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Coastal Adaptation and Resilience: The greatest Challenge in Coastal Engineering

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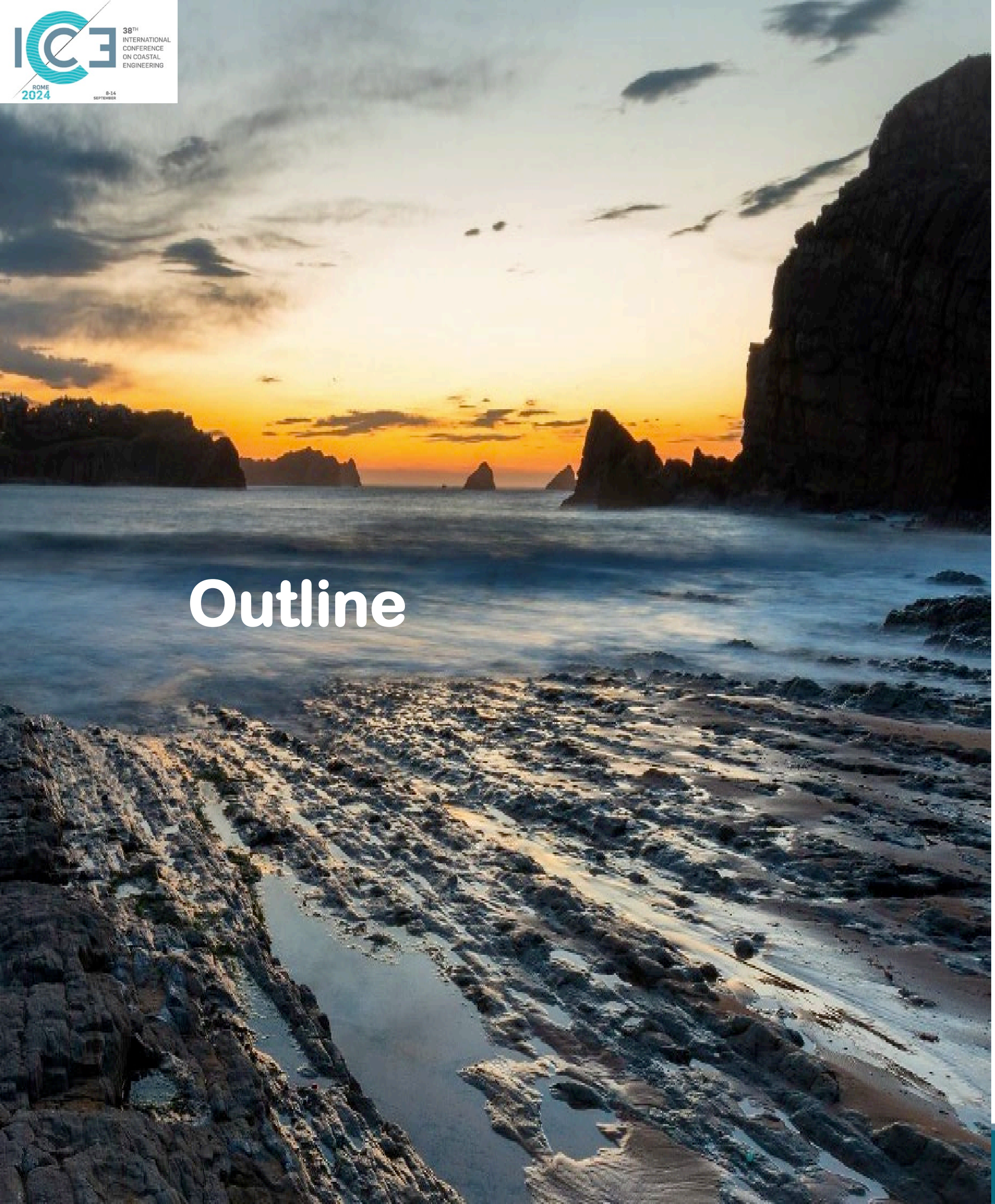


Outline

Climate change: Reasons for concern

Where do we stand in coastal adaptation?

Update on SLR

A first set of questions

A first set of responses

Exploring different pathways

Conclusions

Climate change: Reasons for concern

Reasons for concern

We've reached 1.2^{o}C of global mean surface temperature rise. The warmest temperature on Earth over the past 100.000 years.

We're starting to see and acceleration of warming over the past 50 years (0.18^{o}C/decade [1970-2010] and 0.26^{o}C/decade [2014- onwards]). Following this path, we will get to 2^{o}C within 20 years and 3^{o}C by 2100.

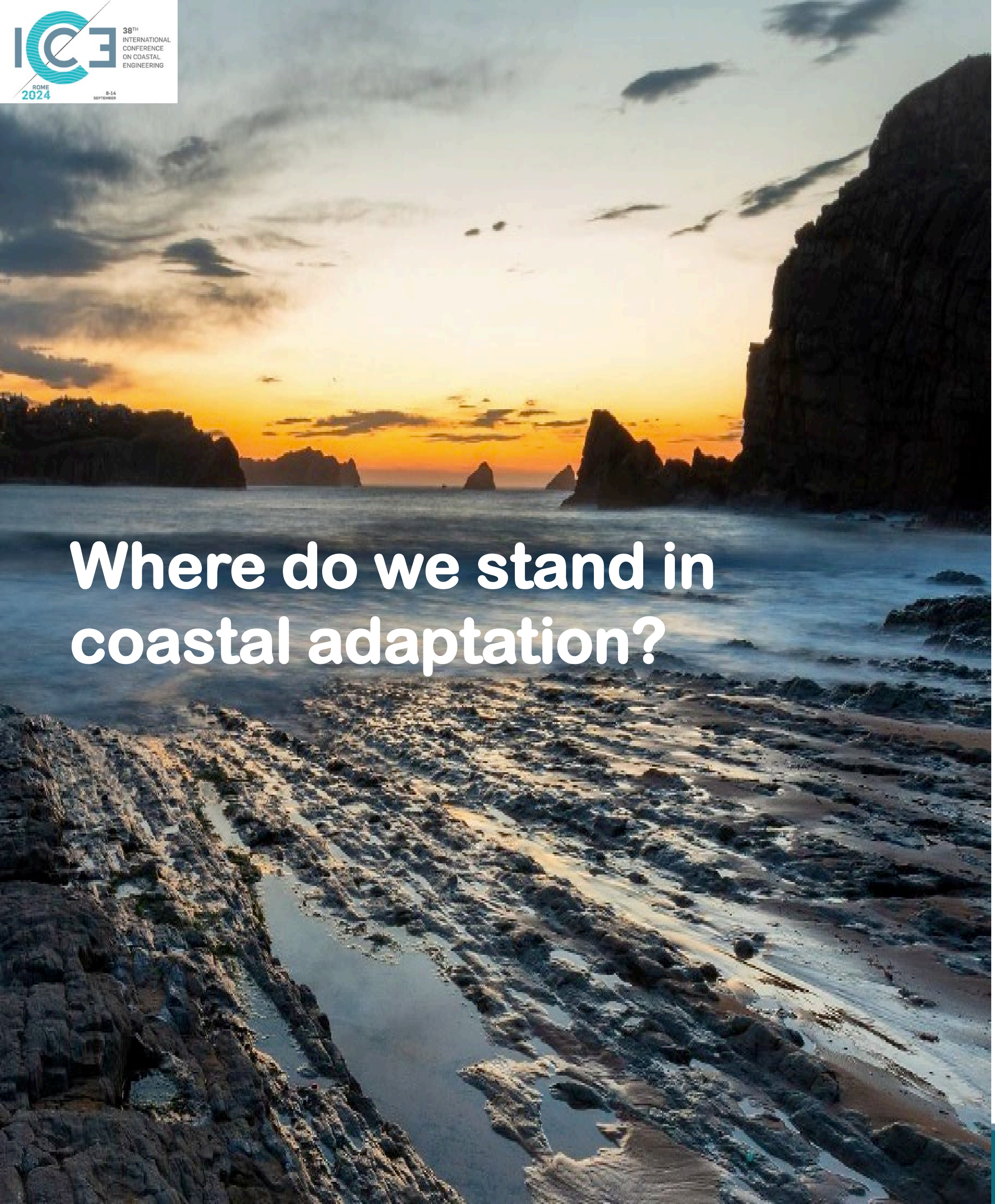
We're now seeing that this warming is already causing impacts across the entire economy including coastal areas worldwide (floods, erosion, enhance storms, droughts..) (already at 1.2^{o}C!).

Exceeding 1.5^{o}C global warming could trigger multiple climate tipping points affecting severely future SLR ranges.

Climate change mitigation and decarbonization efforts are falling short and the Earth land and ocean systems are starting to showing evidence of loosing its buffering effect (uptake capacity of CO_2 and of heat absorption).

There is evidence of the growth of coastal cities and coastal megacities are projected to increase in number during the next decades.

Development of the Blue Economy will increase coastal exposure and pressure on coastal systems.

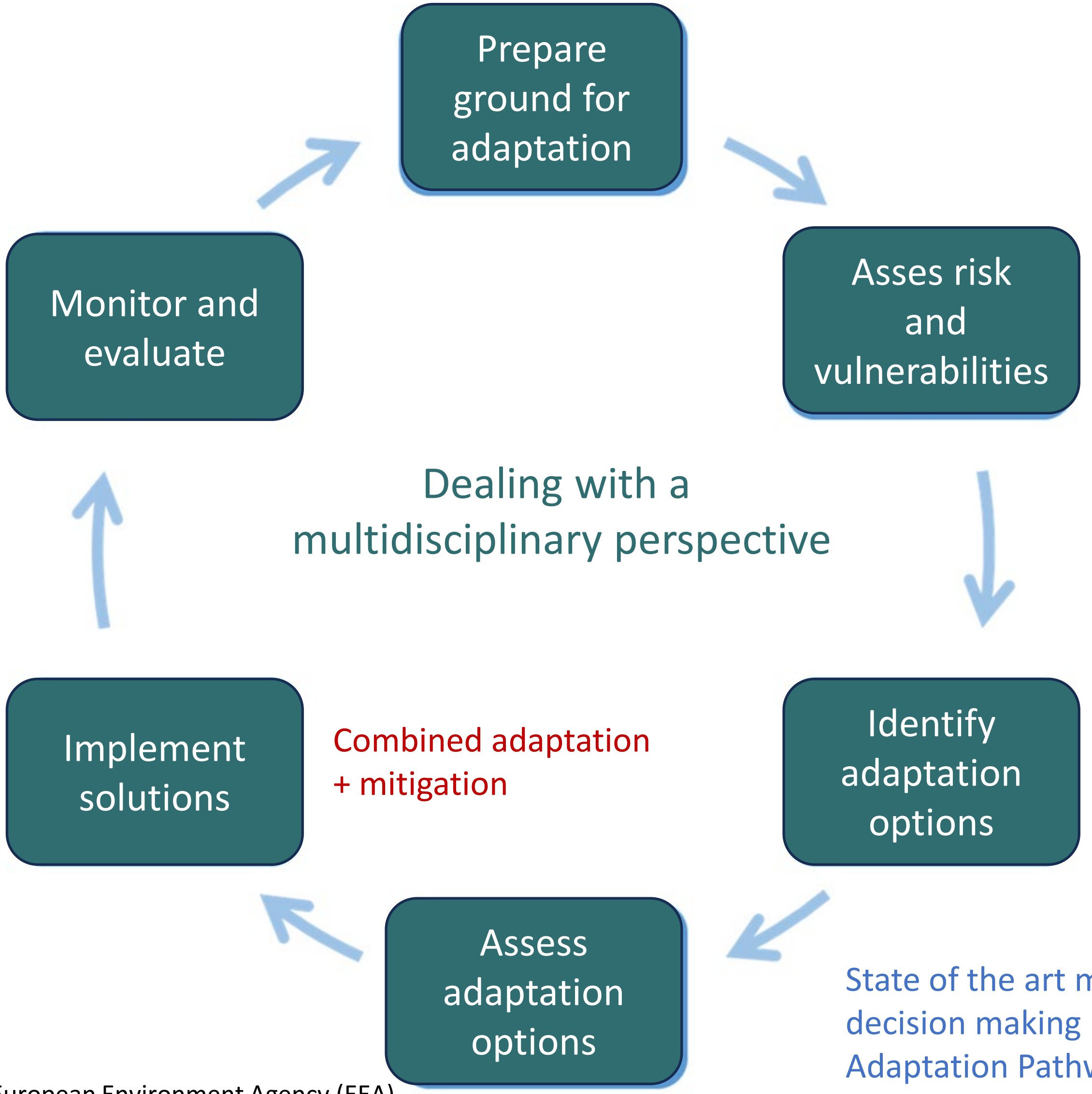


Where do we stand in coastal adaptation?

The adaptation cycle

System at risk: boundaries

Time horizons
Warming levels
SSPs-RCPs



Dealing with
climate projections (continuous, slices, extremes)
Multihazards
Compound events
Impact models

Cascading impacts
Non-stationary exposure, vulnerability
Fragility and damage functions
Adaptive capacity
Protection standards

Integration of engineering probabilistic methods within climate risk frameworks

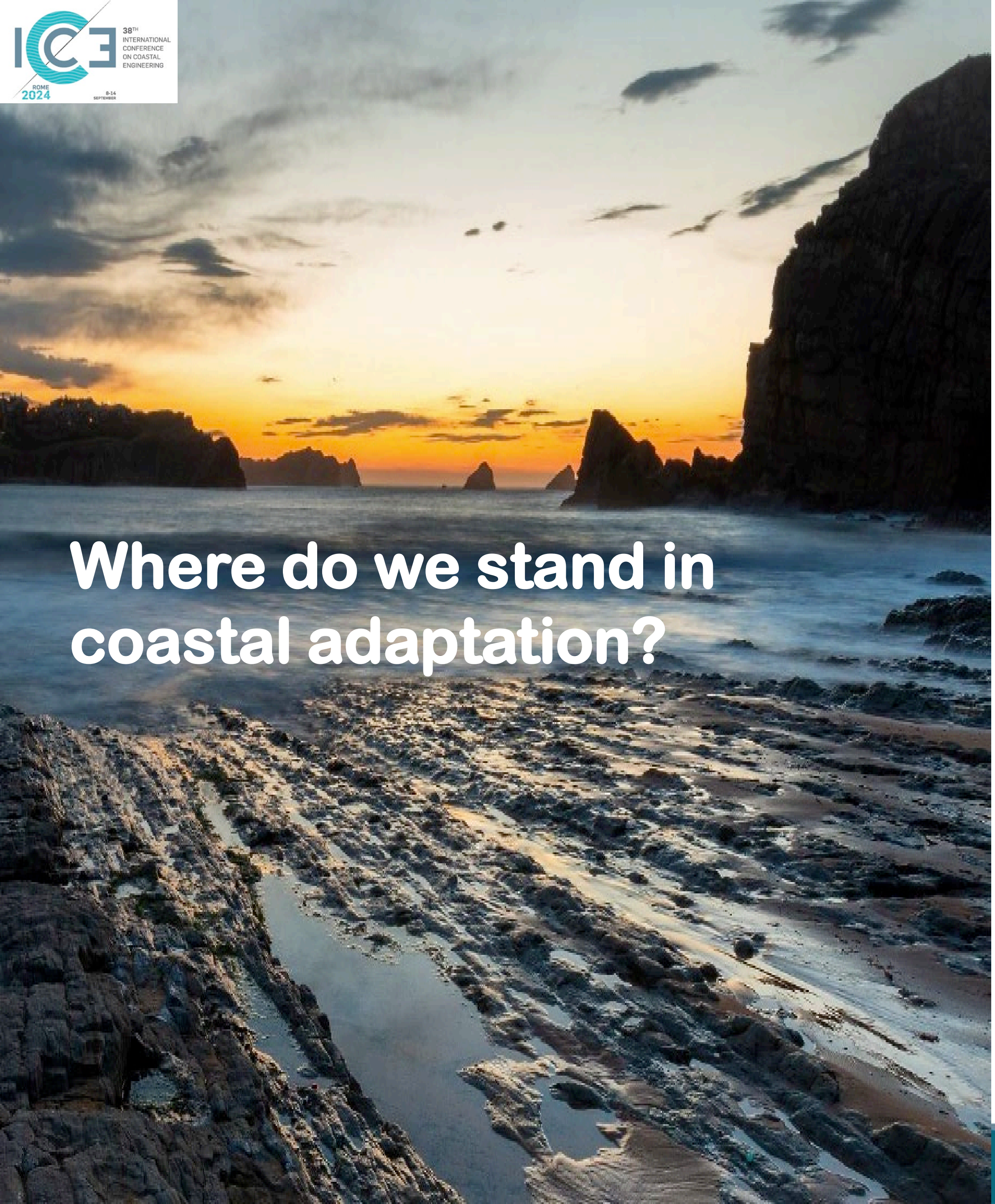
Setting adaptation
Goals
Risk vs Resilience

State of the art coastal engineering practice
+ NBS
+ other options
Combinations
Incremental vs transformative

State of the art modelling +
decision making methodologies dealing with uncertainty
Adaptation Pathways, Robust adaptive strategies

Dealing with and communicating climate-related uncertainties

European Environment Agency (EEA)



Where do we stand in coastal adaptation?

Article | Published: 19 October 2023

Status of global coastal adaptation

Alexandre K. Magnan, Robert Bell, Virginie K. E. Duvat, James D. Ford, Matthias Garschagen, Marjolijn Haasnoot, Carmen Lacambra, Inigo J. Losada, Katharine J. Mach, Mélinda Noblet, Devanathan Parthasaranthy, Marcello Sano, Katharine Vincent, Ariadna Anisimov, Susan Hanson, Alexandra Malmström, Robert J. Nicholls & Gundula Winter

Nature Climate Change **13**, 1213–1221 (2023) | Cite this article

A global assessment aiming at identifying progress and gaps in climate adaptation in coastal areas

Based on structured expert judgement

Multidisciplinary team

Based on local studies and archetypes

Built bottom up to inform the Global Stocktake on adaptation

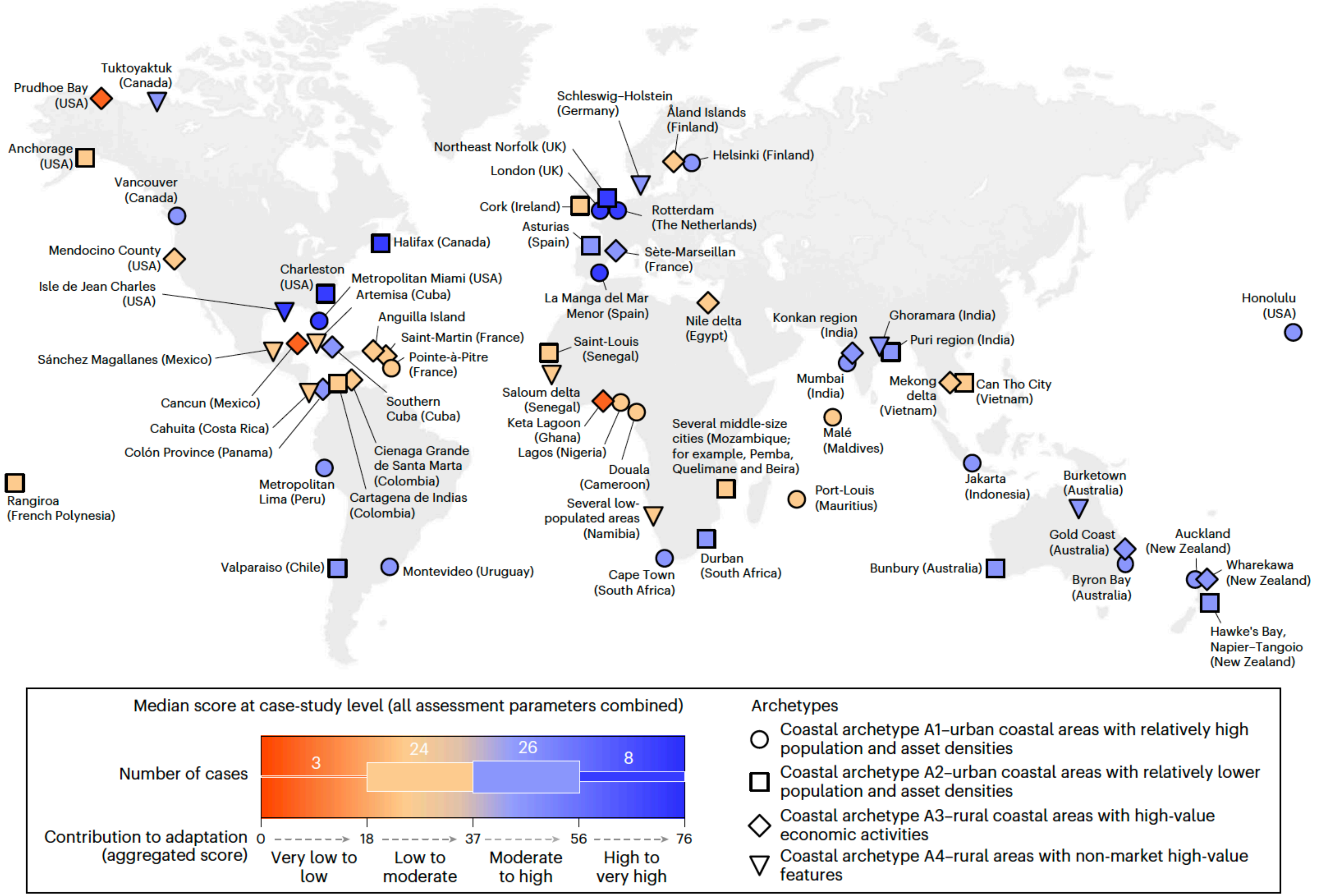


Fig. 1 | The local coastal case studies per aggregated score and archetype. The local case studies are clustered into four archetypes (symbols) and their aggregated scores (colors) are located along the whole scoring scale from 0 to 76 to indicate very low to very high efforts. Source data are available in Supplementary Data 1, sheets 5a–d and 6a.

Results by archetype

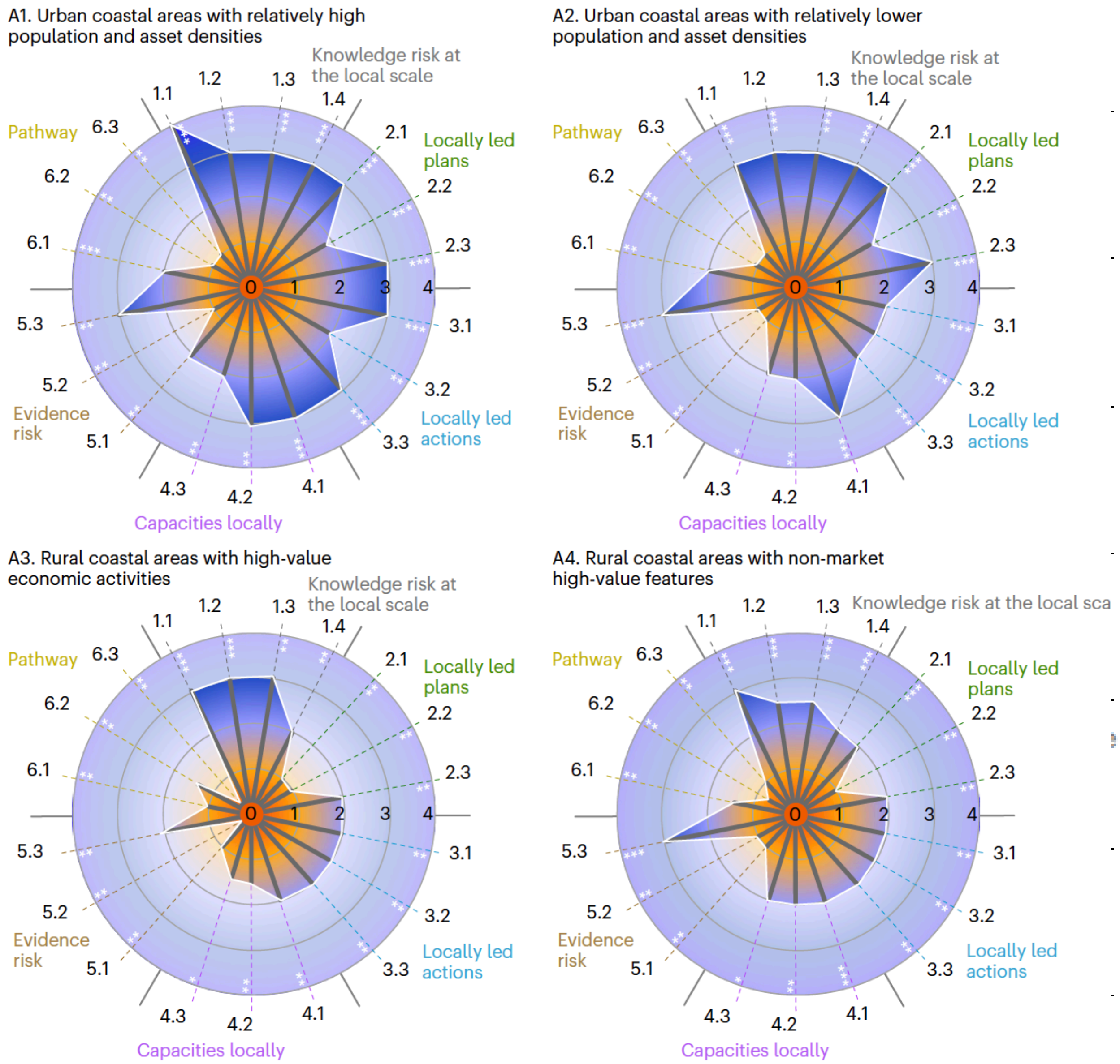
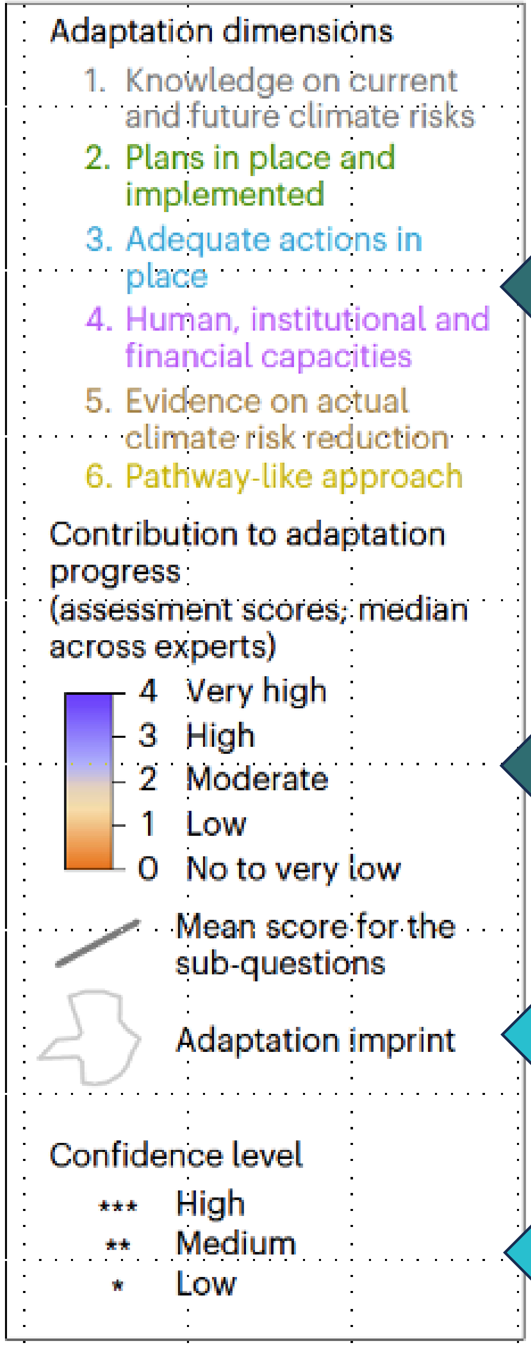


Fig. 2 | The coastal archetype adaptation imprint. The imprint reflects the level of adaptation efforts in each of the six dimensions considered in this study. It is designed based on the median score obtained across the whole case-study sample on the various assessment sub-questions. It also shows the confidence levels associated with all the median scores. background illustrates the scoring system us available in Supplementary Data 1, sheets 4a-



Dimensions assessed

Scoring based on expert judgement Reports (mostly gray literature)

Imprint reflects the level of adaptation effort in each dimension

Similar to IPCC

Global adaptation imprint

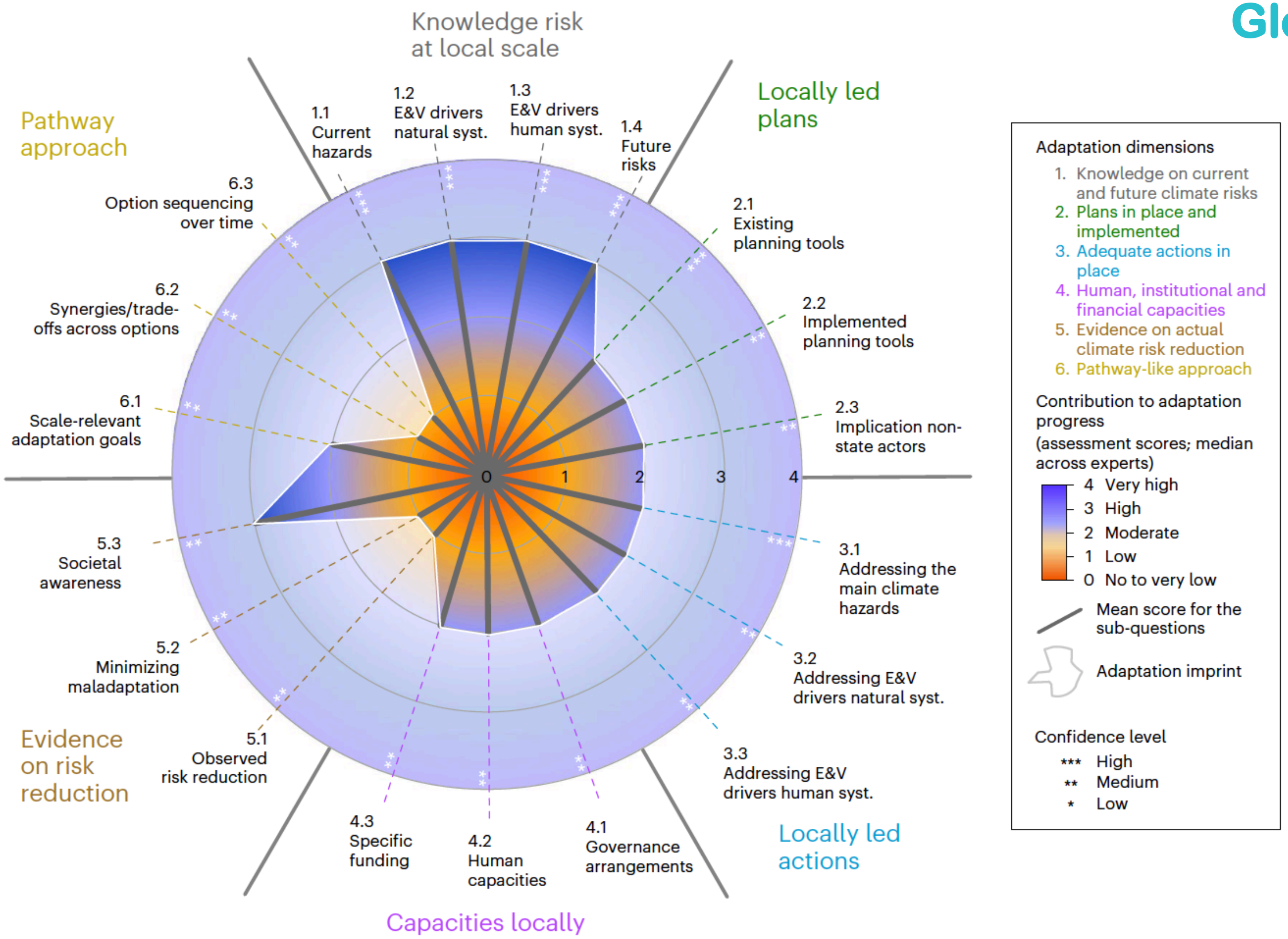


Fig. 3 | The global coastal adaptation imprint. The background circular color graduation illustrates the scoring system used. The non-shaded area is called the 'adaptation imprint' and reflects the level of adaptation efforts across the six overarching dimensions and 19 sub-dimensions assessed. It is designed based on the median scores obtained across the whole case study sample. Stars represent confidence levels. The remaining shaded area represents the adaptation gap. 'E&V' means exposure and vulnerability; 'syst.' means systems. Source data are available in Supplementary Data 1, sheets 4d and 5a–d.

5 global-scale conclusions on the state of coastal adaptation.

- Adaptation is happening on the ground but is not at scales.
  - Moderate level of coastal adaptation efforts,
  - Halfway progress to the full adaptation potential.

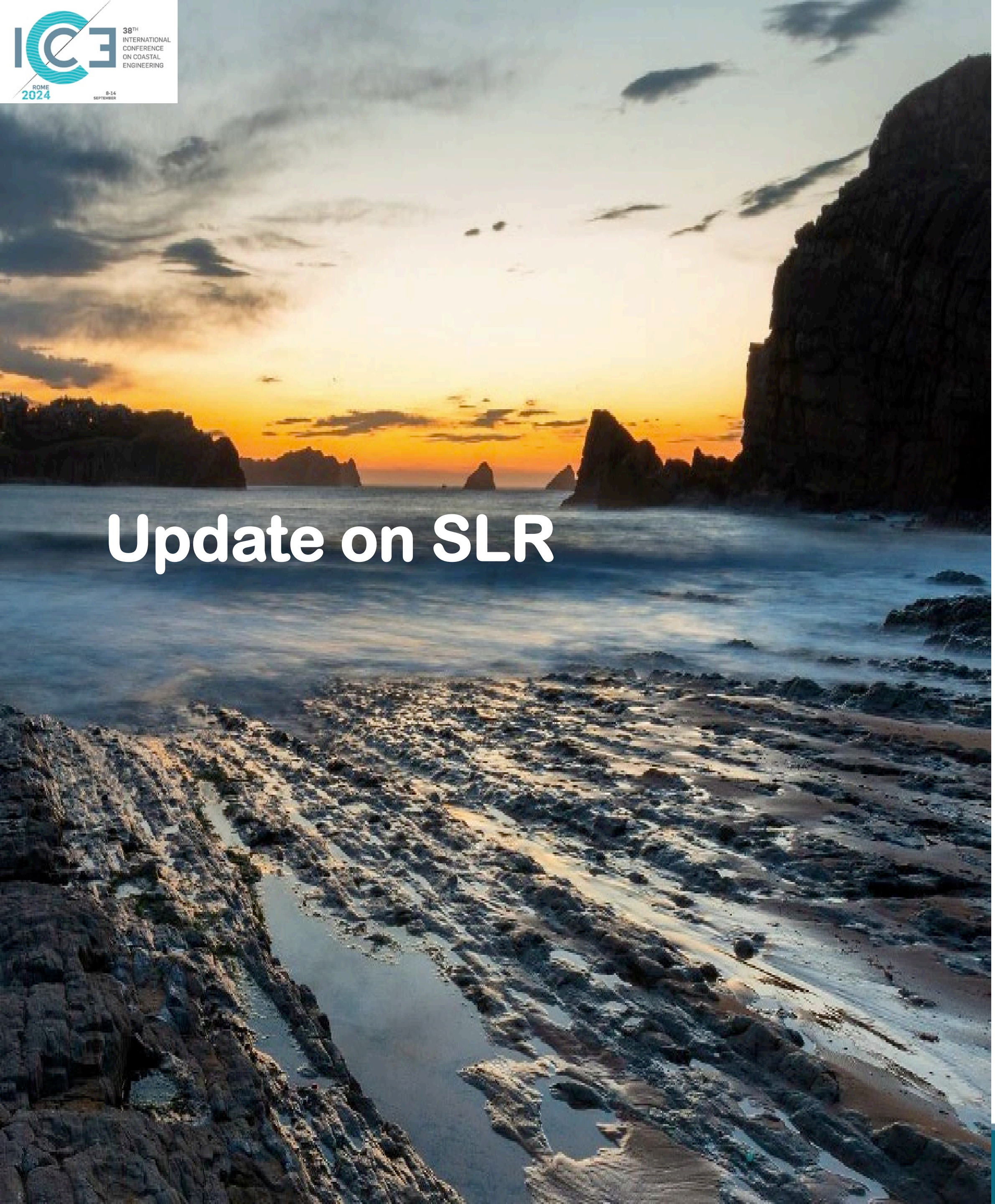
- Globally coastal adaptation imprint is unbalanced, demonstrating relative strengths and weaknesses.
  - Risk knowledge scores relatively high,
  - Locally led planning, action, capacities and evidence of risk reduction rank moderate,
  - Pathway-like approach scores low.

- Adaptation efforts remain too narrow in scope.
  - Locally led actions remain at a moderate level in terms of addressing the main climate hazards and drivers of exposure and vulnerability in natural and human systems
  - By contrast, these elements are relatively well known in general.

- Relative disconnection or inertia between national- and local-level planning, confirming the need to also get a sense of the local perspective in regional to global analyses.

- Local-scale adaptation efforts look incremental rather than transformational globally.

Update on SLR



SEA LEVEL RISE OBSERVATIONS

UN (2024) Surging Seas: in a warming world.

GMSLR
1901-2018: 20 cm [15–25cm]
1993-2018 (satellite record): 8.1cm [7.2–9.0cm]
IPCC AR6

NASA
1993-2023: 9.4 cm [+/- 1cm]

→ the highest level in the modern observation since the 19th century

Average rate of SLR

1901–1971: 1.3 mm [0.6–2.1 mm] per year
1971–2006: 1.9 mm [0.8–2.9 mm] per year
2006–2018: 3.7 mm [3.2–4.2 mm] per year

World Meteorological Organization (WMO)

The rate of SLR in the past ten years has more than doubled since the first decade of the satellite record:
1993–2002: 2.1 mm per year
2014–2023: 4.8 mm per year

→ Recent acceleration in SLR is primarily due to increasing rates of ice loss from the Greenland and Antarctic ice sheets, which are losing ice mass at average rates of around 270 and 150 billion tonnes per year, respectively.

The seven worst years of ice loss on record all occurred in the last decade.

SEA LEVEL RISE AND RATE PROJECTIONS

Scenario (and end-of-century warming)	SSP1-1.9 (1.4°C)	SSP1-2.6 (1.8°C)	SSP2-4.5 (2.7°C)	SSP3-7.0 (3.6°C)	SSP5-8.5 (4.4°C)	'Low-likelihood, high-impact' SSP5-8.5
Relative to 1995–2014						
SLR by 2030 (m)	0.09 [0.08–0.12]	0.09 [0.08–0.12]	0.09 [0.08–0.12]	0.09 [0.08–0.12]	0.10 [0.09–0.12]	0.10 [0.09–0.15]
SLR by 2050 (m)	0.18 [0.15–0.23]	0.19 [0.16–0.25]	0.20 [0.17–0.26]	0.22 [0.18–0.27]	0.23 [0.20–0.29]	0.24 [0.20–0.40]
SLR by 2100 (m)	0.38 [0.28–0.55]	0.44 [0.32–0.62]	0.56 [0.44–0.76]	0.68 [0.55–0.90]	0.77 [0.63–1.01]	0.88 [0.63–1.60]
Rate of SLR (2040–2060; mm per year)	4.1 [2.8–6.0]	4.8 [3.5–6.8]	5.8 [4.4–8.0]	6.4 [5.0–8.7]	7.2 [5.6–9.7]	7.9 [5.6–16.1]
Rate of SLR (2080–2100; mm per year)	4.2 [2.4–6.6]	5.2 [3.2–8.0]	7.7 [5.2–11.6]	10.4 [7.4–14.8]	12.1 [8.6–17.6]	15.8 [8.6–30.1]
Relative to 1850–1900						

Median values (and 'likely' ranges) are shown for all scenarios except for the 'low-likelihood, high-impact' one, which shows the 17th-83rd percentile range.

Our adaptive capacity/resilience is being challenged by:
1993-2023: 0.094 m [+/- 0.01 m]

at 1.2°C

Our adaptive capacity/resilience is being challenged by:
1993–2002: 2.1 mm per year
2014–2023: 4.8 mm per year

at 1.2°C

Source: IPCC AR6 WGI, Chapter 9, Table 9.9.

Country	Tide Gauge Name	Observed SLR from 1990 to 2020 (cm)	Projected SLR from 2020 to 2050 (cm)	Average Flooding Days/Year, 1980s	Average Flooding Days/Year, 2010s	Projected "Average-year" Flooding Days/ Year, 2050s	Projected "Worst-year" Flooding Days/ Year, 2050s
Cook Islands	Penrhyn	9	17 [14–23]	<5	<5	50	155
Cook Islands	Rarotonga	14	17 [13–23]	<5	<5	75	145
Fiji	Suva-B	29	18 [15–23]	<5	<5	25	65
Fiji	Lautoka	13	18 [15–23]	<5	<5	35	60
Micronesia	Kapingamarangi	15	18 [14–24]	<5	<5	15	50
Micronesia	Pohnpei	20	20 [18–24]	<5	<5	30	85
Micronesia	Yap-B	19	17 [16–20]	<5	<5	5	55
Kiribati	Betio, Tarawa	13	19 [17–23]	<5	<5	20	45
Kiribati	Kanton	9	17 [13–22]	<5	5	30	80
Kiribati	Kiritimati	5	18 [14–24]	<5	<5	65	165
Marshall Islands	Kwajalein	11	19 [17–22]	<5	5	45	90
Marshall Islands	Majuro	10	19 [17–22]	<5	<5	30	60
Nauru	Nauru-B	16	19 [14–25]	<5	<5	10	30
Palau	Malakal-B	15	17 [16–20]	<5	<5	30	100
Samoa	Apia	31	23 [20–28]	<5	5	35	90
Tonga	Nuku'alofa	21	18 [15–23]	<5	<5	35	70
Tuvalu	Funafuti	14	19 [15–26]	<5	<5	25	50

SEA LEVEL EXTREMES FREQUENCY

The frequency of present-day, extreme-but rare sea-level events is projected to increase substantially in most regions.

IPCC AR6:
Globally-averaged, the 1-in-100-year extreme sea-level event is projected to become
1-in-30-year by 2050
1-in-5-year by 2100

For RCP4.5 (2.5°C end-of-century warming)

SEA LEVEL RISE PROJECTIONS AND DEEP UNCERTAINTY

Deep uncertainty exists

"when experts or stakeholders do not know or cannot agree on: (1) appropriate conceptual models that describe relationships among key driving forces in a system, (2) the probability distributions used to represent uncertainty about key variables and parameters and/or (3) how to weigh and value desirable alternative outcomes" (IPCC, 2023).

In AR6, attempt to to facilitate the development of robust adaptive strategies in WGII.

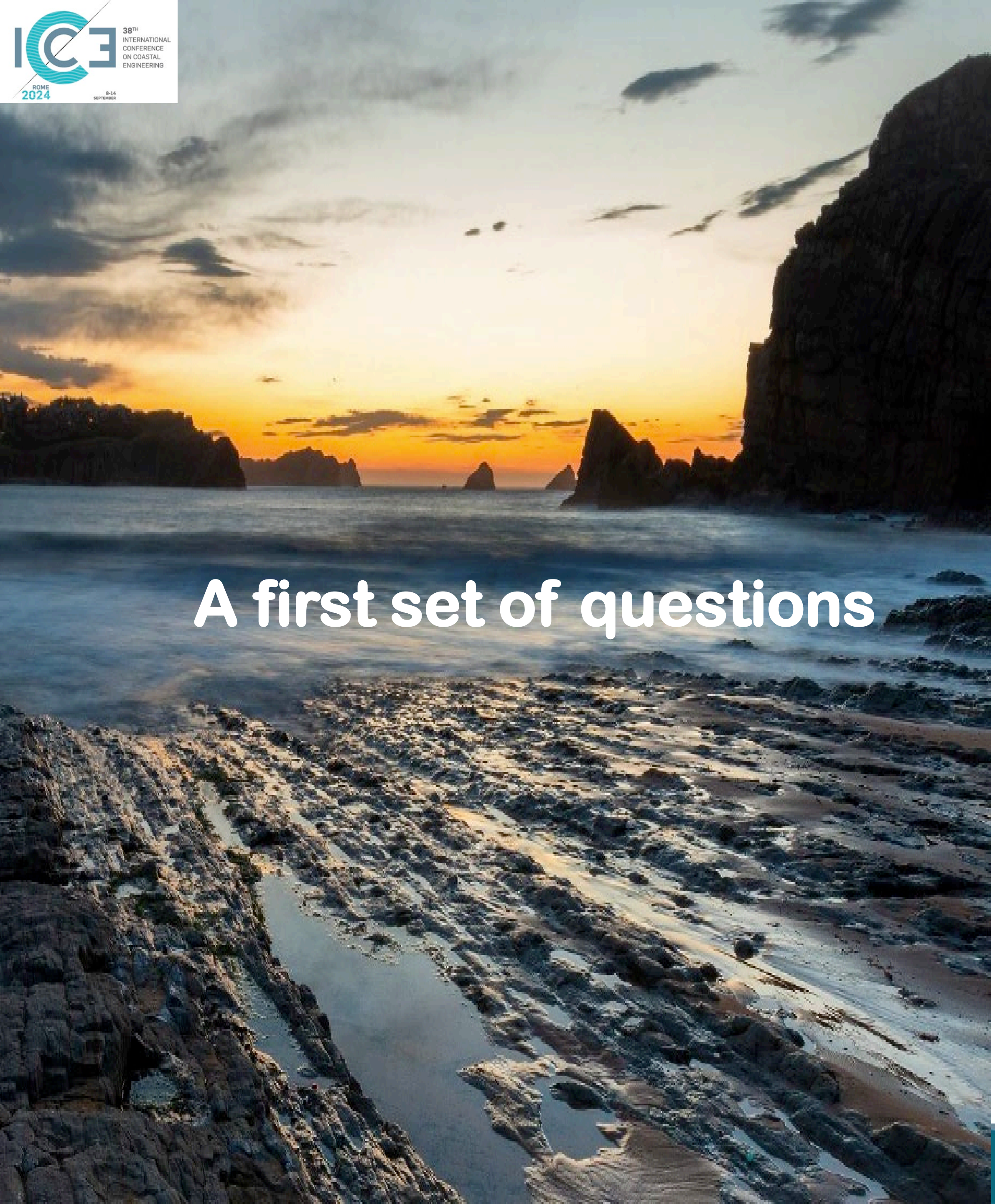
SLR projections include

- a probabilistic description of the components of global and regional mean sea level rise driven by processes in which there is at least medium confidence,
- quantitative assessments of sea-level rise projections incorporating ice-sheet processes in which there is low confidence (using storylines that identify these physical processes in such a way as to facilitate the development of adaptive decision response strategies).

In addition

- sea-level rise projections both in the traditional form estimating the range of rise as a function of time,
- a new format showing the range of times at which a particular level of sea level rise might be experienced depending on the scenario.

Lempert et al. (2024) The use of decision making under deep uncertainty (DMDU) in the IPCC



A first set of questions

Observed and projected

SLR acceleration

SLR impacts at greater scale

SLR increasing the frequency of extreme events

Deep uncertainty in SLR projections

Changes in other relevant coastal hazards

Open questions

How are coastal areas responding to present increase and acceleration?

What is the feasible rate and magnitude of SLR that makes incremental adaptation feasible for natural and socioeconomic coastal systems?

How are these limits affected by other natural and human-induced hazards or by the occurrence of multiple hazards?

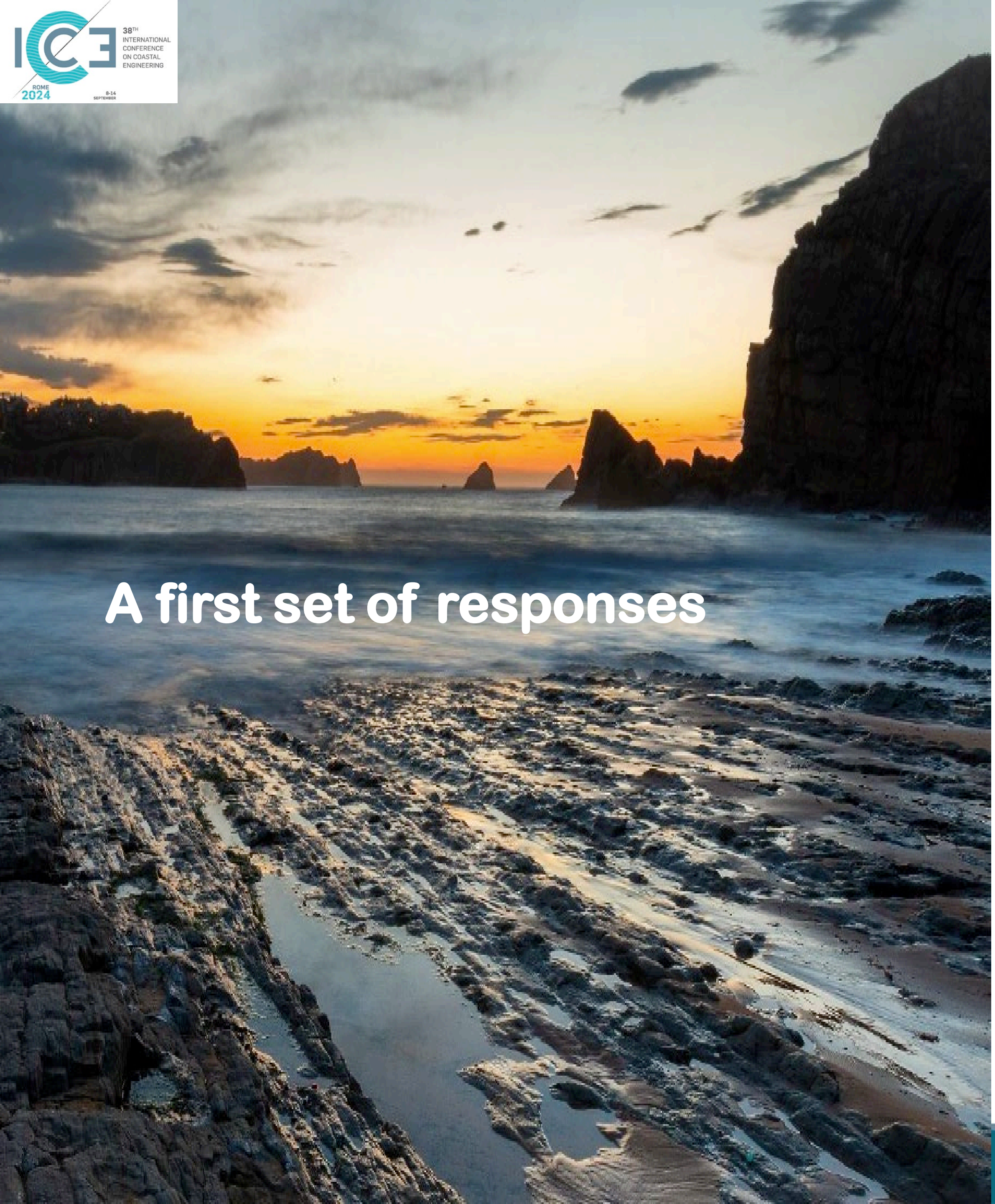
How is the change in frequency and sequence/chronology/time between events of hazards going to affect coastal resilience?

How are these factors going to affect the distribution of impacts regionally?

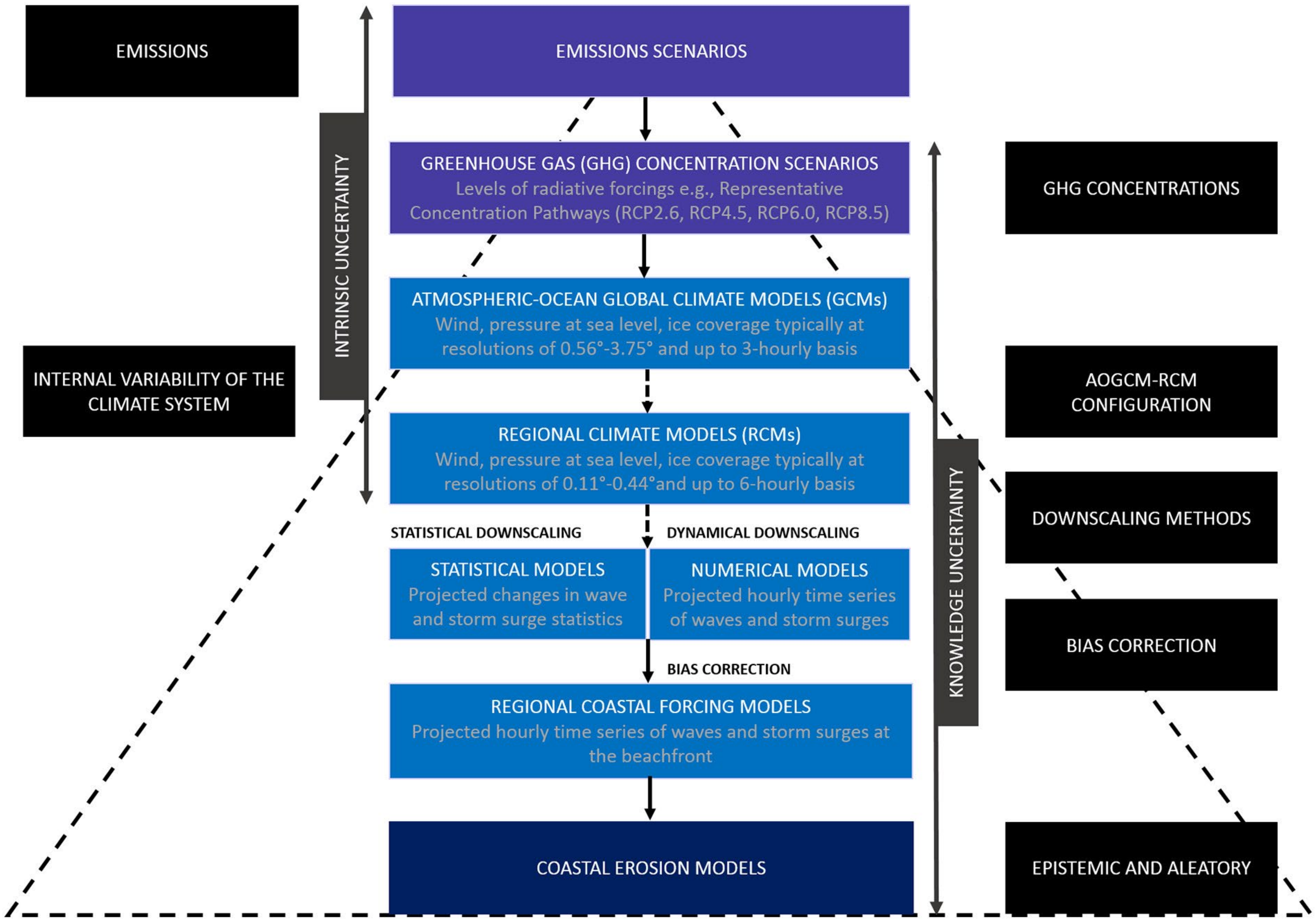
Can we forecast where and when incremental adaptation is going to fail?

How can we deal with deep uncertainty to provide decision makers with robust information?

A first set of responses



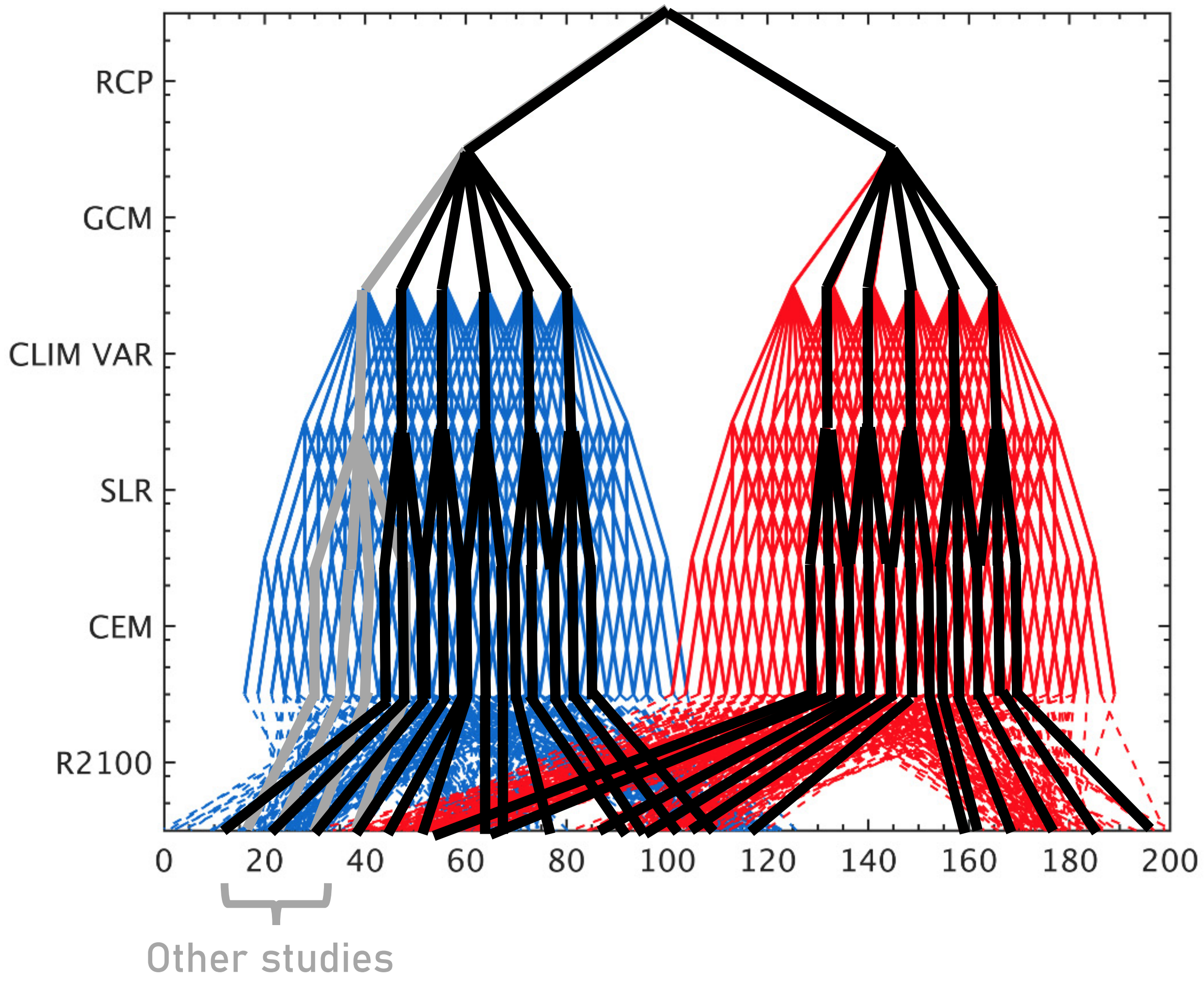
Top-down assessments



Generic sequence of comprehensive steps followed in top-down assessments of climate change-driven coastal erosion and associated sources of uncertainty that cascade through the whole process (based on Ranasinghe, 2016)

Toimil et al. (2020) Climate change-driven coastal erosion modelling in temperate sandy beaches: Methods and uncertainty treatment

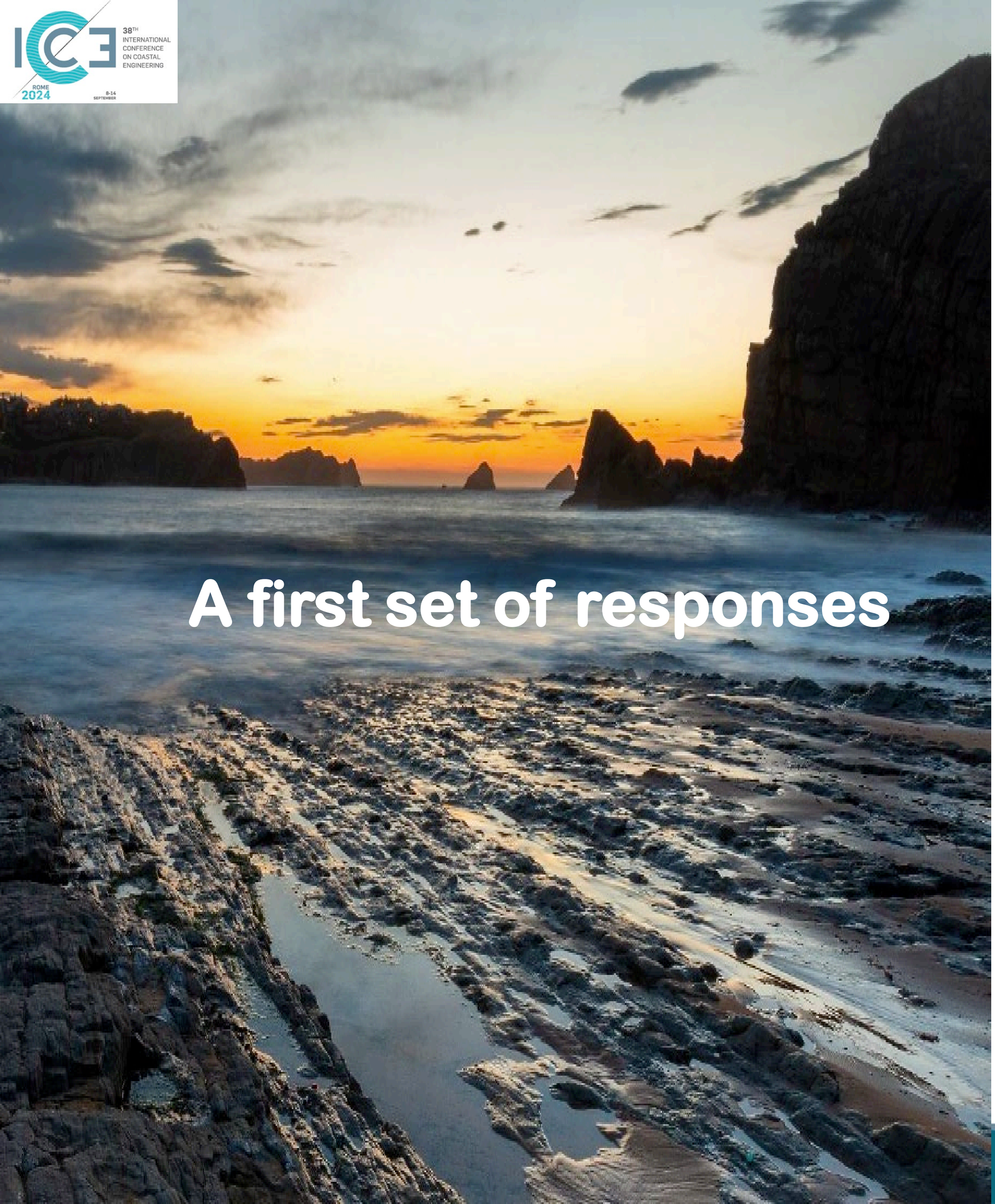
Dealing with climate change uncertainties in coastal impact modelling



Toimil et al. (2021) Visualising the uncertainty cascade in multi-ensemble probabilistic coastal erosion projections

R2100 long-term coastal recession in 2100 relative to 2015

A first set of responses



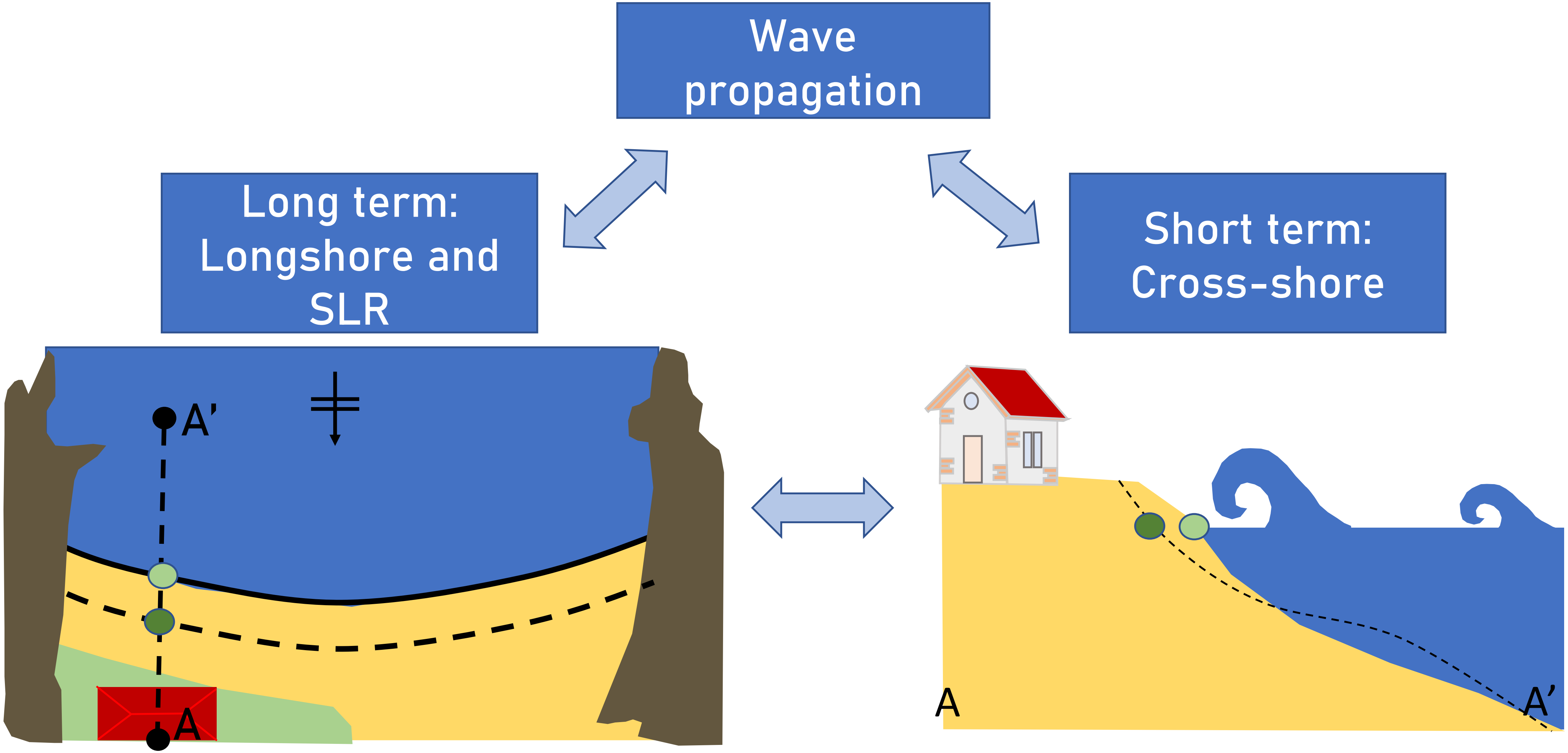
A first set of responses

1. Improved hazard assessments — NOT TODAY!
2. Improved modelling of coastline evolution
3. Robust modelling of coastline evolution projections
4. Coupled erosion-flooding modelling
5. Value of beaches for coastal adaptation -> coastal resilience
6. Quantitative adaptation pathways implementation
7. Quantitative adaptation pathways for ports — NOT TODAY!

IH-LANS (Long-term ANthropized coastlines Simulation tool)

- Long-term coastline evolution at local to regional scales
- Highly anthropized coasts.
- Coupling of a hybrid (statistical-numerical) deep-water propagation module and a data-assimilated shoreline evolution model.
- Longshore and cross-shore processes are integrated together with the effects of man-made interventions.
- Extended Kalman filter that allows to assimilate shoreline observations

Alvarez-Cuesta et al (2021). Modelling long-term shorelline evolution in highly-anthropized coastal areas. Part 1: Model description and validation.



Longshore transport gradients + SLR

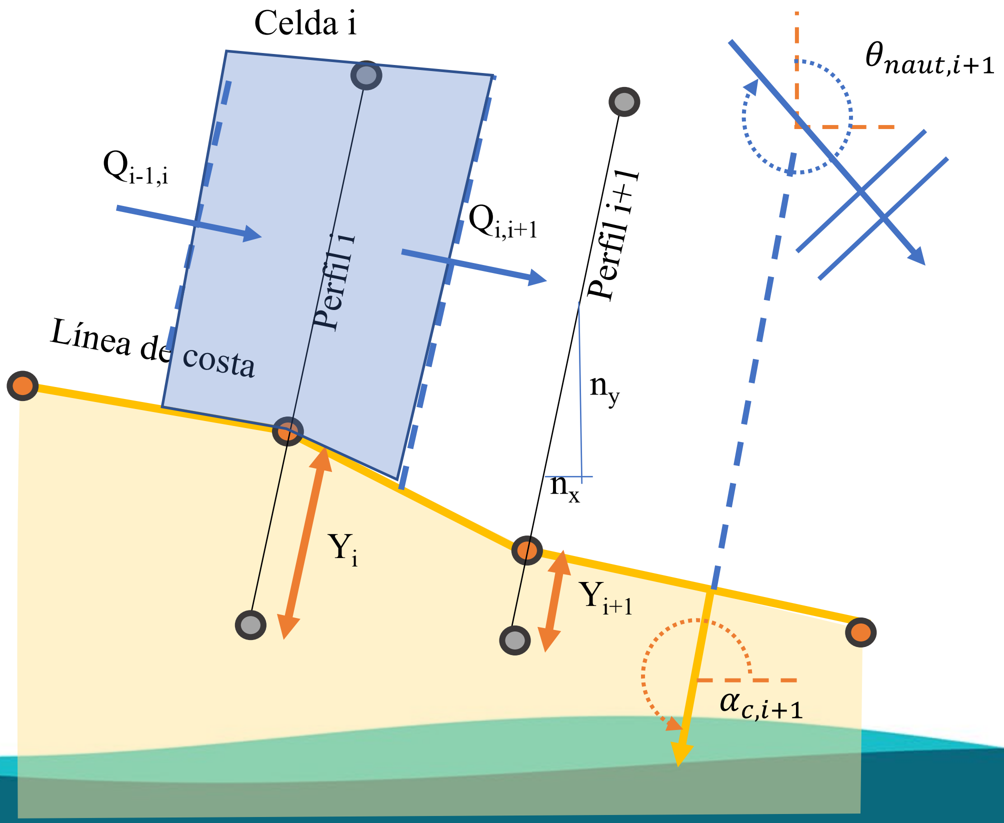
Short-term storms

$$\frac{\partial Y}{\partial t} = -\frac{1}{B+d_c}\frac{\partial Q}{\partial x} + \frac{1}{B+d_c} q + vlt + \mathrm{K_c}\left[Y_c^{eq} - Y_c\right]$$

Shoreline changes

$\frac{\partial Y_l}{\partial t}$ Longshore

$\frac{\partial Y_c}{\partial t}$ Cross-shore



$$Q = K_e K_l H_b^{2.5}\left[\sin(2\alpha) - \frac{1}{\tan\beta_s}\frac{dH_b}{dx}\right]$$

USACE (1984)
O&B (1980)

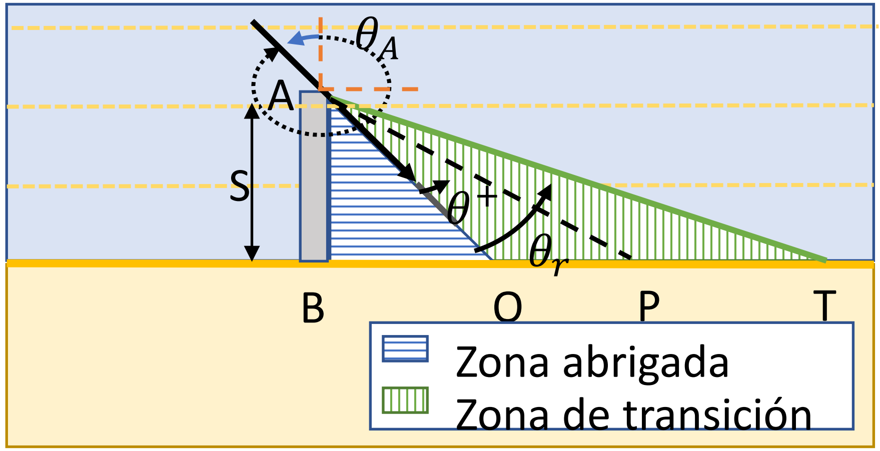
$$\mathrm{Y}_c^{\mathrm{eq}} = \Delta \mathrm{y0} + \Delta \mathrm{Y_{eq}} + \mathrm{R}_{ANMM}$$

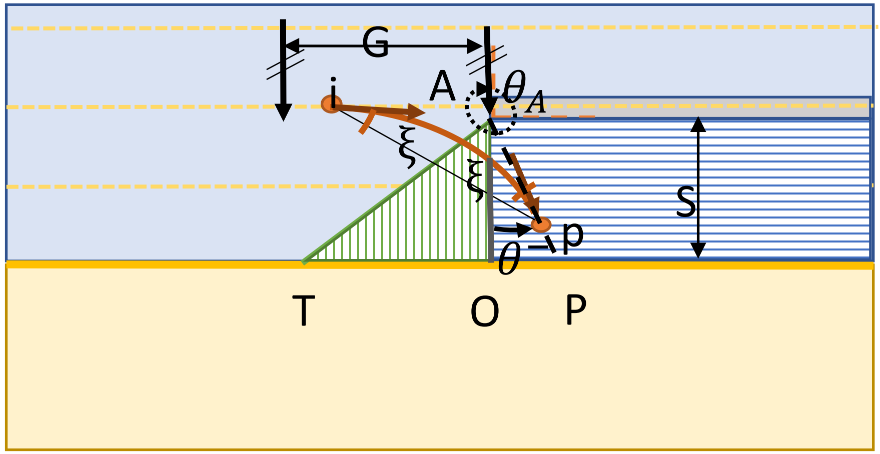
$$\Delta \mathrm{Y_{eq}} = -W_b\left(\frac{0.106H_b + MM + MA}{B + d_b}\right)$$

M&D (2004)
Bruun (1962)
Toimil et al. (2017)

Structures modelling

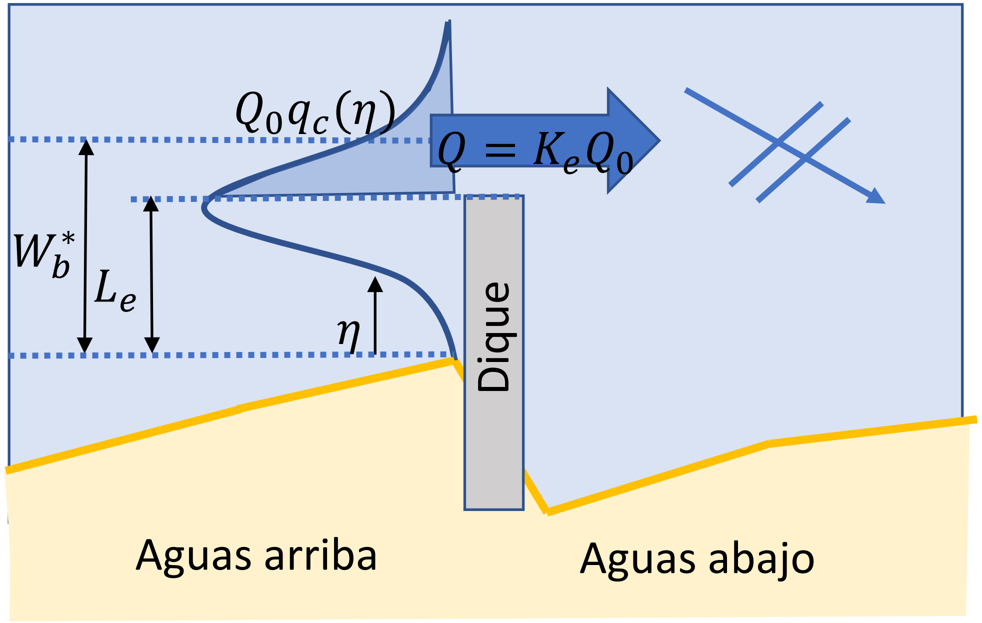
Wave propagation

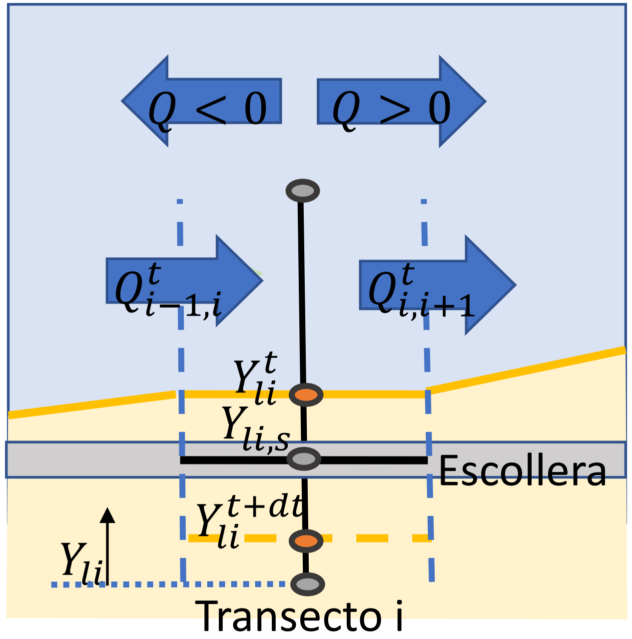




Kamphius (2000)
Dabees (2000)

Sediment transport

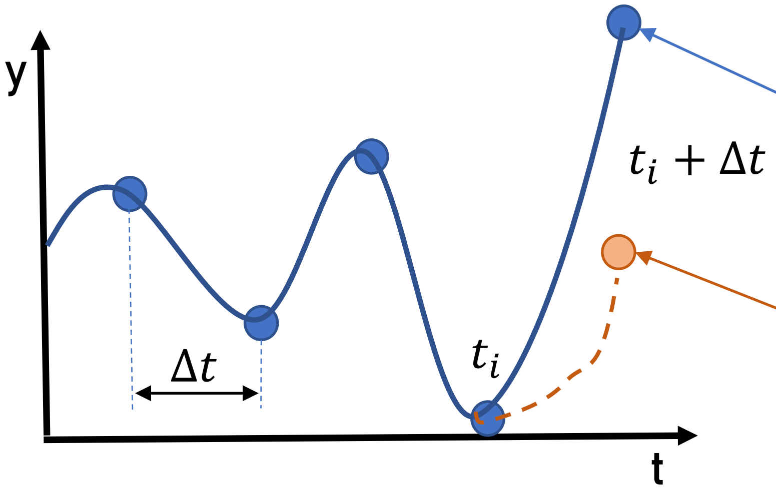




Kristensen et al. (2016)
Hanson (1989)
H&K (1986)

Data assimilation

Sequel: Alvarez-Cuesta et al. (2023) Which data assimilation method to use and when: unlocking the potential of observations in shoreline modelling



$$\bar{y}(t) = f(\bar{\boldsymbol{K}}, t)$$

$\bar{y}(t_i + \Delta t) = y(t) + \dot{f}(\bar{\boldsymbol{K}}, t)\Delta t$

Model prediction

Observation

Kalman filter

Kalman gain

$$y(t_i + \Delta t) = \bar{y}(t_i + \Delta t) + G_y[y_{obs,ti} - \bar{y}(t_i + \Delta t)]$$

$\boldsymbol{G}$ $\boldsymbol{P}$

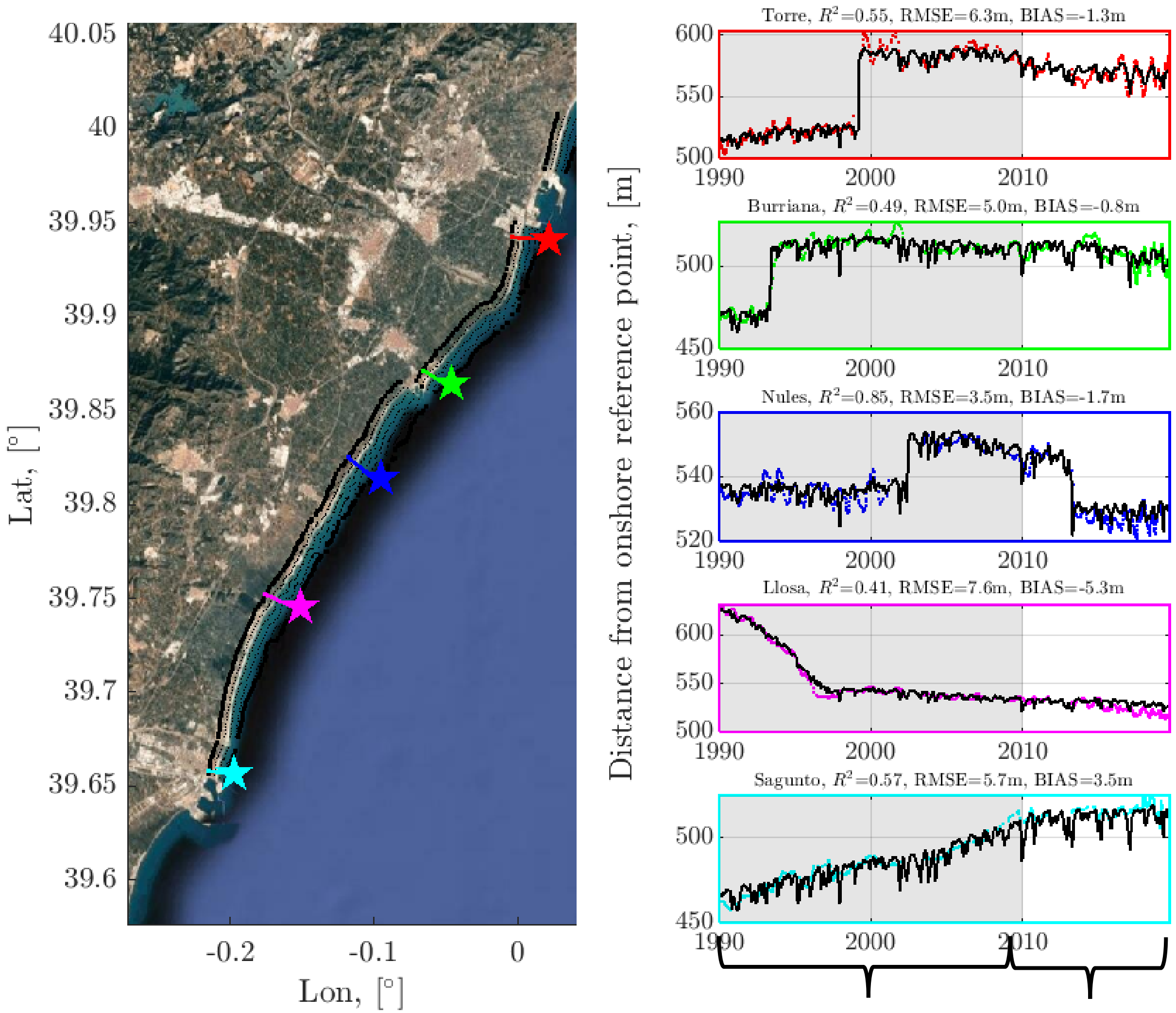
$$\boldsymbol{K}(t_i + \Delta t) = \bar{\boldsymbol{K}}(t_i + \Delta t) - \boldsymbol{G}_k[\bar{\boldsymbol{K}}(t_i + \Delta t)]$$

- Jacobian: $\boldsymbol{F} = \frac{\partial f(\bar{\boldsymbol{K}},t)}{\partial \bar{\boldsymbol{K}}}$
- Uncertainty: $\epsilon(\boldsymbol{K})$, $\epsilon(y_{obs})$
- Process noise: $\delta(\boldsymbol{K})$

Application to a real case

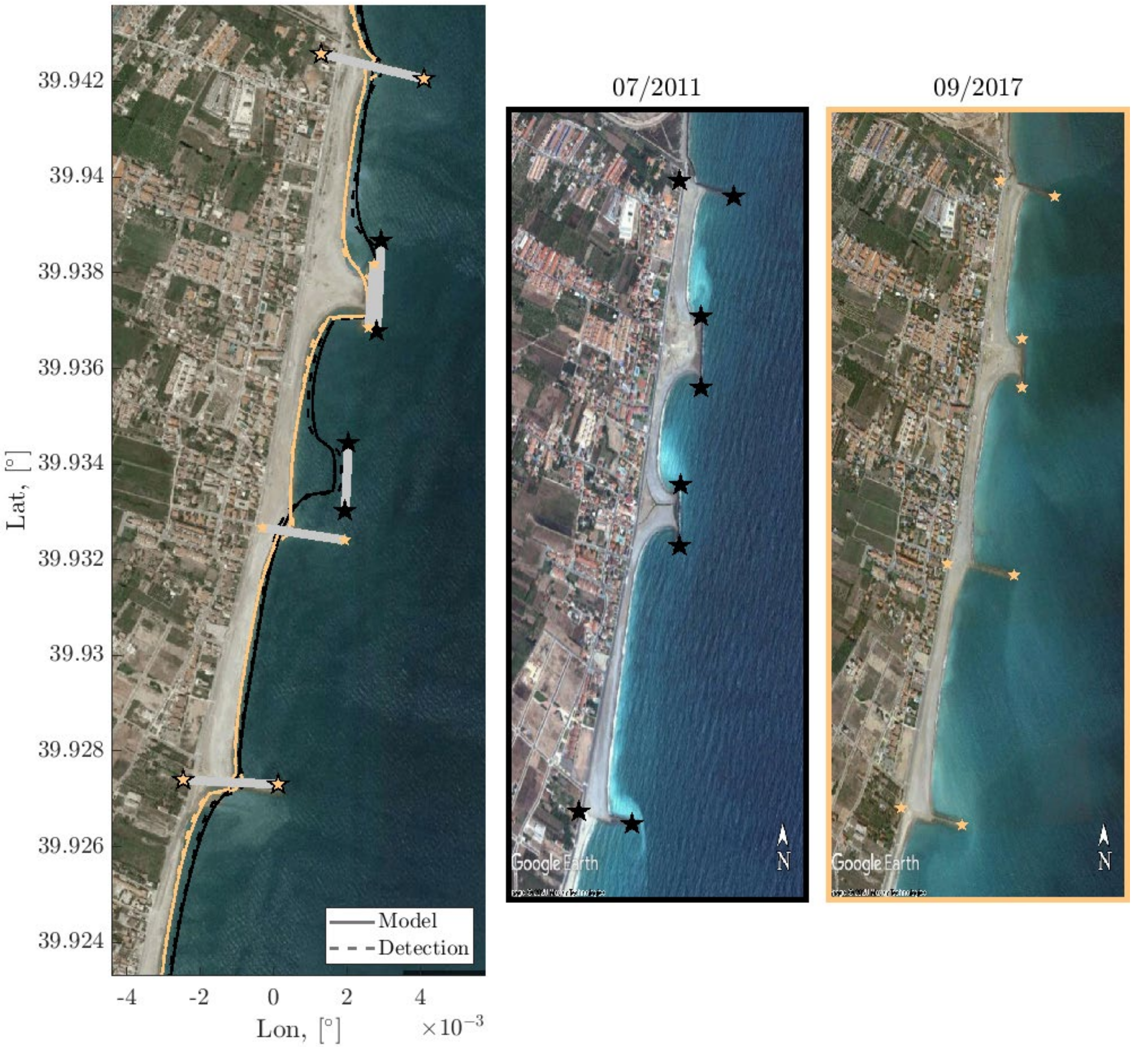
Results

Transects 200 m

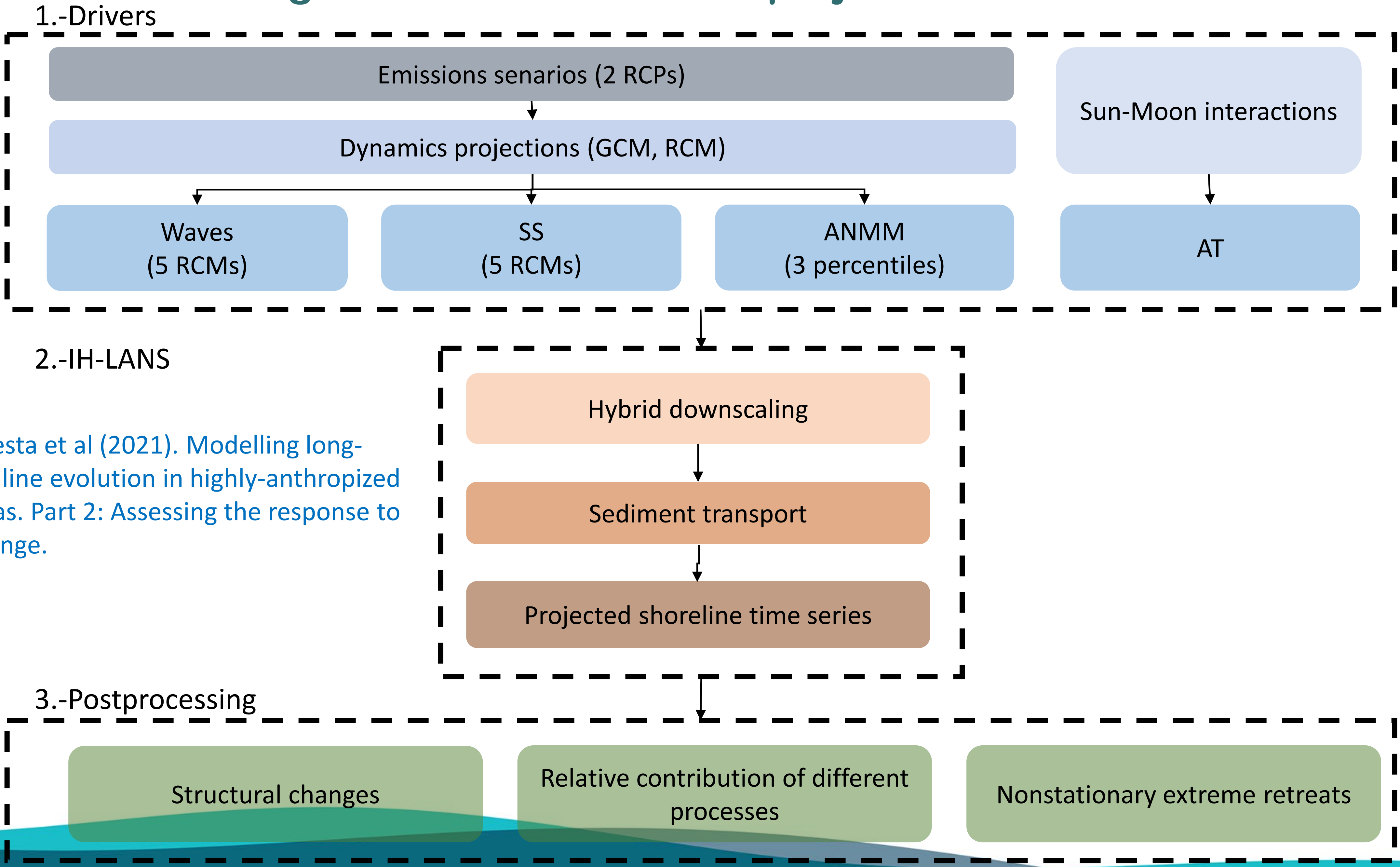


Assimilation Validation

Transects 15 m

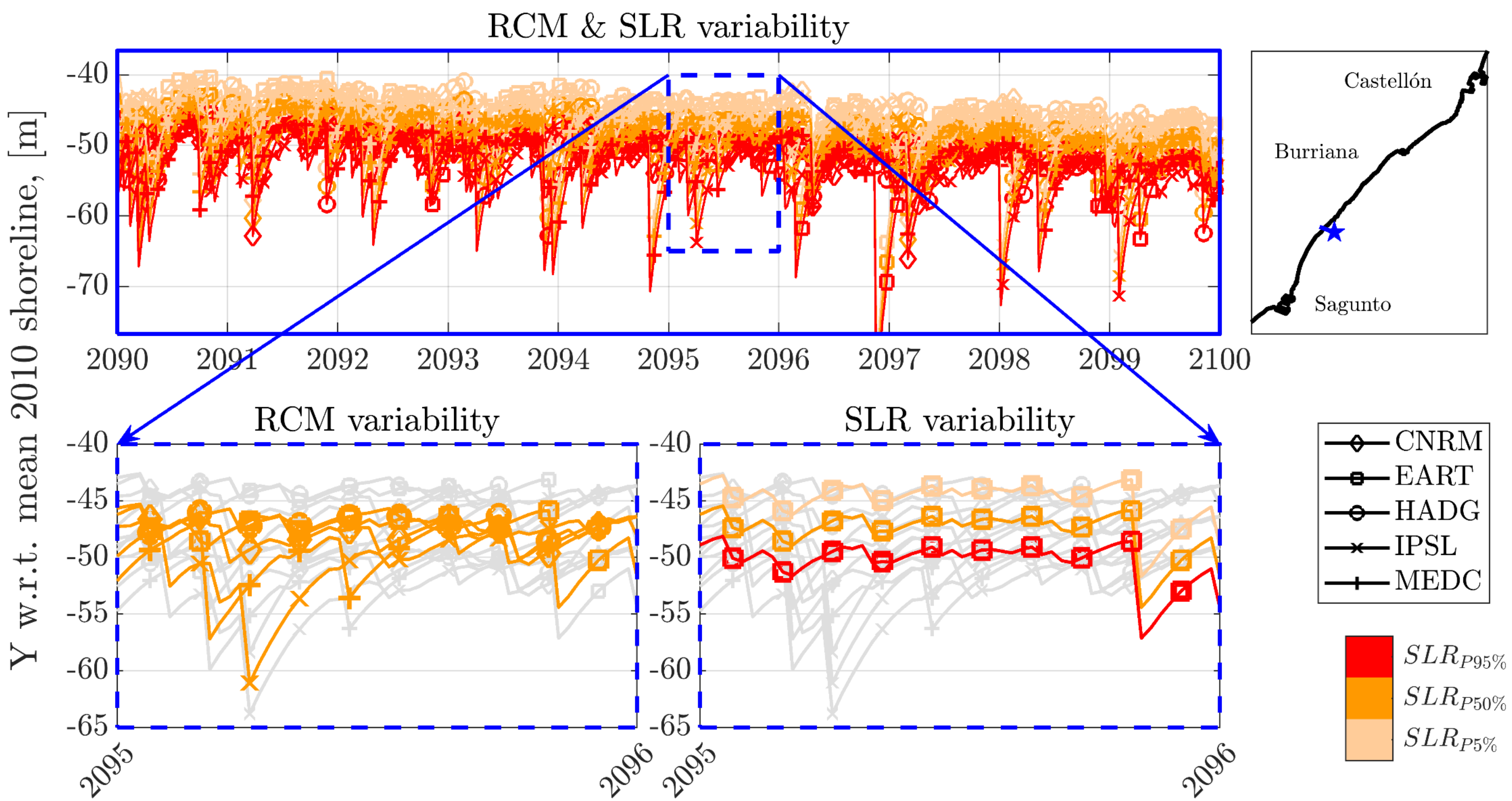


3 Robust modelling of coastline evolution projections



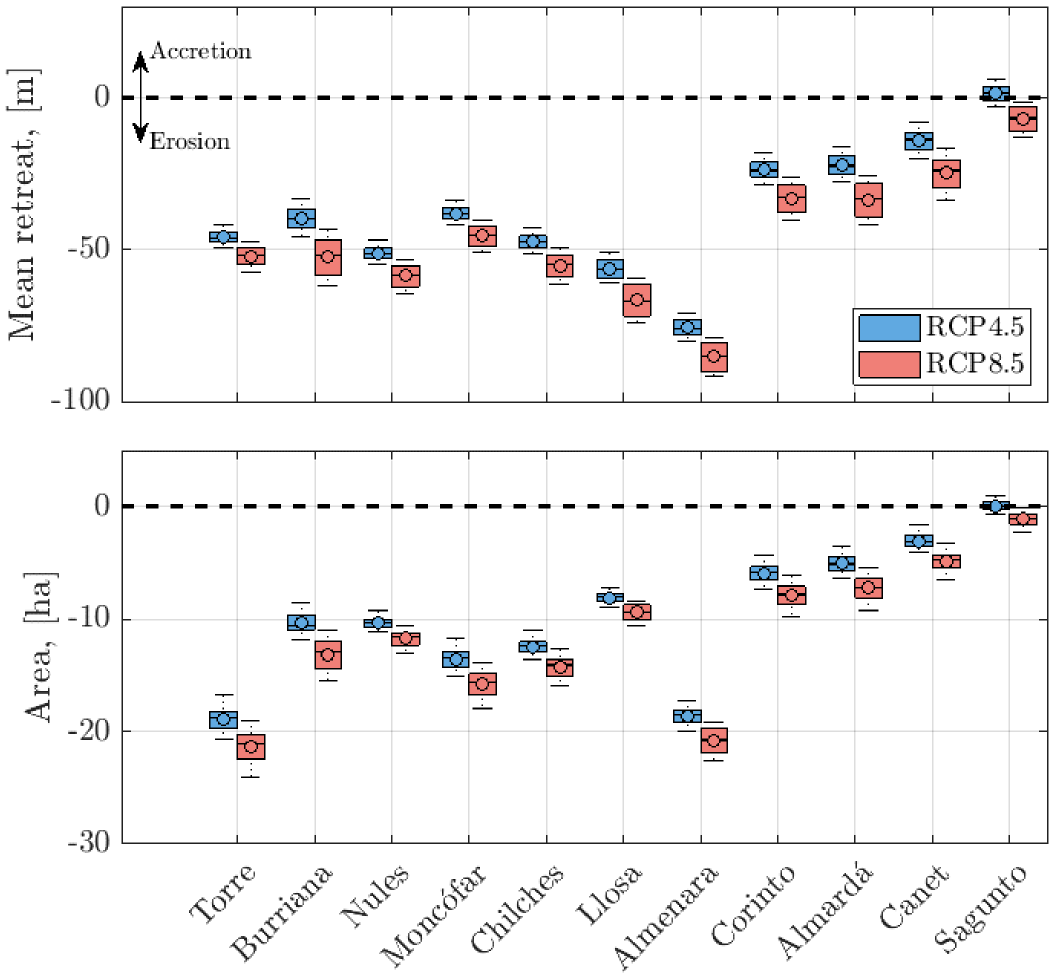
Alvarez-Cuesta et al (2021). Modelling long-term shorelline evolution in highly-anthropized coastal areas. Part 2: Assessing the response to climate change.

Shoreline modelling



Structural shoreline position

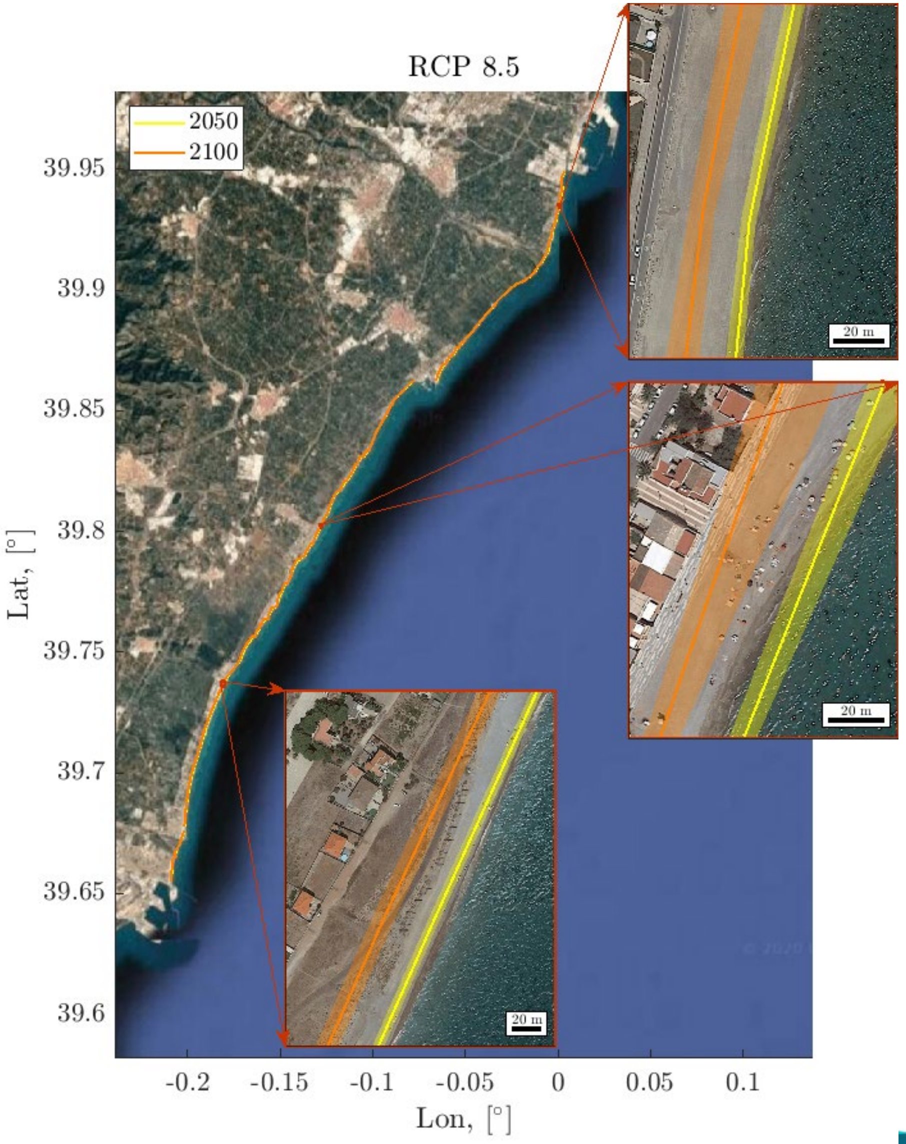
2RCPs, 5 RCMs, 3 percentiles ANMM



Summer season shoreline

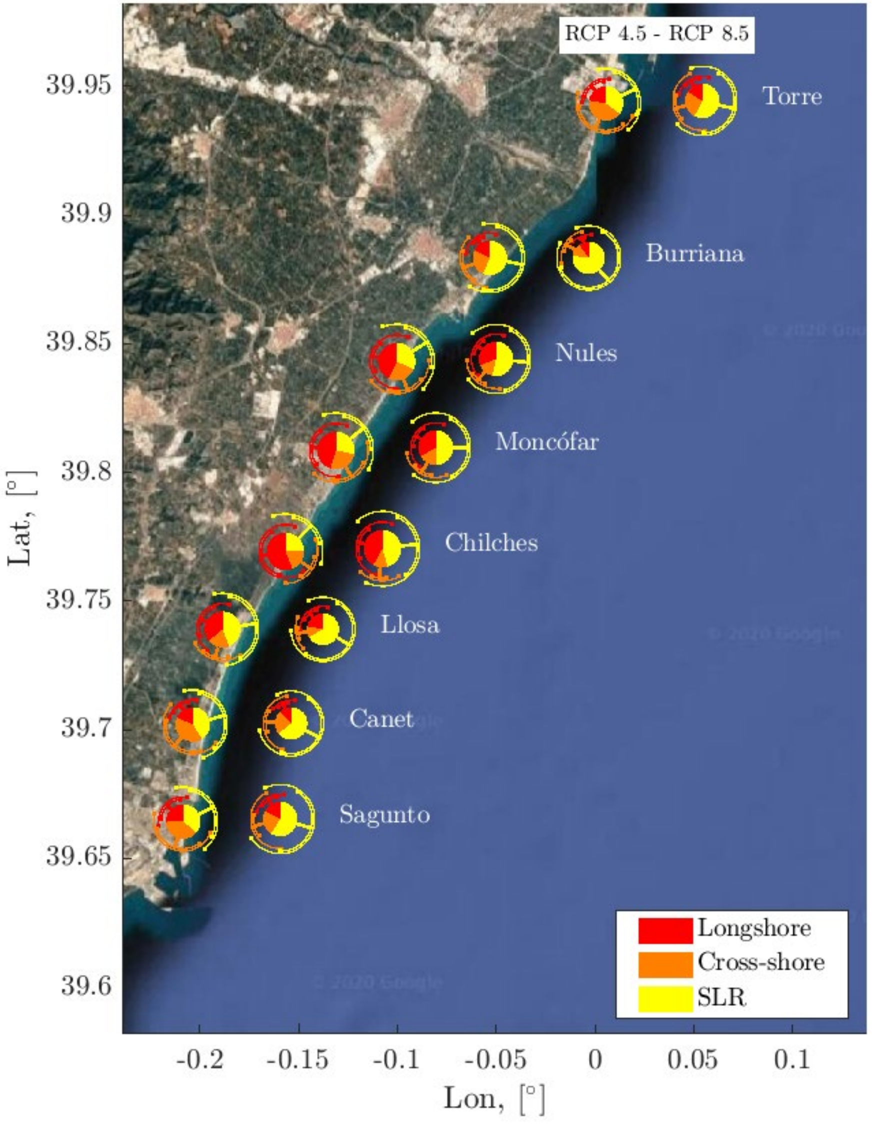
May to September

Median and uncertainty



Relative contribution of coastal processes to shoreline change

Median and uncertainty

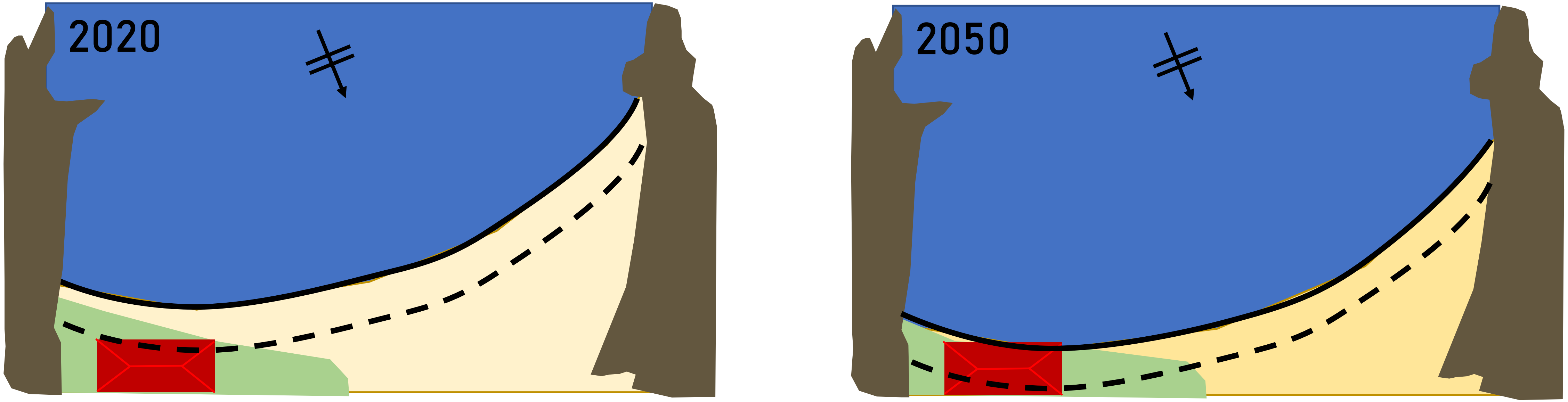


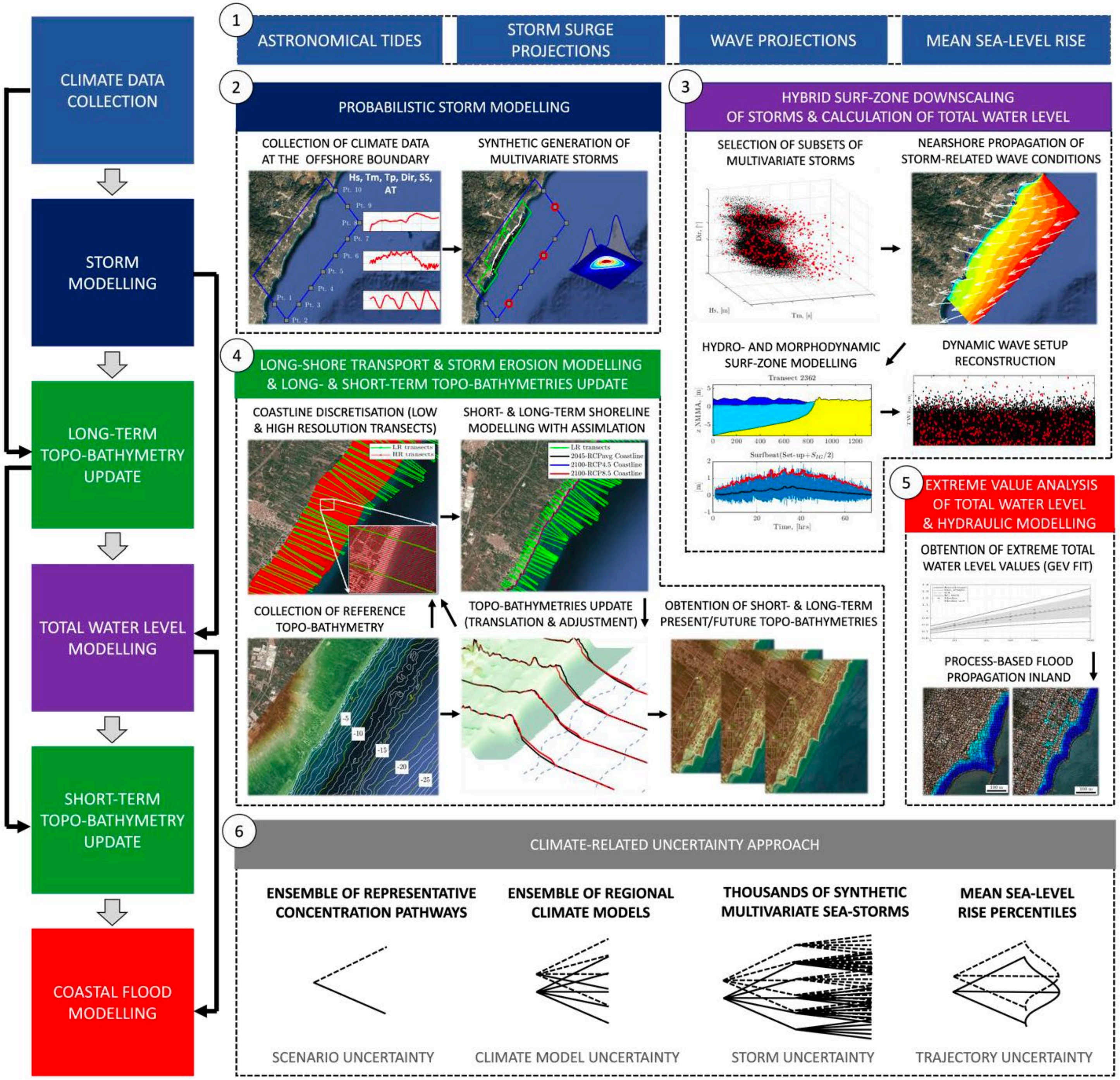
④ Coupled erosion-flooding modelling

Current practice

Neglect the morphological feedback in flooding studies

Grasses et al. (2020), Kirezci et al. (2020), Anderson et al. (2021), ...



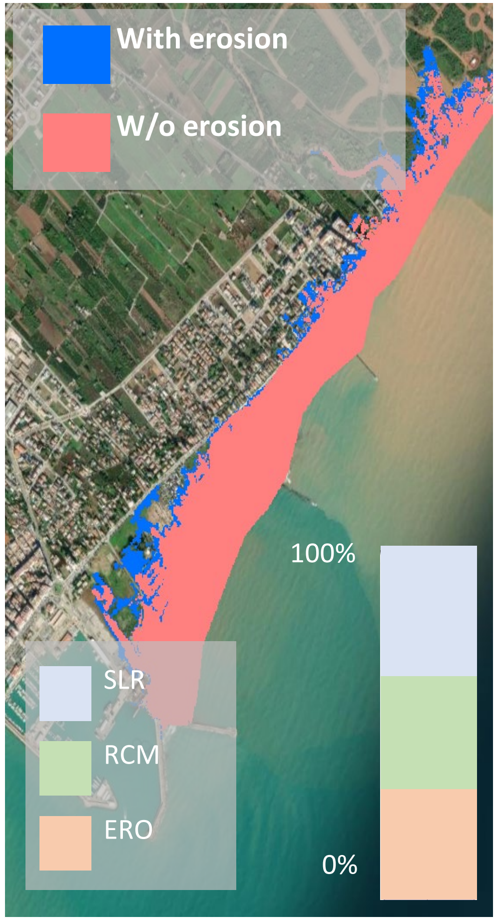


Methodology proposed for the development of coastal flood hazard projections incorporating shoreline change estimates

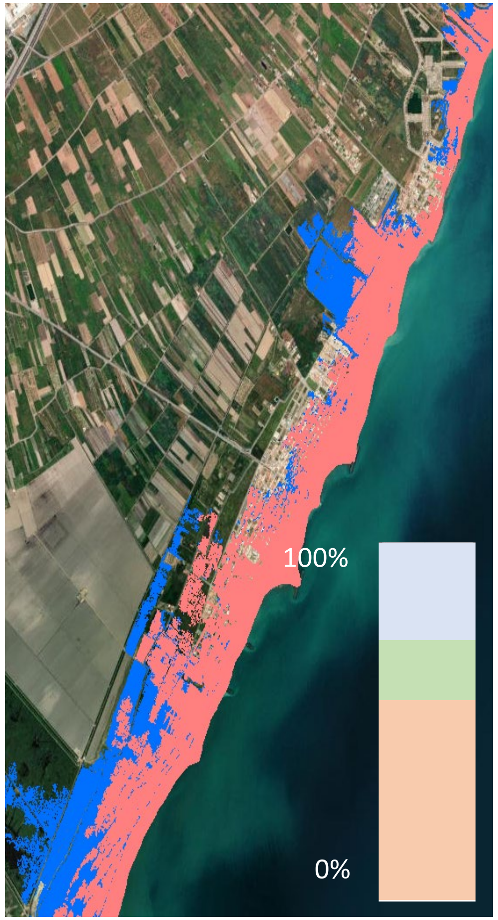
Toimil et al. (2023). Neglecting the effect of long-and short-term erosion can lead to spurious coastal flood risk projections and maladaptation

Erosion effects on coastal flooding

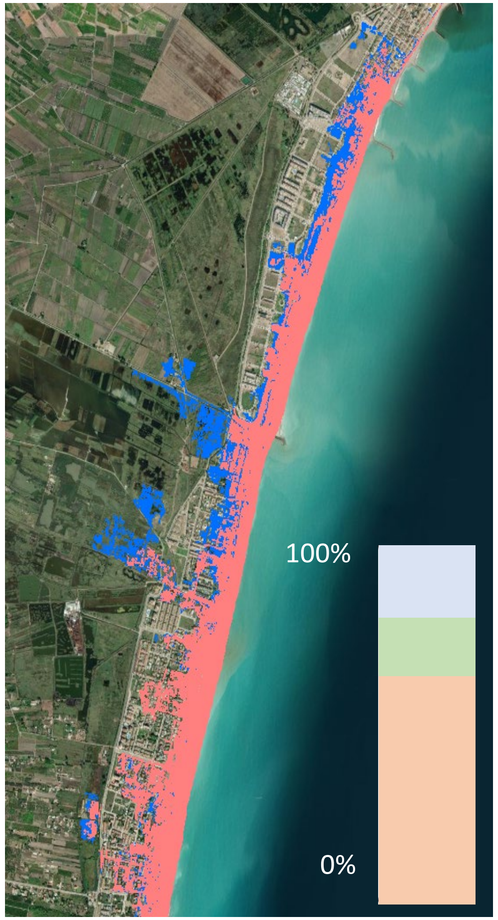
a) Burriana



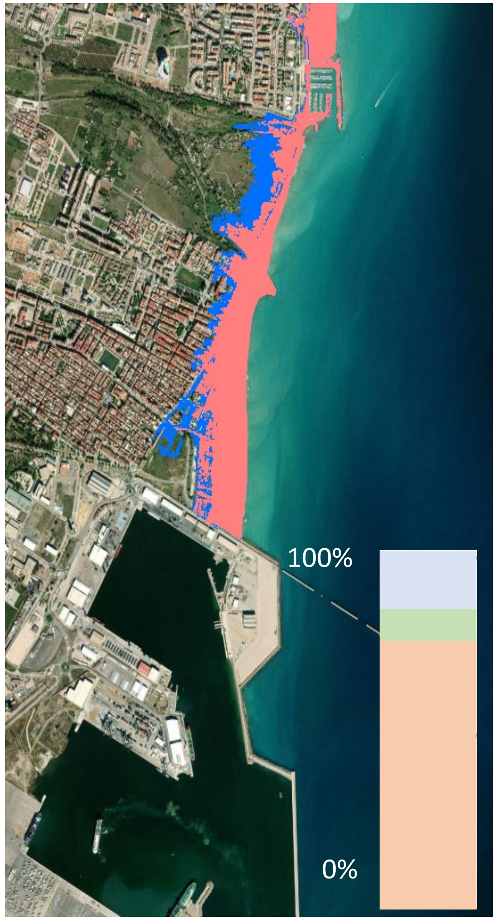
b) Chilches



c) Almenara



d) Sagunto



5 Value of beaches for coastal adaptation -> coastal resilience

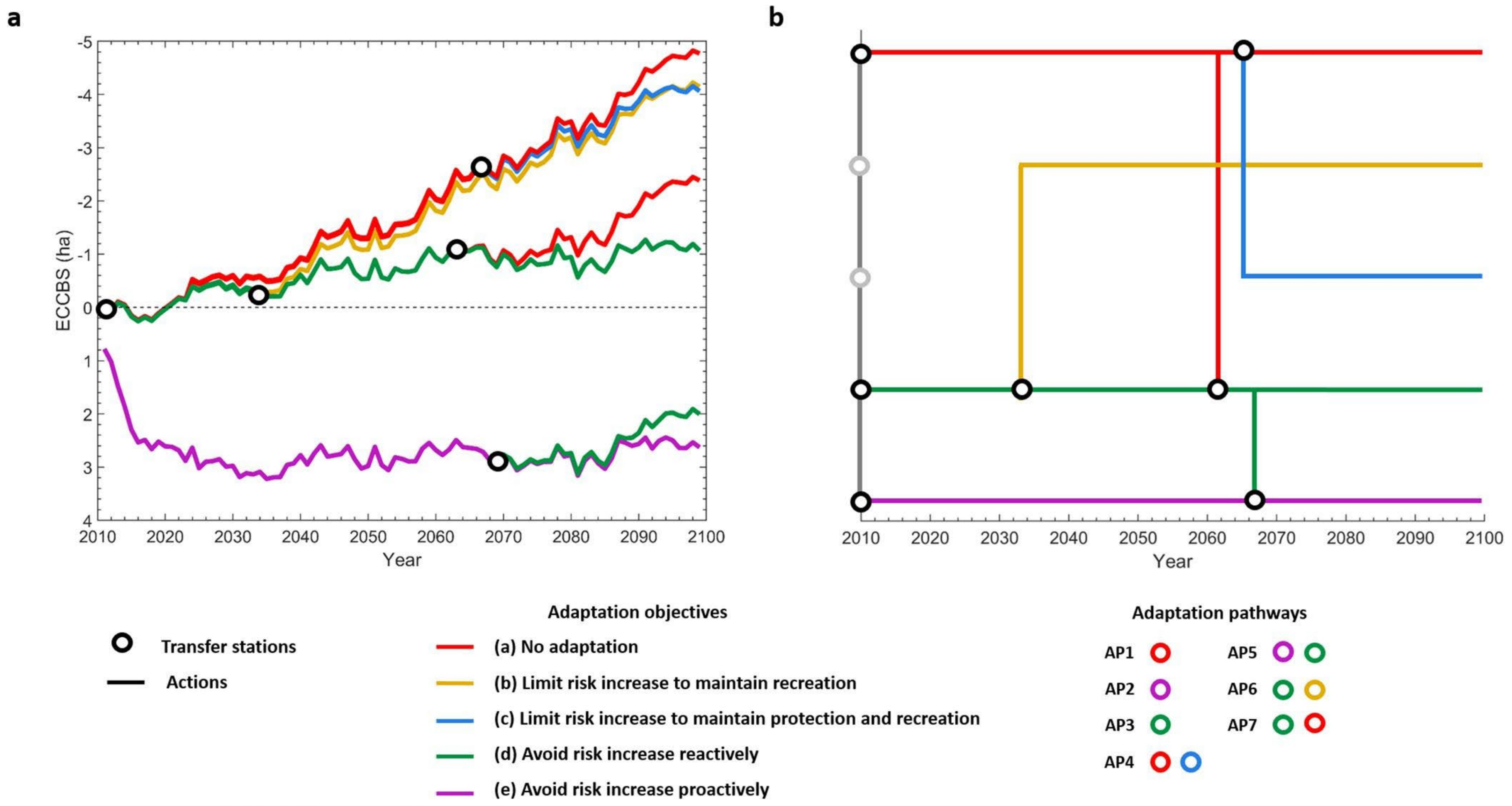
Map Data: Google Earth, Image © 2018 Maxar Technologies, Landsat/Copernicus

Toimil et al. (2023)
Demonstrating the value of beaches for adaptation to future coastal flood risk

Moises Alvarez-Cuesta: Sept 13, Room D: 12:15-12:30

6 Quantitative adaptation pathways implementation

Toimil et al. (2021) Using quantitative dynamic adaptive policy pathways to manage climate change-induced coastal erosion



Adaptation Plan- La Manga del Mar Menor (Spain)

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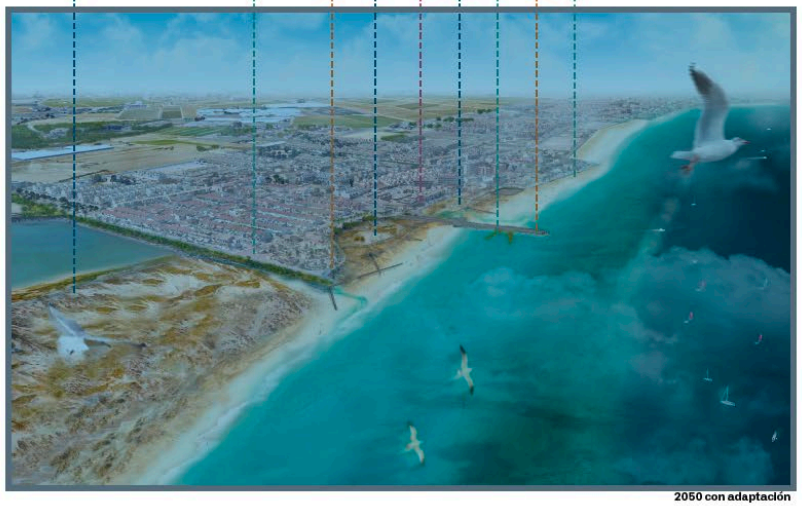
2050 sin adaptación



2050 con adaptación

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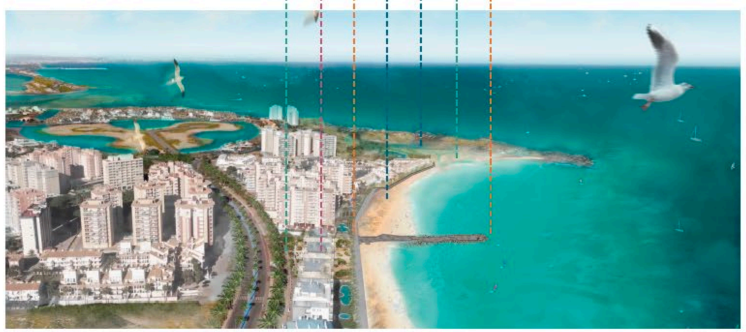
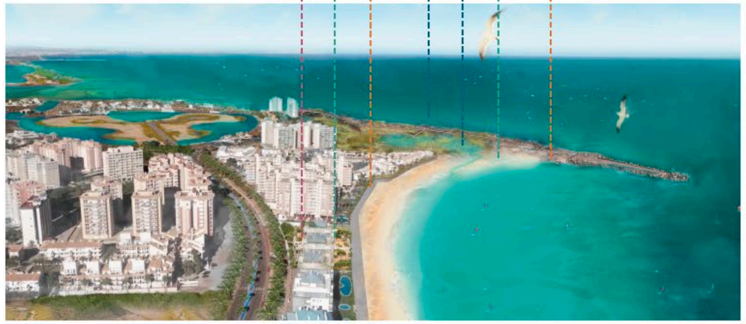
2050 sin adaptación



2050 con adaptación



2050 con adaptación

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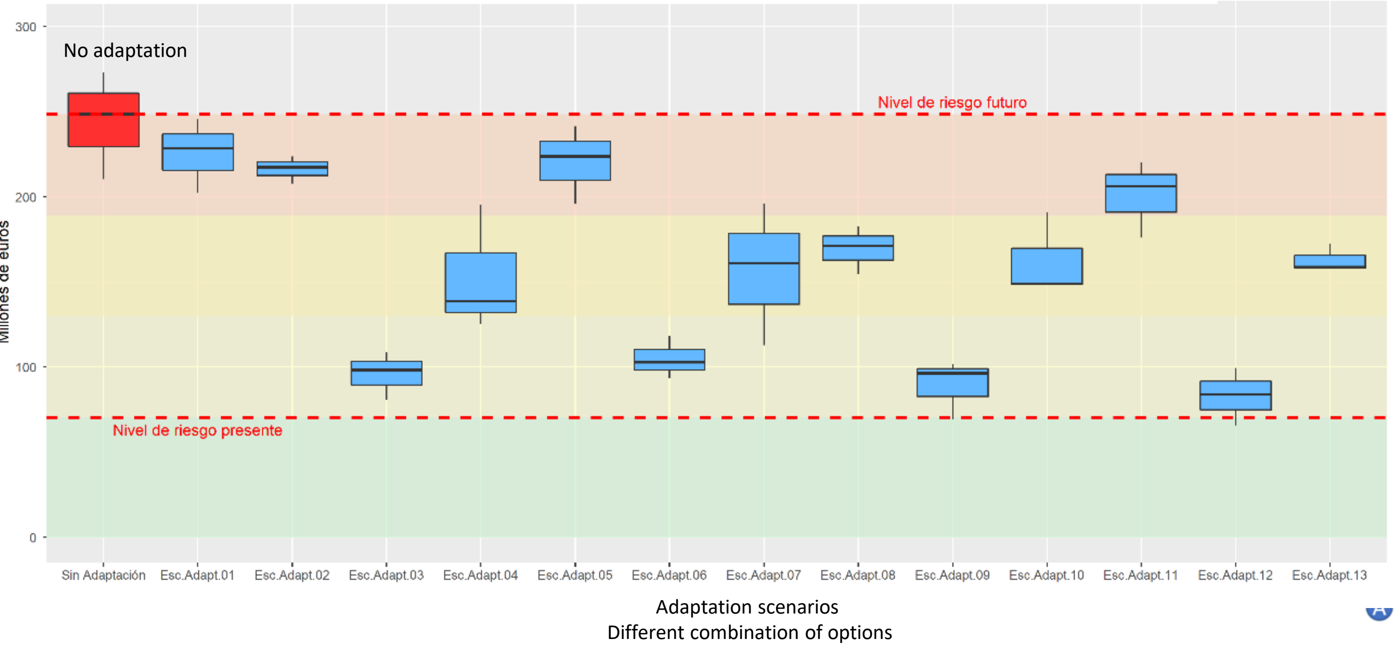
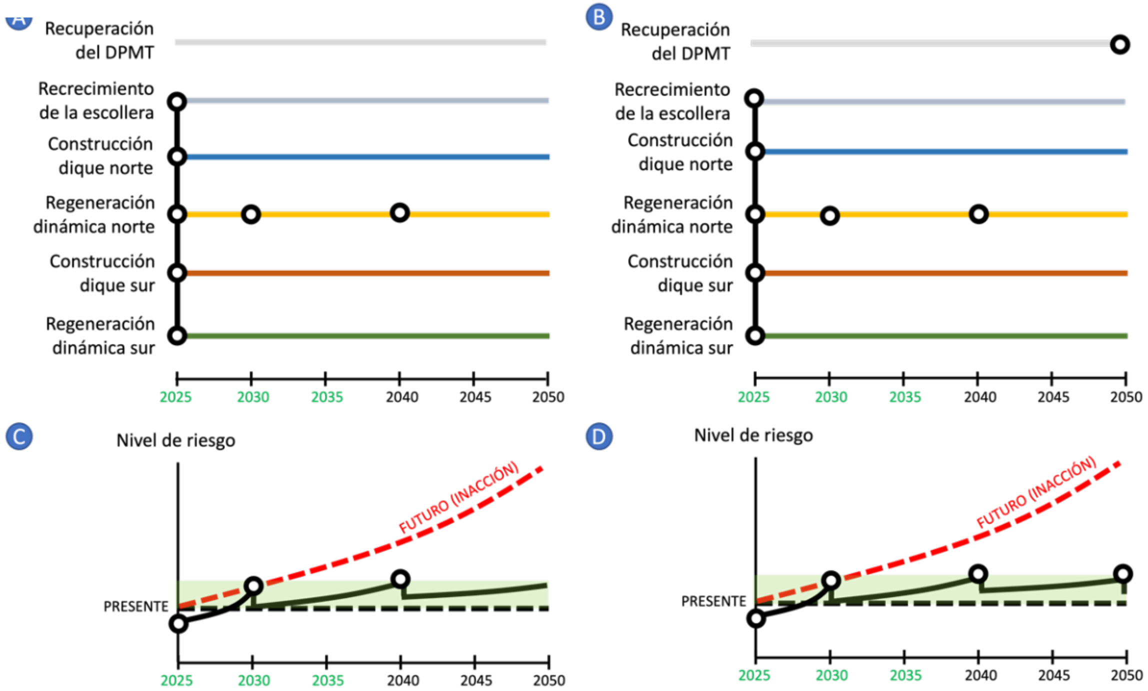
Value at risk (in million €) of buildings due to flooding (RCP8.5. Extreme event) by 2050



Adaptation pathways with and w/o retreat



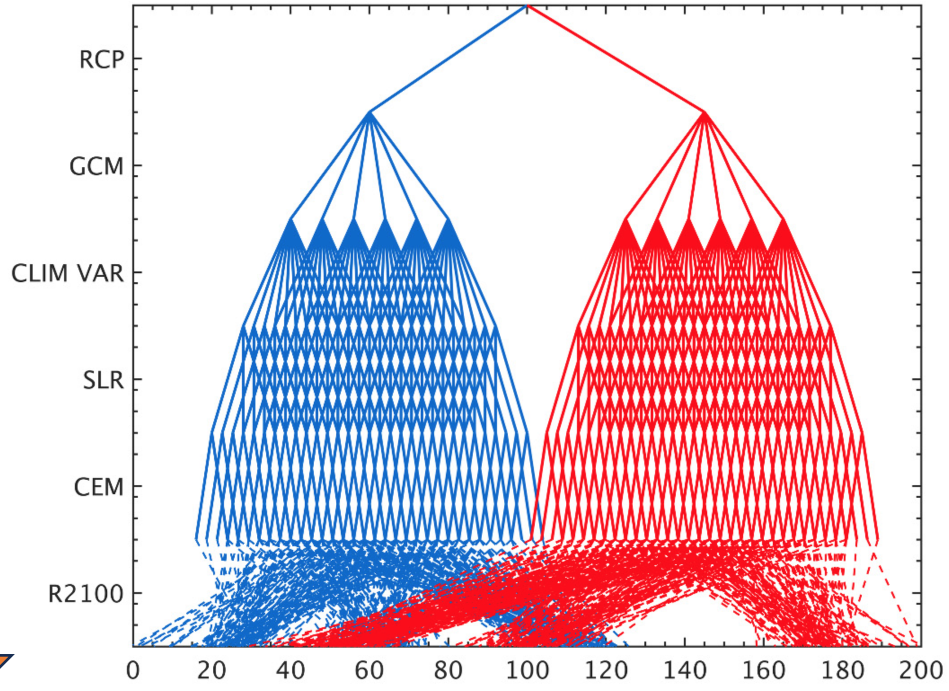
Exploring different pathways

CLIMATE STRESS TESTING COASTAL AREAS

shift from "top-down" to "bottom-up" methods

Climate Stress testing: A special case of sensitivity analysis involving evaluation of how a system performs in different combinations of stressors (i.e., combinations of future conditions) and with an increased focus on identifying combinations that lead to undesirable outcomes. Whateley et al. (2016)

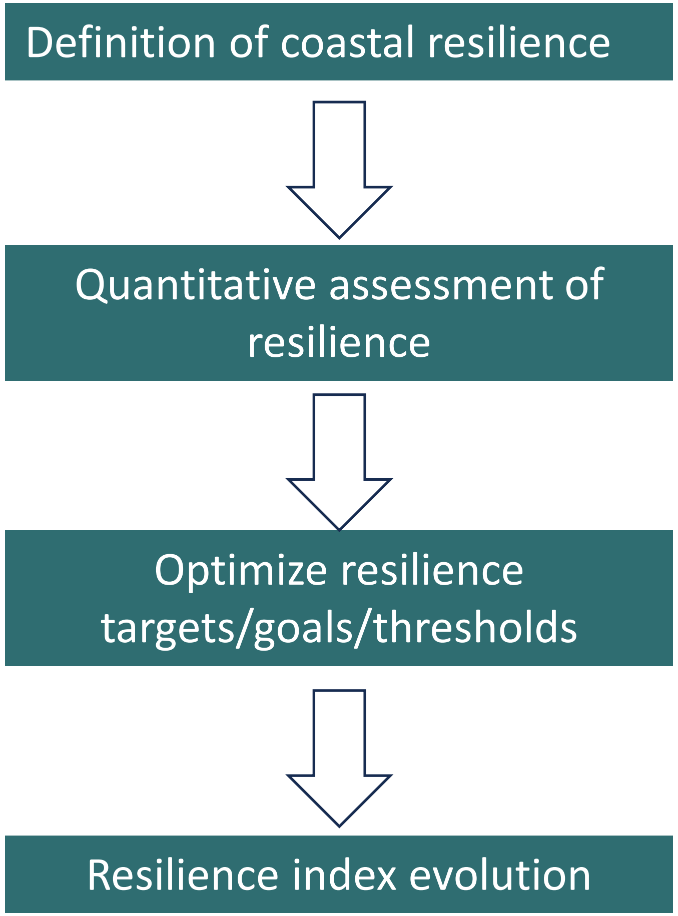
"top-down"



"bottom-up"

- Visualize results
- Test robust acceptable solutions by iteration
- Stress test: what critical conditions cause unacceptable performance? → Check within GCMs
- Develop a quantitative representation of the system
- Select climate and non-climate stressors
- Define the managed system

QUANTITATIVE ASSESSMENT OF COASTAL RESILIENCE



Definition of coastal resilience with a holistic scope and emphasis on systemic functionality:

"Coastal resilience is the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by factors such as sea level rise, extreme events and human impacts, by adapting whilst maintaining their essential functions."

- Against a backdrop of climate change impacts, achieving both socioeconomic and natural resilience in coastal environments in the long-term (>50 years) is very costly.
- Enhancement of socioeconomic resilience typically comes at the expense of natural resilience, and vice versa.
- For practical purposes, optimizing resilience might be a more realistic goal of coastal zone management.

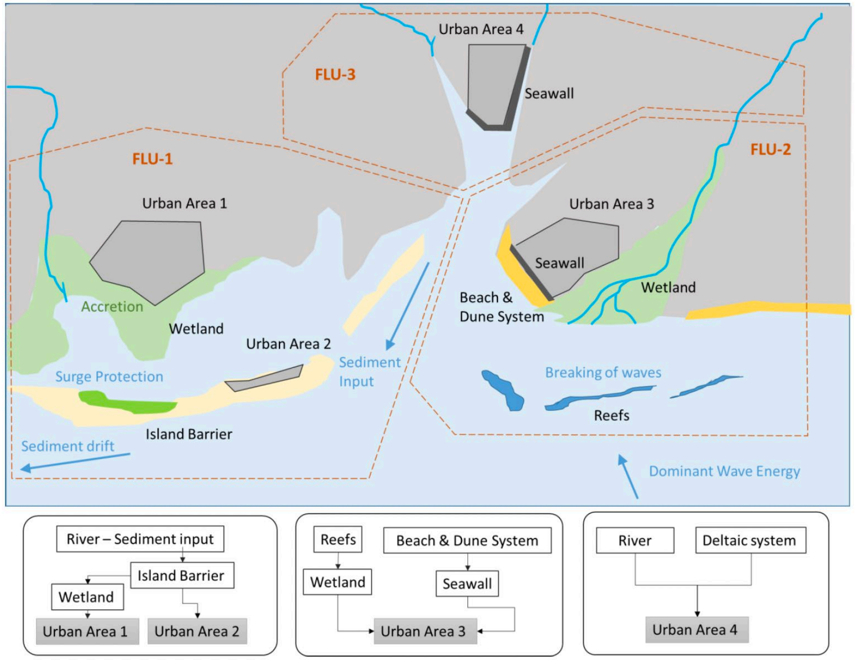
Masselink and Lazurus (2019). Defining Coastal Resilience

MULTI-HAZARD RESILIENCE ASSESSMENT FRAMEWORK

We should aim at assessing resilience of coastal defense networks including both natural and human-made systems

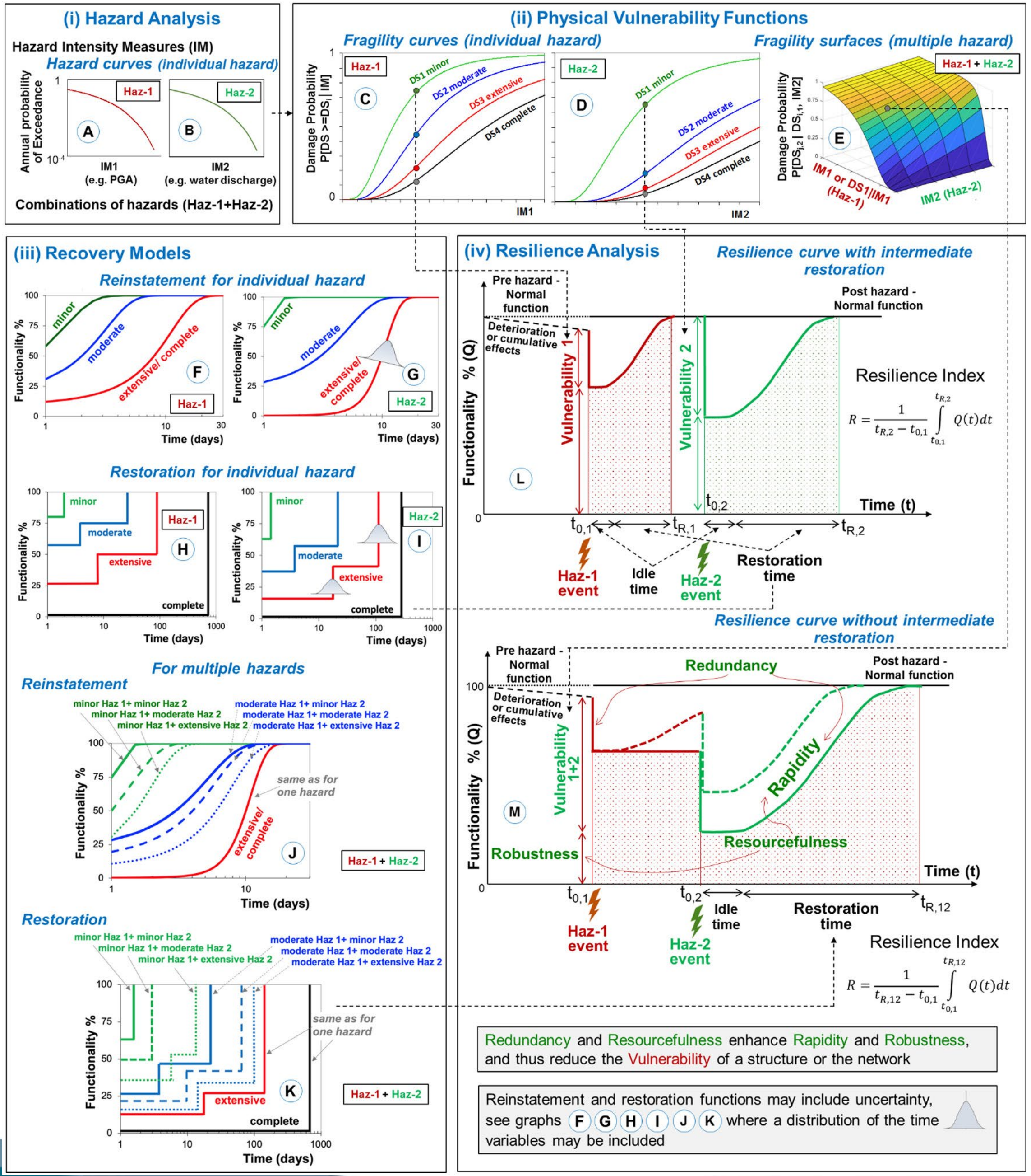
Accounting for:

- The sequence of multiple hazards and their impacts
- The vulnerability of the assets to multiple hazards and effect of occurrence time between hazards
- Different strategies of restoration and adaptation
- The rapidity of damage recovery
- others….

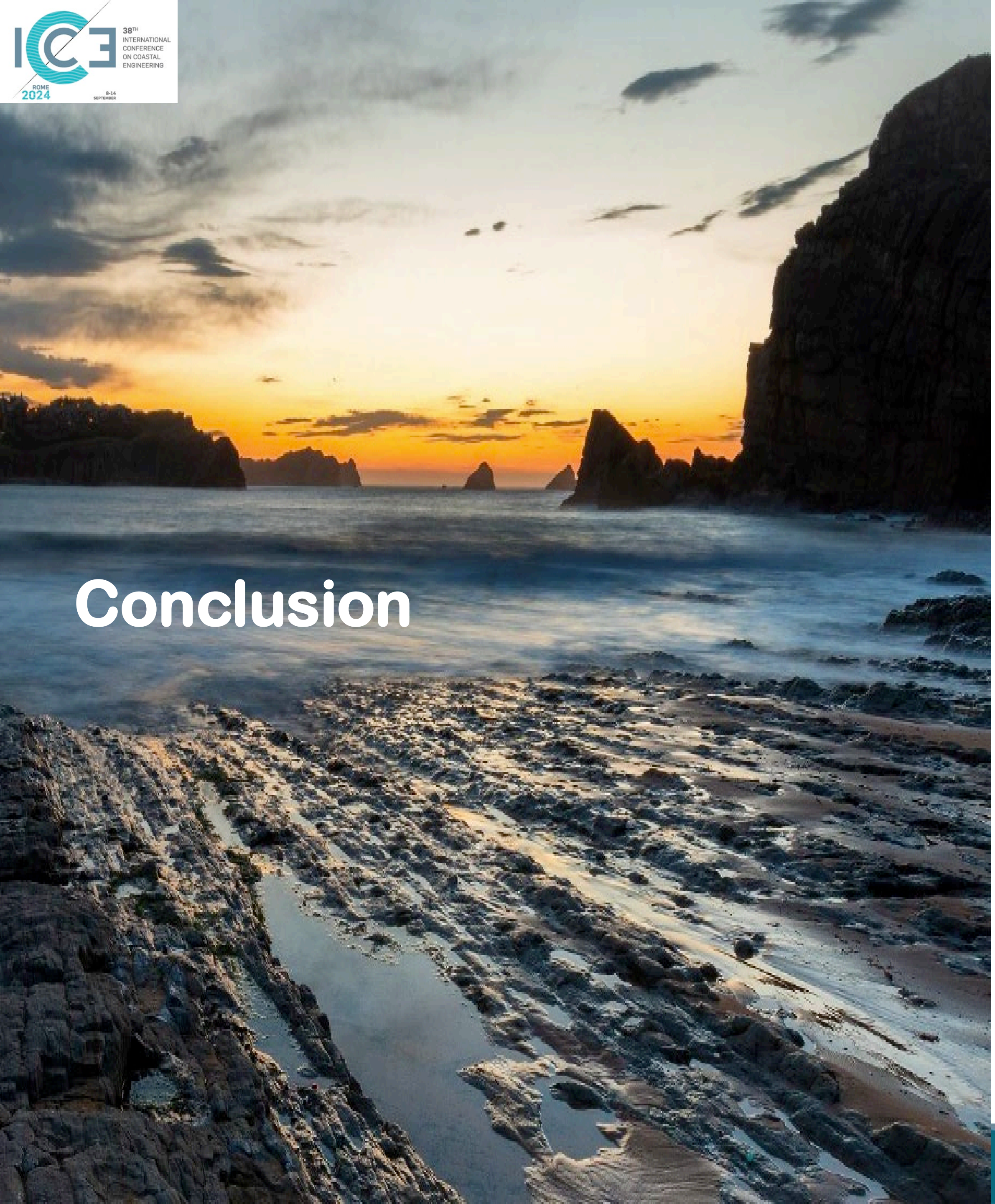


Landscape functional units

Reguero et al.



Argydouris et al. (2020)



Conclusion

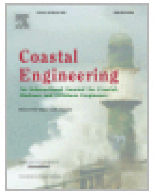
If speed and scale of changes, and available resources is what matters in providing reliable solutions for coastal management .....

Are we at risk of pushing our coasts out of centuries of incremental changes that we’ve been able to cope with, drifting away unstoppably towards retreat, relocation and loss of paramount resources and biodiversity or will we be able to continue trusting technology and standard practice to accommodate changes?

Coastal Engineers are key in responding this question and addressing societal challenges

MORE IN

Coastal Engineering
Volume 156, March 2020, 103611



Addressing the challenges of climate change risks and adaptation in coastal areas: A review

Alexandra Toimil [a], Iñigo J. Losada [a], Robert J. Nicholls [b], Robert A. Dalrymple [c], Marcel J.F. Stive [d]

ICE

38TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING

ROME 2024

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Coastal Adaptation and Resilience: The greatest Challenge in Coastal Engineering

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