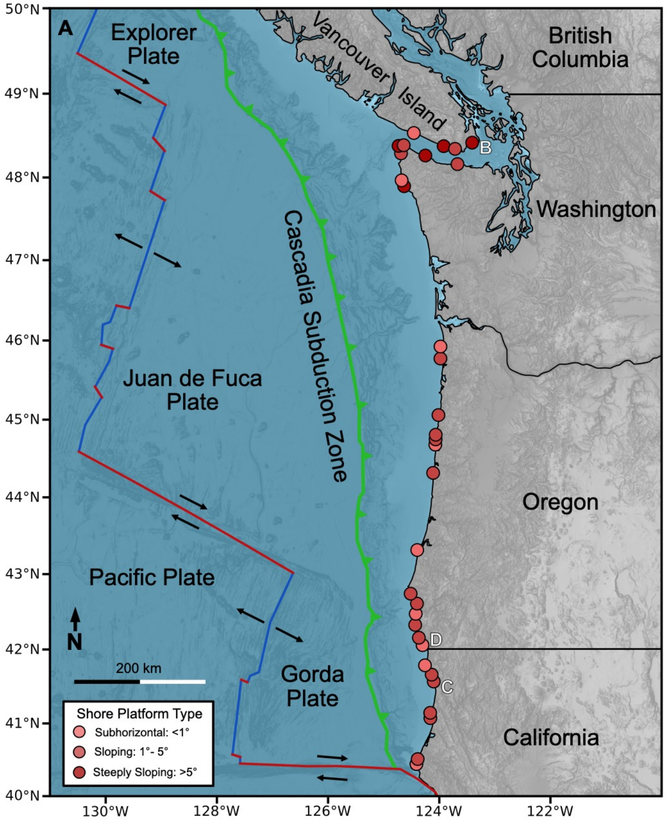


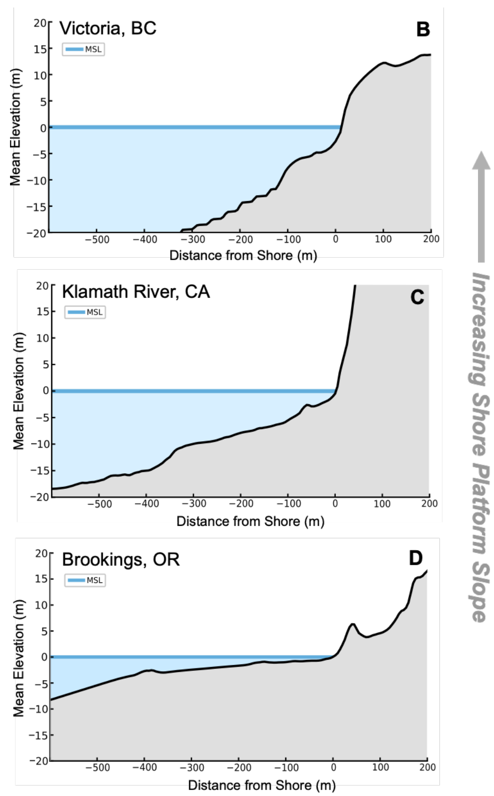
- Projected sea level and wave climate from **SSP2 4.5 & 8.5**
- Coseismic subsidence (**0.5**, **1**, **2 m**) for an EQ every decade from 2030-2100 & ***no EQ control*** *(64 scenarios per site)*
- Calculate number of broken, breaking, and unbroken waves and wave breaking distances
- Estimate wave power at cliff front as:

$$P_{cliff} = P_{breaking} e^{(-k \cdot d_b)}$$

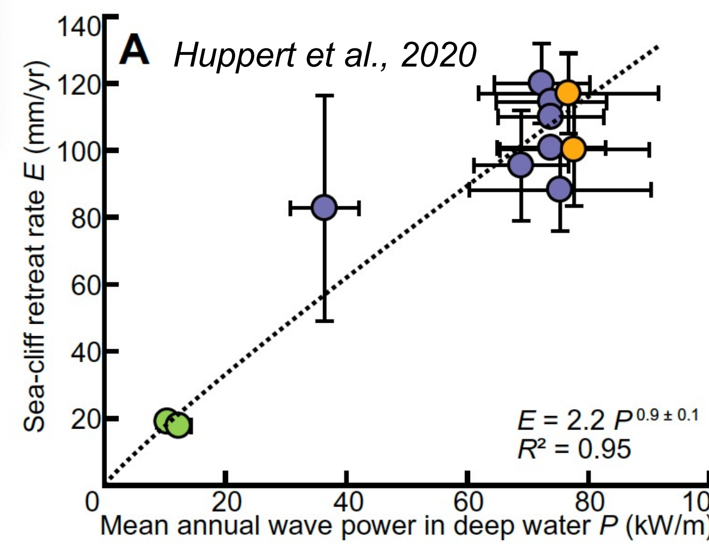
Lopez and Masteller, *in prep*

Modeling **EQ-driven shifts** in coastal wave power delivery across Cascadia



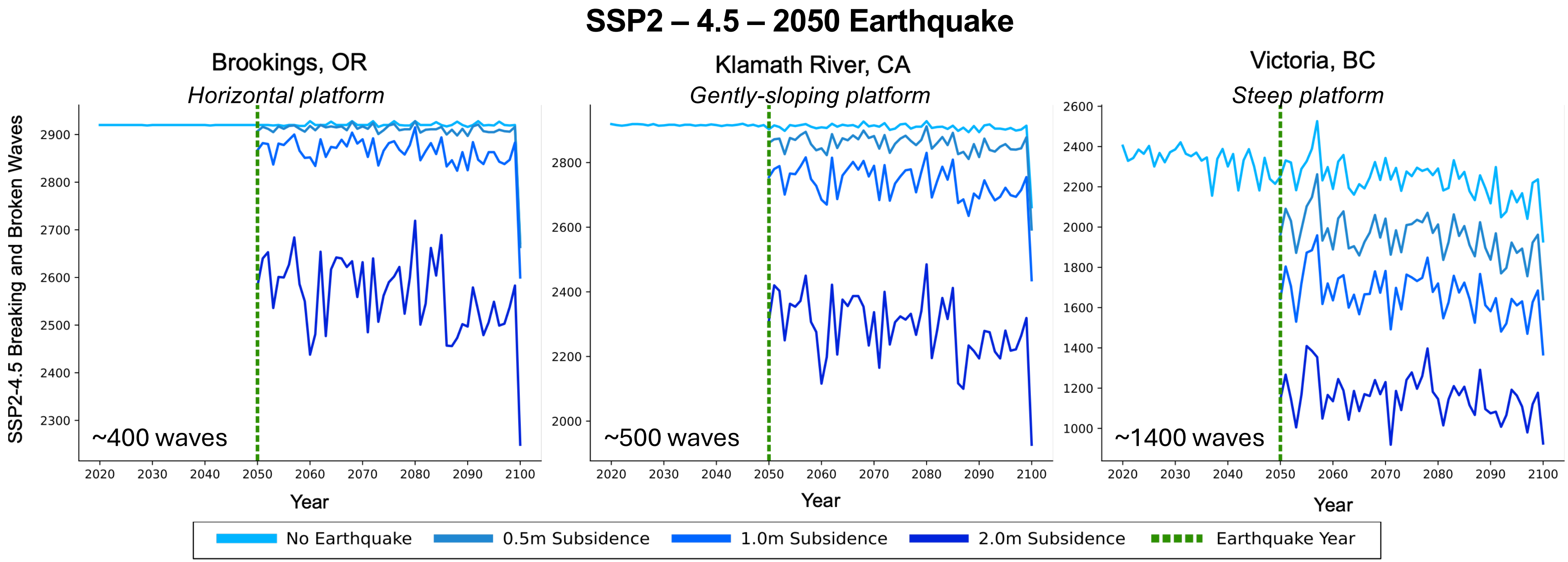


- Cliff front wave power represents **the potential for erosion** across sites



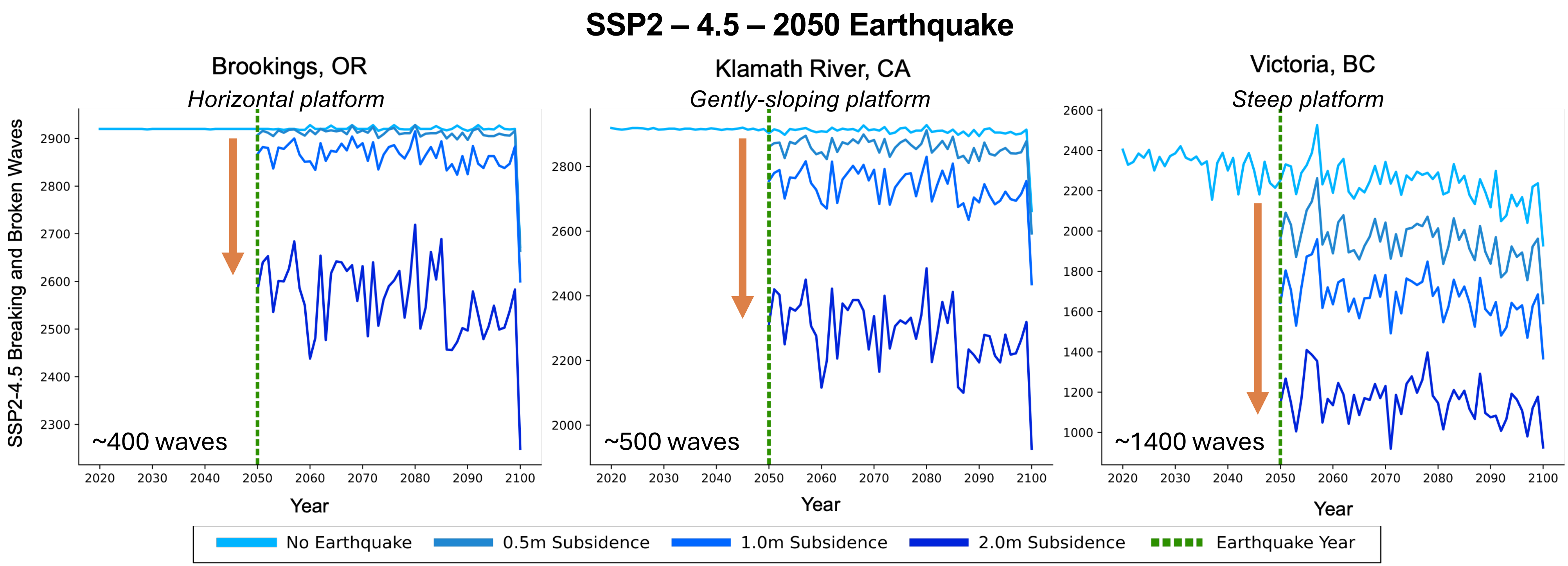
Lopez and Masteller, *in prep*

Wave breaking is **most strongly reduced** on steep shore platforms



Immediate reduction in breaking and broken waves across all sites

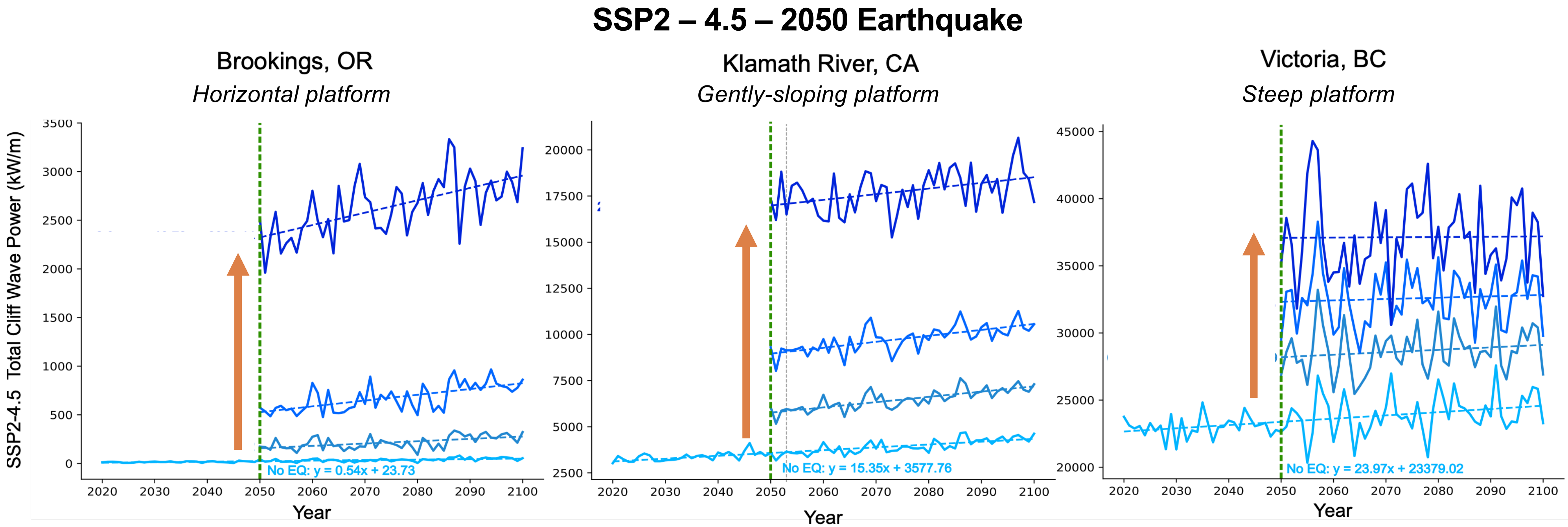
Wave breaking is **most strongly reduced** on steep shore platforms



Immediate reduction in breaking and broken waves across all sites

Lopez and Masteller, *in prep*

Annual cliff front **wave power enhanced** across all sites



Coseismic subsidence increases **potential for coastal erosion**

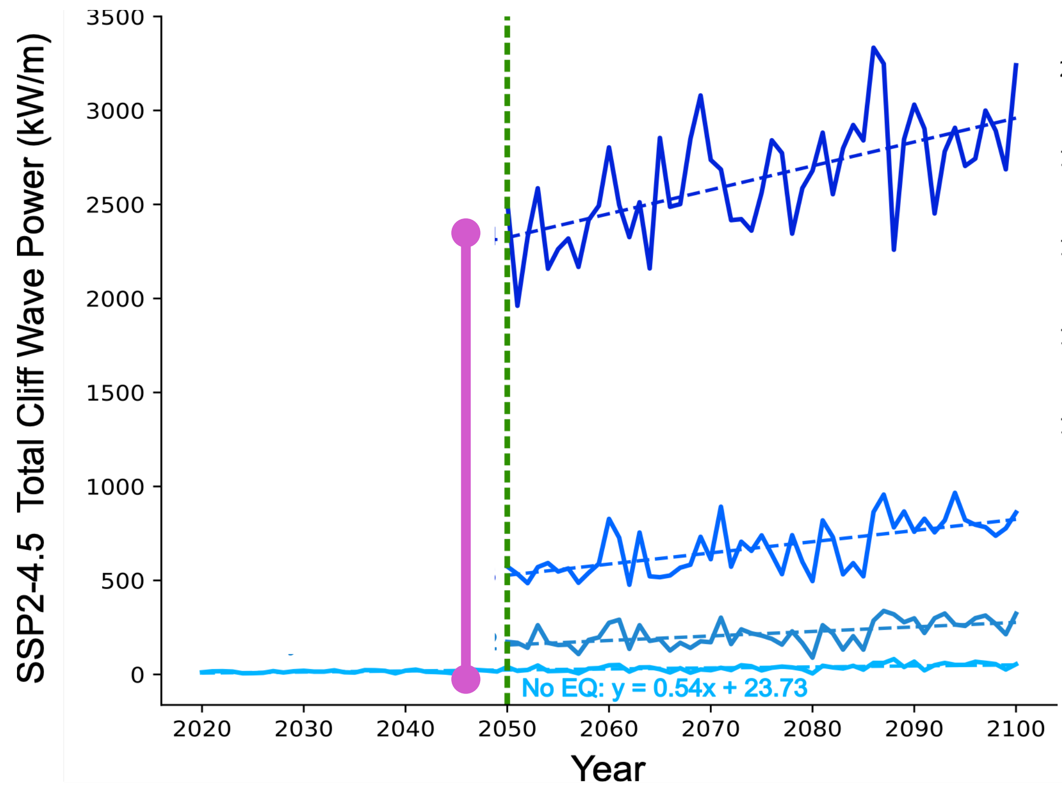
Lopez and Masteller, *in prep*

Quantifying EQ-driven **amplification** of wave power delivery at the coastline

Degree of **wave power amplification** quantified as:

$$\frac{\textbf{Total annual power for EQ scenario}}{\textbf{Total annual power for SLR only}}$$

Values >1 indicate increase in wave power driven by coseismic subsidence



Lopez and Masteller, *in prep*

Wave power amplification is **greatest on horizontal platforms**, reduced at steep slopes

Degree of **wave power amplification** quantified as:

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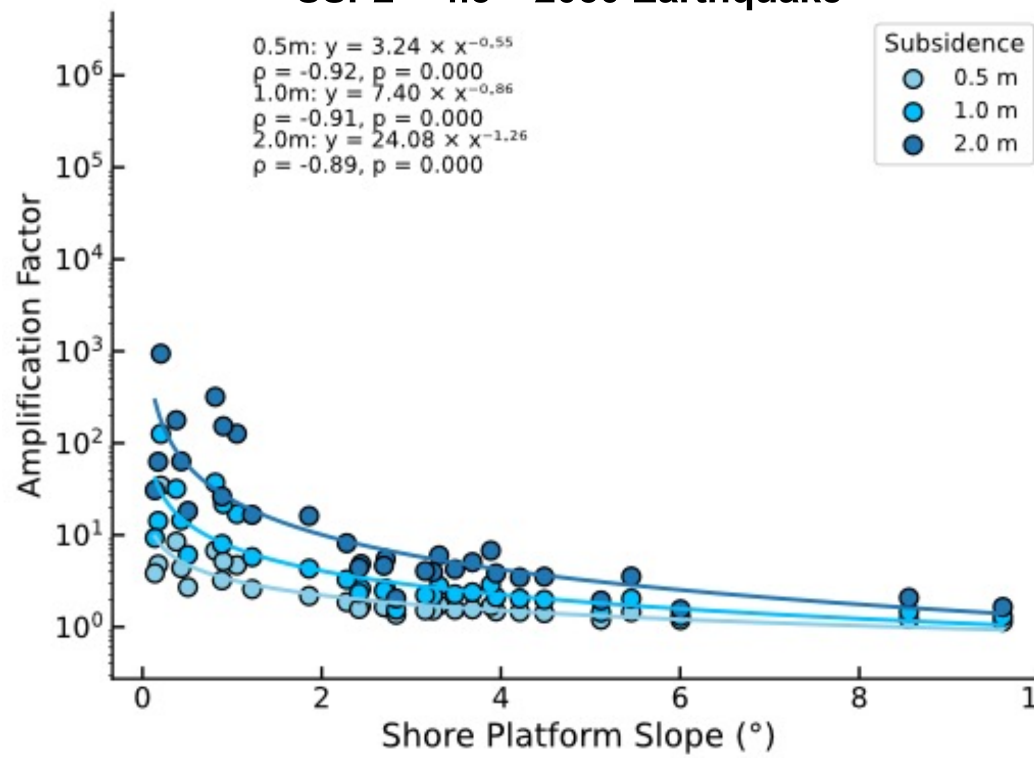
SSP2 – 4.5 – 2050 Earthquake



Lopez and Masteller, *in prep*

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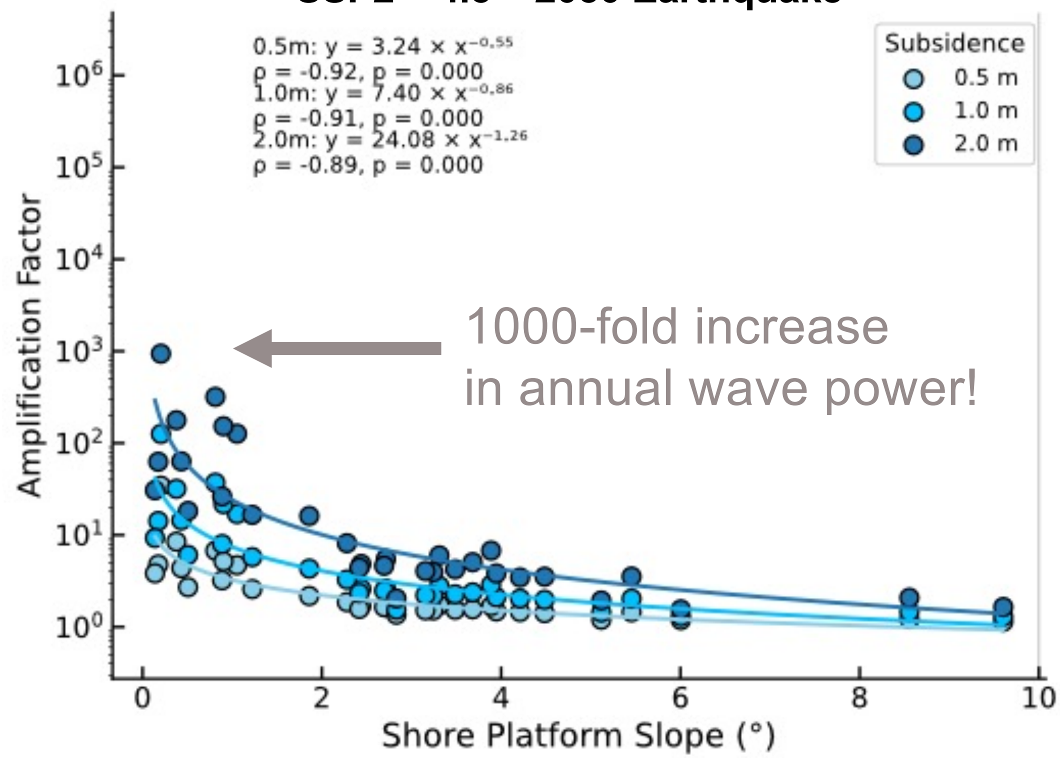

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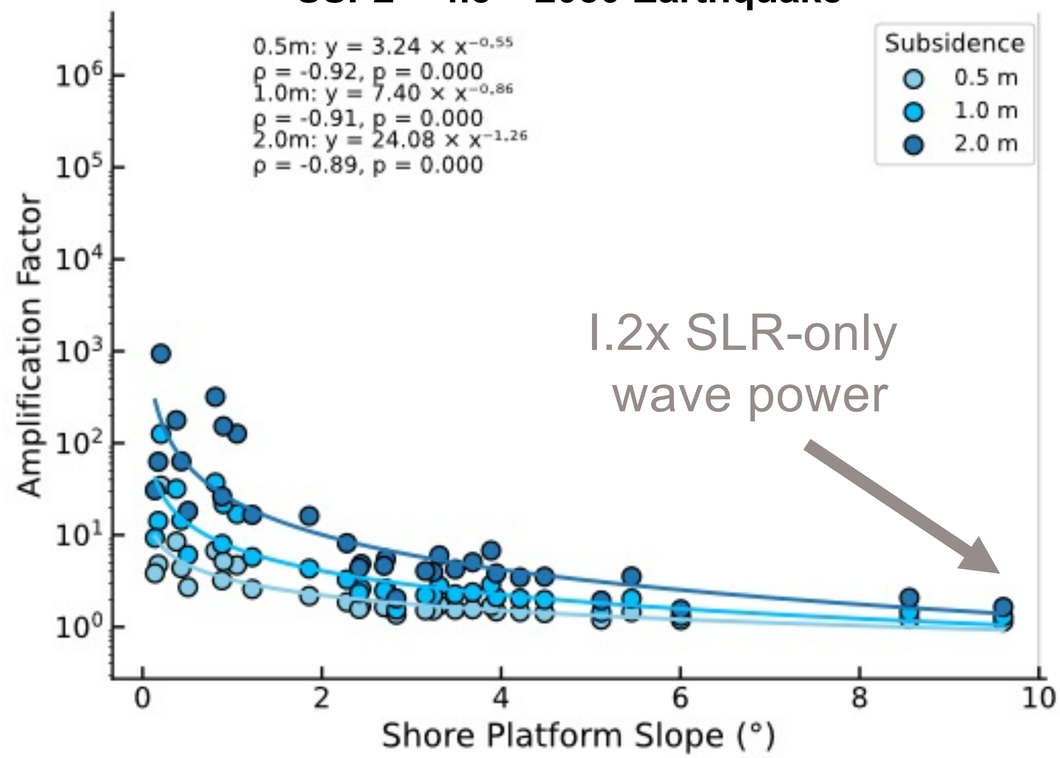

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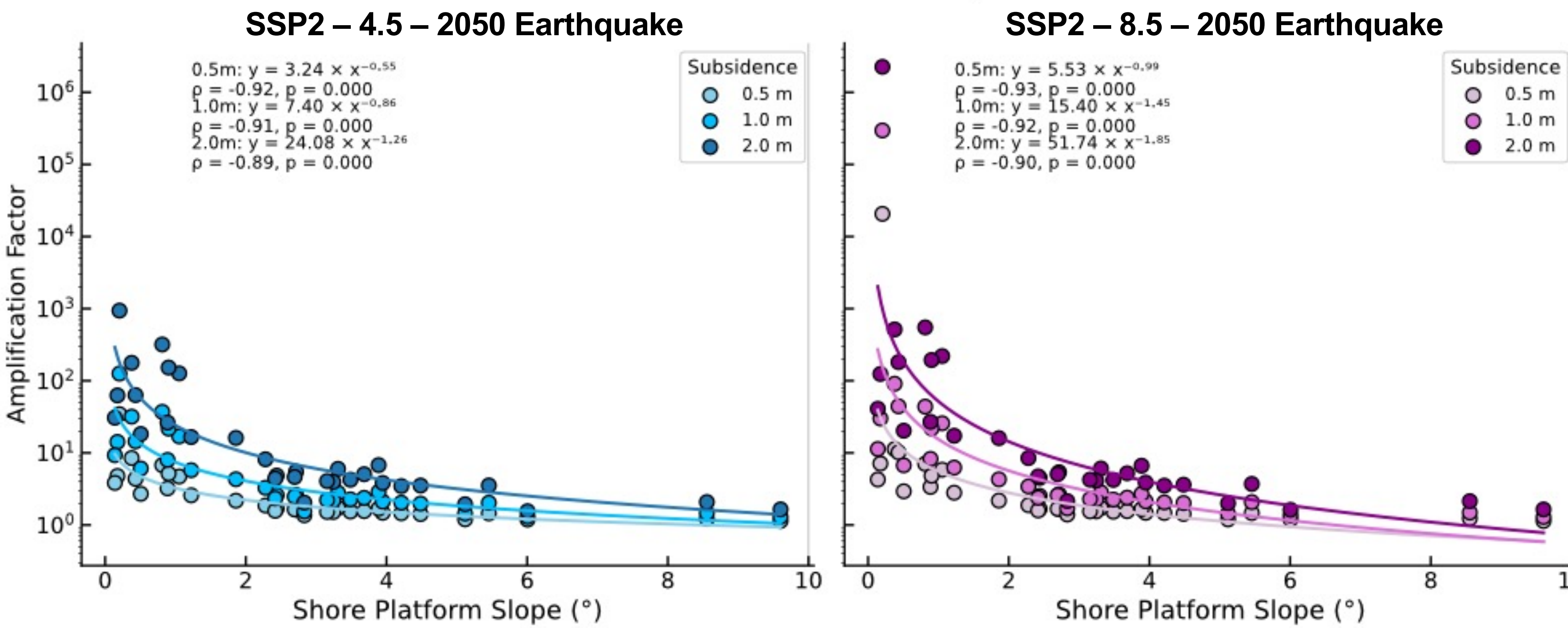
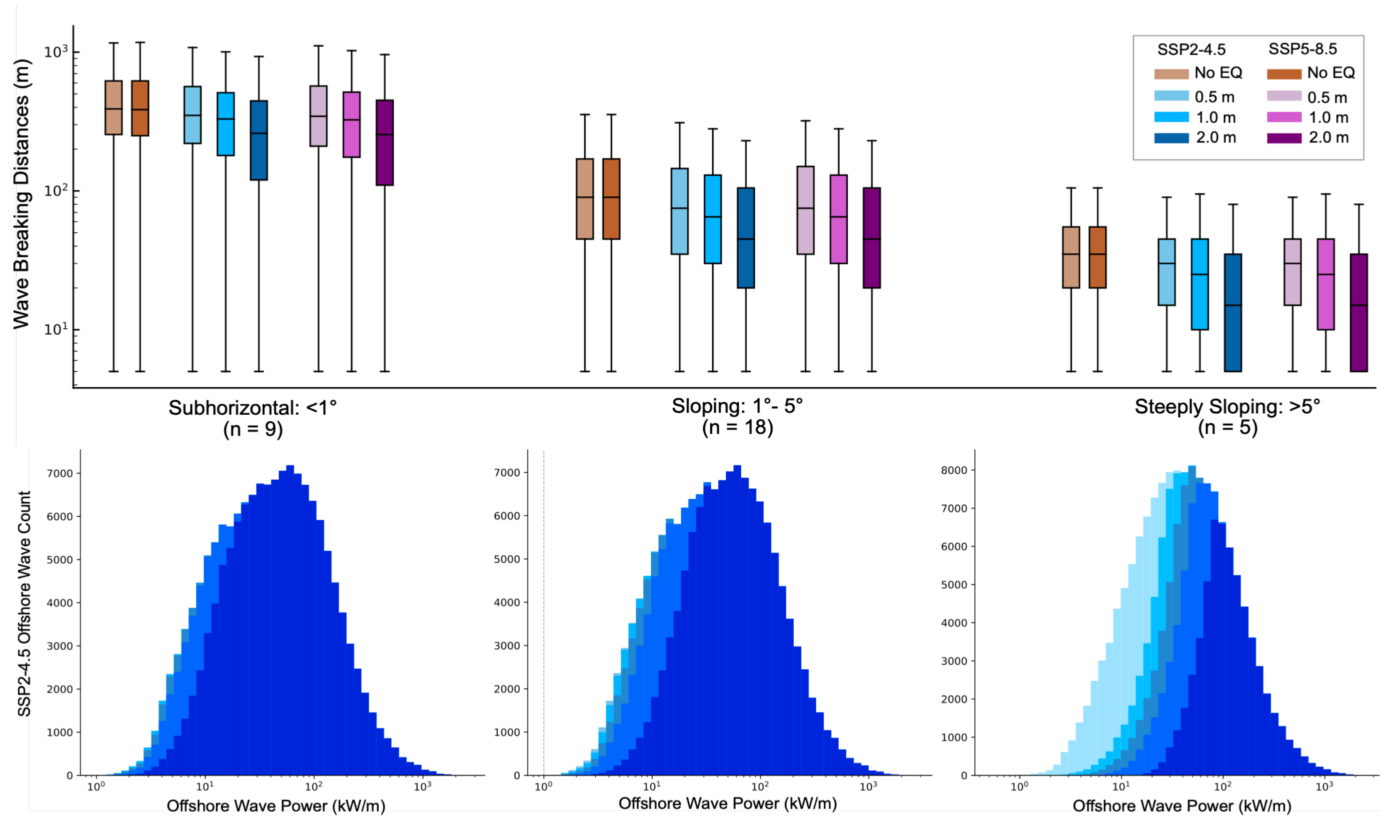


Lopez and Masteller, *in prep*

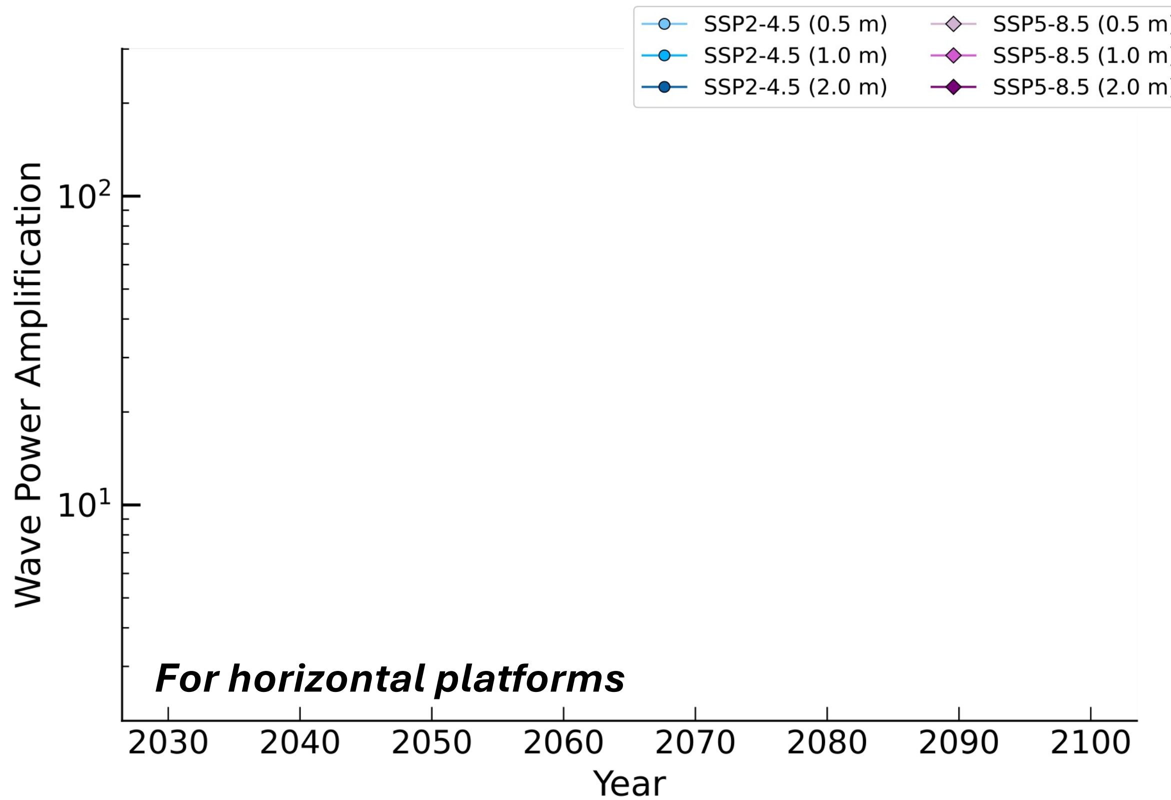
Wave amplification effects dominated by **landward shift in wave breaking**

- Greater subsidence more effectively **concentrates wave breaking**
- Saturation in landward shift effects only in most extreme subsidence scenarios



Lopez and Masteller, *in prep*

How does **EQ timing** influence coastal wave power amplification?



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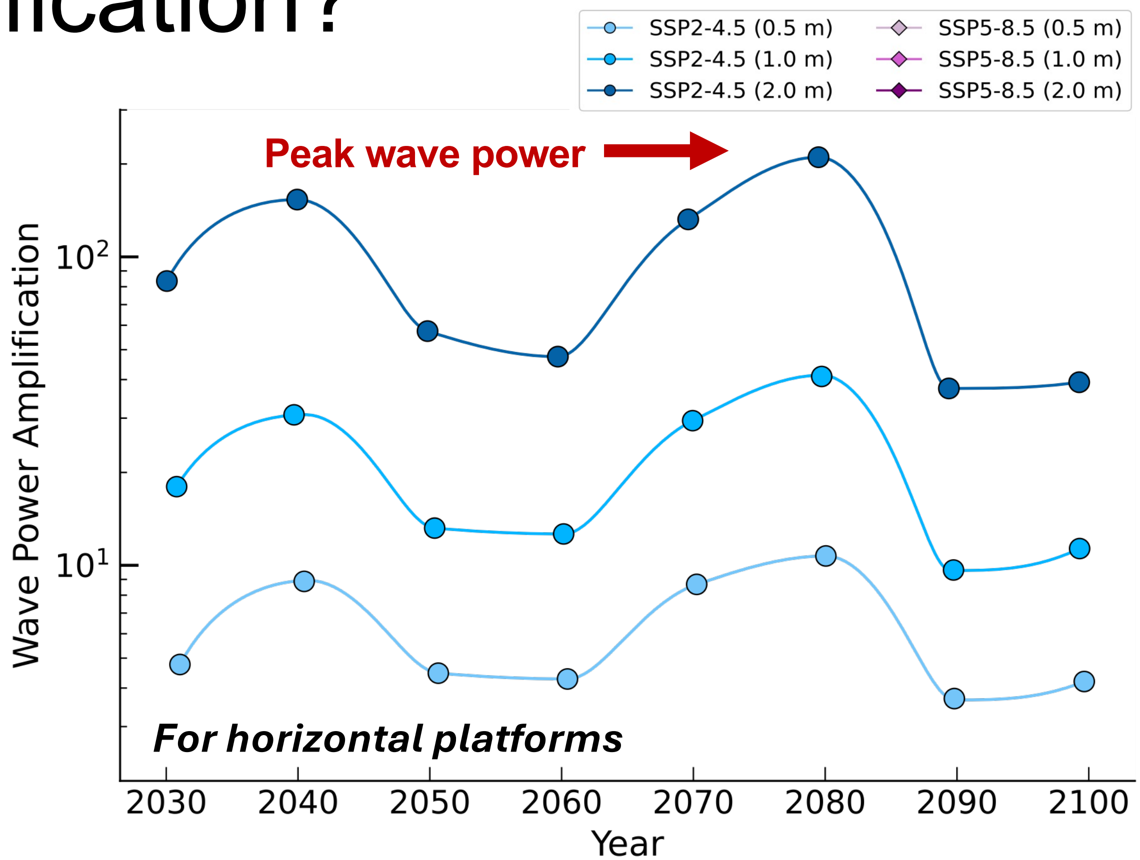
How does **EQ timing** influence coastal wave power amplification?

- Timing matters!
- “Business as usual” scenario wave power amplification peak occurs late (2080)



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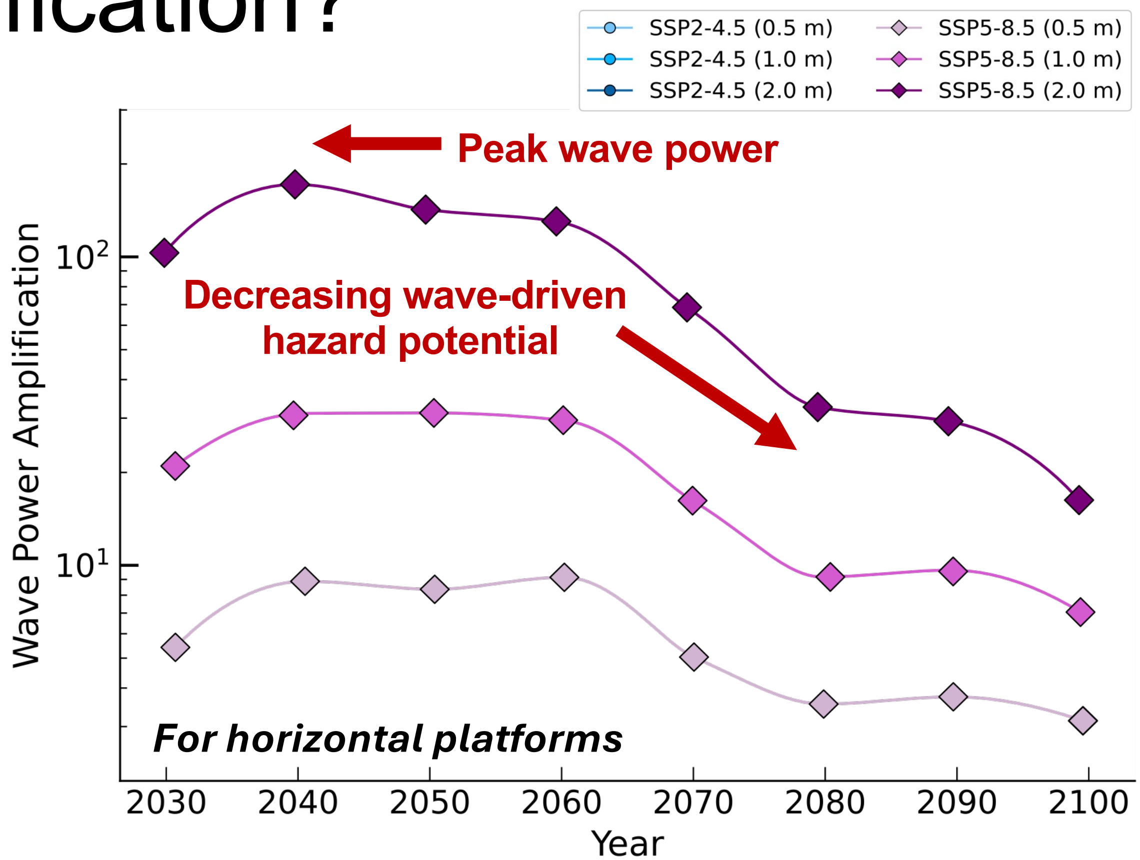
How does **EQ timing** influence coastal wave power amplification?

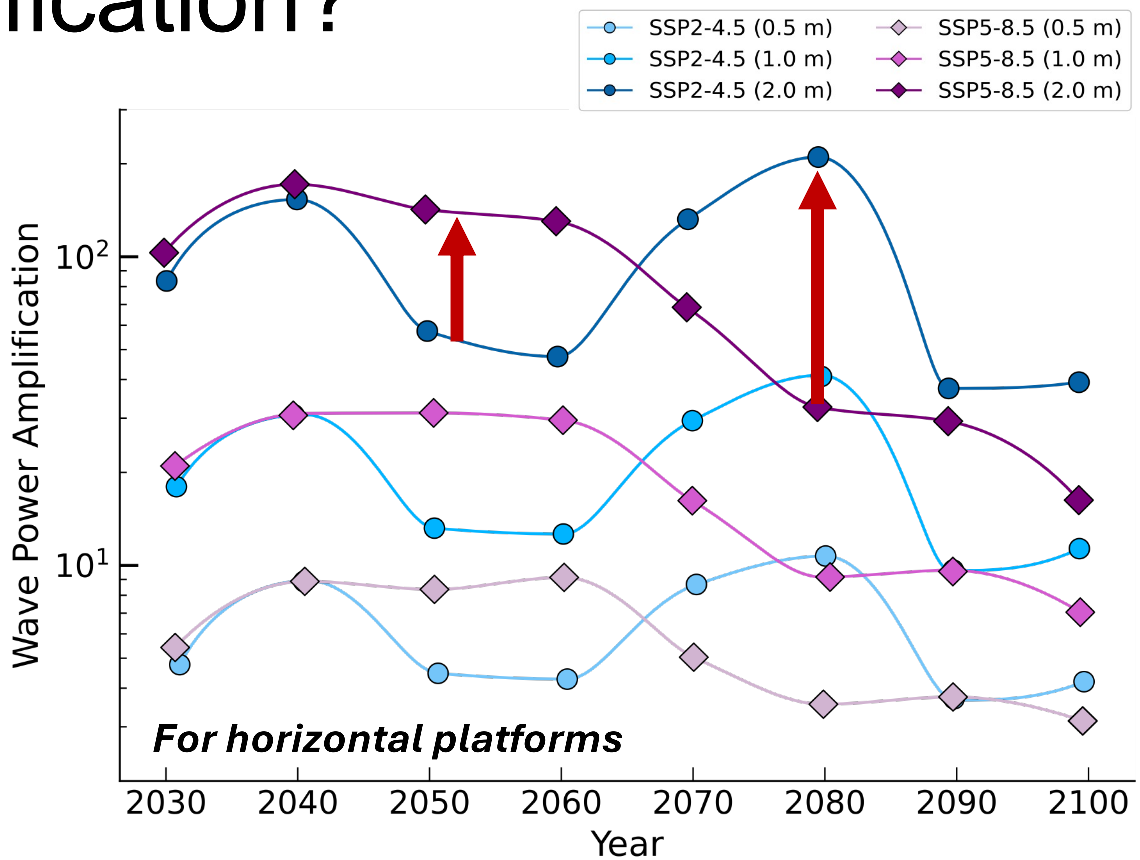
- Timing matters!
- More severe emissions scenario wave power peak occurs early (2040)
- Wave power amplification steadily decays for later EQs



Lopez and Masteller, *in prep*

How does **EQ timing** influence coastal wave power amplification?

- Timing matters!
- **Trade-offs** in peak wave power amplification by emissions scenario depending on EQ timing



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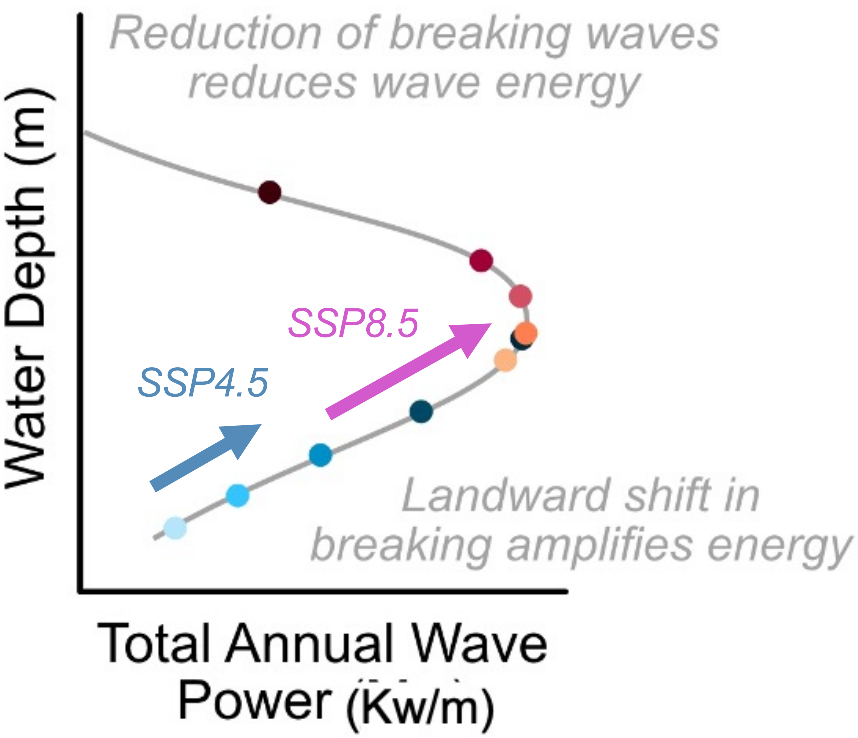

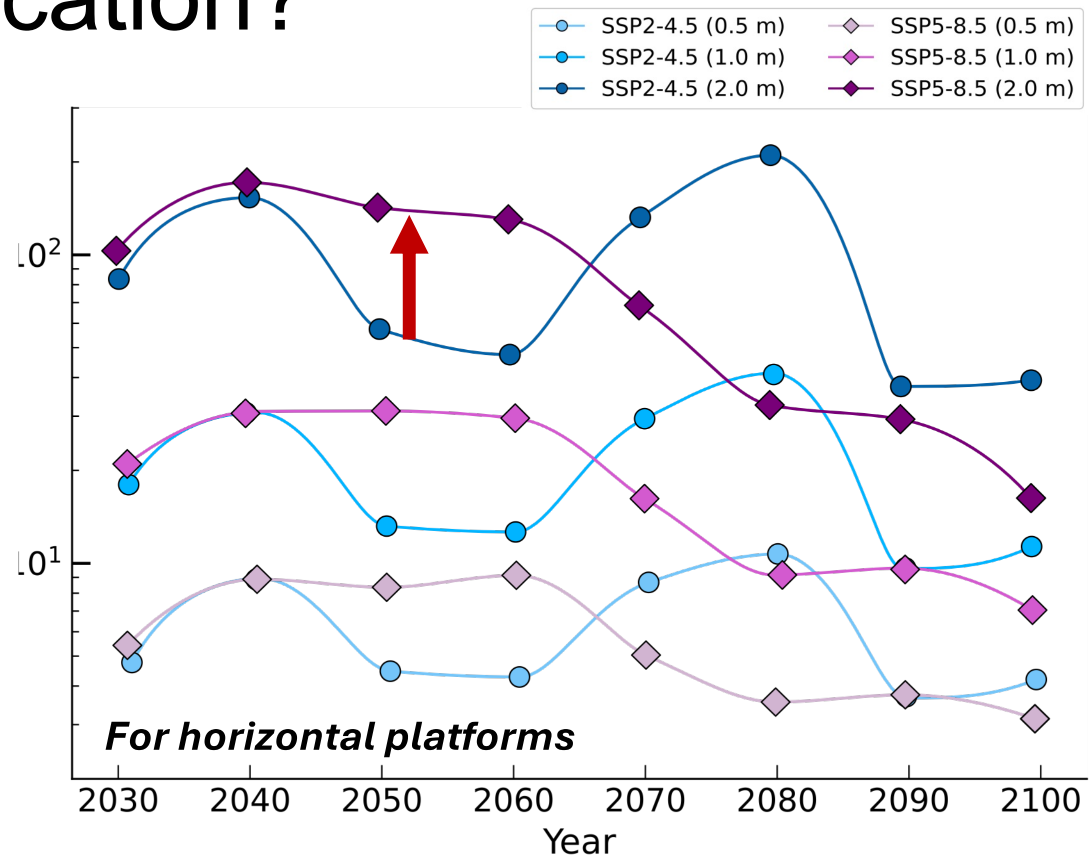

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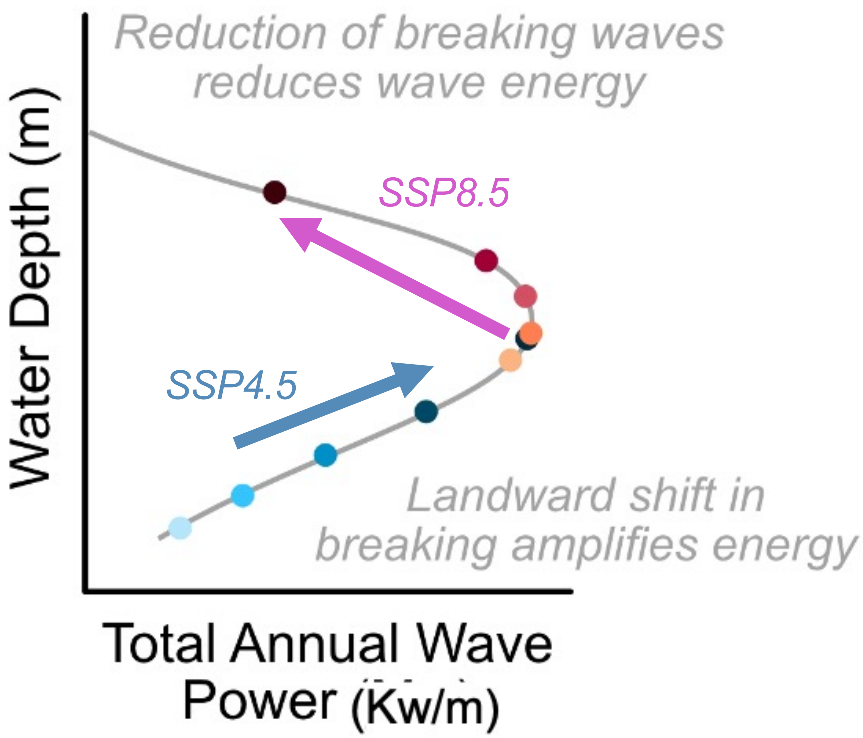
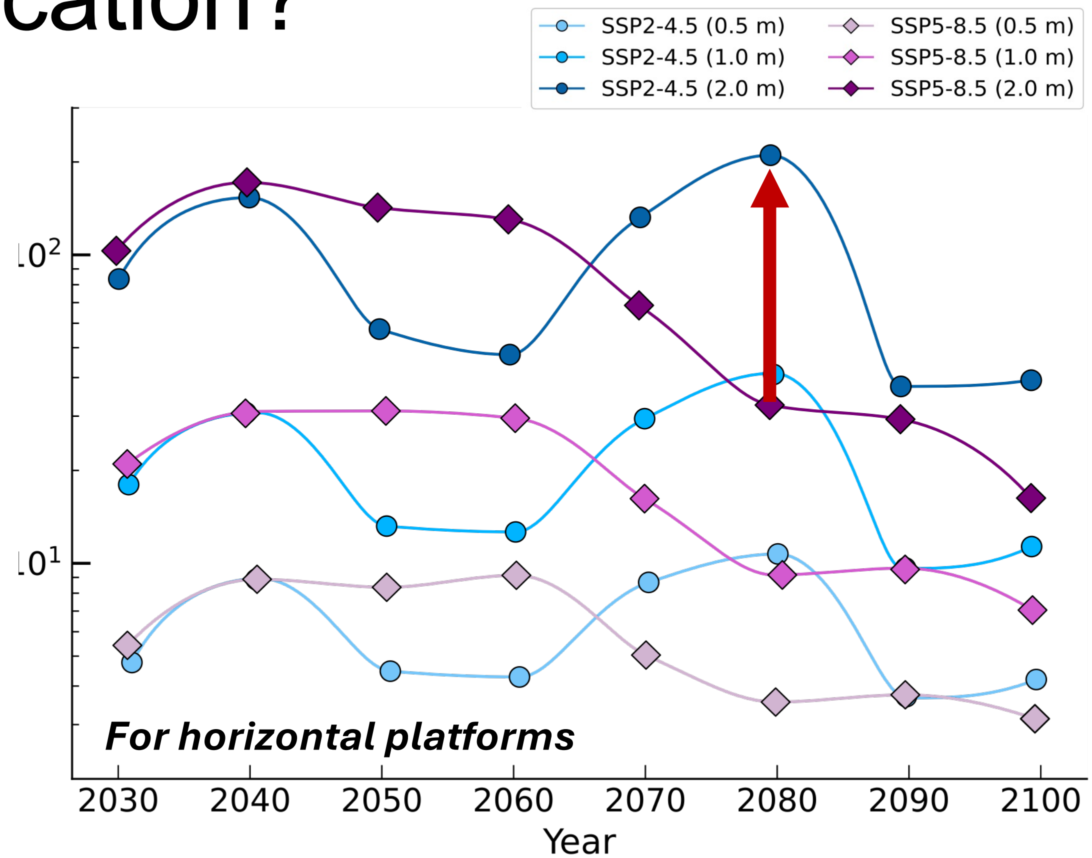




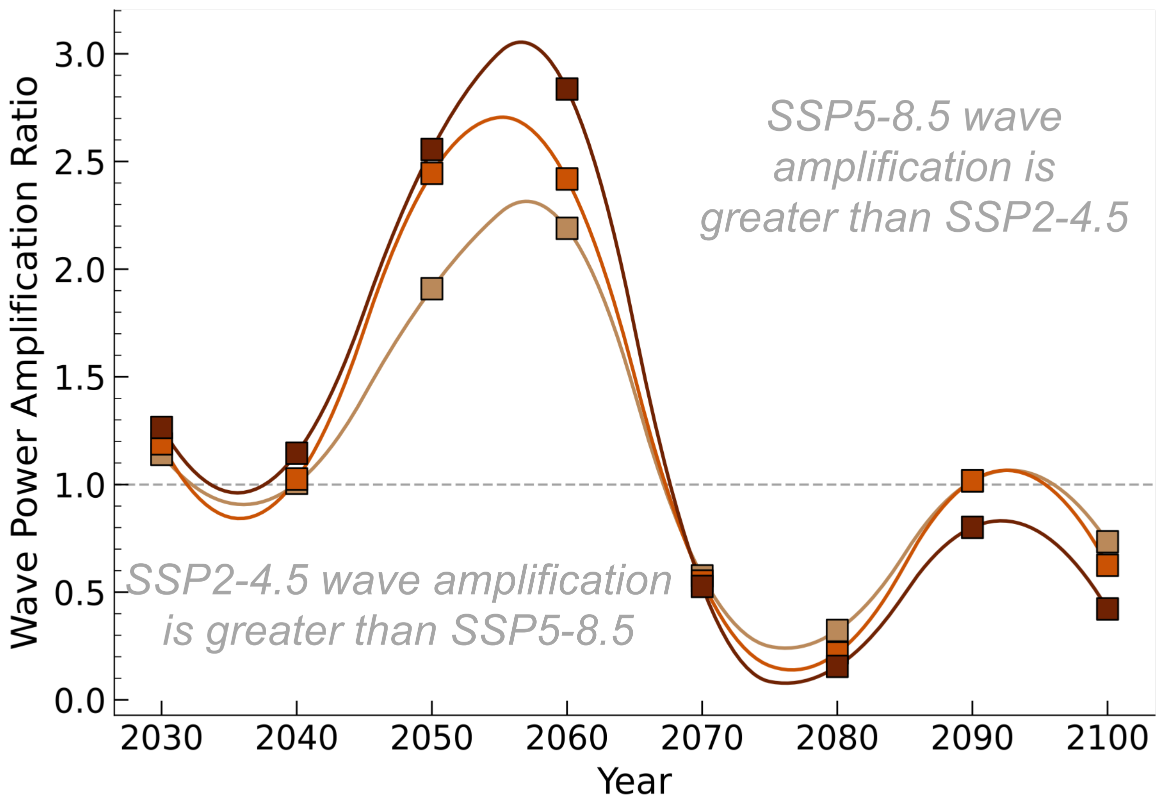
Lopez and Masteller, *in prep*

Climate-solid earth hazard interactions inform coastal erosion rates across Cascadia

Maximum **coastal erosion hazard window** set by EQ timing and emissions scenario

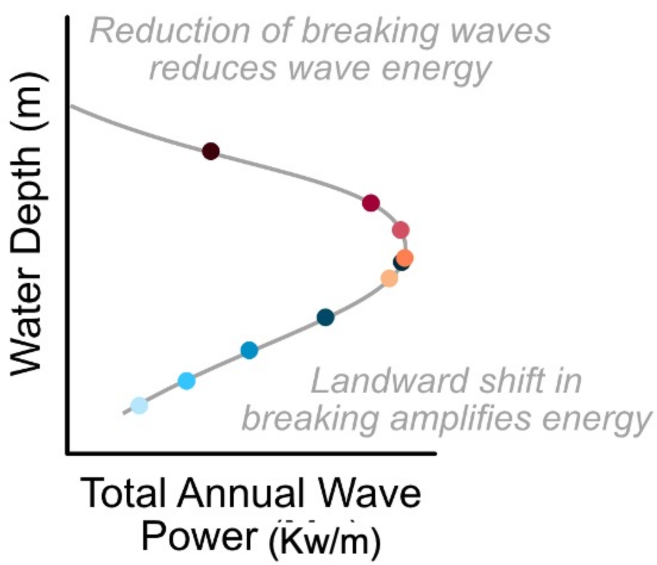
Future work:

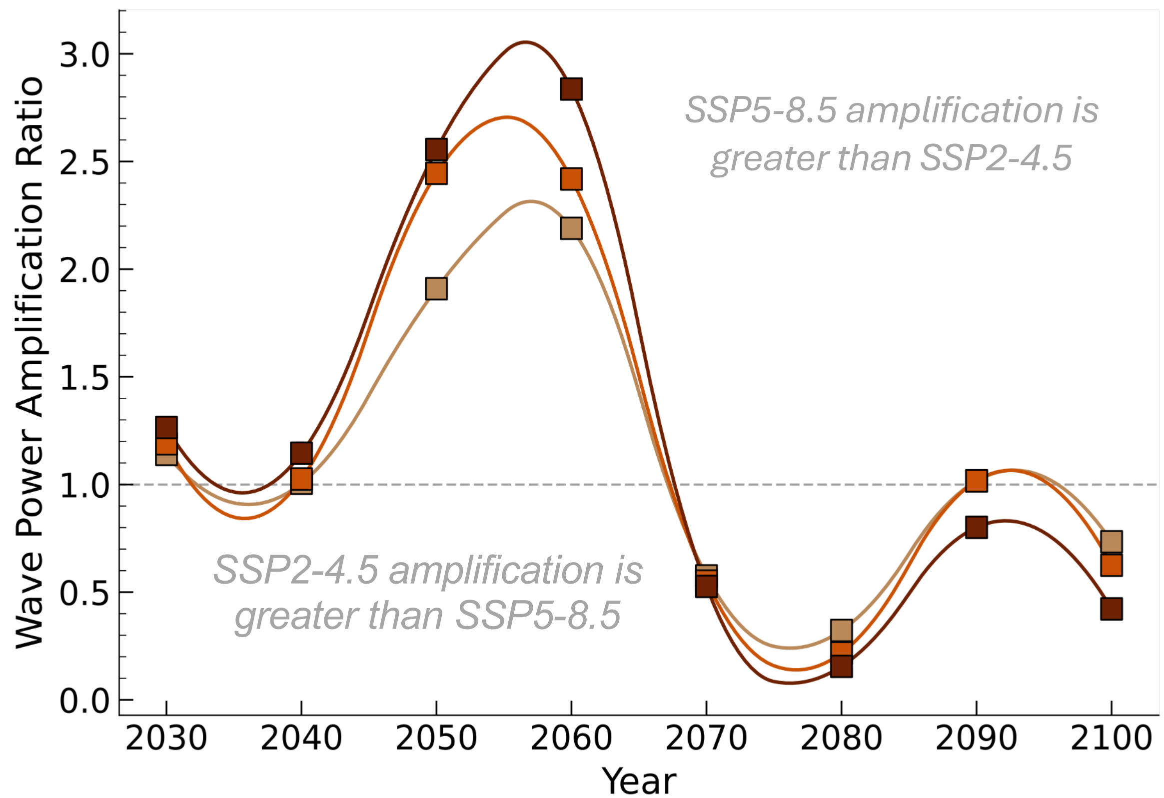
- How does amplified wave power translate into more rapid erosion across sites? *Poorly constrained!*
- Timescales of recovery and coastal change – how does interseismic VLM and rising sea level mediate EQ effects on waves?



Lopez and Masteller, *in prep*

Climate-driven shifts in maximum EQ-driven wave-driven coastal **hazard window**

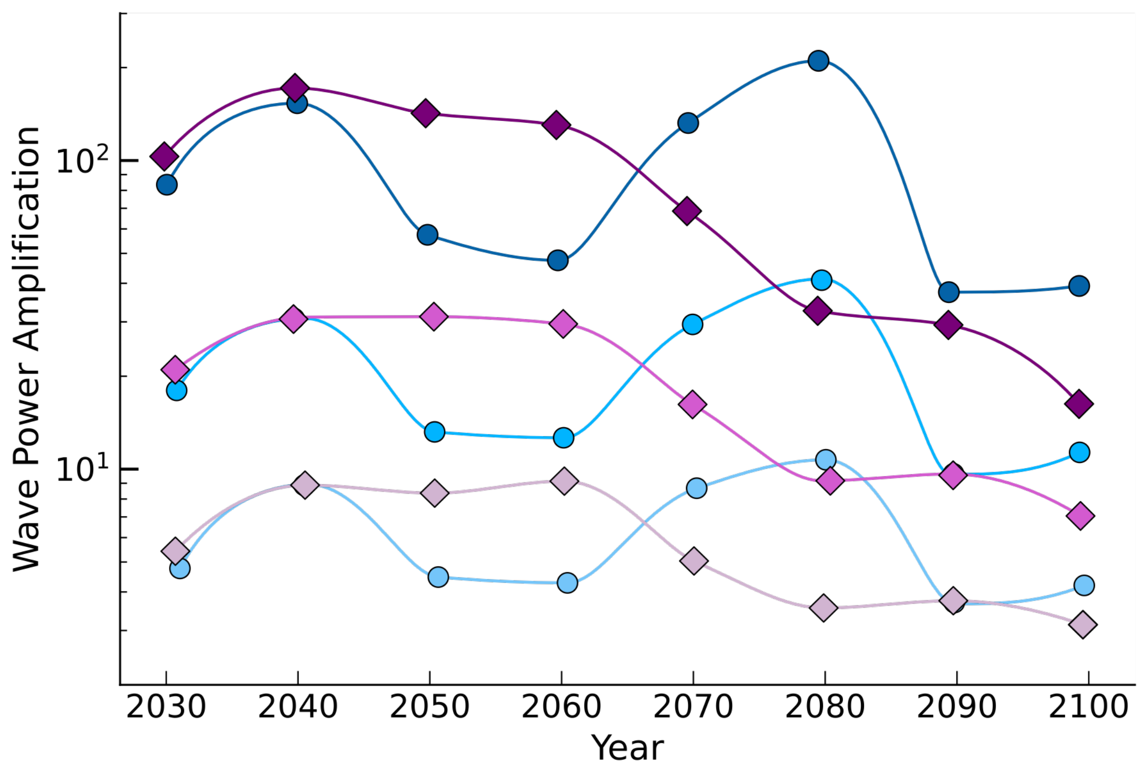




Lopez and Masteller, *in prep*

How does **EQ-timing** influence wave energy amplification effects?

- Timing matters!
- When EQ occurs early, SLR curves have not diverged enough to make a difference
- More severe emissions scenario wave energy peak occurs early (2040)
- "business as usual" scenario wave energy peak occurs late (2080)



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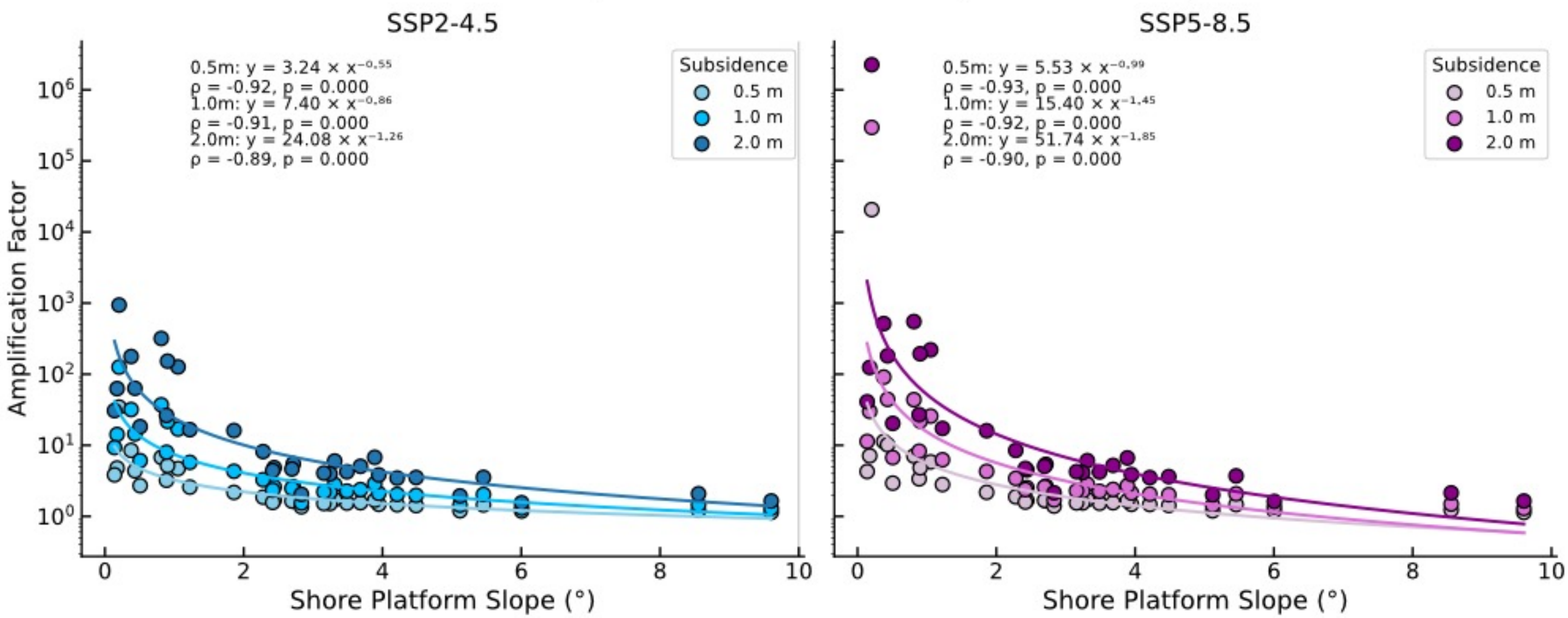
Climate-driven shifts in maximum EQ-driven wave-driven erosion hazard window



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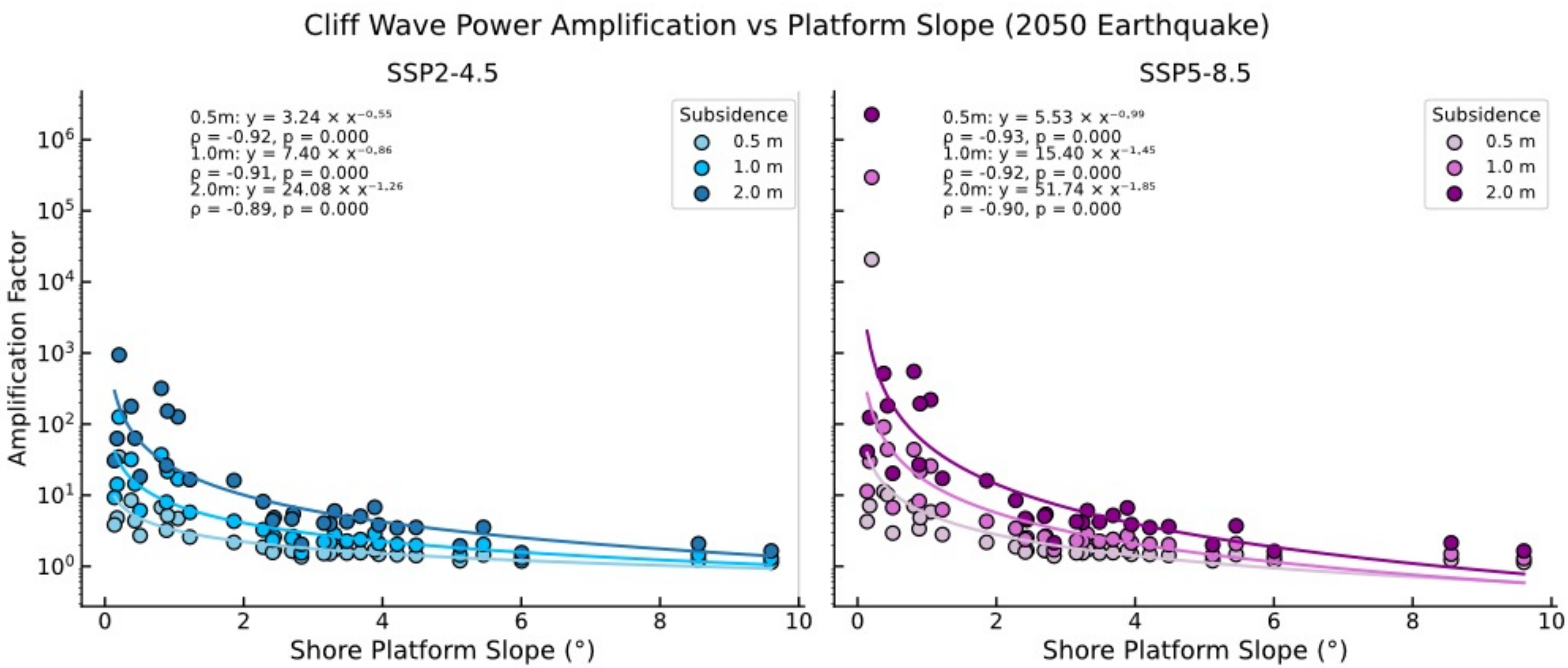

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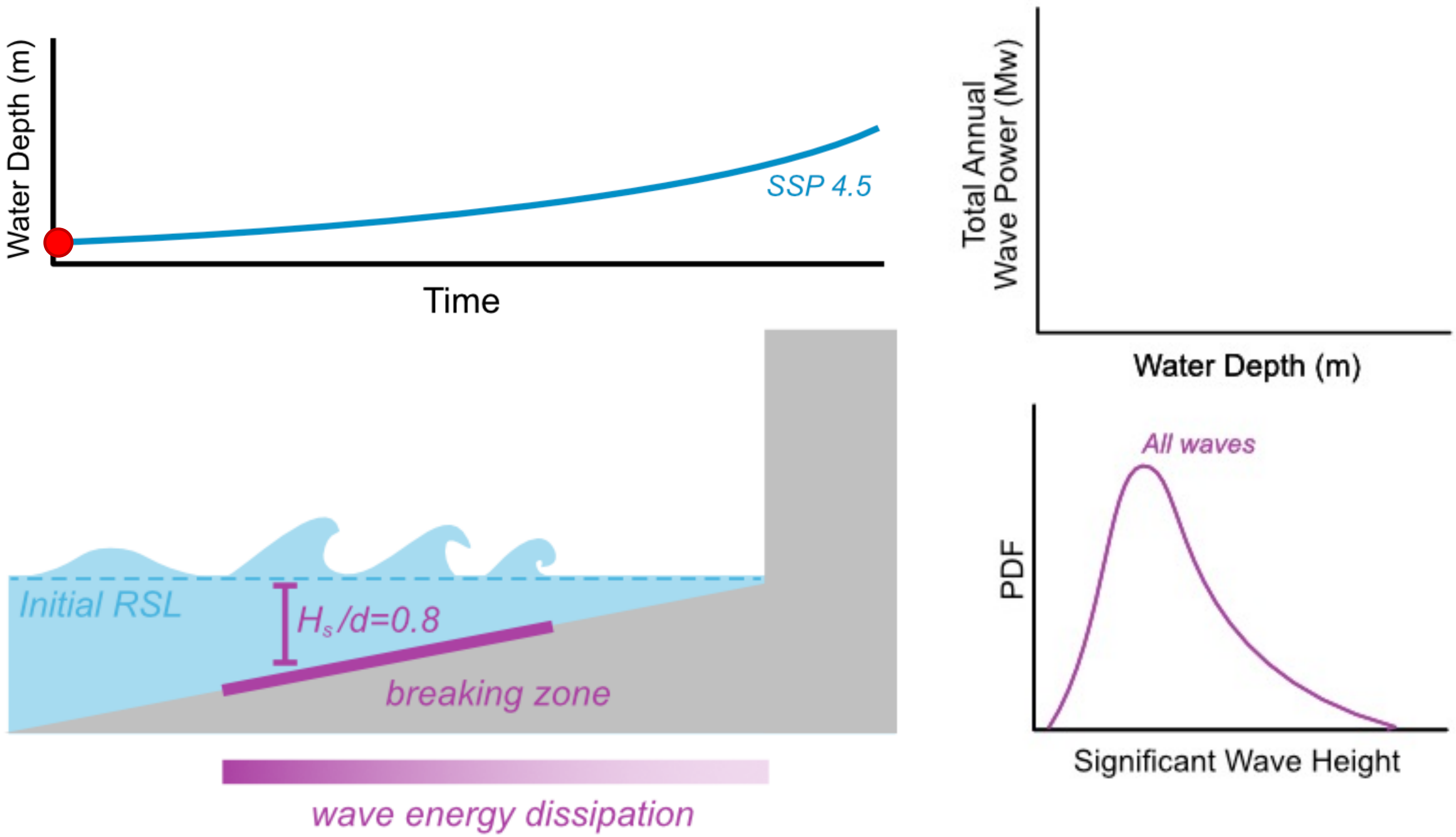
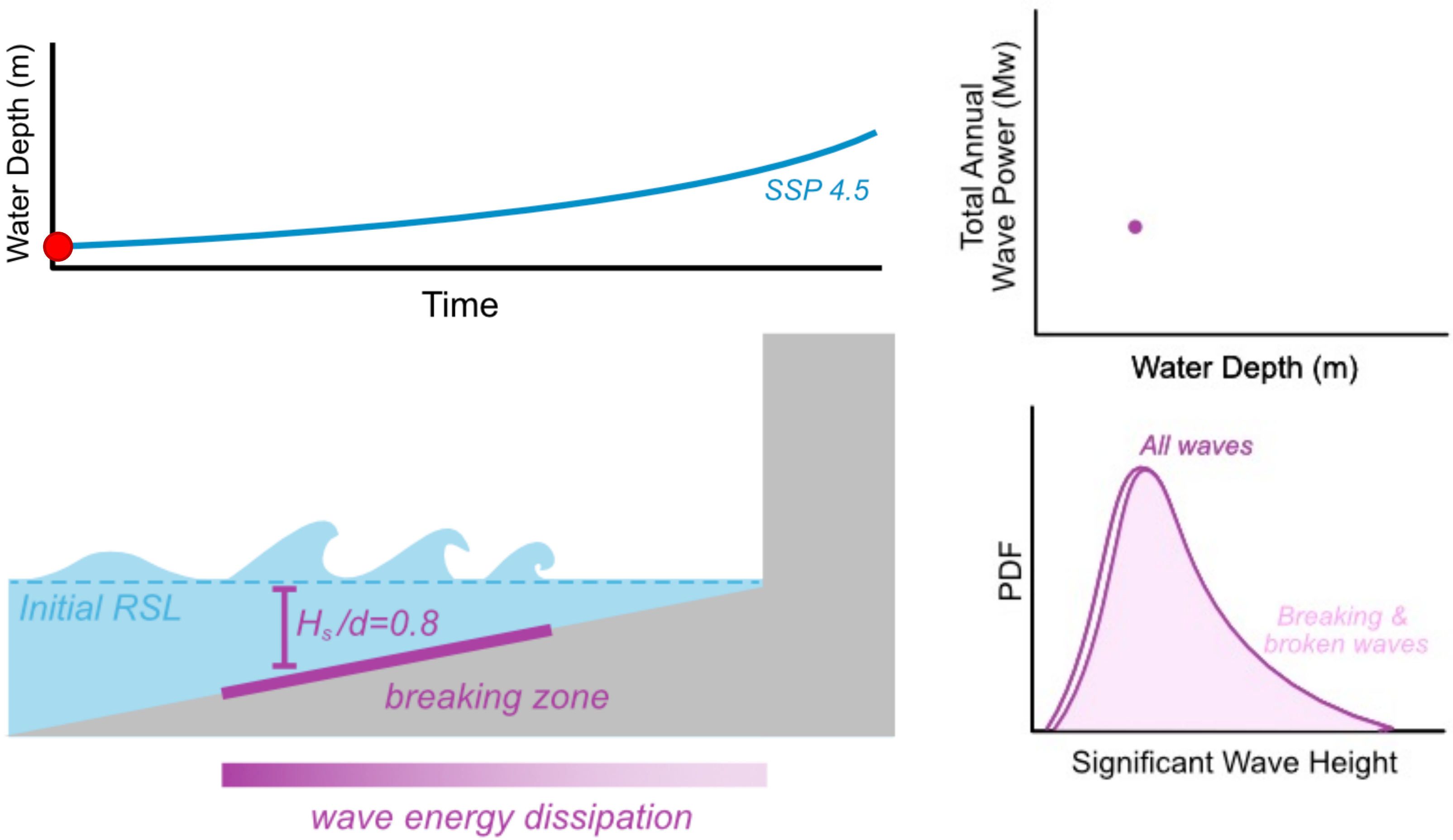


Water Depth (m)
SSP 4.5
Time
Total Annual
Wave Power (Mw)
Water Depth (m)
Initial RSL
H_s/d=0.8
breaking zone
wave energy dissipation
All waves
PDF
Significant Wave Height



Water Depth (m)
Time
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Total Annual
Wave Power (Mw)
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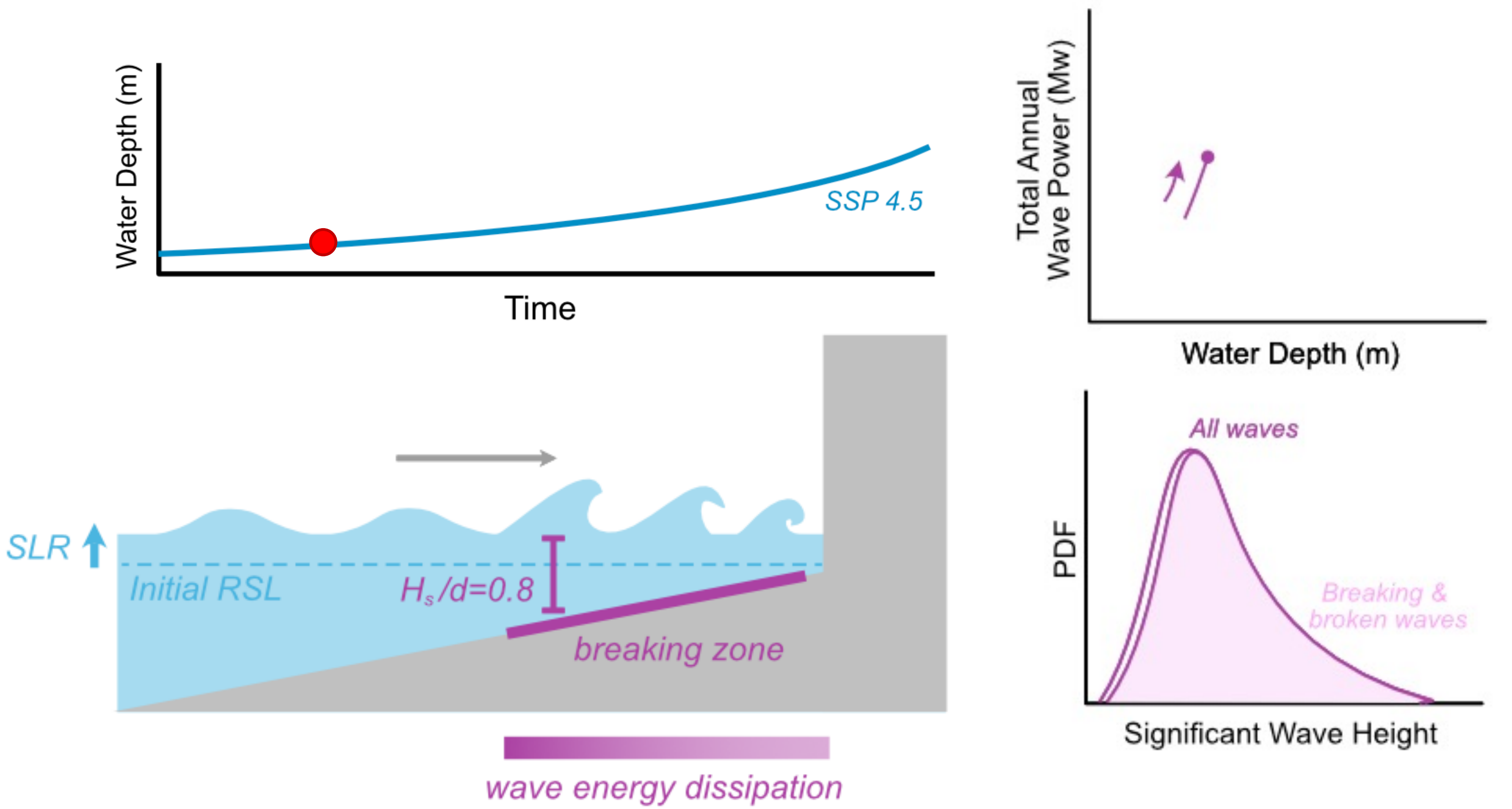
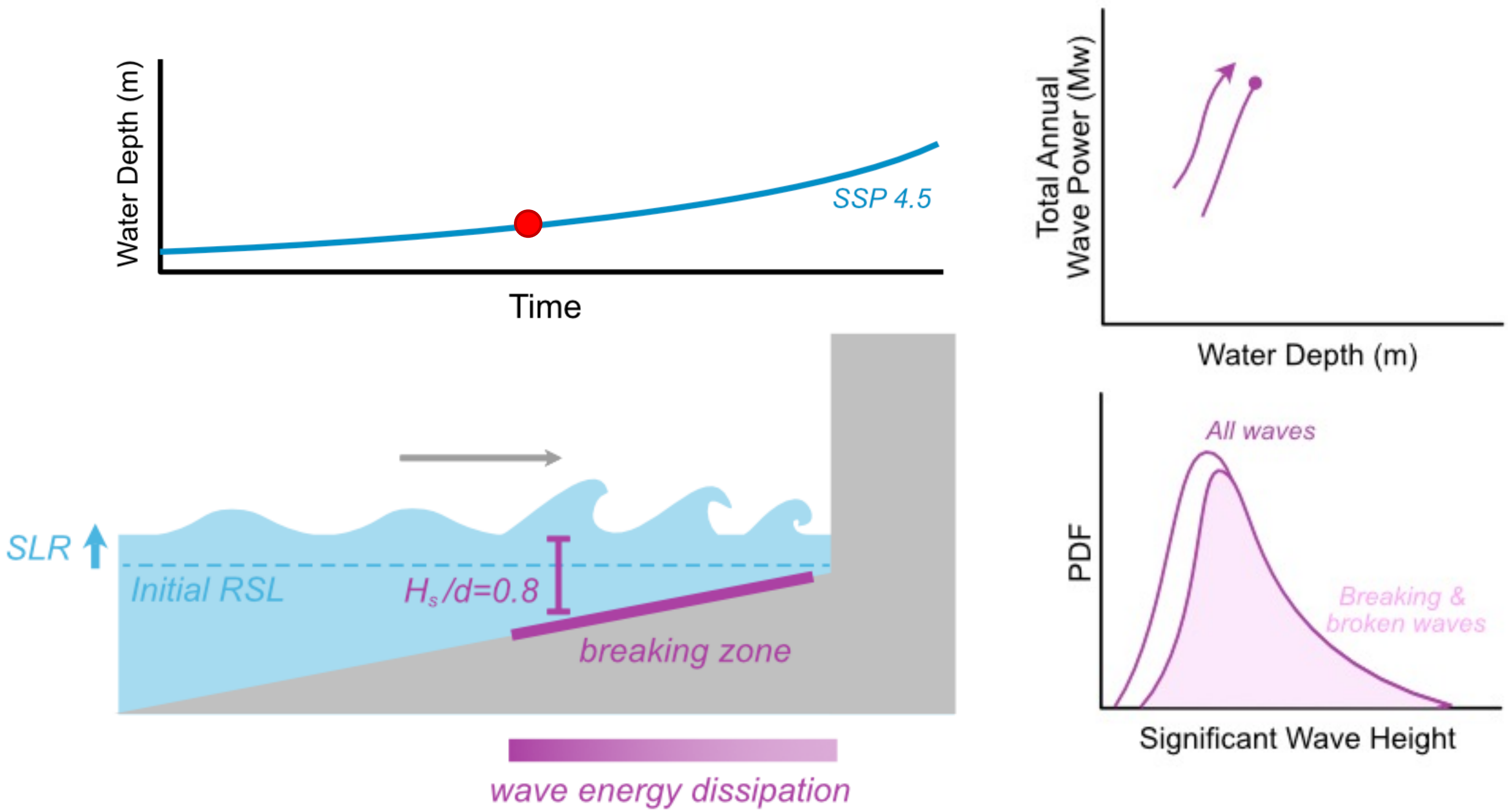
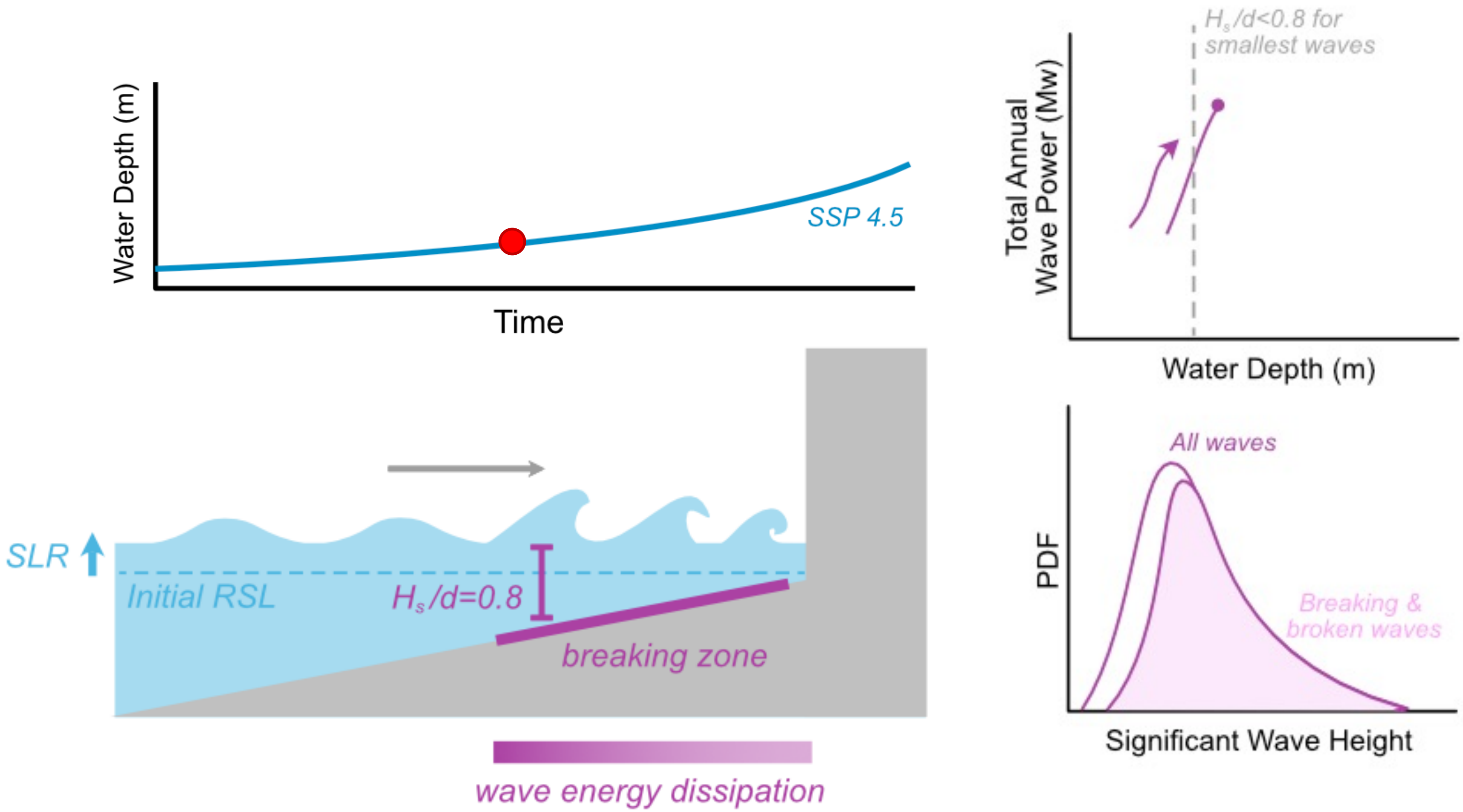


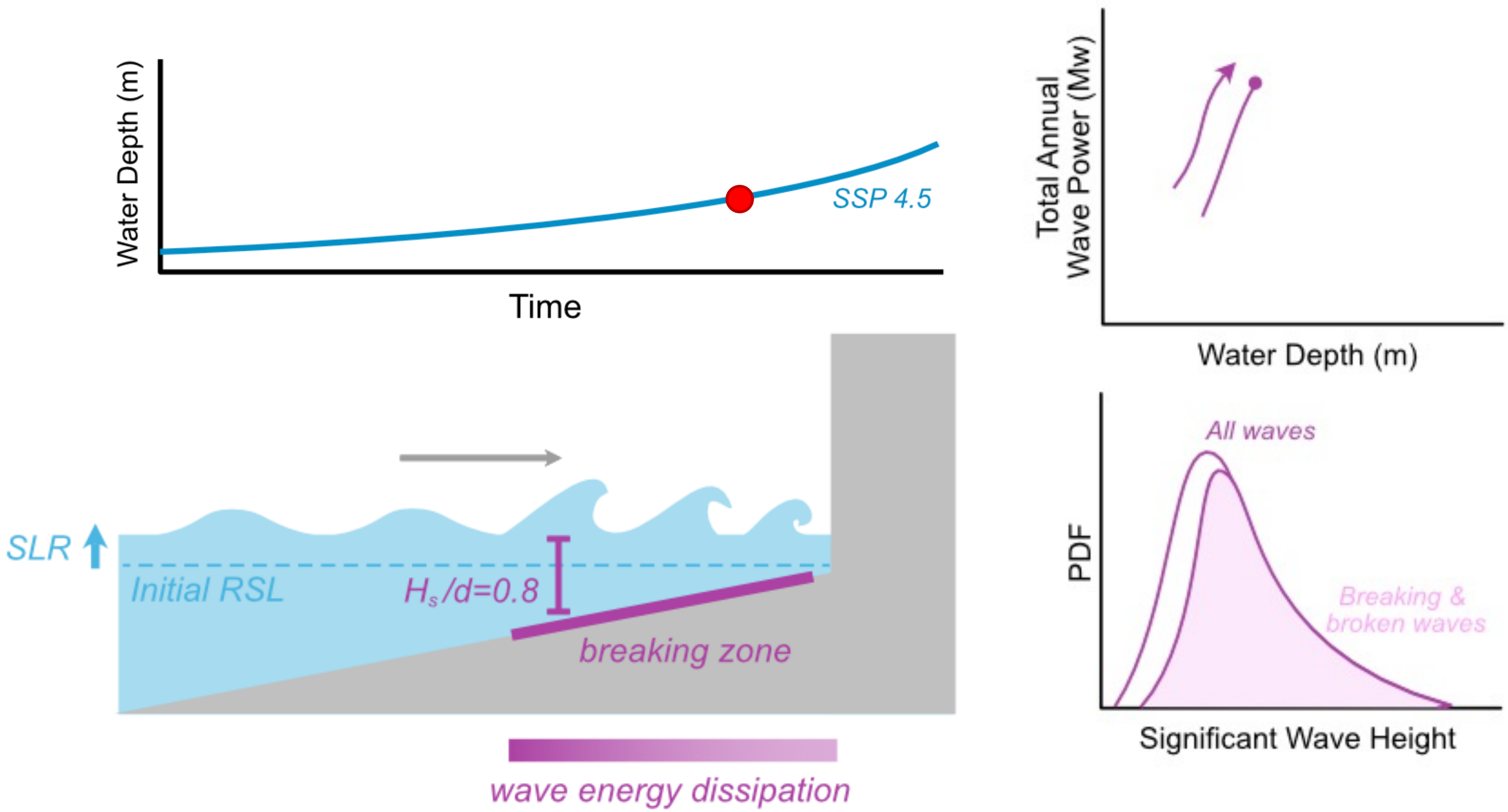
Water Depth (m)
SSP 4.5
Time
SLR
Initial RSL
$H_s/d=0.8$
breaking zone
wave energy dissipation
Total Annual
Wave Power (Mw)
Water Depth (m)
All waves
PDF
Breaking &
broken waves
Significant Wave Height



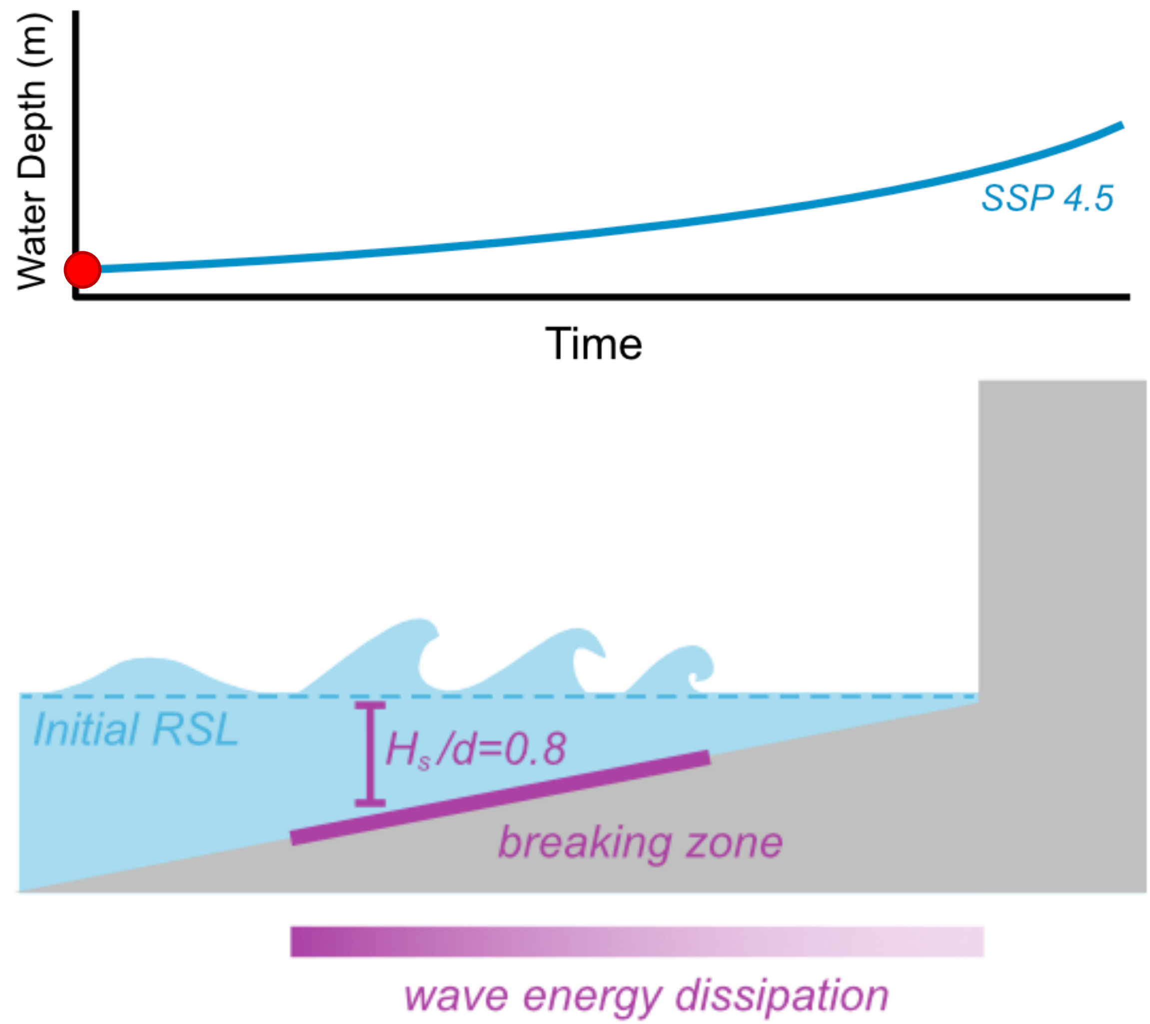
Water Depth (m)
SSP 4.5
Time
SLR
Initial RSL
$H_s/d=0.8$
breaking zone
wave energy dissipation
Total Annual
Wave Power (Mw)
Water Depth (m)
All waves
PDF
Breaking &
broken waves
Significant Wave Height

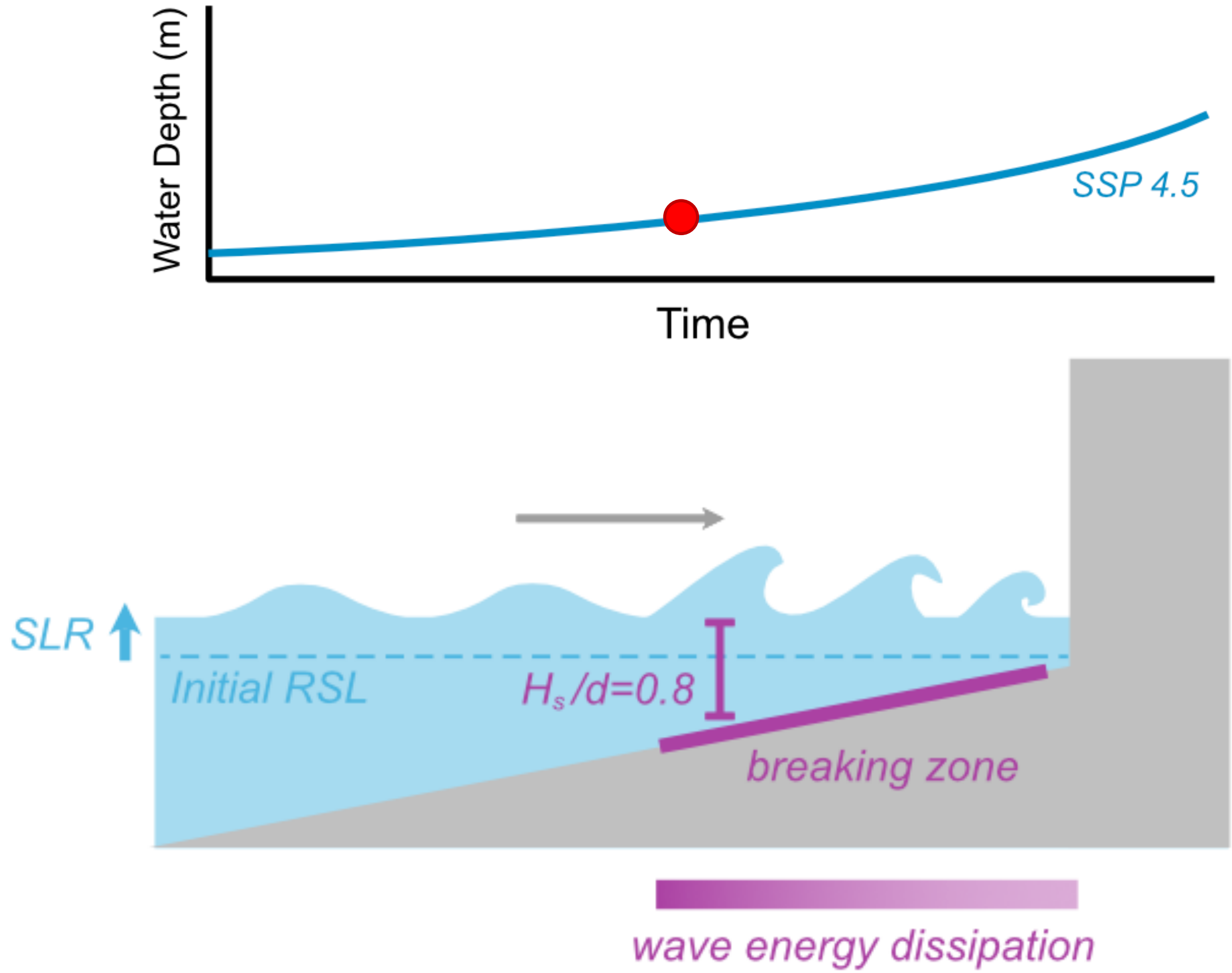


Water Depth (m)
SSP 4.5
Time
SLR
Initial RSL
$H_s/d=0.8$
breaking zone
wave energy dissipation
$H_s/d<0.8$ for smallest waves
Total Annual Wave Power (Mw)
Water Depth (m)
All waves
PDF
Breaking & broken waves
Significant Wave Height

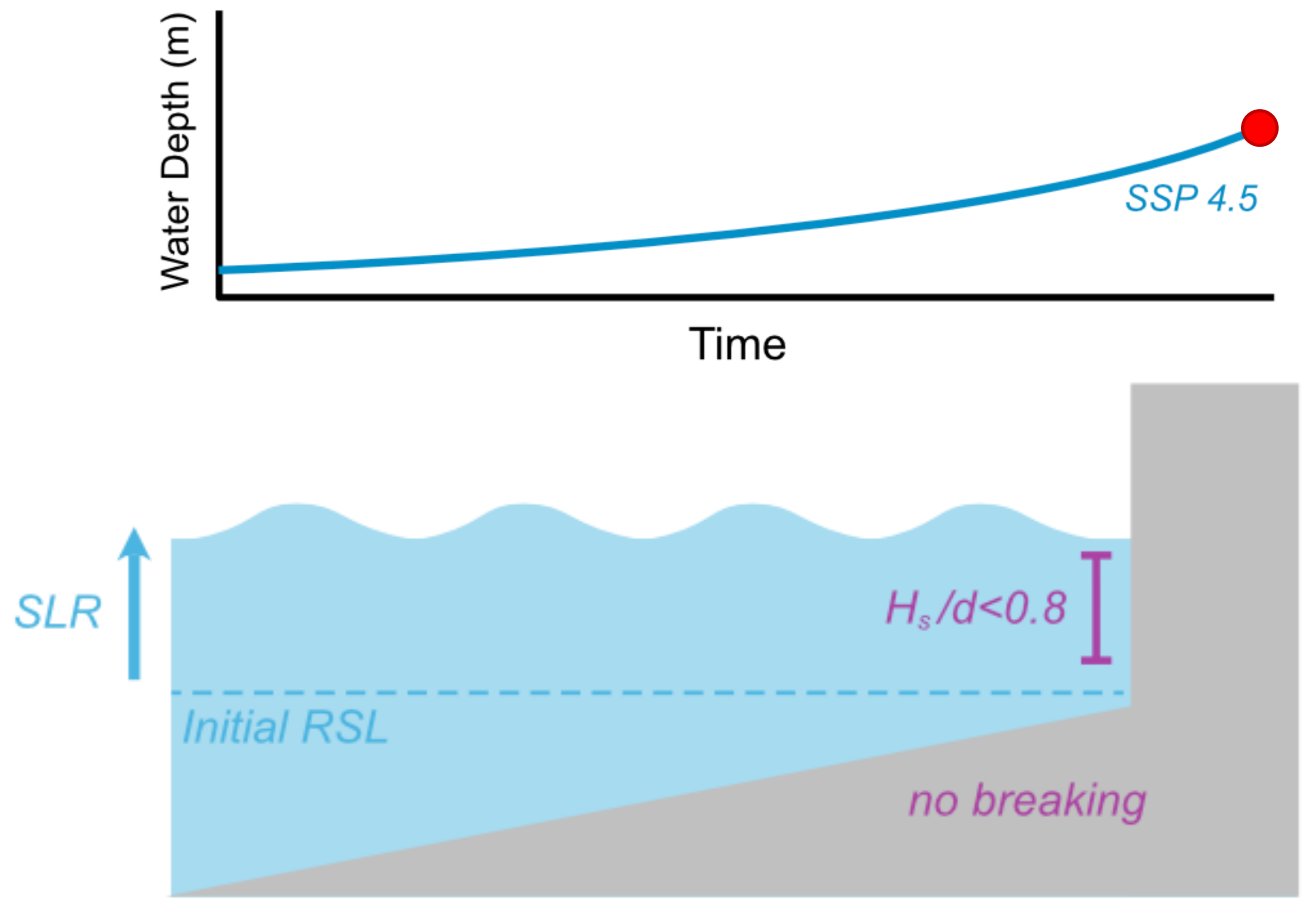


Water Depth (m)
SSP 4.5
Time
SLR
Initial RSL
$H_s/d=0.8$
breaking zone
wave energy dissipation
Total Annual
Wave Power (Mw)
Water Depth (m)
All waves
PDF
Breaking &
broken waves
Significant Wave Height

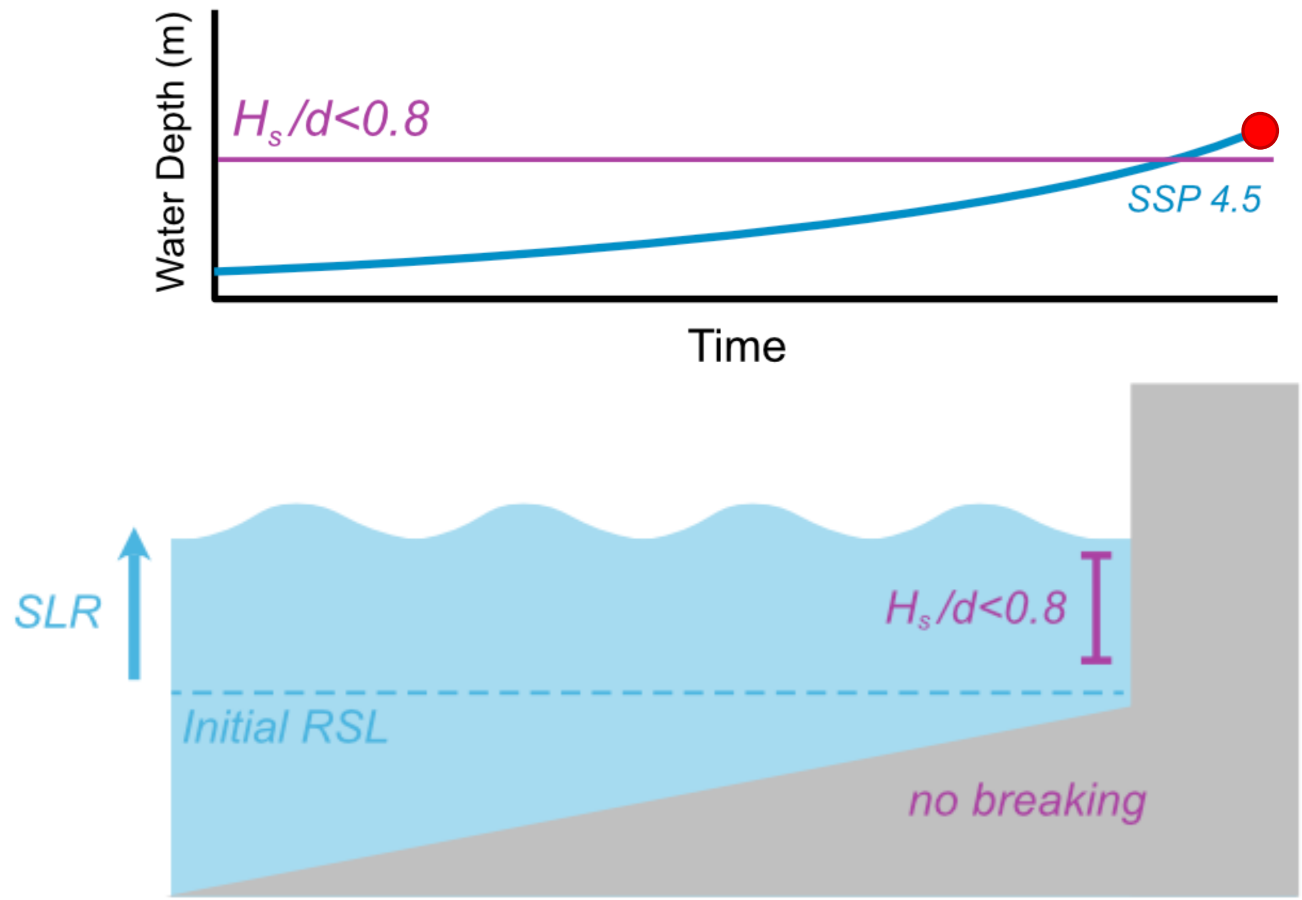

Water Depth (m)
Time
SSP 4.5
Initial RSL
$H_s/d=0.8$
breaking zone
wave energy dissipation



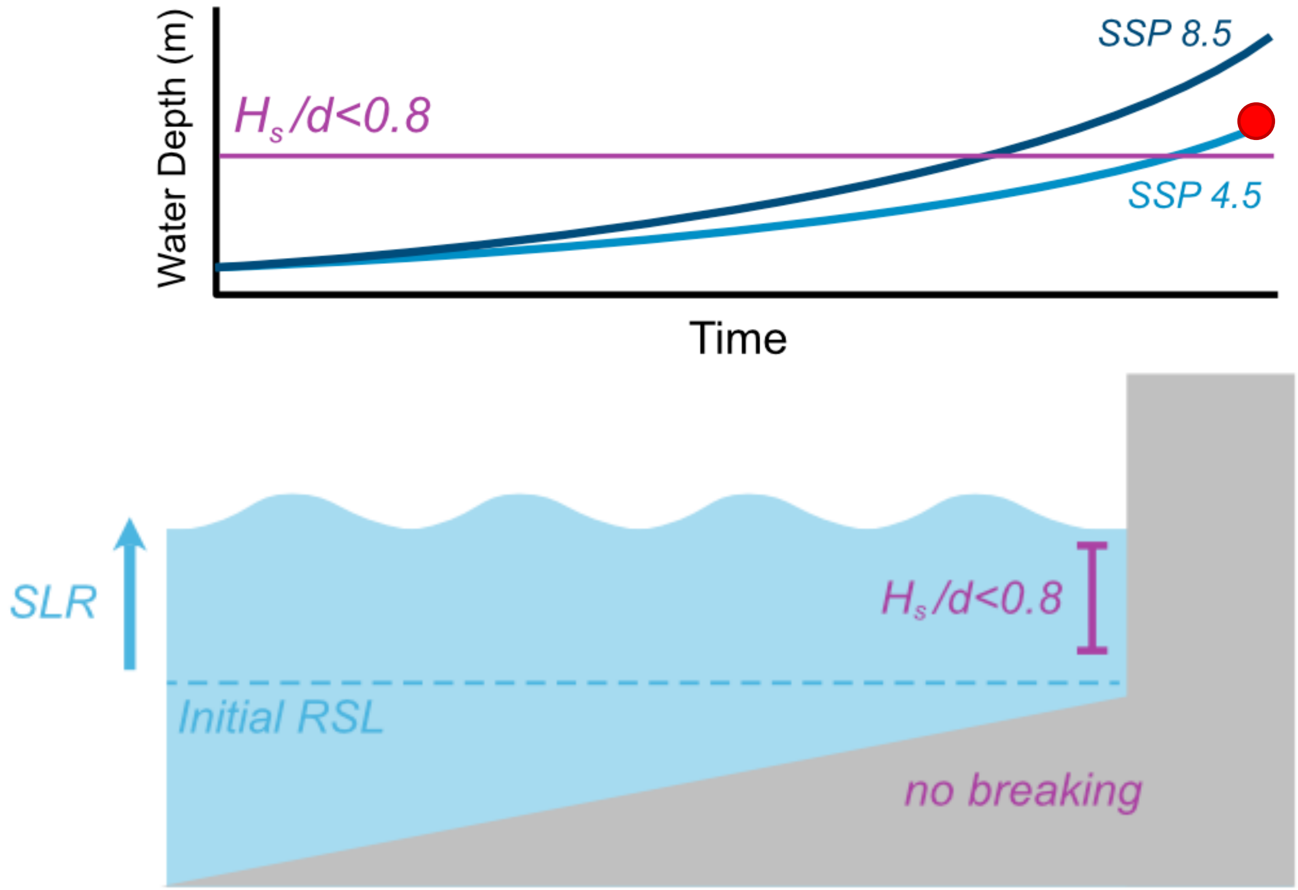
Water Depth (m)
SSP 4.5
Time
SLR
Initial RSL
$H_s/d=0.8$
breaking zone
wave energy dissipation

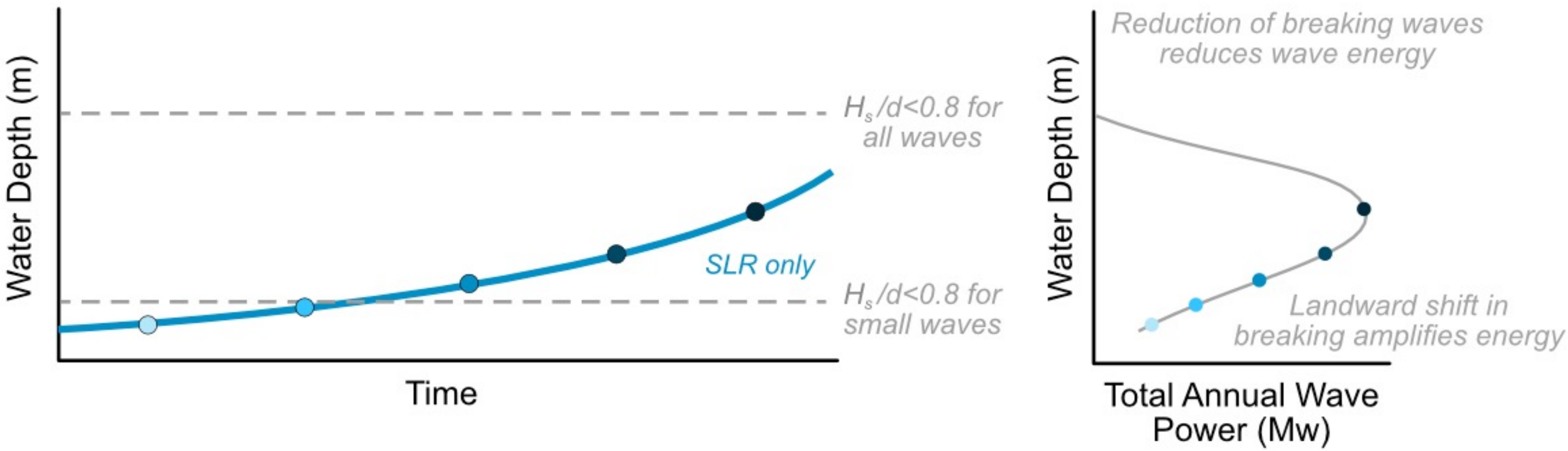


Water Depth (m)
SSP 4.5
Time
SLR
$H_s/d<0.8$
Initial RSL
no breaking

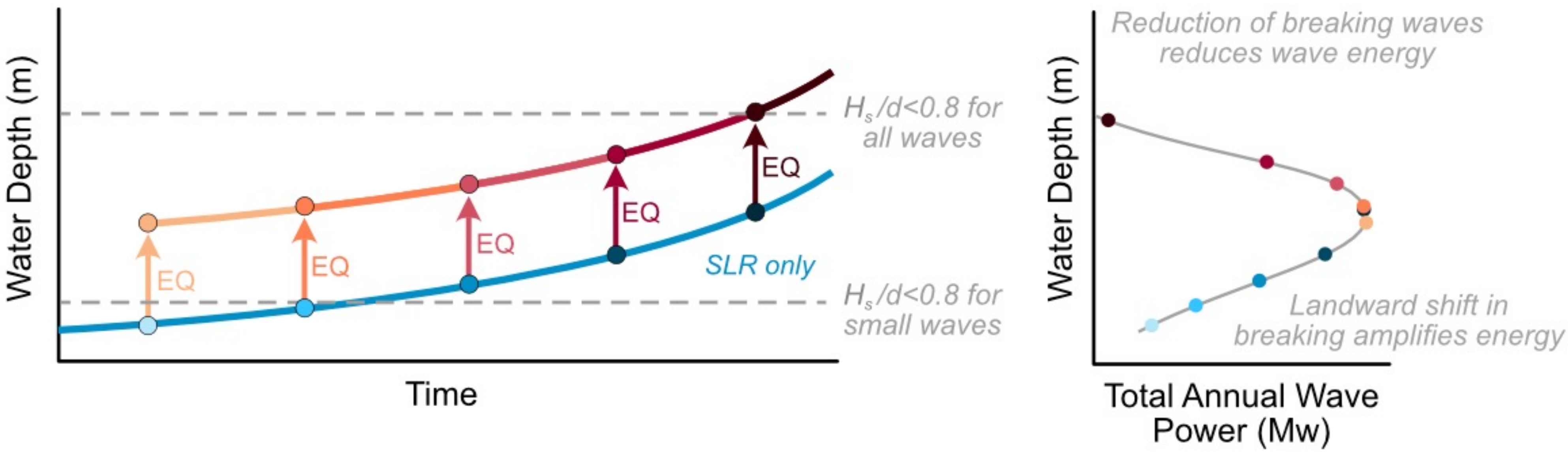


Water Depth (m)
$H_s/d<0.8$
SSP 4.5
Time
SLR
$H_s/d<0.8$
Initial RSL
no breaking

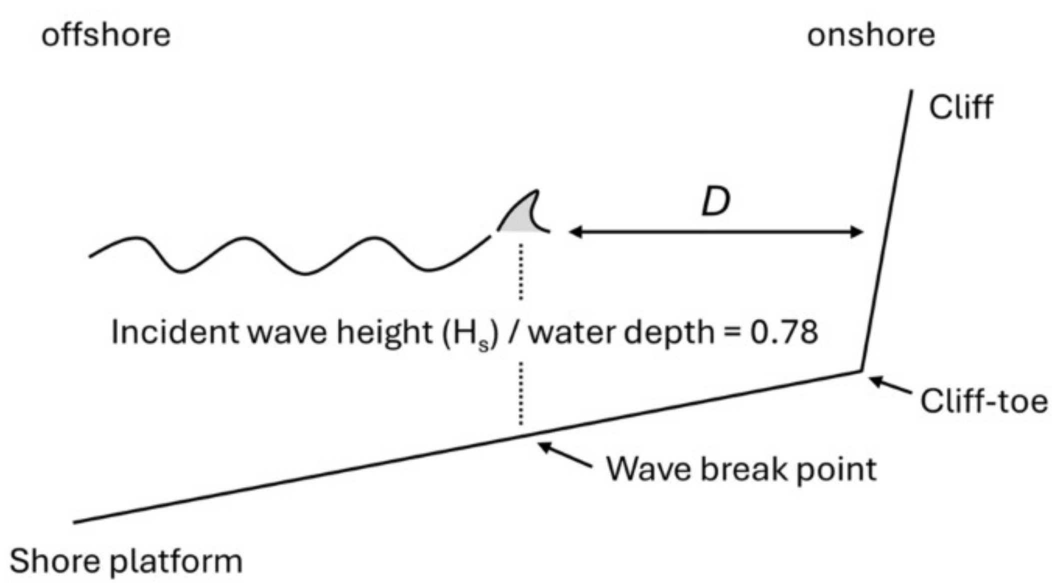

Water Depth (m)
SSP 8.5
$H_s/d<0.8$
SSP 4.5
Time
SLR
$H_s/d<0.8$
Initial RSL
no breaking



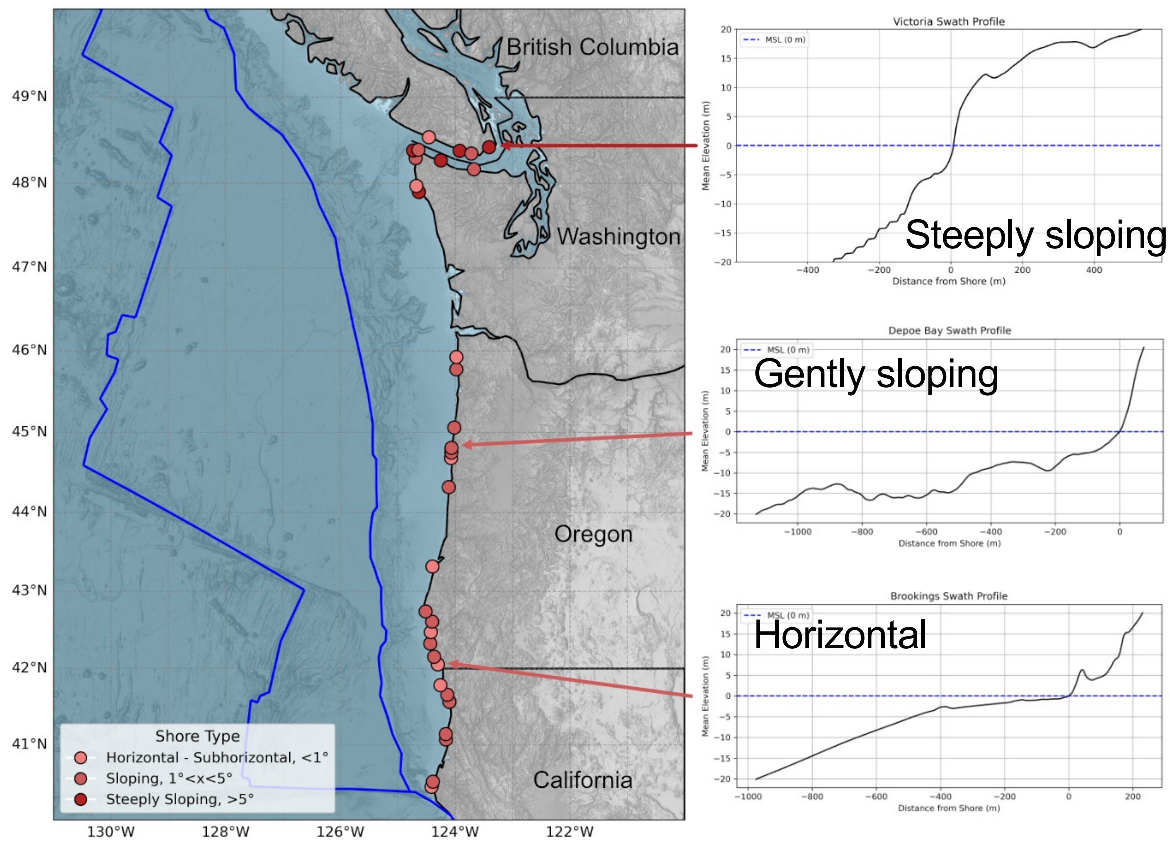
Water Depth (m)
H_s/d<0.8 for all waves
SLR only
H_s/d<0.8 for small waves
Time
Reduction of breaking waves reduces wave energy
Water Depth (m)
Landward shift in breaking amplifies energy
Total Annual Wave Power (Mw)

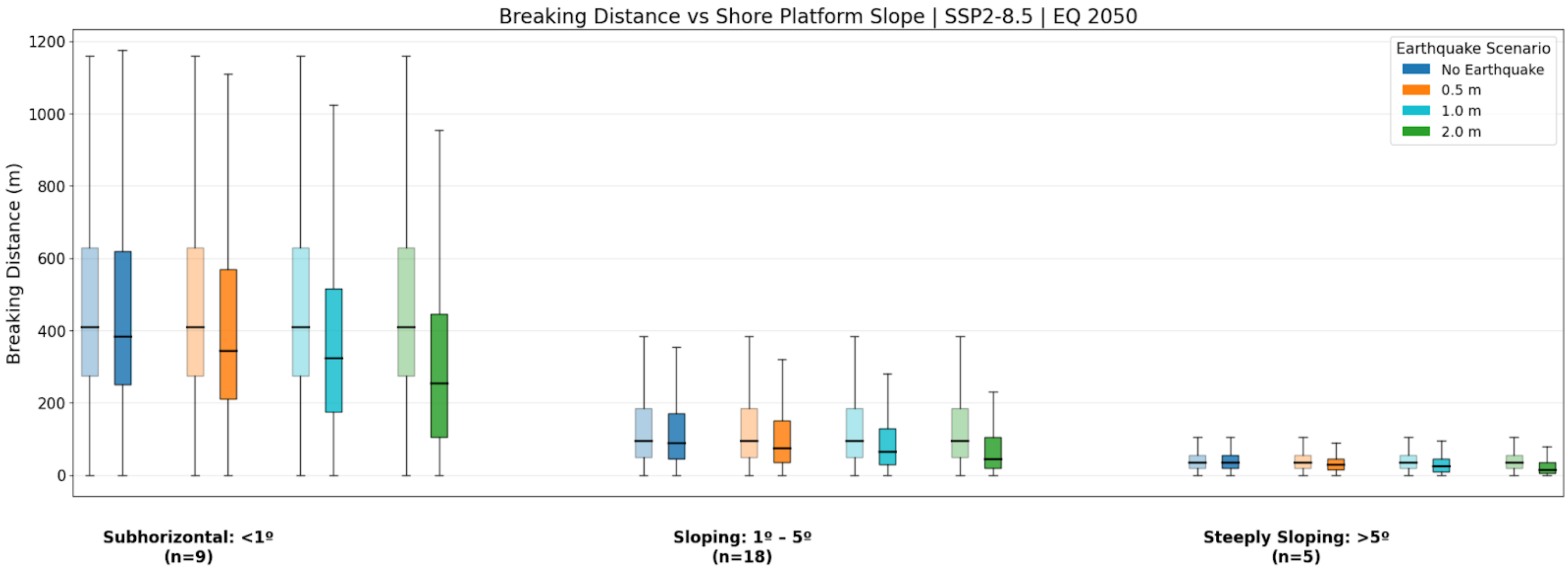


Water Depth (m)
Time
EQ
EQ
EQ
EQ
EQ
SLR only
$H_s/d<0.8$ for all waves
$H_s/d<0.8$ for small waves
Reduction of breaking waves reduces wave energy
Landward shift in breaking amplifies energy
Water Depth (m)
Total Annual Wave Power (Mw)

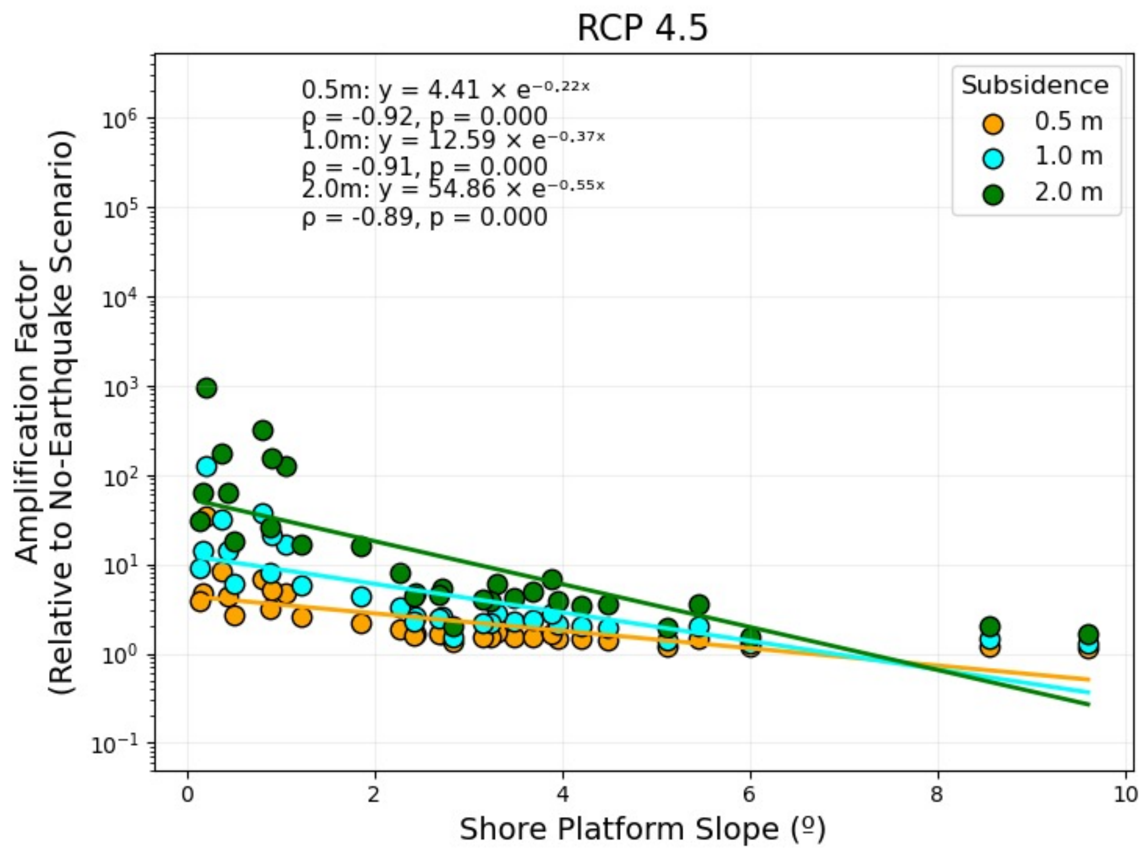


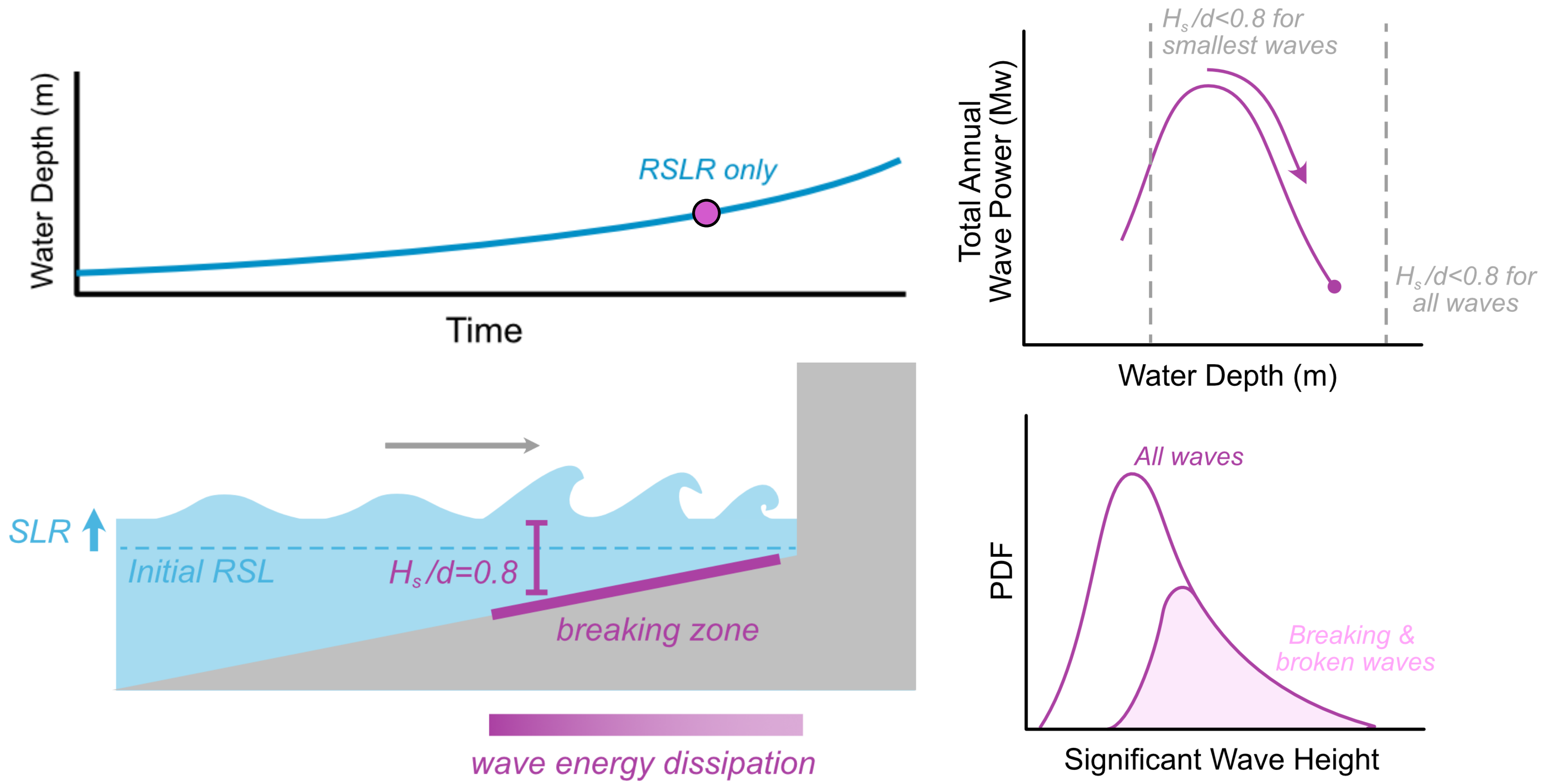
Matsumoto, 2024


British Columbia
Washington
Oregon
California
49°N
48°N
47°N
46°N
45°N
44°N
43°N
42°N
41°N
130°W
128°W
126°W
124°W
122°W
Shore Type
Horizontal - Subhorizontal, <1°
Sloping, 1°<x<5°
Steeply Sloping, >5°
Victoria Swath Profile
Steeply sloping
Depoe Bay Swath Profile
Gently sloping
Brookings Swath Profile
Horizontal
MSL (0 m)
Mean Elevation (m)
Distance from Shore (m)



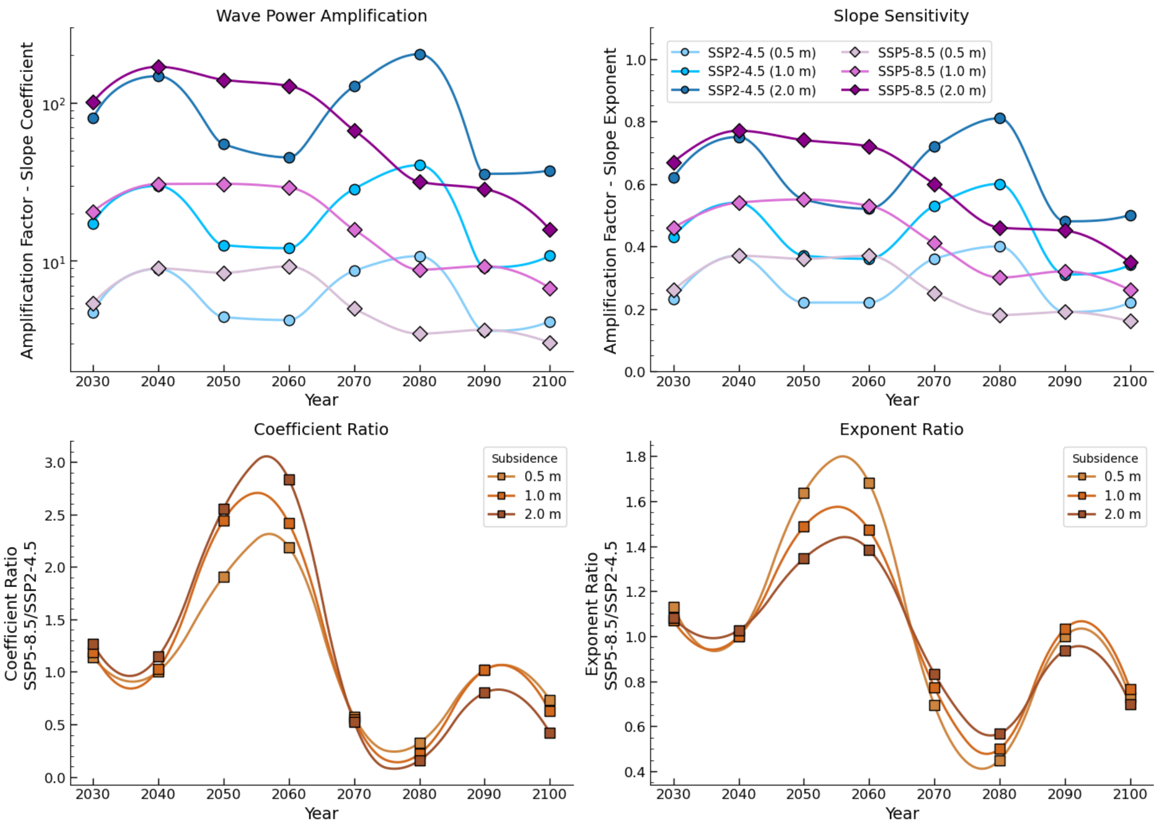
Breaking Distance vs Shore Platform Slope | SSP2-8.5 | EQ 2050
Breaking Distance (m)
0
200
400
600
800
1000
1200
Earthquake Scenario
No Earthquake
0.5 m
1.0 m
2.0 m
Subhorizontal: <1º
(n=9)
Sloping: 1º - 5º
(n=18)
Steeply Sloping: >5º
(n=5)


RCP 4.5
0.5m: y = 4.41 × e^−0.22x
ρ = -0.92, p = 0.000
1.0m: y = 12.59 × e^−0.37x
ρ = -0.91, p = 0.000
2.0m: y = 54.86 × e^−0.55x
ρ = -0.89, p = 0.000
Subsidence
0.5 m
1.0 m
2.0 m
Amplification Factor
(Relative to No-Earthquake Scenario)
Shore Platform Slope (º)

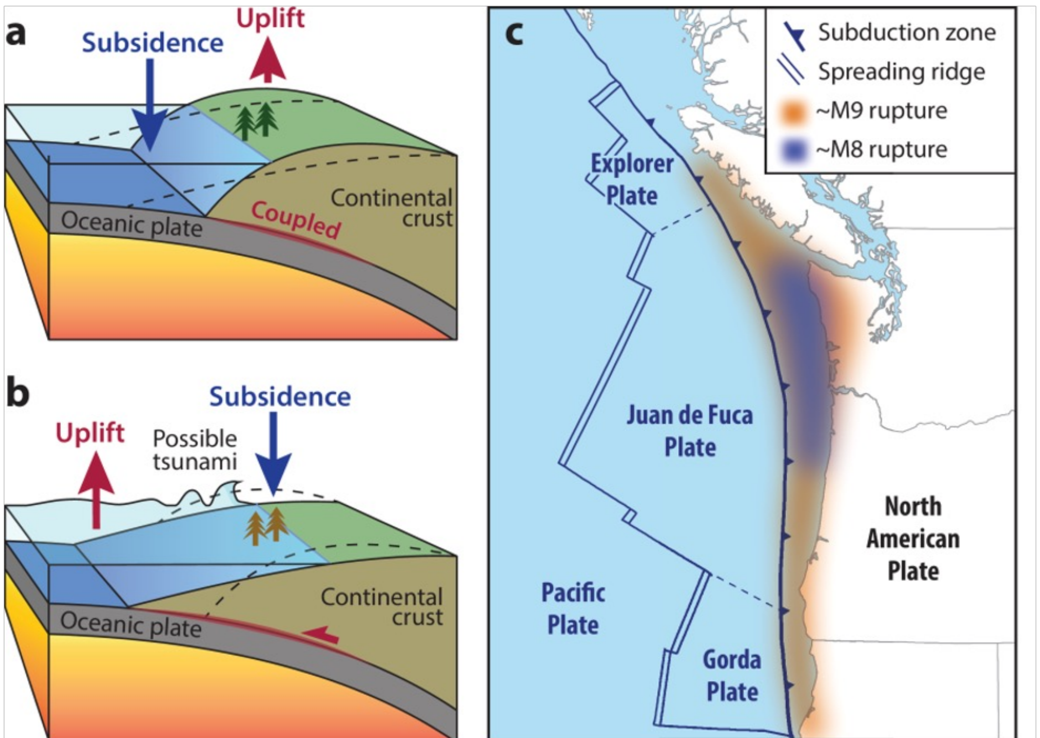


RSLR only
Water Depth (m)
Time
SLR
Initial RSL
$H_s/d=0.8$
breaking zone
wave energy dissipation
$H_s/d<0.8$ for smallest waves
Total Annual Wave Power (Mw)
$H_s/d<0.8$ for all waves
Water Depth (m)
All waves
PDF
Breaking & broken waves
Significant Wave Height

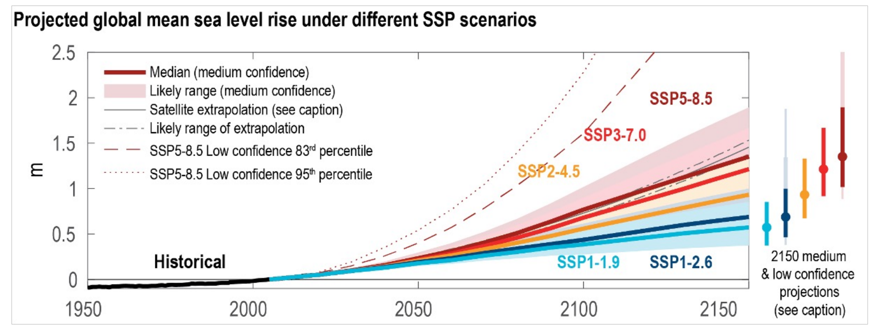
- Peak EQ hazard window for SSP-8.5 from 2050-2060
- Peak EQ hazard window for SSP2-4.5 at 2080

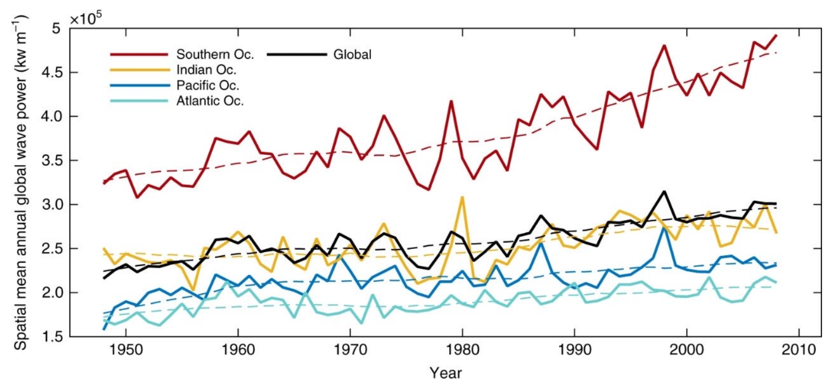


How will co-seismic subsidence combine with sea level rise to transform coastal wave energy delivery?

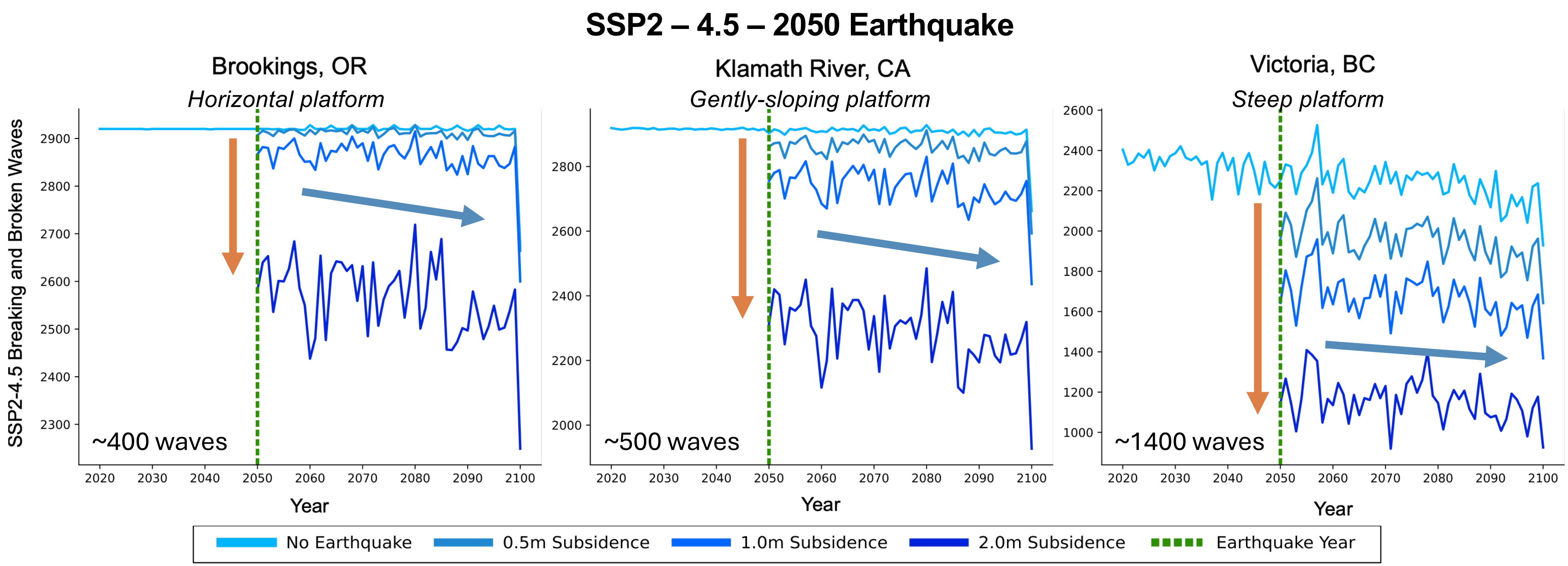


Walton MAL, et al. 2021
Annu. Rev. Earth Planet. Sci. 49:367–98





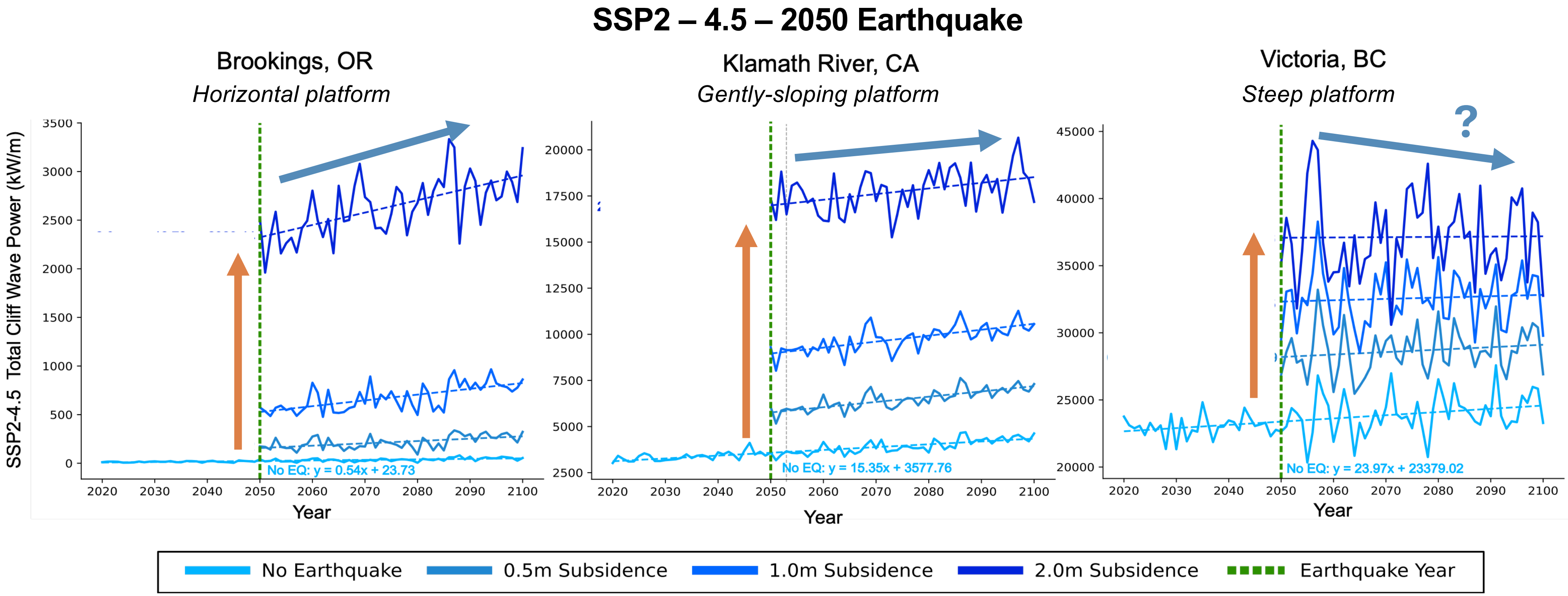
Wave breaking is **most strongly reduced** on steep shore platforms



Continued reduction of wave breaking driven by sea level rise

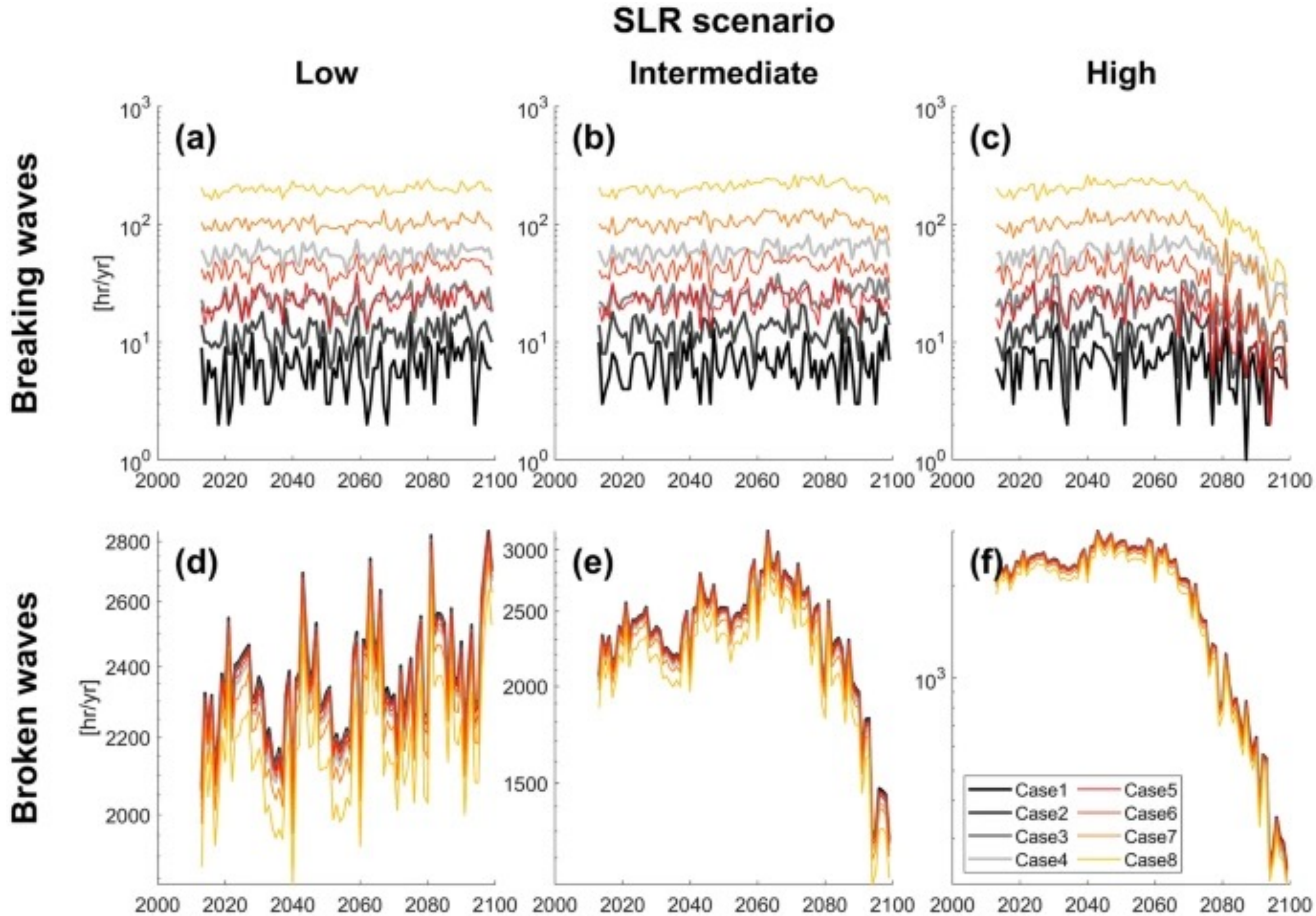
Lopez and Masteller, *in prep*

Annual cliff front **wave power enhanced** across all sites



Post-EQ wave power enhancement variable across sites

Lopez and Masteller, *in prep*



Matsumoto et al., 2024