Coastal Processes, Environments and Systems

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Course content

For this component of the unit, we will use:

1. a *learning website* where you will find all information relative to the lectures themselves: it contains some **notes**, **videos** and **exercises** for each weeks,
2. a *web-based programming platform* based on **Jupyter notebooks** that contains all the materials for the **exercises** and **practicals**.

This part of the course focuses on coastal systems analysis using both ocean data from a variety of sources (hindcast and forecast data, satellite observations, radar, moored buoys) and numerical models of shoreline changes, wave dynamics and coral reef evolution.

The emphasise will be on:

- **How to query and analyse numerical and ocean data?**
- **What can we learn from ocean and wave models on coastal evolution?**
- **How to use these models and what are their limitations?**

Note: Today, numerical modelling and ocean data query techniques are routinely applied by governmental agencies, companies and research organisations to tackle complex coastal problems. It is based on advanced physical models and engineering approaches designed to describe and observe the connections between ocean dynamics and coastal evolution.

Over the last 20 years, major improvements in our understanding of coastal processes have been related to (1) easier access to observational dataset and (2) improved coastal numerical models. **It is now critical for any graduates to have a sense of how to access these dataset efficiently, how to process them using simple coding tools and how to interpret them**.

During this course, we will learn how to do that using web-enabled open source technologies that you will be able to reuse in the future.

Lectures content

Important: We will do **computer-based exercises during both lectures and practicals** so you will need to bring an electronic device (preferably a laptop but a tablet with internet access could work). As there will be a lot to cover, it is also recommended to go through each chapter prior to the lecture to be well prepared and able to get the most of it during classes.

- *Ocean Data Query*
- *Analysing Wave Climate*
- *Quantifying Coastal Changes*
- *Coral Reef Evolution*

CHAPTER

ONE

OCEAN DATA QUERY

1.1 Coastal Ocean Observing Systems

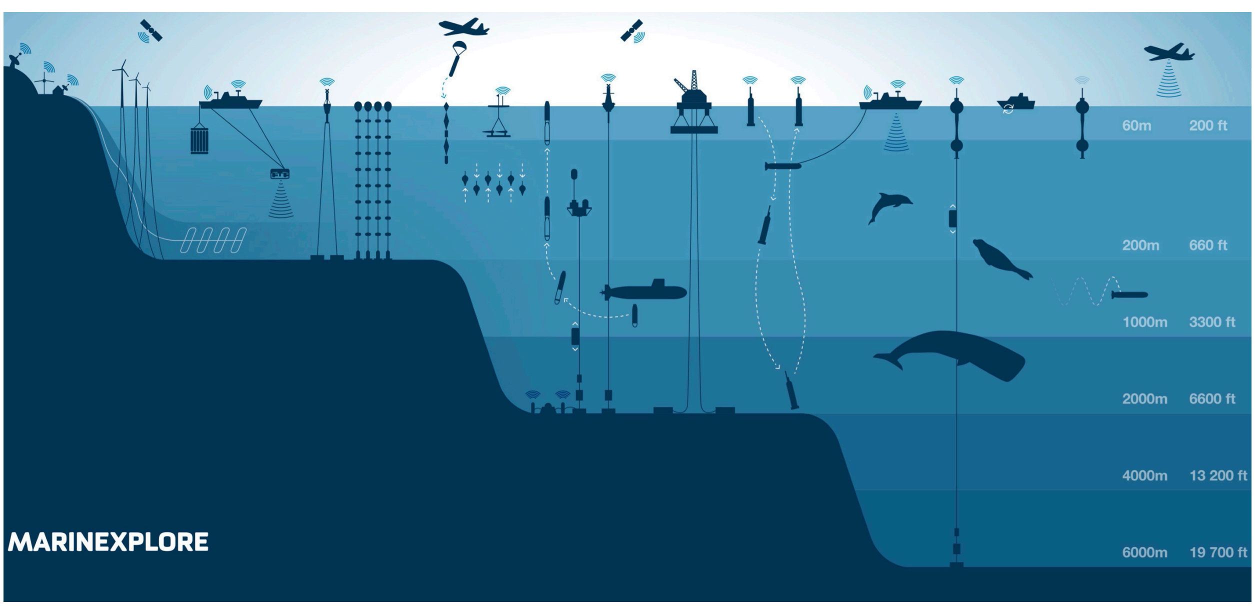
Note: Now, more than ever, there is a need for regional to global observing systems that can provide accurate real-time data and forecasts on coastal ocean conditions.

The ocean plays a role in everyone's life. It affects weather and climate patterns around the globe, hosts an abundance of wildlife that support fishing industries and provide food for the world, serves as a highway for vessels that deliver everyday materials, and supports economies as a tourism destination.

The coastal ocean is the part of the earth system where land, water, air, and people meet together. Populations, businesses, and infrastructure are increasing along coastlines, which are all susceptible to changing coastal ocean conditions.

Coastal ocean observing systems (COOS) are necessary for advancing our understanding on the state of the coastal ocean worldwide and its impact on matters of societal importance. These systems integrate a network of people, organisations, technologies, and data to share advances, improve research capabilities, and provide decision-makers with access to information and scientific interpretations.

1.1.1 Data acquisition



Important: Data, observations, and models integrated into the **COOS** come from a variety of platforms, including, for example, **moorings**, high-frequency (HF) **radars**, underwater **gliders** and profilers, **satellites**, and **ships**. The resulting data are used to better understand, respond to, and prepare for **short-term** events such as oil spills, harmful algal blooms, and fish kills, **longer term** changes in our oceans resulting in acidification, hypoxia, and sea level rise, and in everyday decisions related to maritime operations, public health, and management of healthy ecosystems.

1.1.2 A bit of history

Matthew Fontaine Maury (1806/1873) was an American astronomer, Confederate Navy officer, historian, oceanographer, meteorologist, cartographer, author, geologist, and educator.

He was nicknamed **Pathfinder of the Seas** and **Father of Modern Oceanography and Naval Meteorology** and later, **Scientist of the Seas** for his extensive works in his books, especially *The Physical Geography of the Sea* (1855), the first such extensive and comprehensive book on oceanography to be published. *Maury made many important new contributions to charting winds and ocean currents, including ocean lanes for passing ships at sea*.

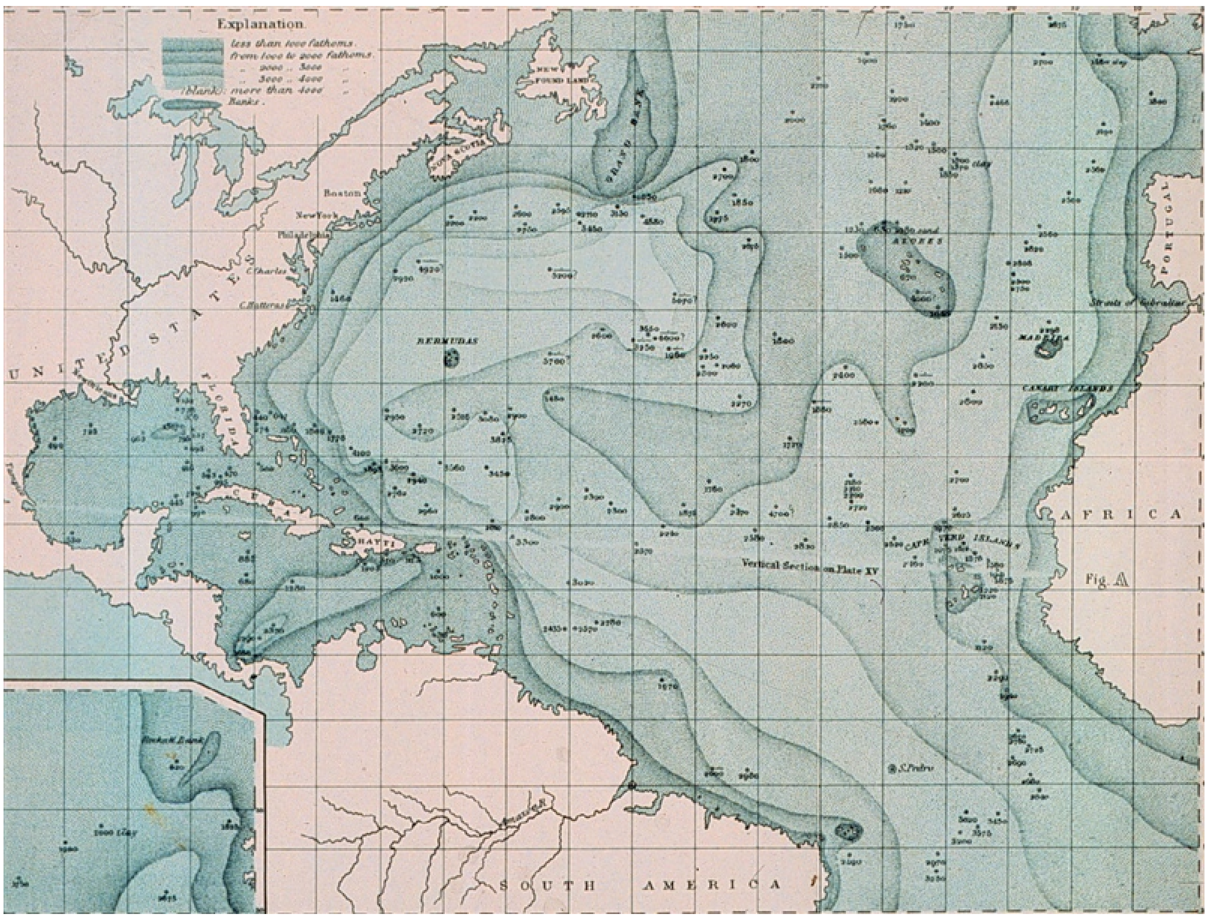
As a sailor, Maury noted that there were numerous lessons that had been learned by ship masters about the effects of adverse winds and drift currents on the path of a ship. The captains recorded the lessons faithfully in their logbooks, but they were then forgotten. At the US Naval Observatory, Maury uncovered an enormous collection of thousands of old ships' logs and charts in storage in trunks dating back to the start of the US Navy. He pored over the documents to collect information on winds, calms, and currents for all seas in all seasons. His dream was to put that information in the hands of all captains.

Maury became convinced that adequate scientific knowledge of the sea could be obtained only by international cooperation. He proposed for the United States to invite the maritime nations of the world to a conference to establish a **universal system** of meteorology, and he was the leading spirit of a pioneer scientific conference when it met in *Brussels in 1853*.

As a result of the Brussels Conference, a large number of nations, including many traditional enemies, agreed to cooperate in the sharing of land and sea weather data using uniform standards. It was soon after the Brussels conference that Prussia, Spain, Sardinia, the Free City of Hamburg, the Republic of Bremen, Chile, Austria, and Brazil, and others agreed to joined the enterprise.

Within a few years, nations owning three fourths of the shipping of the world were sending their oceanographic observations to Maury at the Naval Observatory, where the information was evaluated and the results given worldwide distribution.

Note: Maury's idea set the scene for what is now a *Global Ocean Observing Infrastructure*! Over the 19th and early 20th century a lot of measurements were made by diverse communities for their **own needs** (scientists, fishermen, commercial navigators…). However as more and more data was collected by divers communities, data was shared only among small communities and was not properly archived and it wasn't done in a organised way. In situ archeology is a hard job providing questionable databases!


Explanation
UNITED STATES
FLORIDA
BERMUDAS
AZORES
MADEIRA
CANARY ISLANDS
AFRICA
PORTUGAL
Straits of Gibraltar
NOVA SCOTIA
GRAND BANK
NEWFOUNDLAND
Boston
New York
Philadelphia
C. Charles
C. Hatteras
HAYTI
CUBA
CAPE VERD ISLANDS
Vertical Section on Plate XV
SOUTH AMERICA
St. Paul
Fig. A

1.2 Why do we need ocean observing tools?

Until recently, the ocean was viewed as *being an unlimited resource to be exploited* (source: *US National Academies of Science report on Economic Benefits of Oceanographic Research, 1964*). Subsequent science, including that from national and international observing efforts, has changed what we know about the ocean.

Nowadays, we recognise that **the ocean is a finite and shared resource** that needs to be manage regionally, nationally, and worldwide.

Societal threats and challenges

There are a number of significant societal threats and challenges facing humans due to the changing ocean:

- The increased frequency and intensity of coastal storms and resulting storm surges will affect our coastal communities and disrupt commerce, nationwide.
- Sea level changes are threatening critical infrastructure worldwide.
- Harmful algal blooms and oxygen-deficient dead zones threaten water supplies, fisheries, and coastal recreation.
- Ocean acidification is negatively impacting coral reefs and shellfish harvesting.
- The increasing size and number of vessels calling on ports present challenges for our already inadequate maritime infrastructure, and pose potential environmental risks as well.
- The world's growing population will increasingly rely on the ocean for food, but fishing must be done sustainably.

To be able to understand and manage the ocean, we need meaningful measures of the ocean's state.

1.3 National & Global Ocean Observing Infrastructure

Observing systems are expensive; Australia invests billions of dollars in civil Earth observations to ensure that the nation's decision-makers and managers have the information they need about climate and weather, disaster events, land-use change, ecosystem health, natural resources, and many other characteristics of the planet.

The ocean is a harsh environment in which to operate an observing system, from corrosion due to salinity to bio-fouling. The costs of maintaining instrumentation in this environment, accessing remote locations, and establishing sufficient communications with deployed technologies are significant.

IMOS had as its prime focus improving scientific understanding of ocean conditions, but the information it generates is increasingly being used by government agencies and other users to inform decisions. The main activities of IMOS are based around:

- Deploying, maintaining, and developing advanced observations technologies
- Providing free and open access to data in support of a wide range of users
- Advancing modeling
- Focusing on education

In addition to providing observations and data to a large and growing number of research projects, student projects, and academic courses, IMOS is now recognised as an essential partner in large, multi-institutional research programs across multiple sectors. It has contributed to 180 postgraduate projects, over 400 journal publications, and 250 research projects.

1.3.1 Coastal ocean observing systems development

Most large-scale coastal ocean observing systems are funded through national governments for their own interests, often with different foci, but the world's oceans are connected, therefore partnering is the key to success. As an example, the U.S. Integrated Ocean Observing System (IOOS), **Australia's Integrated Marine Observing System** (IMOS), or European Ocean Observing System (EOOS) are progressing in their respective regions and are working together to observe and compile ocean information in a way that is easily accessible to scientists and managers.

IMOS advances have benefited from an evolving set of ocean observing efforts. The envisioned concept was a coordinated national and international network of observations, data management, and analyses that systematically acquired and disseminated data and information on past, present, and future states of the oceans. The coastal ocean observing efforts are implemented via regional programs distributed around coastal regions.

Each program is designed to assess and predict the effects of weather, climate, and human activities on the state of the coastal ocean, its ecosystems and living resources, and on the world's economy.

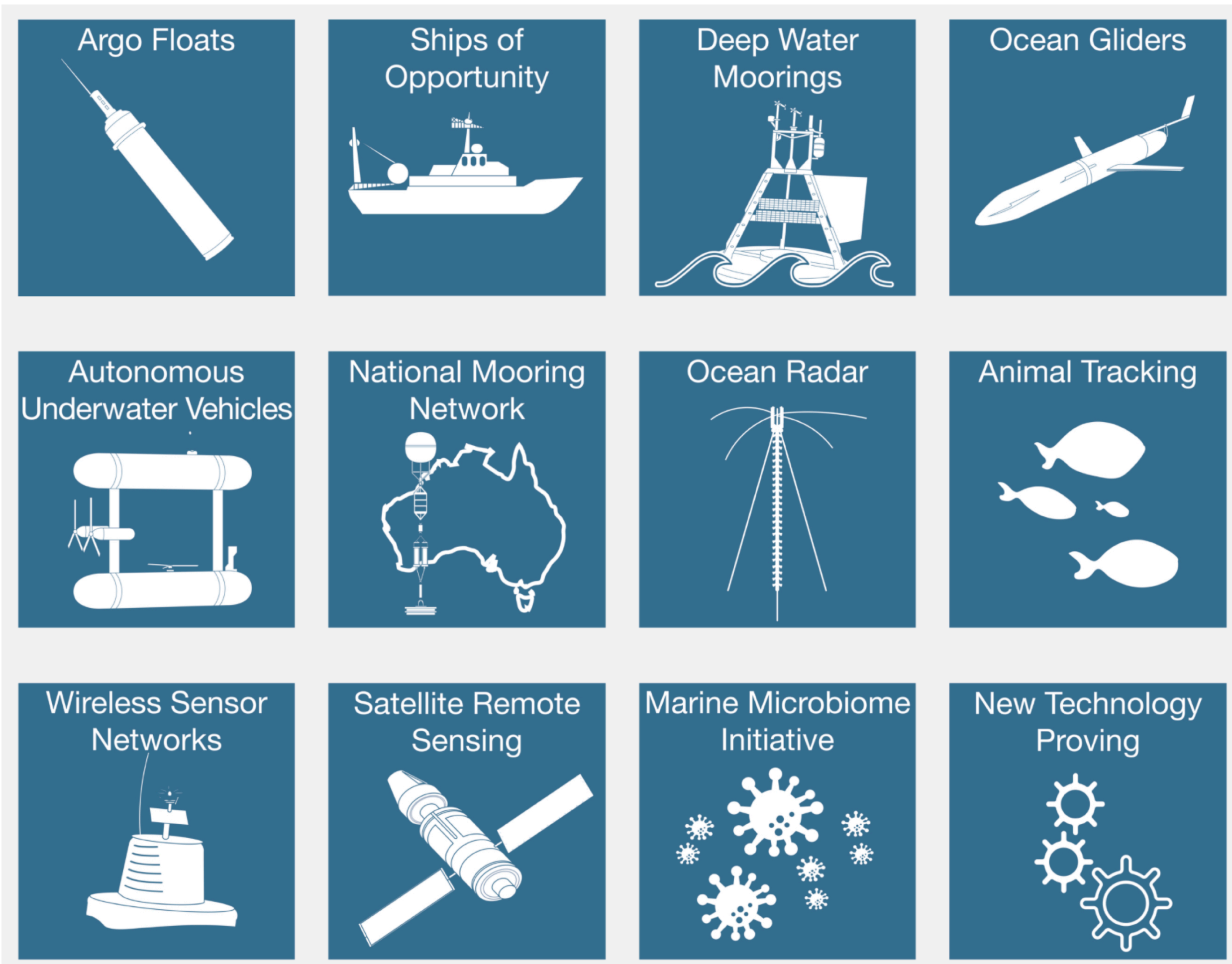
Note: The Australian IMOS was formed in 2007, with equipment deployed from the next year onward. Scientific 'nodes' were formed broadly around state boundaries with both nationally unified overarching science goals and local priorities. The **NSW-IMOS** is an example of a successfully implemented ocean observing system along the coast of southeastern Australia. The current observational array is designed around pertinent science questions, leveraged existing data streams, and opportunities for further oceanographic research.

IMOS currently has a portfolio of **13 Facilities** that undertake systematic and sustained observing of Australia's marine environment, across scales (from open ocean, onto the continental shelf, and into the coast), and across disciplines (physics, biogeochemistry, and biology and ecosystems).

1.3.2 Ocean observing technologies

It is a complex task to measure the ocean in ways that deliver useful products for people. For example, to deliver a five-day weather forecast for any local region, meteorologists must sample the whole planet. **Satellites** are key tools that provide multispectral images, atmospheric soundings, and sea surface characteristics needed for these forecasts. While satellites enable us to see through the atmosphere, they can only measure the surface of the ocean, and this does not provide the detail needed for accurate weather prediction. Therefore, we also need a complement of in situ measurements that extend our reach to the depths of the oceans at all relevant scales of phenomena. In situ refers to systems that measure on or under the surface of the ocean in continuous and event-driven modes, automatically and by humans.

IMOS is a global leader in ocean observation. It has infrastructures that operate on continental scales, field observing technologies, shares best practices for a broad suite of variables, and generate masses of data. IMOS is partner with IOOS and OTN (this later is a global ocean research and technology development platform, in the area of animal tagging and tracking). To understand animal movements and survival, you also have to understand how the animals respond to changes in environmental conditions. Thus, the animal tracking effort is tightly integrated with the observation of the physical and chemical environment, and all networks depend on common platforms for oceanographic observations. Other observing technologies include Argo, moored buoys, high-frequency radar (HFR), and autonomous underwater vehicles known as gliders.


Argo Floats
Ships of Opportunity
Deep Water Moorings
Ocean Gliders
Autonomous Underwater Vehicles
National Mooring Network
Ocean Radar
Animal Tracking
Wireless Sensor Networks
Satellite Remote Sensing
Marine Microbiome Initiative
New Technology Proving

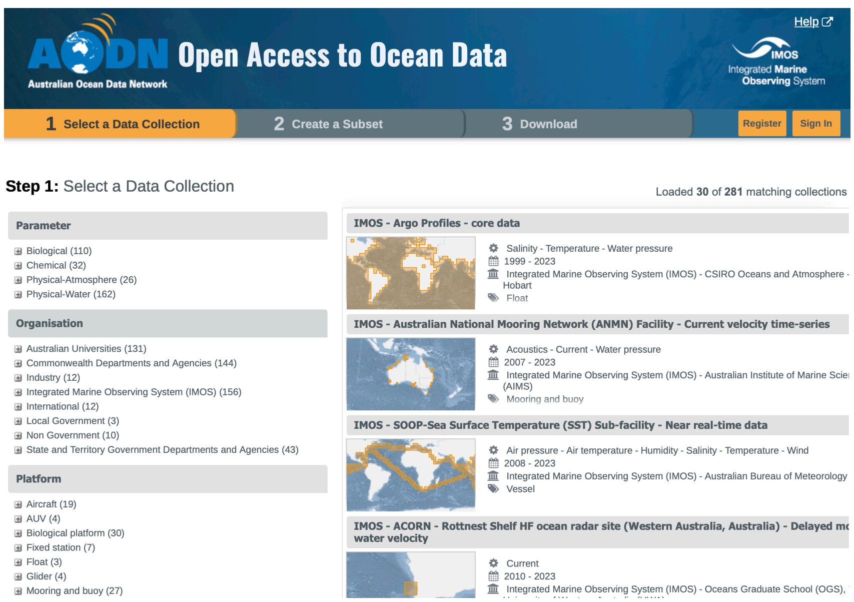
1.4 Access to ocean data

All the national systems that participate in the Global Ocean Observing System (GOOS) and the Group on Earth Observations (GEO) subscribe to the principal of **free and open data**. It is **policy** within Australia that all observational data collected with governmental funding support are made freely and openly available, which makes sense from scientific, disaster response, and economic perspectives.

Important: One challenge IMOS faces is the need to support operational systems, often with unique data formats, while simultaneously working to create mutually compatible data access systems and services, and common data formats and metadata standards, in order to facilitate access to this public resource through the internet.

IMOS provides marine data such as *temperature*, *salinity*, *currents*, *wind speed/direction*, *waves*, and other primarily physical observations for model assimilation through the GTS (Global Telecommunication System). For broader access, IMOS uses three standards to convey the information in an interoperable manner:

- Open-source Project for a Network Data Access Protocol (**OPeNDAP**),
- Sensor Observation Service (**SOS**) and Open Geospatial Consortium (**OGC**) Standard, and
- Web Map Services (**WMS**) OGC Standard.



1.5 Modeling & Analysis

To access the Notebooks exercises using the following link:

launch binder

Prediction of future conditions is critical to deliver the full benefits of an ocean observing system. The Australian ocean and coastal modeling community is a partnership between multiple universities and national organisations (CSIRO, IMOS, GA, BOM to cite a few) that is being asked to provide greater resolution models that cover not only traditional physical water circulation, which remains a critical need, but also expand outputs to include inundation forecasting and ecosystem modeling.

In May 2014, IMOS published the **IMOS Strategy 2015-25**. In this plan, one can read that:

Note: IMOS has a concerted focus on making **data available** and **seeing that it is used**. IMOS has worked with the coastal modeling community to make sure that available data are informing numerical models. Going forward, IMOS will use its infrastructure to be a coordinating entity to advance the assimilation and further development of coastal modeling. IMOS has begun a structured engagement with the coastal and ocean modeling communities through development of joint products (e.g., in ocean reanalysis), national workshops, and targeted infrastructure investment at the model-data interface (such as virtual laboratories).

1.5.1 Hands-on examples

As we just saw, access to quality data is **essential to understand marine processes**.

Over the last 20 years, **ocean data portals** have emerged and are routinely used to better understand the complexity of the ocean and its interactions with climate and life. These portals facilitate seamless access to marine data/services and promote the exchange and dissemination of ocean-related information.

Important: The information that is stored, processed, and exchanged, is at the heart of modern marine science. Ocean scientists routinely perform *data crunching* to understand a particular system and need to *access* and *query* extensive lists of dataset. **Understanding how these data are stored, their origin and how to quickly retrieve particular information from them are crucial skills that you will need in your job!**

Wave height measurements taken every day by a buoy offshore Sydney are data. A graph showing the evolution of the significant wave height over time, at a given place, is information. The fact that the number of extreme storms hitting Australian's coast increases as a result of climate change is knowledge. These three notions are very closely linked.

1.5.2 Exercises for the lecture

Roughly speaking, here is how you should use them:

- A piece of data provides a basic description, typically numerical for our purposes, of a given reality.
- Drawing on the collected data, information is obtained by organising and structuring data so as to derive meaning.
- By understanding the meaning of information, we obtain knowledge.

Note: One of the great challenges for Ocean Data users is to understand **where** and **how** to find technologies that make it possible to evaluate, validate, verify, and rank information to help them in their jobs. This involves understanding how the ocean data providers are organised, the main standards, vocabularies and formats which are used by the community as well as the best approach for accessing and querying these information routinely.

Important: Before starting the exercise, take some times to familiarise yourself with the environment. You will see in the `IntroNotebook` ipython notebook in your main repository a link to an introduction notebook that I highly recommend to do!

After following the video and the introduction notebook, you will open the workspace in **binder** and from the bottom of the `IntroNotebook` notebook you will click on the **Ocean Data Query** link. It will open a folder containing exercises and practicals:

- `OceanData1.ipynb` and `OceanData2.ipynb` are 2 exercises that complement what you learned during this lecture,
- `Oceanforecast.ipynb` and `Waverider.ipynb` are Python notebooks that you will use for your practicals.

Loading and checking IMOS NetCDF dataset

Exercise 1.1

In this first example (`OceanData1.ipynb`), we will work with the IMOS Portal using Python via Jupyter Notebooks. There are several advantages of using Python as a general data analysis language and the notebook environment is a versatile tool that is designed to be interactive, user-friendly, open-source and sharable.

We will see how to load NetCDF data into a Python environment, and show how to use the data once loaded.

Querying and analysis Coastal Ocean Radar dataset

Exercise 1.2

In this second example (`OceanData2.ipynb`), the Australian Coastal Ocean Radar Network (ACORN) facility comprises a coordinated network of HF radars delivering real-time ocean surface velocity data. We will export the dataset file (**NetCDF**) for a given region and then we will plot the velocity field at a given time in a latitude/longitude grid.

1.5.3 Exercises for the Practical

You will run a series of examples that will introduce some aspects of marine data querying.

- Offshore Sydney wave buoy data from Australian Integrated Marine Observing System (IMOS) and
- Different dataset from the Bureau of Meteorology, CSIRO as well as forecast model outputs from NOAA.
- Extract Ocean Radar dataset for Turquoise Bay from IMOS and plot them on a map.

Download the practical documentation from Canvas website and answer the questions using: the `Waverider.ipynb` and `Oceanforecast.ipynb` notebook.

1.6 Summary

Working together, agencies like IMOS or IOOS help to manage our oceans by measuring them and connecting observations to people. Yet, ocean observing systems are only as good as our ability to observe and accurately model ocean systems.

Finding the resources to sustain coastal observations over relevant time scales is a big challenge.

Important: As coastal data users - we need to understand how ocean dataset are obtained, managed and stored. We also need to know how to efficiently load these dataset, query and analyse them.

As a growing population continues to stress our planet, quality observations will increase in importance. But it is not good enough to measure the planet, we also need to work to ensure this information comes into play in our communities, our economies, and in management decisions.

CHAPTER

TWO

ANALYSING WAVE CLIMATE

Overview of this chapter content

Waves are a defining characteristic of water-bodies worldwide, transporting energy that impacts numerous physical and ecological processes. Since World War II, there has been a substantial increase in scientific understanding of wave formation, propagation and resulting impacts on coastal and marine features.

Initial wave studies were restricted to data from voluntary ship observations, which were limited in accuracy and sample size, particularly during extreme conditions. The development of technology such as wave buoys has provided accurate, hourly data of wave height, period and direction. This data enables almost immediate knowledge of the **sea state**, which is the present wave conditions.

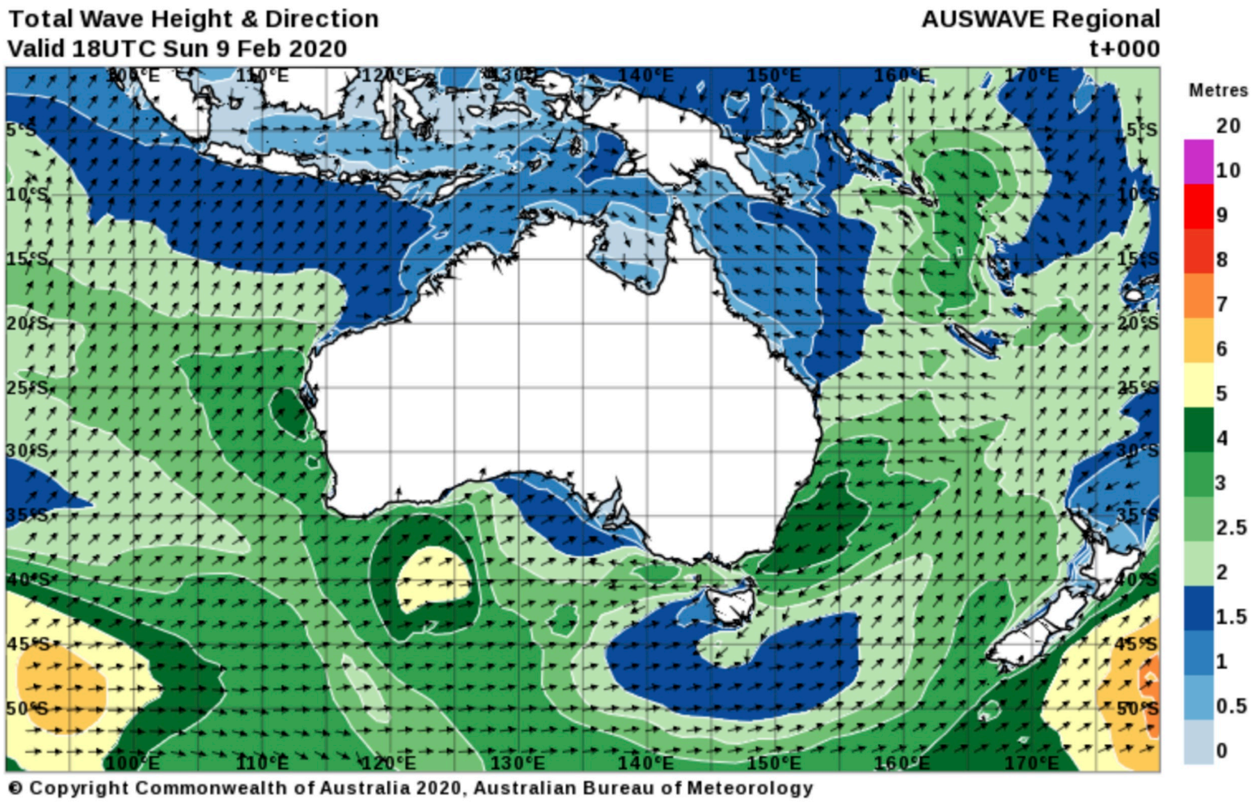
2.1 Wave Climate from the Australian Bureau of Meteorology.

Wave records in Australia

In Australia, waves have been officially recorded since 1974 with the deployment of the first Waverider buoy in Port Kembla, New South Wales (Hemer et al. 2007). This was the start of an increasing network of *buoys*, *High-Frequency radars* and other wave measurement technology leading to significant knowledge of wave dynamics around the Australian coastline. A further technological leap in wave monitoring was achieved in 1985, with the launch of the GEOSAT satellites with a mounted *altimeter*. As a remote sensing technique, altimeters provide wave data observations with unparalleled spatial and temporal resolution (Ribal & Young 2019). Long-term analysis of wave conditions can lead to the characterisation of a wave climate, which is the modal wave conditions of an area (Godoi et al. 2016).

Variation from the modal wave climate can occur due to *extreme events* such as large **storms**, **Tropical Cyclones** (TC) or **tsunamis**. For Australia, it is critical to understand these extreme conditions and to analyse their role in ecological disturbance, as well as to predict present and future vulnerability, particularly with anthropogenic climate change likely to increase the frequency of intense TCs along our coasts.

The wave climate of a region is further impacted by **climate oscillations**, which are semi-regular cyclical changes that have well-defined effects on regional and global weather patterns. These fluctuations typically influence atmospheric temperature, sea surface temperature, wind or precipitation. Oscillations operate on different timescales and can therefore occur together, enhancing or diminishing the effects of each event (Godoi et al. 2019). A key example is the El Nino-Southern Oscillation (**ENSO**), which plays an integral role in climate modulation over the Pacific Ocean and surrounding continents. Both the Australian modal and extreme wave climates can be substantially influenced by these climate oscillations, primarily due to changes in wind patterns and changes to extreme event frequency and intensity.



2.1.1 Wave formation

Ocean waves are formed by different mechanisms and as a result, can have a wide range of properties. In this course, we focus on **ocean surface gravity waves** (henceforth referred to as waves), also known as *wind-generated waves*.

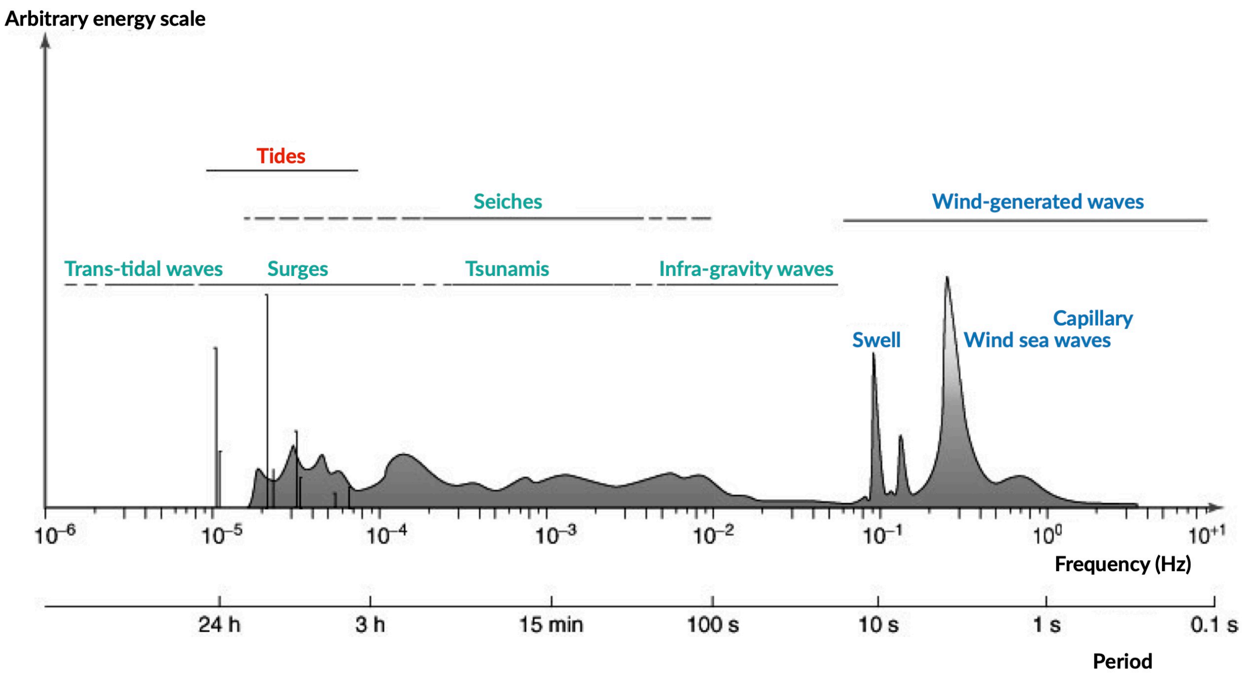
Important: At the atmosphere-ocean interface, kinetic wind energy is transferred to the ocean, which with sufficient wind, generate waves (Holthuijsen 2007). Several factors influence wave formation, including the *strength* and *duration* of the wind, and the *fetch*, the distance over open ocean which the wind blows.

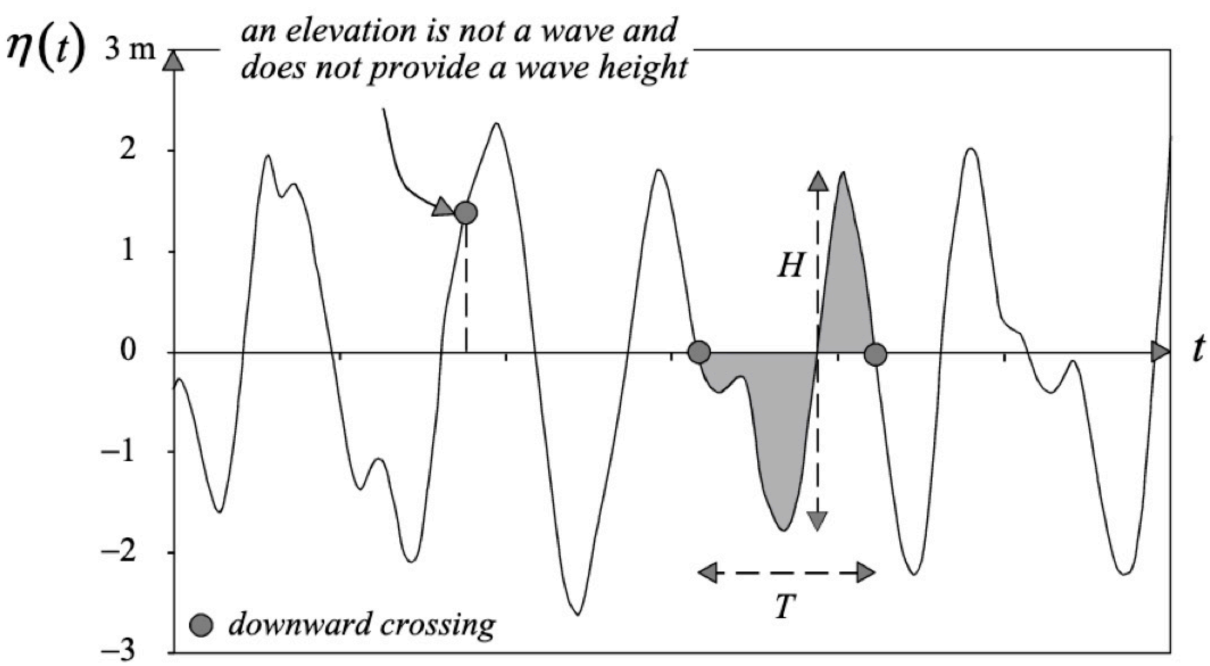
When wind blows over only a short distance, wind-waves are formed. In Australia, these locally-generated waves typically have a short period of **1-8 s**, and travel slower than the prevailing wind. In contrast, swell-waves are generated by distant storms and have propagated out of the wave-generation area. Swell has a longer period of **8-30 s**, and is only minimally influenced by local wind conditions. In many instances, these two wave types occur simultaneously and can travel in opposite directions, creating chaotic seas.

2.1.2 Wave Parameters

Waves can be characterised by parameters such as *wave period*, *height*, *power* and *direction*. Distinctions between different wave classes are based on these measurements and are used to describe both individual waves and the wave climate of a region.

The vertical distance between the maximum and minimum surface elevation over one wave period is referred to as **wave height** (Holthuijsen 2007). To define the overall wave height of many waves, typically the significant wave height is calculated (H_s). Mathematically, H_s is the mean of the highest third of waves in a given sample period (Holthuijsen 2007); traditionally, it is the height a trained observer would see when attempting to estimate average wave height, as humans would not see or consider the smallest waves.


Arbitrary energy scale
Tides
Seiches
Wind-generated waves
Trans-tidal waves
Surges
Tsunamis
Infra-gravity waves
Swell
Capillary
Wind sea waves
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
10⁺¹
Frequency (Hz)
24 h
3 h
15 min
100 s
10 s
1 s
0.1 s
Period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3 m
an elevation is not a wave and
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2
1
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downward crossing

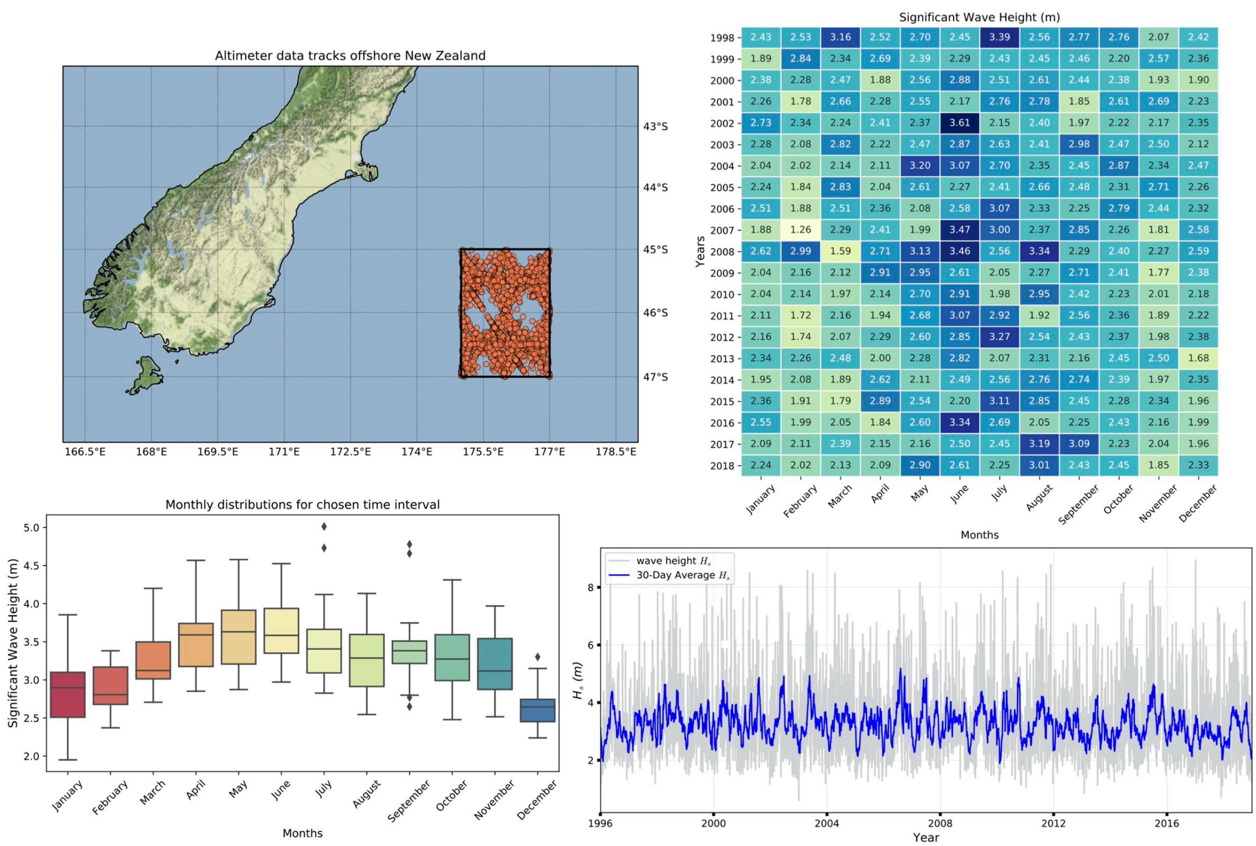
Wave period is the time for one full wavelength to pass a given point, from the beginning to the end of the wave (Holthuijsen 2007). Usually, the zero-crossing period is used (T_z) that measures the time for a wave to go below the mean elevation, rise above, then return to mean elevation.

As waves propagate across the ocean surface, energy is also transferred, referred to as **wave power** (P) or **wave energy flux**. The P of each wave is proportional to the T_z and the square of H_s, with higher values producing more powerful waves (Airy 1841). This parameter is important as it combines both H_s and T_z, providing an overall understanding of the wave conditions and the energy it transports. For example, a wave with a H_s of 1 m and T_z of 5 s will have less power than a wave with an H_s of 1m and T_z of 8 s.

Propagation direction (θ) is the direction from which waves are coming from. In certain regions a particular wave direction can indicate different swell characteristics, for example, large waves from the South-East in Queensland, Australia, indicate strong Southern Ocean swell or Extra-Tropical Cyclone swell, whilst large waves from the north indicate Tropical Cyclone waves.

2.2 Characterising wave climate

The modal wave climate of a region is determined through a long-term analysis of several wave parameters, including H_s, T_z, P and θ.



There are numerous techniques that can be used to measure these parameters. However, most methods do not measure all parameters: a deliberate choice must be made, with consideration to the advantages and disadvantages of each technique. Frequently, the method chosen is customarily calibrated with other techniques or used in combination.

Common methods include:

- wave buoys,
- wave hindcast models and
- satellite altimeters.

2.2.1 Wave buoys

Wave buoy data is routinely considered ground truth, as it is a physical measurement of individual waves instead of remote sensing (Hemer et al. 2007). Buoys also provide the most reliable and accurate records, particularly for extreme values. Despite this, variations in sampling, calibration and computational methods can lead to significant errors by both over and under-estimating wave parameters.

Note: Bender et al. (2010) revealed buoys can overestimate H_s by 26%, and overestimate during hurricane peak by up to 56%, leading to significant and highly misleading errors.

Buoys are also spatially limited, measuring only waves that propagate directly through the site, leading to a restricted understanding of regional wave climates. Furthermore, many locations do not have buoys in operation, thereby inhibiting the analysis of wave climate through buoys alone.

2.2.2 Wave hindcast models

Wave hindcast models use **reanalysed wind fields** to investigate **past** waves. Wind speed and duration are required parameters that are calculated alongside fetch and water depth to determine H_s, T_z and θ. This provides data sets that are used globally to establish wave climate and can evaluate conditions at different temporal and spatial scales.

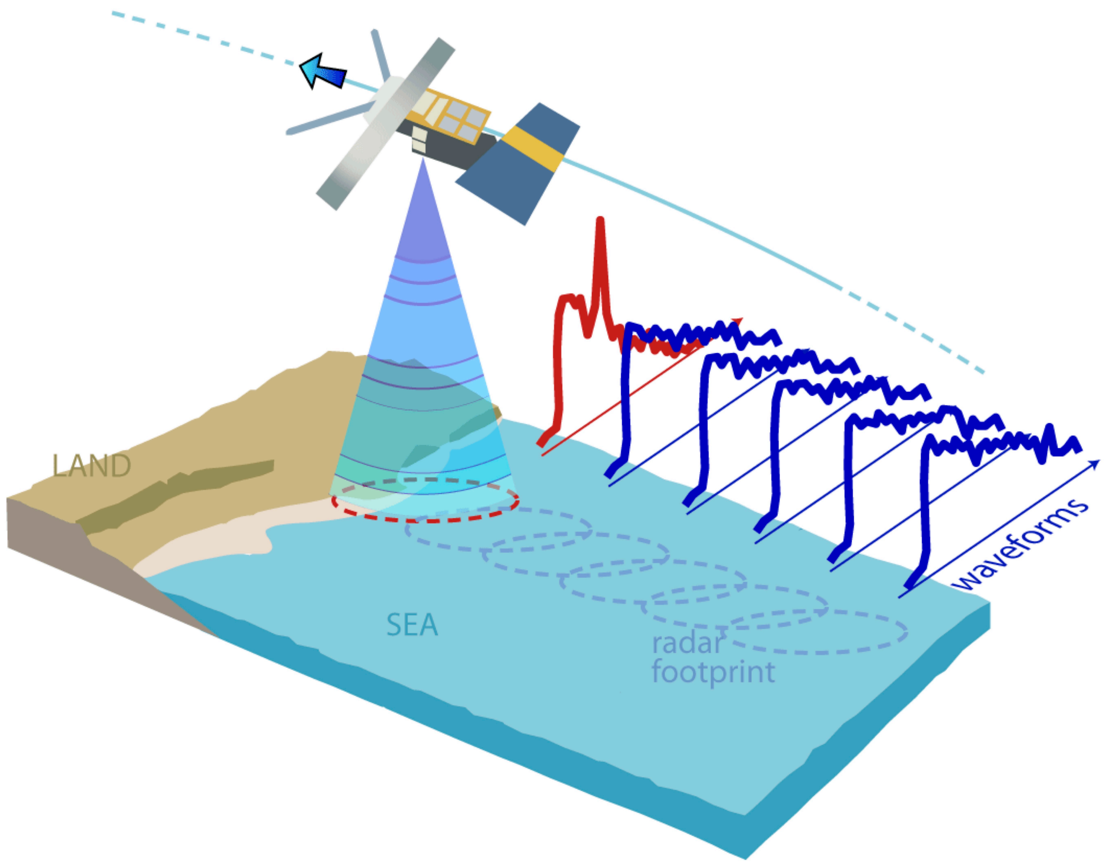
Tip: A widely used wave hindcast is the *National Oceanic and Atmospheric Administration* (NOAA) **WaveWatch III model** (Tolman 2009) as shown in the introduction to this lecture.

However, significant problems can arise through error with forced wind condition. For example, extreme events such as TCs can cause abrupt, localised changes to wind speed and direction. Since models such as **WaveWatch III** have relatively coarse spatial-temporal resolution, insufficient energy from wind is inputted leading to significant underestimation of wave conditions during these extreme events. The accuracy of the hindcast model is also dependent of additional source term parameters and generation, propagation and dissipation equations.

Note: In Australia, this is a significant problem in reef areas, where wave propagation is modified substantially by reefs. With coarse spatial detail, identification and accounting for reefs are reduced, thus leading to potentially incorrect wave conditions in areas sheltered by reefs.

Therefore, whilst wave hindcast models can provide excellent information of wave conditions, particularly in areas where there are no buoys, inherent limitations regarding spatial detail and reliance on source terms means that it is currently unsuitable for wave climate characterisation for reef or areas with complicated bathymetry.

2.2.3 Wave-sensing technology



A remarkable wave-sensing technology with high spatial-temporal density is the radar altimeter, widely established as a pinnacle remote sensing technique to determine wave climates globally (Ribal & Young 2019).

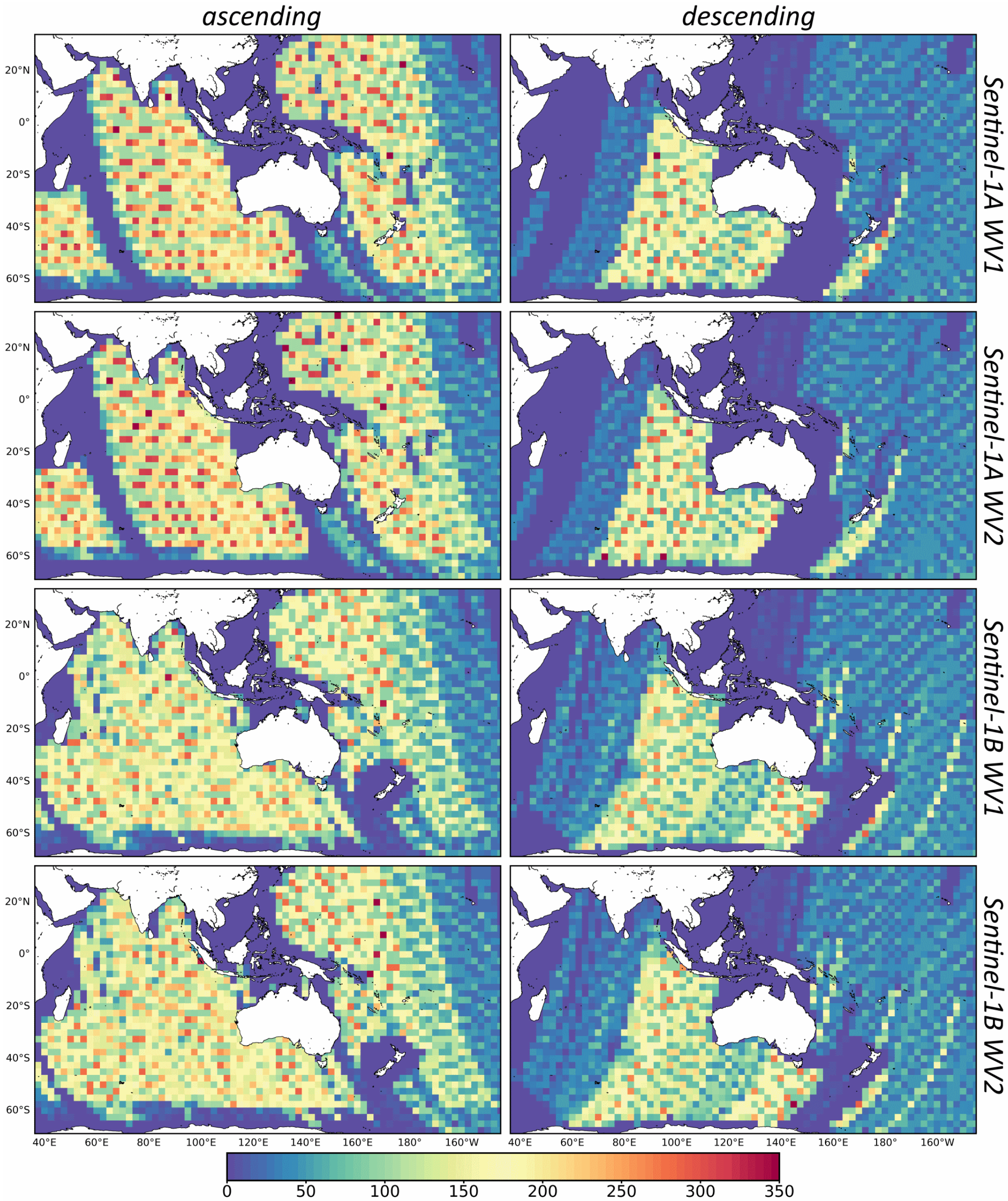
Radar altimeters are mounted on satellites and measure a footprint of the ocean directly under the satellite, between 5-7 km wide. When the water surface is calm and flat, the reflection of the radar pulse back to the altimeter is almost instantaneous. In contrast, when waves are present the pulse is first reflected at the crest of the wave, then progressively reflected as the pulse reaches the wave trough.

Important: The altimeter interprets this signal to determine wave height and wind speed. Therefore, this remote sensing technique **does not provide individual wave statistics**, but rather **returns the average value over the footprint**, up to 7 km wide.

In comparison to a buoy, altimeters provide excellent spatial coverage, with observations along the ground track every second, approximately every 5-7 km. Since the launch of the first altimeter in 1985, (GEOSAT), altimeters have been used to determine wave climate. With the increased number of altimeters in orbit, the global coverage and temporal density are increasing, resulting in a technology highly suited to characterising wave climate, particularly in areas with no buoys, complicated bathymetry and in remote locations.

Example of wave analyse from satellites measurements

Visualising Australian Ocean Surface Wave by extracting information from synthetic aperture radar (**SAR**) satellites with a **Jupyter Notebook**. **Demo in BinderHub**.



Wave period

For waves that have been locally generated by wind, the local wind speed and wave height, both of which are accurately measured by altimeters, can be used to determine T_z. More accurate results are achieved when the *wave age* is calculated first, which is the length of time wind has been acting on a wave.

First, the wave age is calculated through:

$$\epsilon = 3.25 \frac{H_s g}{U_{10}}$$

where H_s is the significant wave height, g the acceleration by gravity and U_{10} the wind speed. Wave age ϵ can then be used to estimate T_z:

$$T_z = (((\epsilon - 5.78)/(\epsilon + (U_{10}/H_s \times (U_{10}/H_s) + H_s))))) + (H_s + 5.70))$$

Wave energy, group velocity & power

Mean wave energy density (E) (J/m^2) is calculated by:

$$E = \frac{1}{8}\rho g H_s^2$$

with ρ the density of seawater (set to 1027 kg/m^3). Wave group velocity (C_g) in deep water conditions is approximated with:

$$C_g = \frac{gT_z}{2\pi}$$

And wave power P can, therefore, be estimated through:

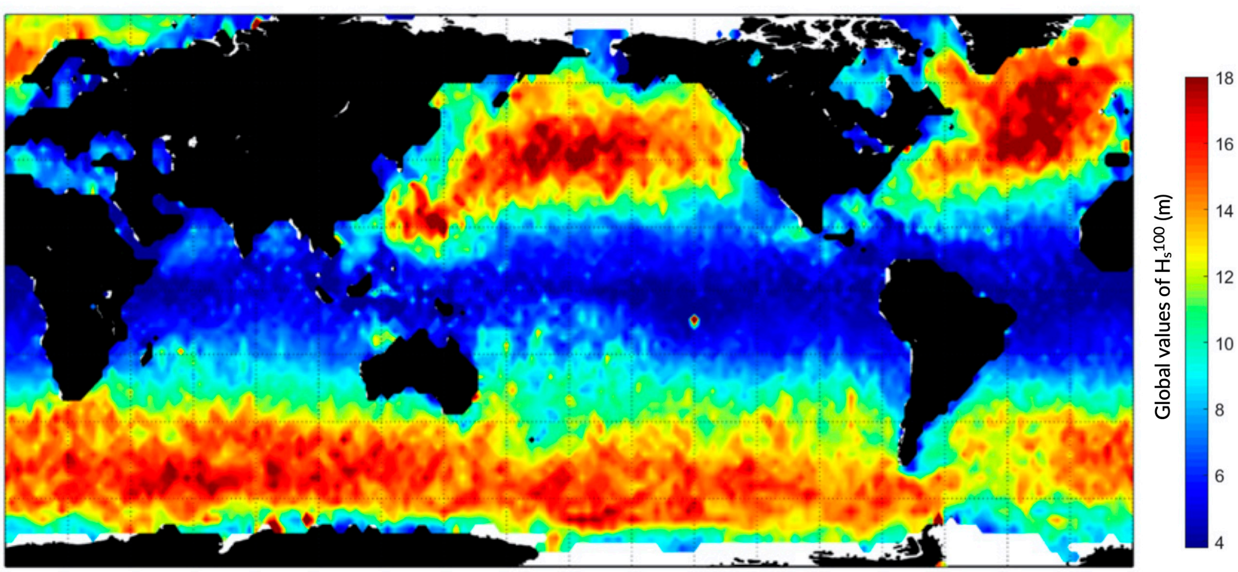
$$P = EC_g$$

which is the wave energy flux per metre of wave-crest (W/m).

2.3 Extreme wave climate

Globally, extreme waves are generated by:

- cyclones,
- tsunamis,
- rogue waves and
- large storms.



Takbash & Young 2019

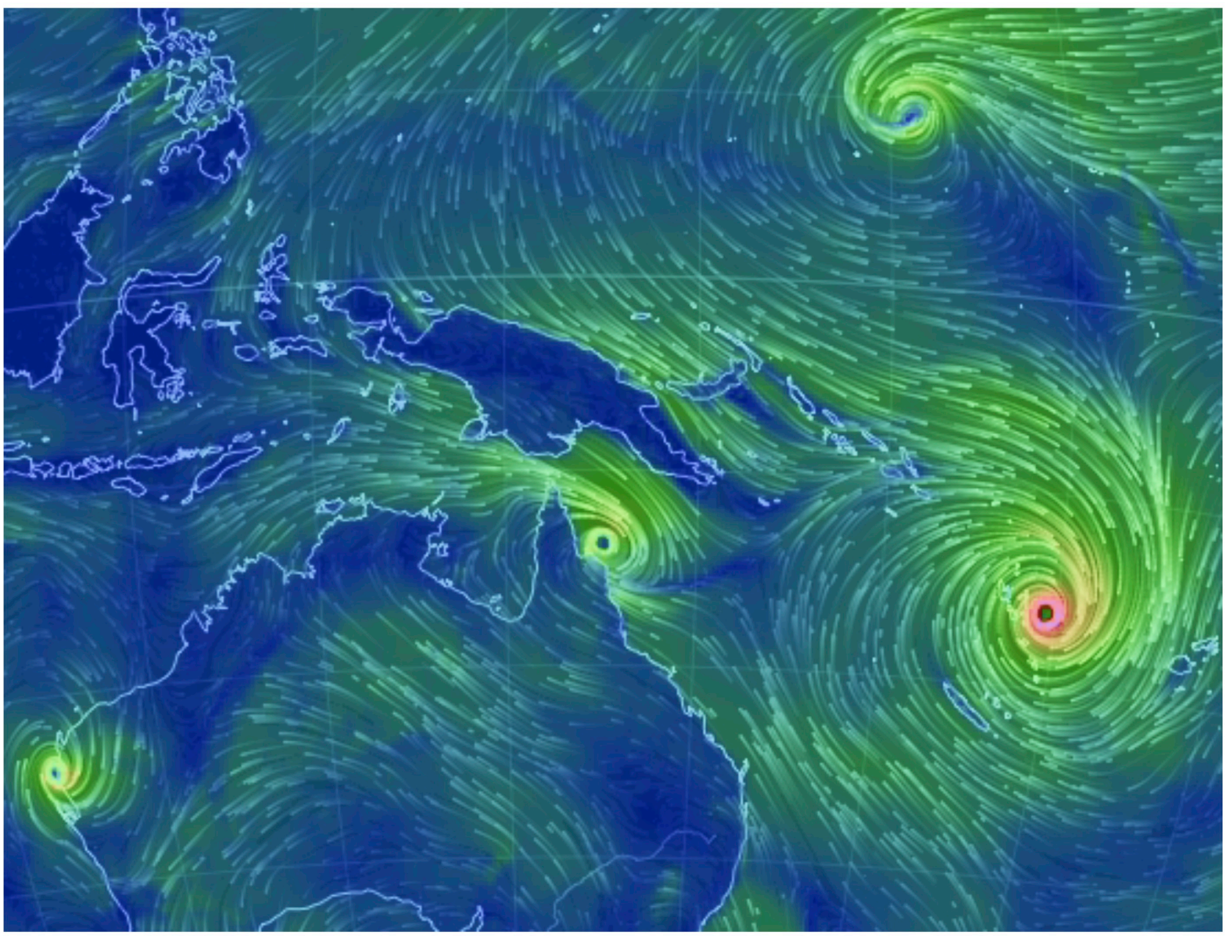
Above figure depicts the estimated 1-in-100 year significant wave height globally, with larger waves predominate in the higher latitudes due to extended fetch and frequent storms, whilst equatorial regions experience smaller extreme waves (Takbash & Young 2019).

Cyclones are a broad category of weather systems that can cause extreme waves, characterised by strong winds around a low pressure centre. TCs are formed over tropical or sub-tropical regions, whilst Extra-Tropical Cyclones form in the mid- or high-latitudes.

Note: **East Coast Lows** (**ECL**) are one such Extra-Tropical Cyclone that is generated near southeastern Australia, from either tropical or mid-latitude controls (Dowdy et al. 2019).

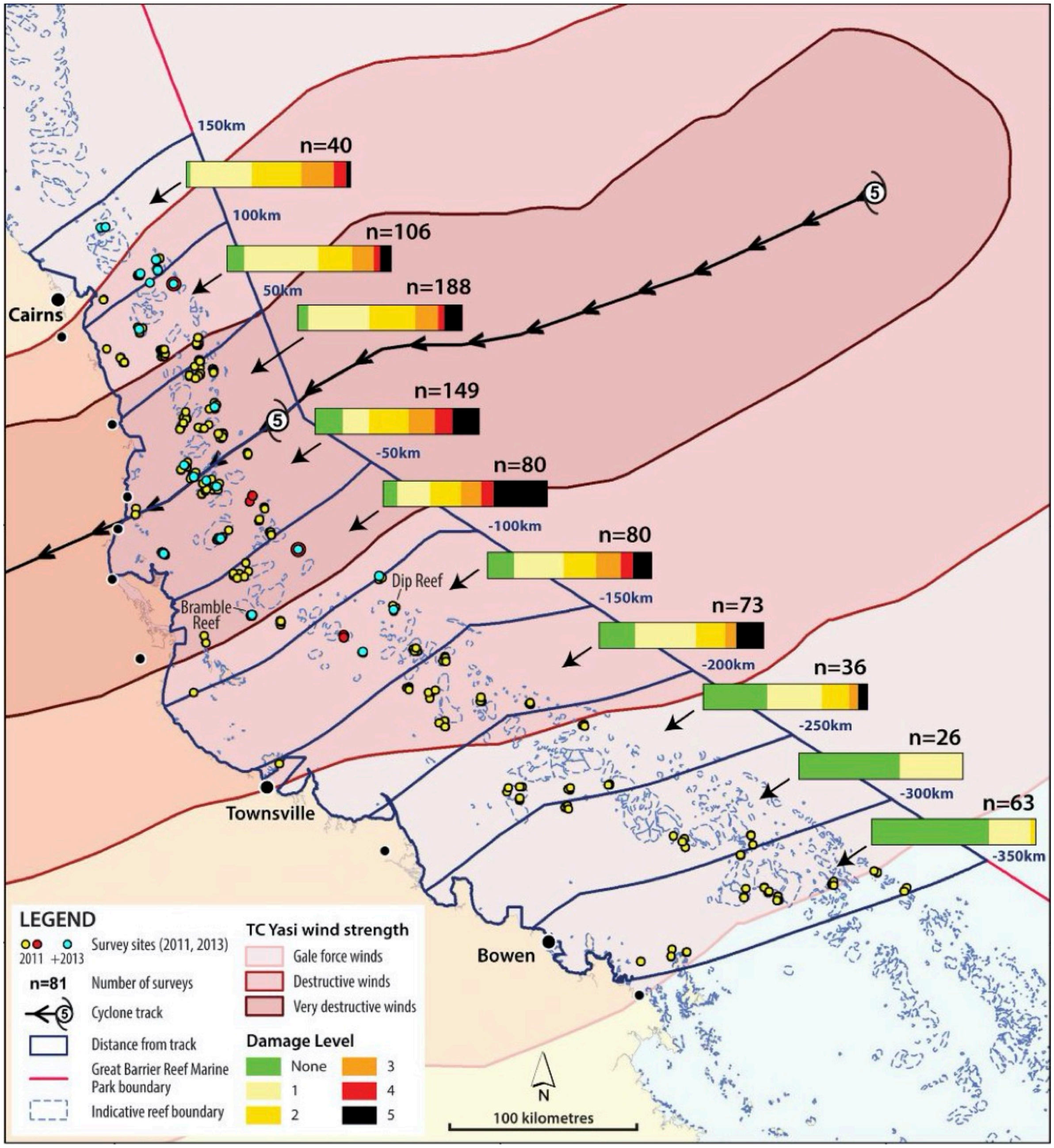
Tropical cyclones (**TC**) are low pressure systems that periodically develop over warm oceans. Sea surface temperature is a key driver of TCs, with a positive temperature anomaly leading to increased intensity and kinetic energy of the TC, as well as enhanced storm surges.

Strong winds and heavy rain can extend hundreds of kilometres from TC centres, and can last from days to weeks. The consequent destructive wind, rainfall, waves and storm surges are highly dangerous, causing extensive risk to life and millions of dollars in property damage. For example, severe TC Justin caused the death of over thirty people due to storm surges and large waves (source: *Bureau of Meteorology*).



TCs are major drivers of coral reef disturbance and destruction, with reefs close to a cyclone experiencing a decrease in hard coral cover, taxonomic richness and coral density that can last for decades. Lagoon flooding, increased sediment load, decrease in local salinity and pH levels are further impacts which negatively affect coral growth and recovery.

Note: Along with severe storms, cyclone waves are key producers of coral rubble. Together with carbonate sand, coral rubble constitutes the majority of reef volume. Over time and subsequent extreme events, the coral rubble progrades and can form rubble spits and islands. Despite the catastrophic nature of these impacts, TC are spatially bound, and thus reefs will typically go a number of years before another major disturbance tracks through the same area.



ECLs are a different type of cyclone that has significant effects on the Eastern Australian coastline. Formed by a temperature gradient between cold air in the upper atmosphere and warm Tasman Sea air, ECLs generate extreme winds, precipitation and large waves (Dowdy et al. 2019). They typically develop in the winter months close to the New South Wales coast, however, impacts can spread to southern Queensland and Victoria. Whilst typically not as severe as TCs, gusts over 170 km/hr and waves of over 14 m have been recorded, resulting in dangerous maritime conditions and coastal destruction.

2.4 Wave climate variability

Seminar on global wind & wave climate by Young et al. (2019)

The broadcasted seminar below investigates: global ocean wind and wave climate and ocean extremes. It describes changes in ocean winds and waves over the last 30 years and projections for future changes out to 2100. It also looks at projections for sea-level rise and the role waves play in determining coastal flooding. The results presented use measurements from a unique dataset of more than 20 satellite missions which have been combined to produce a single long-term global database of wind speed and wave height.

Various meteorologically driven changes in atmosphere-ocean coupling can substantially alter surface wind fields and, as a result, influence wave climate on both regional and ocean basin scales (Godoi et al. 2016).

Many studies have shown that the Pacific Ocean wave climate is altered by the **El Nino Southern Oscillation** (ENSO) and the **Southern Annular Mode** (SAM), however, the response to these can be variable in both space and time. Several regions, including islands in the Pacific, are projected to be more at risk from a changing wave climate than risks from sea level (Hemer et al. 2011). Thus, an understanding of the current variability of the wave climate is an important step to understanding the influence of global climate processes and potential links to climate change (Godoi et al. 2018).

2.4.1 Seasonal changes

Along eastern Australia, the strength of south-east trade winds fluctuate throughout the year and occur predominantly during the austral winter during *April-October* (dry season). From *November-March* (wet season) the trade winds lessen and can even reverse, linked to the Australian Monsoon and the location of the **Intertropical Convergence Zone** (ITCZ) (Hemer et al. 2011). During the wet season, the ITCZ moves closer to Australia, decreasing the strength of trade winds. Periodically, increased strength north-west winds occur due to the presence of the Australian Monsoon. This could have a significant impact on wave climate, with **decreased modal wave heights** during the wet season, however with **small periods of higher waves** due to intense storm and precipitation events during monsoons.

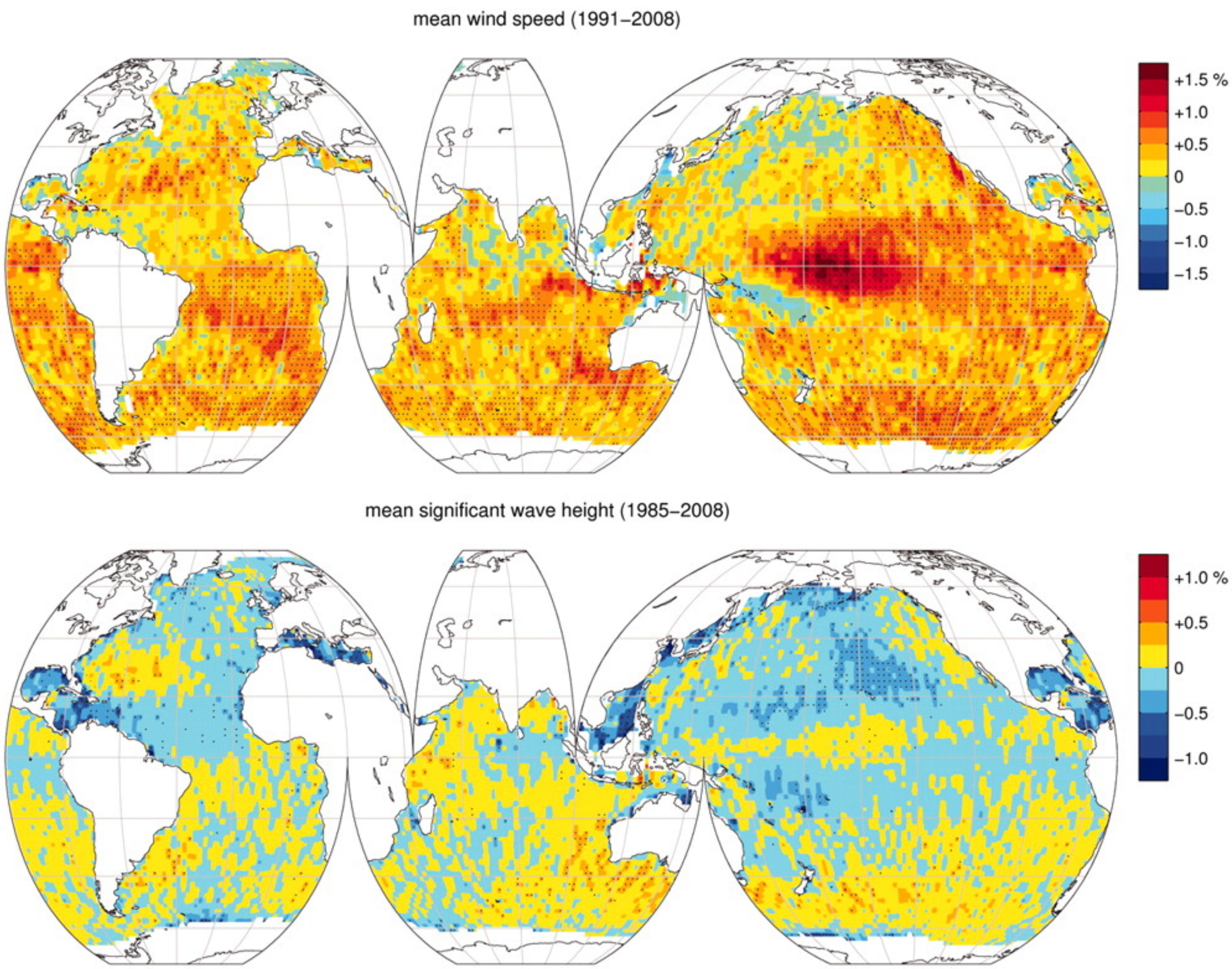
2.4.2 Long-term trends

Several regions of the global ocean have statistically significant positive and negative trends in H_s. An analysis of 33 years of altimeter data by Young & Ribal (2019) (see figure above) determined that extreme 90th percentile waves in the Southern Ocean are increasing by 1 cm/year, and in the North Atlantic by 0.8 cm/year. This is often correlated to an increase in extreme wind strength in the region.

Note: However we can see some differences, as a matter of fact, despite mean local wind speed increasing globally, the mean H_s show less explicit trends in all regions. Several areas, such as the Southern Ocean, have a slight positive increase, whilst other regions have slight negative trends. This implies that upper percentile trends are increasing faster than mean trends.

Many regions, such as Southern Australia, can be dominated by swell rather than local wind sea, and therefore increases in mean local wind speed may not have direct effects on the local wave climate. Instead, increasing wind speed in the higher latitudes may increase swell size, which propagates into the middle latitudes.

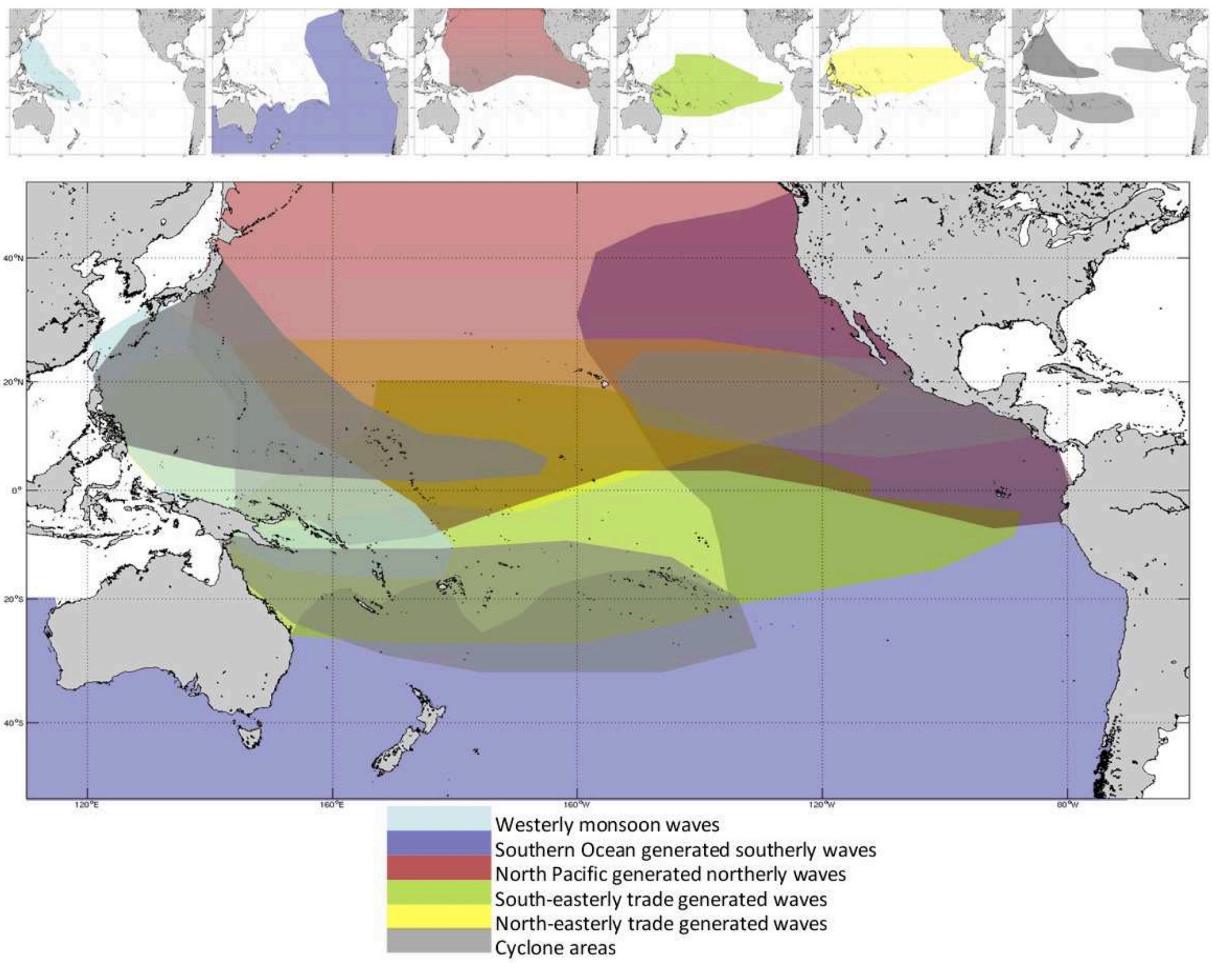
Important: Long-term decadal trends in wave height are occurring at different rates around the globe, with mean and extreme waves exhibiting different behaviours.


mean wind speed (1991–2008)
+1.5 %
+1.0
+0.5
0
−0.5
−1.0
−1.5
mean significant wave height (1985–2008)
+1.0 %
+0.5
0
−0.5
−1.0

2.4.3 Climate oscillations

The **ENSO** phenomenon is the largest and most influential mode of climate variation that operates on a seasonal-to-interannual timescale. It is a complex ocean-air coupling in the equatorial region of the Central and Eastern Pacific Ocean that has significant influence over global climate.

- The positive **La Nina** phase leads to **reduced atmospheric convection** over the Pacific Ocean, causing **increased precipitation**, a **greater number of TCs**, and **cooler maximum temperatures** in Australia. There are stronger than normal trade winds, which could lead to **larger wave heights**.
- In contrast, the negative **El Nino** phase leads to a shift in atmospheric circulation, with a **weakening or reversal of the dominant south-easterly trade winds** and **decreased frequency of TC** for Australia.



Note: There is a substantial connection between the **two ENSO extreme phases** to inter-annual wave height and direction variability (Hemer et al. 2011). This typically results in **atypical coastal erosion** around the Pacific Ocean, with different locations experiencing diverse effects).

For example, the West Coast of the United States experiences an **increase in winter wave energy during El Nino phases**, leading to substantial beach erosion and coastal flooding. The region also experiences a more dominant southerly wave direction during the El Nino phase, which drives abnormal erosion in beaches normally protected from severe swell.

Understanding ENSO

In contrast, the **La Nina phase is linked to higher wave energy on the Eastern Australian coastline and more extreme storms**.

In New Zealand, increased H_s occurs during both of the ENSO extreme phases, resulting in increased coastal and marine operational risk alongside potential changes to biological and physical marine processes.

Note: Climate change is predicted to bring more frequent and extreme ENSO events of both phases, which could lead to atypical wave conditions. Therefore, it is imperative to understand the historical impacts of ENSO on wave climate to predict the future conditions for marine and coastal vulnerability globally.

The **SAM**, also known as the **Antarctic Oscillation**, is the principal mode of variability in the Southern Hemisphere extra-tropics and high latitudes. The SAM controls the north and south movement of the westerly wind belt that circulates Antarctica and is measured by the difference in zonal mean sea level pressure between 40S and 65S. SAM phases can significantly influence wave height and directional variability, influencing the entire Pacific Ocean.

- During the **positive phase**, the wind belt contracts towards Antarctica and is often **correlated to stable, dry conditions in Australia**.
- In the negative phase, the belt expands north and can lead to **increased storm frequency and precipitation in Australia and New Zealand** Godoi et al. 2016).

Understanding the Southern Annular Mode (SAM)

Thus, climate oscillations can significantly modulate the wave climate around the globe, leading to diverse effects in different regions. Oscillations can also enhance or detract the effects of other oscillations, leading to complex interactions and influence on both atmospheric and wave climate.

2.5 Modeling & Analysis

To access the Notebooks exercises using the following link:

launch binder

2.5.1 Hands-on examples

As we discussed, satellite radar altimeters can be used to determine significant wave height and wind speed. Analysis of past records bring new insights into inter-annual, seasonal and decadal variations of regional wave climates.

For this part of the course and to illustrate what we've seen today, we will use **RADWave** a Python package that provides a mechanism to access altimeter datasets through web-enabled data services (**THREDDS**).

We will work with the Australian Ocean Data Network database that spans from 1985-present and that has already been calibrated and validated.

With this tool we will query a range of spatial and temporal scales altimeter parameters in specific geographical regions and calculate:

- significant wave heights,
- periods,
- group velocities,
- average wave energy densities and
- wave energy fluxes.

Using **Jupyter Notebooks** as last week, you will:

- Extract data from different regions along Australia and evaluate wave modal conditions and seasonal changes in climate variability. Then calculate long-term trends and associated modulation by large-scale climate oscillations.
- Estimate the wave heights along Tropical Cyclone tracks.

2.5.2 Exercises for the Practical

Long-term observational data sets of beach profile variability and underlying trends that have been measured regularly and uninterrupted for several decades are very rare. Only a few sites around the world have sustained routine decadal-scale monitoring of the coastline, with notable examples that include the US Army Corps of Engineers Field Research Facility in the United States, the Hazaki Oceanographical Research Station in Japan, and Narrabeen-Collaroy Beach in Australia (http://www.narrabeen.wrl.unsw.edu.au).

Note: These unique data sets are critical for understanding how beaches respond to processes over a range of time scales, including storms that last hours to days, inter-annual climatic cycles such as the El Niño-Southern Oscillation (ENSO), and longer-term processes such as mean sea level rise. This type of knowledge is essential for predictive modelling and for making appropriate coastal management and planning decisions.

The purpose of this practical is to utilise online resource of beach profile data from Narrabeen-Collaroy Beach in New South Wales, Australia, to assess how the subaerial beach and the shoreline position vary (1) **spatially due to alongshore-variable wave conditions**, and (2) **over multiple time scales in response to changing wave conditions and climate cycles**.

CHAPTER

THREE

QUANTIFYING COASTAL CHANGES

Chapter content

In this chapter, you will investigate nearshore to beach processes from wave run-up to beach profiles. You will also look at different numerical approaches to analyse shoreline changes.

3.1 Context

Small changes in the magnitude or direction of storm waves have the ability to profoundly disturb our coastlines by modifying beach stability and enhancing coastal erosion.

The coastal region is the most heavily urbanised land zone in the world and is regarded as a critical resource in view of its recreational, environmental and economic importance.

Note: Ocean coasts are affected by variations in mean sea level, extreme waves, storm surges and river flow through a range of physical processes. Recent intensification in mean wave energy, extreme coastal wave energy and oceanic wind speeds, coupled with rising sea levels, suggest that coastal areas will be exposed to increasing hazards in coming decades. It is therefore critical to observe and quantify changes along coastlines vulnerable to extreme as well as subtle changes in oceanographic forcing.

3.2 Nearshore and beach processes

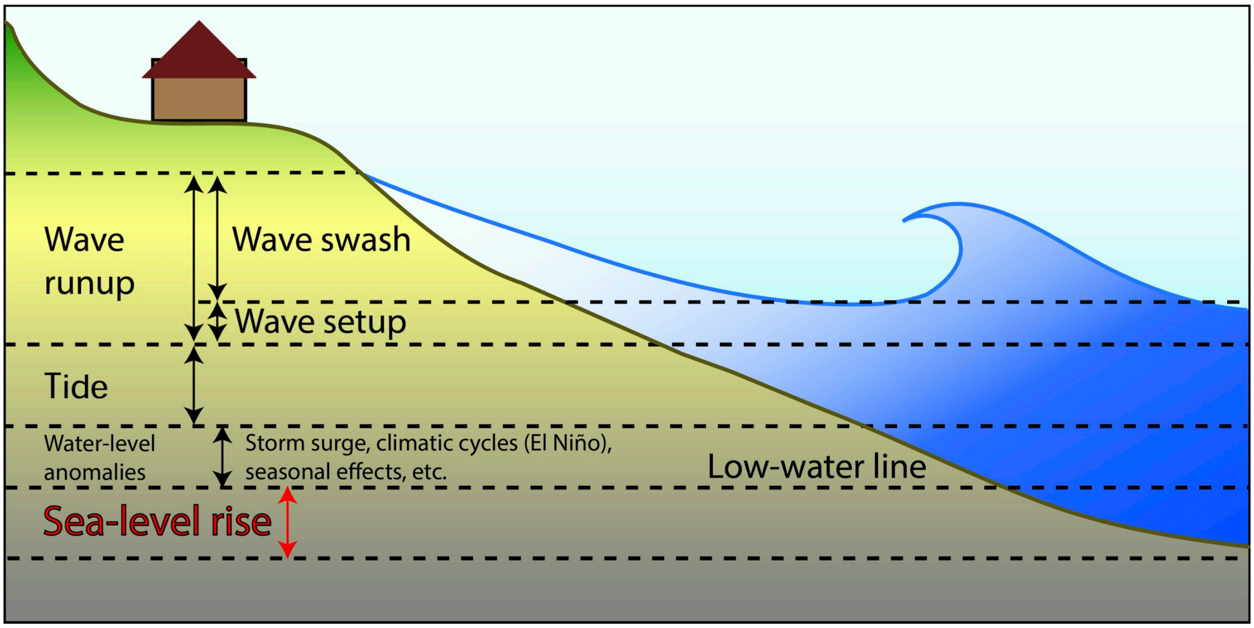
In this video, we will first look at the mechanisms that influences nearshore environments especially we will discuss the different temporal and spatial scales involved. Then, we will analyse which processes become dominant as waves propagate from offshore towards the coast. Finally, we will have a quick introduction to the existing models that can be used to simulate these processes.

3.2.1 Wave runup

Wave runup refers to the final part of a wave's journey as it travels from offshore onto the beach. It is observable by anyone who goes to the beach and watches the edge of the water *runup* and *rundown* the beach. It is comprised of two components:

- **setup**: the height of the time averaged superelevation of the mean water level above the Still Water Level (**SWL**)
- **swash**: the height of the time varying fluctuation of the instantaneous water level about the setup elevation

Setup, swash and other components of Total Water Level (**TWL**) rise are shown in this handy figure below from Vitousek et al. (2017).



Wave runup can contribute a significant portion of the increase in TWL in coastal storms causing erosion and inundation. For example, Stockdon et al. (2006) collated data from numerous experiments, some of which showed wave runup 2% excedence heights in excess of 3 m during some storms.

Given the impact such a large increase in TWL can have on coastlines, there has been much research conducted to try improve our understanding of wave runup processes.

Note: Although there are many processes which can influence wave runup (such as nonlinear wave transformation, wave reflection, three-dimensional effects, porosity, roughness, permeability and groundwater), **many attempts have been made to derive empirical relationships based on easily measurable parameters**.

Typically, empirical wave runup models include:

- H_s: significant wave height
- T_p: peak wave length
- β: beach slope

The **py-wave-runup** (here) is a Python package that implements different published wave runup empirical models based on H_s, T_p, and β.

Wave runup models from the py-wave-runup model

Using **py-wave-runup** , we will evaluate the accuracy of the Stockdon et al. (2006) runup model. To do this, we will use the compiled wave runup observations provided by Power et al (2018).

The Stockdon et al. (2006) wave runup model comprises of two relationships, one for dissipative beaches (*i.e.* Iribarren number $\zeta < 0.3$):

$$R_2 = 0.043(H_s L_p)^{0.5}$$

and a seperate relationship for intermediate and reflective beaches (*i.e.* Iribarren number $\zeta > 0.3$):

$$R_2 = 1.1 \left(0.35\beta(H_s L_p)^{0.5} + \frac{H_s L_p(0.563\beta^2 + 0.004)^{0.5}}{2} \right)$$

Exercise

Open the **BinderHub** link in the menubar to assess 2 runup models and evaluate wave runup observations against the Iribarren number with the above link.

3.2.2 Beach profiles

Sandy coastlines typically comprise two key parts: a **beach** and **dune**.

Note: The **beach** is the section of sandy coast that is *mostly above water* (depending upon tide) and actively influenced by *waves*, while **dunes** are elevated mounds/ridges of sand at the *back of the beach*.

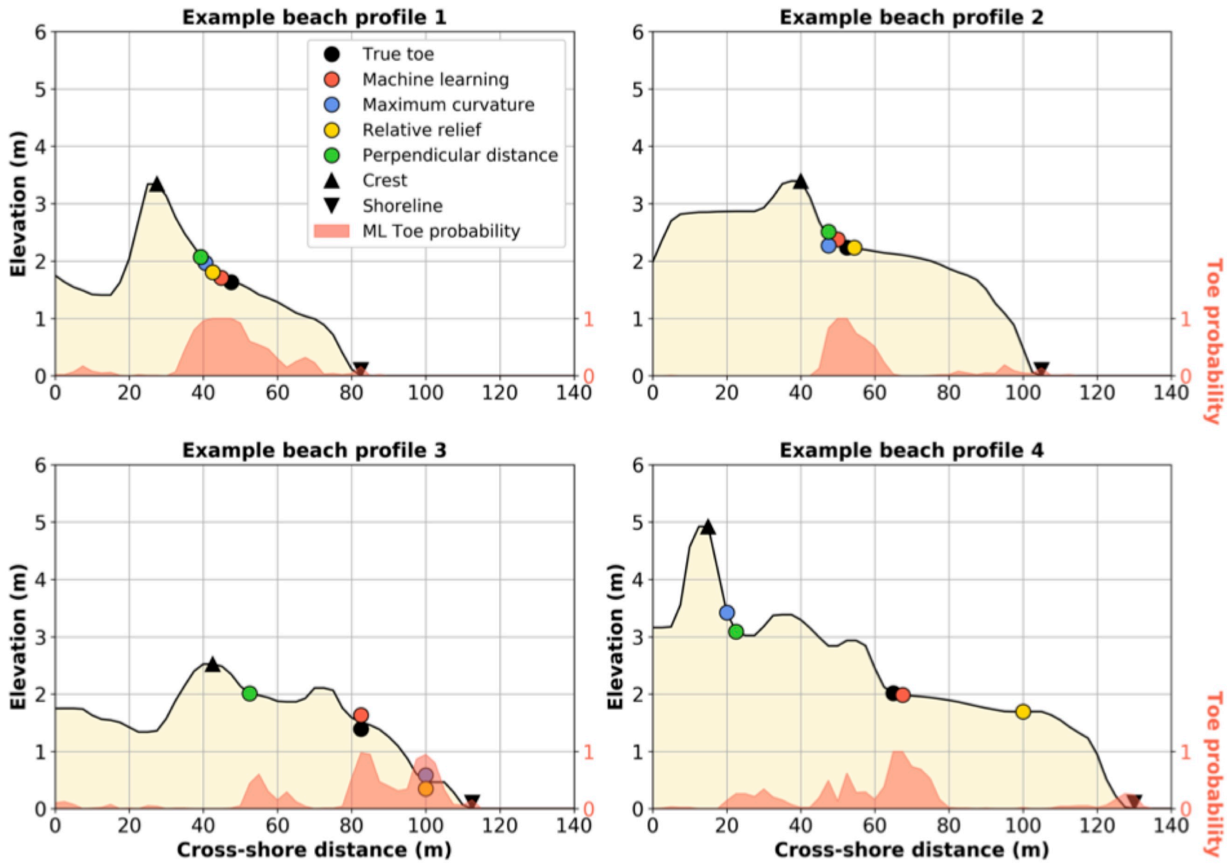
The interface between the beach and dune is often *characterised by a distinct change in ground slope* (with the dune having a steeper slope than the beach). Dunes are particularly important along sandy coastlines because they provide a natural barrier to coastal hazards such as storm-induced waves and surge. The capacity of sandy dunes to provide coastal hazard protection depends in large part on their geometry.

Important: The location of the **dune toe** (the transition point between the beach and dune) is a key factor used in coastal erosion models and for assessing coastal vulnerability to hazards (Sallenger, 2000).

Domain experts are generally able to identify the location of the dune toe given a 2D beach profile. However, recent improvements in coastal monitoring technologies (such as optical, Lidar, and satellite remote sensing), have resulted in a significant increase in coastal topographic data, for which analysis by an expert is infeasible. As a result, there has been increased need for reliable and efficient algorithms for extracting important features such as dune toes from these large coastal datasets.

There are many different algorithms currently available for automatically detecting the dune toe on 2D cross-shore beach profiles:

1. **Maximum curvature** (Stockdon et al., 2007) - the dune toe is defined as the location of maximum slope change;
2. **Relative relief** (Wernette et al. 2016) - the dune toe is defined based on relative relief (the ratio of local morphology to computational scale);
3. **Perpendicular distance** - the dune toe is defined as the point of maximum perpendicular distance from the straight line drawn between the dune crest and shoreline; and,


Example beach profile 1
Example beach profile 2
Example beach profile 3
Example beach profile 4
True toe
Machine learning
Maximum curvature
Relative relief
Perpendicular distance
Crest
Shoreline
ML Toe probability
Elevation (m)
Toe probability
Cross-shore distance (m)
0
20
40
60
80
100
120
140
0
1
2
3
4
5
6

4. **Machine learning** (ML) using Random Forest classification.

Locating the dune toe using Machine Learning

As shown in the figure above using **pybeach** code from Beuzen the performance of these algorithms in extracting dune toe locations on beach profiles varies significantly. While experts can generally identify the dune toe on a beach profile, it is difficult to develop an algorithm that can consistently and reliably define the dune toe for the large variety of beach profile shapes encountered in nature.

In such cases, the use of machine learning (ML) can help improving toe detection. It consists in *feeding* the ML algorithm with existing dataset. In **pybeach** three pre-trained ML models are provided:

1. a **barrier-island** model. This model was developed using 1046 pre- and post- "Hurricane Ivan" airborne LIDAR profiles from Santa-Rosa Island Florida (this data was collected in 2004);
2. a **wave-embayed** model. This model was developed using 1768 pre- and post- "June 2016 storm" airborne LIDAR profiles from the wave-dominated, embayed southeast Australian coastline (this data was collected in 2016).
3. a **mixed** model. Developed using a combination of the two above datasets.

For each dataset described above, the true location of the dune toe on each individual profile transect was manually identified and quality checked by multiple experts and verified using satellite imagery, digital elevation models and/or in-situ observations where available. This resulted in the best possible data to facilitate the creation of the ML models in **pybeach**.

Within **BinderHub**, you could have a look at how **pybeach** could be used to locate the dune toe on cross-shore beach profile transects.

3.3 Coastline evolution

3.3.1 Longshore drift

Longshore drift is induced by longshore current and transport sediments (clay, silt, pebbles, sand and shingle) along coastlines parallel to the shoreline and depends on oblique incoming wave direction.

Oblique incoming waves push water along the coast, and generate a water current which moves parallel to the coast. Longshore drift is the sediment movement associated with this longshore current. This sediment movement occurs within the surf zone.

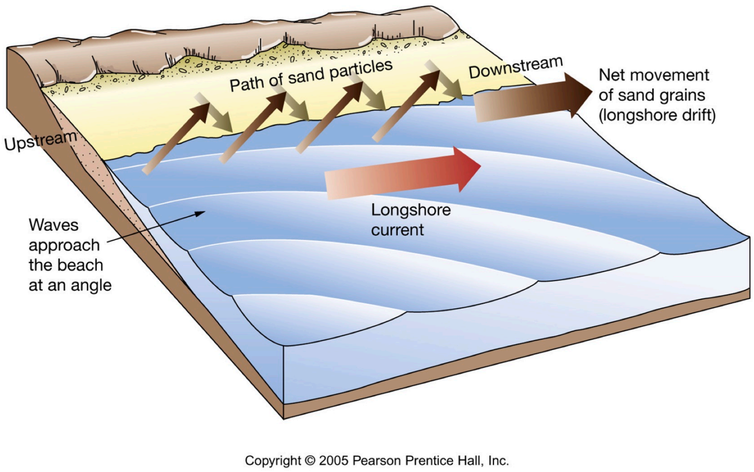
One-line model

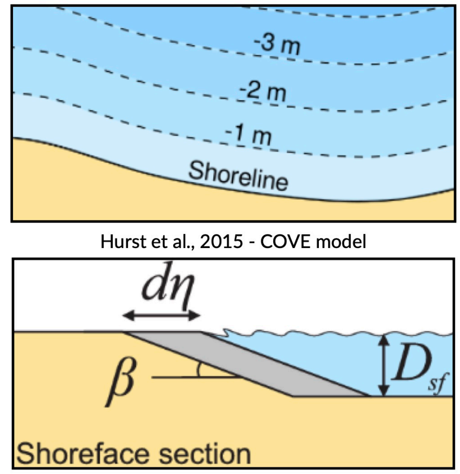
This video explains how longshore drift is simulated using 1-line model.

As we have seen in the previous video, one-line models of shoreline evolution can reproduce embayed beach morphology in the lee of a headland or promontory. They are based on simple rules to describe the adjustment in wave height and direction due to diffraction in the shadow of a promontory and demonstrated that the resulting bay forms were similar in form to a logarithmic spiral.

In one-line models, the shoreline is represented by a single line (or contour) that advances or retreats depending on the net alongshore sediment flux. One-line models make a number of simplifying assumptions to conceptualise the coastline allowing the 'one-line' representation of the coastline:

1. Short-term cross-shore variations due to storms or rip currents are considered temporary perturbations to the long-term trajectory of coastal change (i.e. the shoreface recovers rapidly from storm-driven cross-shore transport).





2. The beach profile is thus assumed to maintain a constant time-averaged form, implying that depth contours are shore-parallel and therefore allows the coast to be represented by a single contour line (right panels in top figure).
3. Alongshore sediment transport occurs primarily in the surf zone, and cross-shore sediment transport acts to maintain the equilibrium shoreface as it advances /retreats.
4. Alongshore sediment flux occurs due to wave action in the surf zone, parameterized by the height and angle of incidence of breaking waves. Gradients in alongshore transport dictate whether the shoreline advances or retreats.

Bulk alongshore sediment flux is driven by waves breaking on the shoreface. Typically in alongshore transport laws, flux depends on the height H_b and angle α_b of breaking waves. For example, the **CERC equation** is given by:

$$Q_{ls} = K_{ls} H_b^{5/2} sin(2\alpha_b)$$

where K_{ls} is a transport coefficient. The transport coefficient K_{ls} may be modified to account for the size of beach material (D_{50}). Calibration of this coefficient can be made from estimates of bulk alongshore transport or by calibration against a historical record of coastal change (*e.g.* Barkwith et al. (2014)).

3.3.2 Analysing shoreline changes

Space-borne observations have been employed in a wide range of change detection applications, including the analysis of meandering river morphodynamics, delineation of wetland footprints and identification of oil spills.

Recently, optical imaging satellites have begun to be used to measure the location of the shoreline, which is regarded by coastal managers, planners, engineers and scientists as a key indicator of how coastlines vary and evolve over time.

Nowadays, it is possible to use image composites from satellites to map the position of the shoreline with a horizontal accuracy of the order of half a pixel (i.e., **15 m** for Landsat images and **5 m** for Sentinel-2 images). Some studies have even managed to detect shoreline at a sub-pixel resolution technique in low-energy microtidal beach and reported horizontal accuracies of less than 10 m using Landsat 7, Landsat 8 and Sentinel-2 images.

Important: Satellite remote sensing can provide low-cost long-term shoreline data capable of analysing multi-decadal temporal changes relevant to coastal scientists and engineers at sites where no in-situ field measurements are available.

CoastSat is an example of such open-source package developed at the Water Research Laboratory in Manly that can be used to obtain time-series of shoreline position at any coastline worldwide from 30+ years (and growing) of publicly available satellite imagery.

It enables the non-expert user to extract shorelines from Landsat 5, Landsat 7, Landsat 8 and Sentinel-2 images. The shoreline detection algorithm implemented in **CoastSat** is optimised for sandy beach coastlines. It combines a sub-pixel border segmentation and an image classification component, which refines the segmentation into four distinct categories such that the shoreline detection is specific to the sand/water interface.

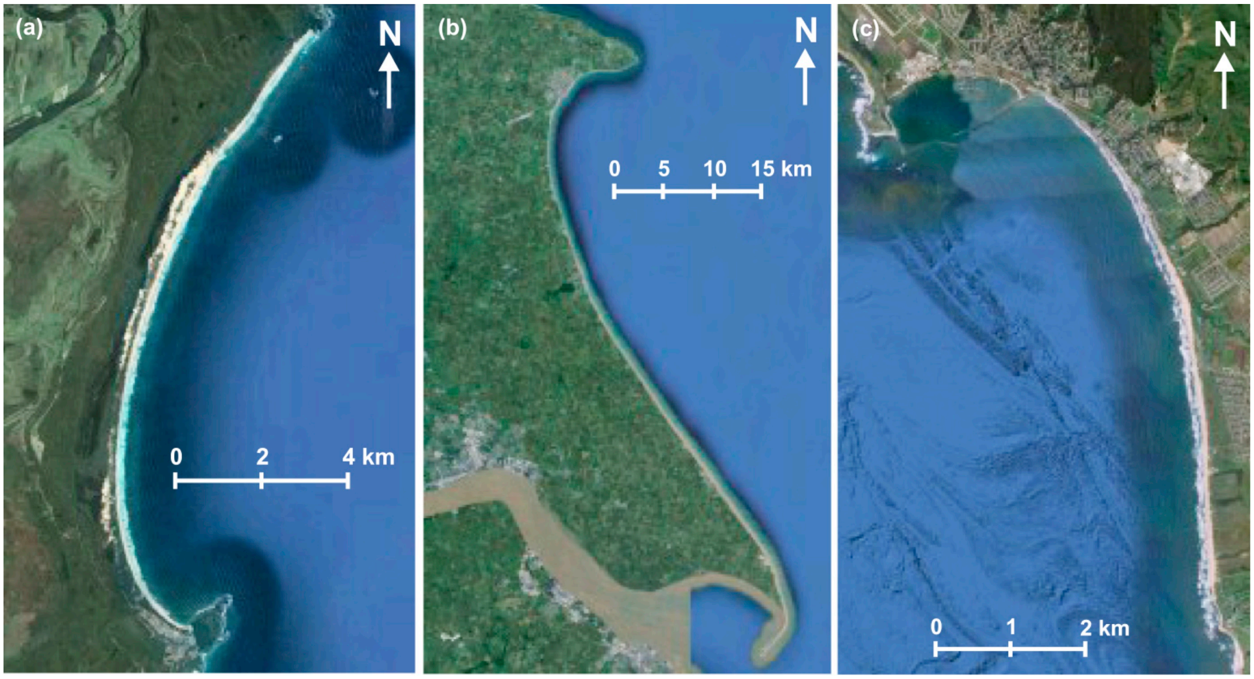
The toolbox has three main functionalities:

1. assisted retrieval from Google Earth Engine of all available satellite images spanning the user-defined region of interest and time period.
2. automated extraction of shorelines from all the selected images using a sub-pixel resolution technique
3. intersection of the 2D shorelines with user-defined shore-normal transects

3.3.3 Embayed beaches

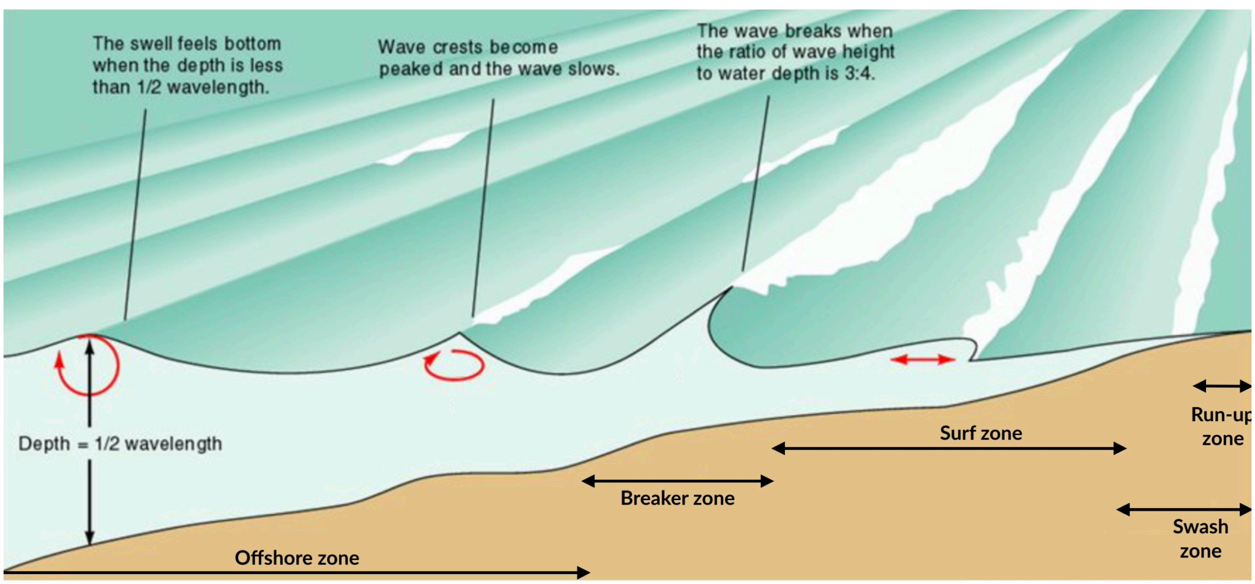
The curved planform morphology of embayed beaches can be observed at various length-scales at coastlines, from a few hundred meters to several kilometers. These bays occur in the lee of headlands or man-made coastal structures where erosion and/or littoral drift is inhibited in the face of a dominant direction of wave incidence (Hurst et al., 2015). A highly concave portion of shoreline forms on the down-drift side of the headland where the coastline is shadowed from the dominant wave direction and subject to waves that diffract around the headland.

Note: Embayed beaches tend toward an equilibrium form under a prevailing wave climate. The planform morphology will adjust until gradients in alongshore sediment flux are minimised (net alongshore sediment flux is constant). Alongshore sediment flux will be negligible on an equilibrium coastline when there are no external sediment inputs. Subsequent changes in planform morphology may occur such as beach rotation, driven by changes in wave climate characteristics that alter alongshore sediment transport.



3.4 Regional scale models

Many complex models exist to evaluate the complex interactions between ocean hydrodynamics and sediment transport like XBeach, ROMS, Delft3d, FVCOM, CEM to cite a few.



As an example, the nearshore wave propagation model XBeach solves coupled 2D horizontal equations for wave propagation, flow, sediment transport and bottom changes, for varying (spectral) wave and flow boundary conditions. It is a public-domain model that can be used as stand-alone model for small-scale (project-scale) coastal applications, but could also be integrated within more complex coupling frameworks. For example, it could be driven by boundary conditions provided by wind, wave or surge models and its main outputs (time-varying bathymetry and possibly discharges over breached barrier island sections) could be then transferred back.

Now, we will look at a more simple approach based on a **reduced complexity model** that adopts the most basic known principles of wave motion, *i.e.*, the linear wave theory (Airy derived wave parameters description). Wave celerity c is governed by:

$$c = \sqrt{\frac{g}{\kappa} tanh\, \kappa d}$$

where g is the gravitational acceleration, κ the radian wave number (equal to $2\pi/L$, with L the wave length), and d is the water depth.

In deep water, the celerity is dependent only on wave length $\sqrt{gL/2\pi}$; in shallow water, it depends on depth ($\sqrt{gd}$).

From wave celerity and wave length, we calculate wave front propagation (including refraction) based on a **Huygens-principle** method.

Wave diffraction & refraction

From this, we deduce the wave travel time and define main wave-induced current directions from lines perpendicular to the wave front. Wave height is then calculated along wave front propagation. The algorithm takes into account wave energy dissipation in shallow environment as well as wave-breaking conditions.

As mentioned above, shoaling and refraction are accounted for from a series of deep-water wave conditions through time in the absence of wind forcing. Hence to compute wave field generation, the model requires **bathymetric conditions** and definitions of offshore significant **wave height**, characteristic **period**, and wave **direction**.

Note: To evaluate marine sediment transport over several thousands of years, the approach taken here does not examine temporal evolving wave fields, such as those produced during storm events and relies on stationary representation of prevailing fair-weather wave conditions. The wave transformation model is generally performed for time intervals varying from 5 to 50 years.

The model simulates realistic wave fields by imposing a sequence of wave forcing conditions. At any given time interval, we define a percentage of activity for each deep-water wave conditions and the bathymetry is used to compute associated wave parameters.

To simulate wave-induced sediment transport, it is necessary to model the **water movement near the bottom**. The wave height H and the wave period T govern the maximum wave-orbital speed $u_{w,b}$ at the bed at any given depth and is expressed using the **linear wave theory** as:

$$u_{w,b} = \frac{\pi H}{T sinh \kappa d}$$

assuming the linear shallow water approximation (Soulsby), the expression is further simplified as:

$$u_{w,b} = (H/2)\sqrt{g/d}$$

Under pure waves (*i.e.*, no superimposed current), the wave-induced bed shear stress τ_w is typically defined as a quadratic bottom friction:

$$\tau_w = \frac{1}{2}\rho f_w u_{w,b}^2$$

with rho the water density and f_w is the wave friction factor. Considering that the wave friction factor is only dependent of the bed roughness k_b relative to the wave-orbital semi-excursion at the bed A_b (Soulsby), we define:

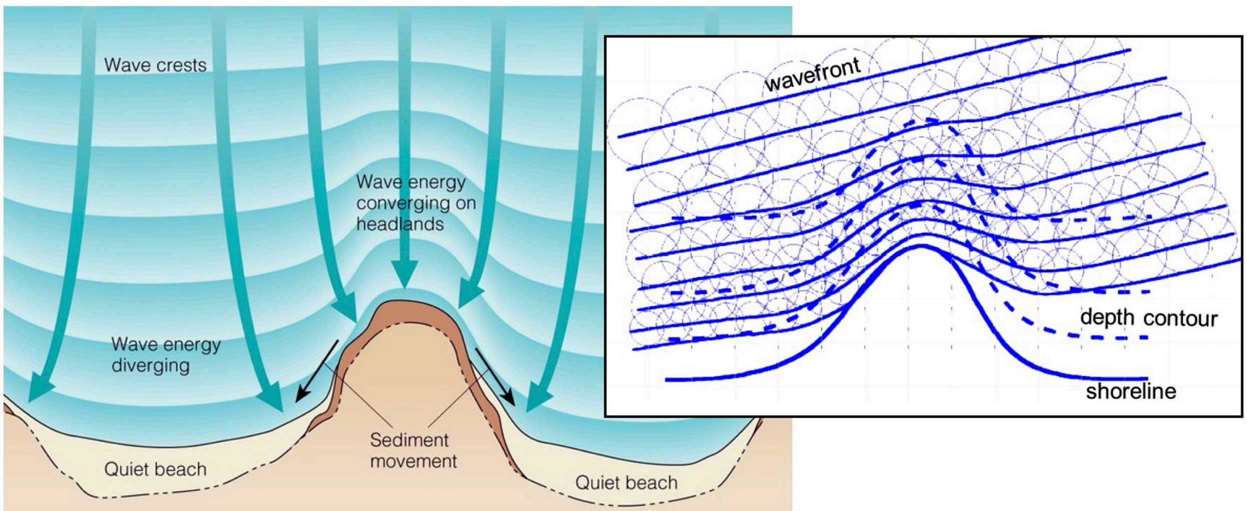
$$f_w = 1.39(A_b/k_b)^{-0.52}$$

where $A_b = u_{w,b}T/2\pi$ and $k_b = 2\pi d_{50}/12$, with d_{50} median sediment grain-size at the bed.

For each forcing conditions, the wave transformation model computes and returns:

- the significant wave height,
- the mean wave direction and
- the shear stress induced by the maxima of the orbital velocity near the bottom.

These parameters are subsequently used to evaluate the **long-term sediment transport** active over the simulated region.



In nearshore environments, longshore current runs parallel to the shore and is generated by the radiation stresses associated with the breaking process from obliquely incoming waves and by the surplus water which is carried across the breaker zone towards the shoreline (Hurst et al., 2015]. This current significantly contributes to sediment transport in nearshore waters.

Following Komar, the longshore current velocity ($\vec{v_l}$) in the middle of the breaking zone is defined by:

$$\vec{v_l} = \kappa_l u_{w,b} cos(\theta) sin(\theta) \vec{k}$$

with θ the angle of incidence of the incoming waves, κ_l a scaling parameter and $\vec{k}$ the unit vector parallel to the breaking depth contour.

For wave rays approaching shallow regions at on oblique angle, the component of wave energy flux parallel to the shore will drives this longshore velocity. The calculation of the angle of incidence is deduced from bathymetric contour and wave directions (obtained from the wave transformation model) and requires an estimate of wave breaking depth (user defined parameter *wavebase*).

From the definition of bed sediment mean grain size, the adimensional particle parameter $d_\star$ is first derived:

$$d_\star = d_{50} \left[(s-1) \frac{g}{\nu^2} \right]^{1/3}$$

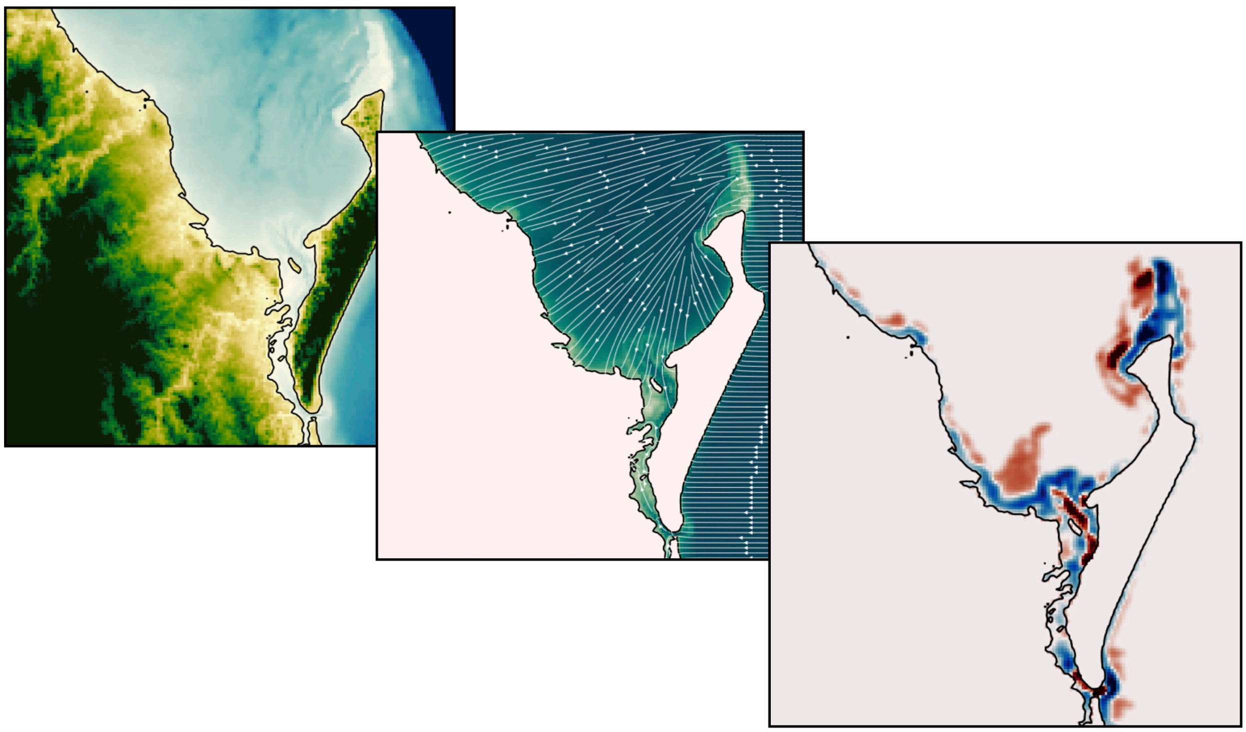
where $s = \rho_s / \rho$ is the relative density and ν the kinematic viscosity. Then the threshold Shields parameter θ_c is calculated based on Van Rijn formulation.

$$\begin{cases} \theta_c = 0.24/d_\star & \text{if } \theta_c \leq 4 \\ \theta_c = 0.14 d_\star^{-0.64} & \text{if } 10 \geq \theta_c > 4 \\ \theta_c = 0.04 d_\star^{-0.1} & \text{if } 20 \geq \theta_c > 10 \\ \theta_c = 0.013 d_\star^{0.29} & \text{if } 150 \geq \theta_c > 20 \\ \theta_c = 0.055 & \text{if } \theta_c > 150 \end{cases}$$

In regions where wave-induced shear stress is greater than the critical shear stress derived from the Shields parameter ($\tau_c = \theta_c g d_{50} (\rho_s - \rho_w)$), bed sediments are entrained. The erosion thickness h_e is limited to the top sedimentary layer and for simplicity is assumed to follow a logarithmic form:

$$h_e = C_e \ln(\tau_w/\tau_c) \text{ where } \tau_w > \tau_c$$

where C_e is an entrainment coefficient controlling the relationship between shear stress and erosion rate. Once entrained, sediments are transported following the direction of longshore currents and are deposited in regions where wave shear stress is lower than the critical shear stress for entrainment.



Marine sediments are further mobilised by a diffusion law similar to the one referred to as soil creep in the aerial domain to simulate long-term sediment dispersal induced by slope.

Long-term, reduced complexity model

Click on the **BinderHub** button in the menubar to run the described long-term model around Fraser Island.

3.5 Exercises for the Practical

To access the Notebooks exercises using the following link:

launch binder

Through these exercises, you will use **beach survey program** to evaluate long term changes in shoreline trajectory and run **longshore drift models** to evaluate the impact of wave height and direction on embayed beaches morphologies.

Important: You will need to download the practical information sheet available from **Canvas**.

CHAPTER

FOUR

CORAL REEF EVOLUTION

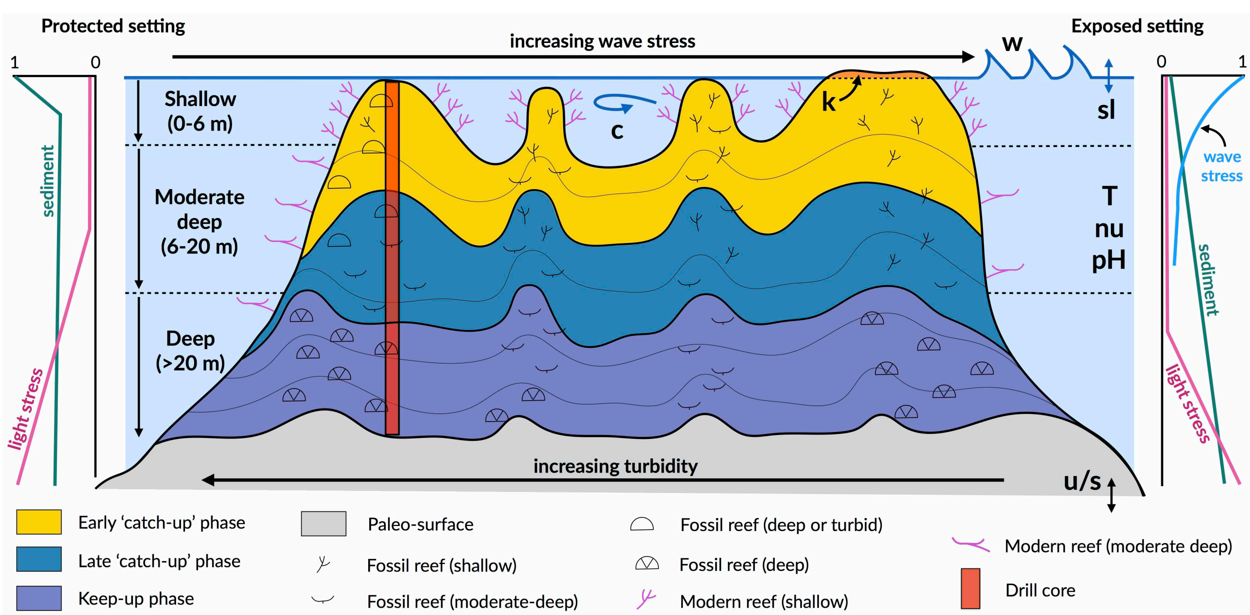
Chapter content

In this chapter, we will discuss the dynamics of coral reefs with a focus on their long term evolution. We will see different types of modelling approaches that focus on long-term (century to millennial scale) and large-scale (regional to continental) evolution.

Amongst the approaches available to study coral reef platform formation, **Stratigraphic Forward Modelling** (SFM) has become a powerful tool. SFM simulates processes acting over geologic timescales and consists in iteratively refining parameters to improve the match between observed and predicted morphologies and stratigraphies. Through this iterative procedure, it helps to *evaluate* and *quantify* parameters that cannot be observed directly such as sedimentation or carbonate production rates. In that sense, SFMs address the short-comings of qualitative investigation techniques applied to carbonate systems.

4.1 Main physical forces acting on carbonate platform

Corals are calcium-carbonate-secreting, and their ability to grow and build reef structures is dependent upon favourable environmental conditions. Environmental factors affecting growth have been classified by Veron (1995) as **latitude-correlated** factors, and those that are **regional or local** in character.



Latitude-correlated factors include sea surface temperatures (SSTs), solar radiation and water chemistry. These factors are likely to be affected most by climate change, potentially shifting the *optimal* environmental suitability for coral calcification toward the poles.

Regional and local environmental factors include wave climate, salinity, water clarity, nutrient influx, sedimentation regime and depth/composition of the initial substrate. These factors affect coral species to different extents, controlling the distribution of coral communities across a reef. Over longer time scales, they also shape the rate of calcium-carbonate production, framework building by corals, and the accumulation of sedimentary deposits.

Note: Despite the significant, short-term impacts cyclonic storms and terrigenous sediment input have on reef systems, pulse disturbances are smoothed out on geologic scales where reef systems are characterised by remarkable persistence and resilience. The slow and persistent factors (*e.g.*, sedimentation, wave climate and accommodation) are those that exert a stronger effect on the distribution of coralgal communities across a reef.

4.1.1 Accommodation

Accommodation is the vertical and lateral space in the water column above the substrate within which corals can grow. The effect of accommodation on coral growth is the most well-understood constraint on the waxing and waning of reef growth, governed by the rate of vertical accretion of reefs, sea-level rise, subsidence and uplift.

Accommodation affects coral growth in two ways:

- Firstly, light attenuates with depth in the ocean, and as corals are photosynthetic organisms, carbonate production decreases with increasing water depth.
- Secondly, wave energy and water flow also decreases with depth, such that corals growing with reduced accommodation (*i.e.*, in shallow depth) experience increased hydrodynamic energy.

Important: The effect of light is assumed to dominate over the effect of water movement in limiting carbonate production, however both effects play a role in determining coral composition and, in turn, rates of vertical accretion.

Generally, assemblages within 20 m depth have the highest accretion rates (10-20 m/kyr) than those deeper (< 10 m/kyr). Holocene reef growth largely occurred due to initially rapid sea-level rise (~10-6 ka), which created new accommodation and favourable conditions for reef '**turn-on**' on the Great Barrier Reef (GBR). Some reefs were able to keep pace with sea level rise ('**keep-up**' reefs), while others caught up after sea level stabilised ('**catch-up**' reefs), and others drowned ('**give-up**' reefs).

Examples of reef architecture evolution modelling

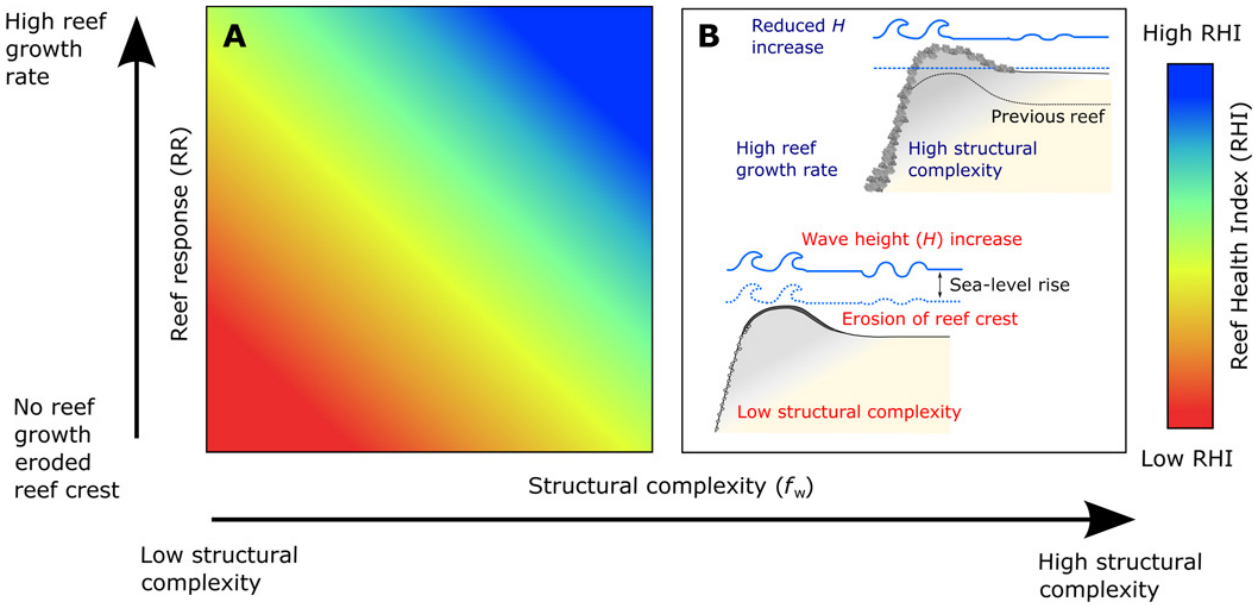
The 2 movies above are based on a numerical model of reef architecture evolution proposed Husson et al. (2018) and illustrate the response of reef productivity to the changing pace of sea level oscillations during Pleistocene under different tectonic settings.

4.1.2 Hydrodynamic energy

At the organism level, **currents**, **water flow** and **oscillatory motion** induced by waves are critical in modulating physiological processes in coral and thus influencing coral growth rates.

High water flow increases rates of photosynthesis by symbiotic algae, nutrient uptake by corals, particle capture and facilitates sediment removal from coral surfaces, all of which contribute to enhanced primary production.

At the extremes, too little flow can be lethal in corals by inducing anaerobiosis, whereas extreme wave events cause mechanical destruction and can lead to long-term changes in community diversity and structure.



Note: Waves exert a strong spatial control on hydrodynamics of reef systems. Wave energy is dissipated on shallow reefs from bottom friction and wave breaking, with the former effect dominating the latter on reefs with high surface rugosity of coral communities (Harris et al. 2018). Furthermore the geomorphology and high-rugosity of reefs cause wave refraction, such that wave energy is highest on the ocean-facing margin (**exposed setting**) and lower in back reef (**protected setting**) lagoonal and marginal environments that are protected from the prevailing winds and wave energy. As a result, wave-induced bottom stress strongly influences coral cover and community composition.

While overall, corals tend to grow more rapidly in higher-flow environments, high wave energy also has a depressive effect on reef growth in shallow (<6 m) environments. Field studies demonstrate that coral communities form where species that are capable of thriving in particular hydrodynamic conditions grow together and adopt forms suitable to those conditions. Hence, wave-induced bottom stress affects community organisation spatially, with a clear zonation pattern from the reef crest to the reef slopes.

4.1.3 Sediment input

Important: High fluxes of both terrigenous and autochthonous sediments are widely identified to have both direct and indirect inhibitory effects on coral reef growth.

Firstly, elevated turbidity **attenuates ambient photosynthetically active radiation** (PAR), which inhibits the ability of corals to meet energy requirements through photosynthesis. Secondly, smothering and abrasion by sediment blankets can **impair feeding and cause physical damage and direct mortality**.

While the lethality of sediment exposure is determined by the intensity and duration to exposure, generally the long-lasting impact of turbidity regimes is known to depress coral growth and survival. For instance, elevated turbidity on mid-outer platform reefs caused by the suspension of sediment on the Pleistocene GBR reef substrate during initial flooding ~9 ka is hypothesised to be responsible for a delayed initiation of coralgal growth.

Autochthonous carbonate gravels and sediments (*i.e.* aragonite, calcite and high-magnesium calcite), produced by the growth and mechanical destruction of reef organisms through physical, biochemical and bio-erosive processes, are important determinants of the spatial and temporal distribution of coralgal communities on long timescales.

Prevailing wave and current conditions of even moderate energy resuspended fine-grained carbonate sediments are key in generating stable turbidity regimes on reef systems, particularly in lagoons, on leeward rims and on reef slopes at moderate depths due to the decreasing water energy gradient both laterally and with depth. Similarly, prevailing turbid conditions are less common at shallow sites, especially on the windward rim due to wave-driven sediment removal.

Note: The spatial variation of suspended sediment loads is a critical environmental factor influencing coral community distribution across the reef and with depth. Turbid conditions are inimical to certain communities such as shallow-water corals, yet some species and communities are tolerant of elevated turbidity conditions on leeward rims or species that thrive on reef slopes at depth. Hence, the spatial variation in turbidity is reflected in coral community distribution both across the reef and with depth.

4.2 Coral reef modelling approaches

The organisation of coral reef systems is known to be large and complex and **we are still limited in our understanding of their temporal and spatial evolution**.

Additionally, most datasets of carbonate systems are often linguistic, context-dependent, and based on measurements with large uncertainties. Alternative modelling approaches, such as **fuzzy logic** or **cellular automata** algorithms, have proven to be viable options to simulate these types of system.

4.2.1 Cellular Automata

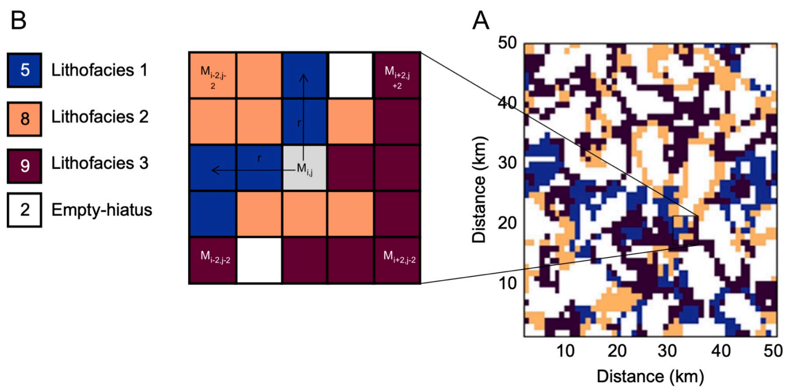
Cellular Automata (**CA**) are a type of discrete numerical model that have been used to simulate carbonate platform development. They can be entirely deterministic in their calculation, generate relatively complicated results from relatively simple rule-based computational algorithms, and are at least loosely related to biological concepts of space, competition, and population dynamics.

CA are composed of a regular grid of cells, each of which has one of a finite, usually small, number of possible states. Cell state is determined with reference to surrounding cells some specified distance away, for example, one or two cells distant. Other cells within this surrounding area are referred to as the current cell's neighbourhood.

Cellular automata applications to coral reef

Application of simple rules, for example, based on the number of cells in the neighbourhood with the same state, is used to determine the future state of a cell at the next iteration, or generation, of a cell.

Results from **CARBOCAT** model illustrate the potential of cellular automata models for generating simulated heterogeneous platform top strata and hence better understanding the origins of carbonate heterogeneities found in natural systems (from Burgess 2013).



4.2.2 Fuzzy logic

Fuzzy logic methods are able to create *logical propositions* from qualitative data by using **linguistic logic rules** and **fuzzy sets**. These fuzzy sets are defined with either continuous or crisp (discontinuous) boundaries.

Based on a fuzzy logic approach, carbonate system evolution can be driven entirely by a set of rules whose variables are fully adjustable. The utility and effectiveness of the approach is mostly based on the user's understanding of the modelled carbonate system. The technique is specifically useful to estimate how particular variable, in isolation or in combination with other factors, influences carbonate depositional geometries and reef adaptation.

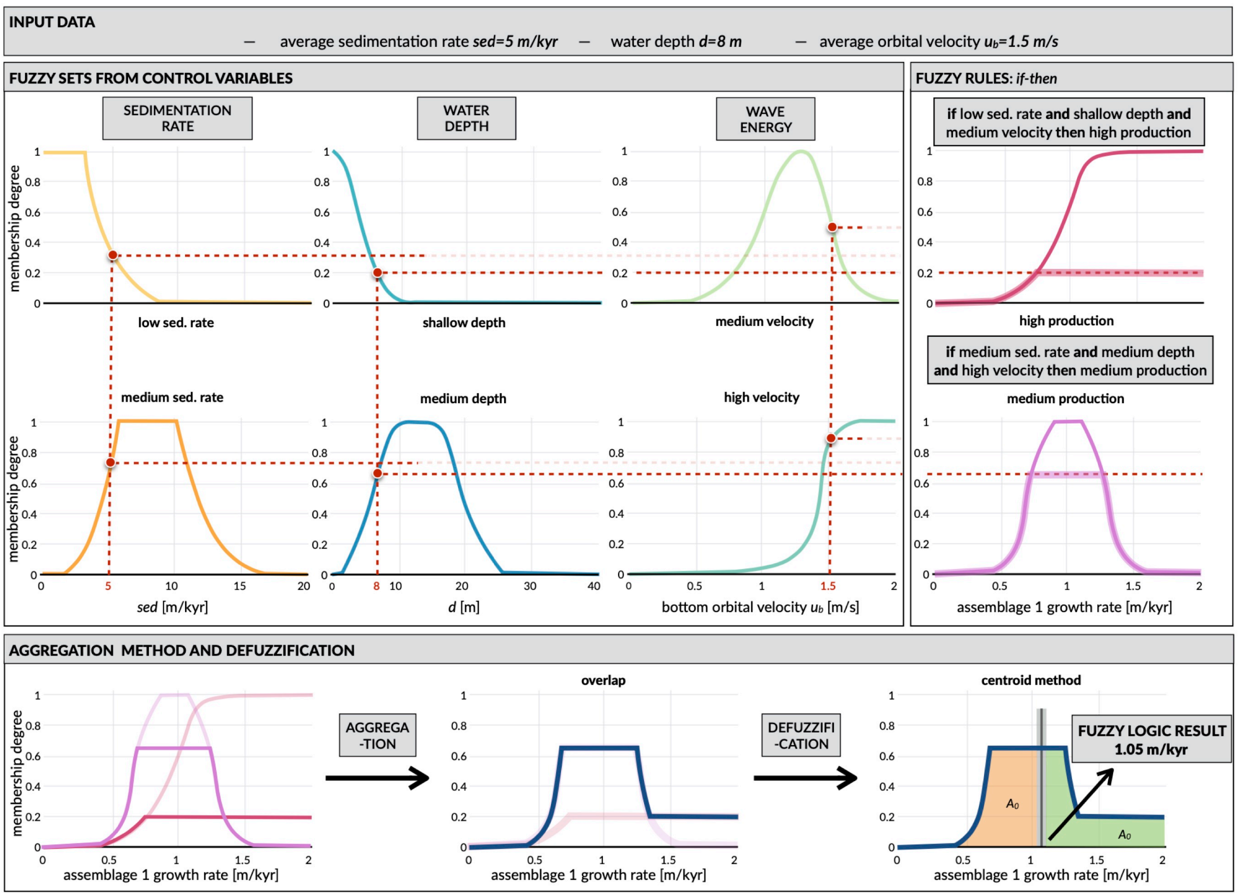
In the example of fuzzy logic set above, carbonate growth depends on three types of control variables:

- **depth** (or accommodation space),
- **wave energy** (derived from ocean bottom orbital velocity) and
- **sedimentation rate**.

Note: For each of these variables, one can define a range of fuzzy sets using membership functions. A membership function is a curve showing the degree of truth (i.e. ranging between 0 and 1) of membership in a particular fuzzy set. These curves can be simple triangles, trapezoids, bell-shaped curves, or have more complicated shapes as shown above.

Production of any specific coral assemblage is then computed from a series of fuzzy rules. A fuzzy rule is a logic **if-then** rule defined from the fuzzy sets.

In the above algorithm, the combination of the fuzzy sets in each fuzzy rule is restricted to the **and** operator. The amalgamation of competing fuzzy rules is usually referred to as a **fuzzy system**. Summation of multiple rules from the fuzzy system by truncation of the membership functions produces a fuzzy answer in the form of a membership set. The last step consists in computing a single number for this fuzzy set through **defuzzification**.



INPUT DATA
— average sedimentation rate sed=5 m/kyr — water depth d=8 m — average orbital velocity ub=1.5 m/s
FUZZY SETS FROM CONTROL VARIABLES
SEDIMENTATION RATE
WATER DEPTH
WAVE ENERGY
FUZZY RULES: if-then
if low sed. rate and shallow depth and medium velocity then high production
membership degree
low sed. rate
shallow depth
medium velocity
high production
if medium sed. rate and medium depth and high velocity then medium production
medium sed. rate
medium depth
high velocity
medium production
sed [m/kyr]
d [m]
bottom orbital velocity ub [m/s]
assemblage 1 growth rate [m/kyr]
AGGREGATION METHOD AND DEFUZZIFICATION
AGGREGA-TION
overlap
DEFUZZIFI-CATION
centroid method
FUZZY LOGIC RESULT
1.05 m/kyr
A0

4.3 Modelling GBR past evolution

4.3.1 Evolution since Last Glacial Maximum

Using badlands, a reduced-complexity model developed in the School of Geosciences, we compute over geological time: sediment transport from landmasses to coasts, reworking of marine sediments by longshore currents, and development of coral reef systems.

Note: The code links together the main sedimentary processes driving mixed siliciclastic-carbonate system dynamics. It offers a methodology for objective and quantitative sediment fate estimations over regional and millennial time-scales.

Examples of badlands simulation for the entire GBR.

Simulations of the Holocene evolution of the Great Barrier Reef show: (1) how high sediment loads from catchments erosion prevented coral growth during the early transgression phase and favoured sediment gravity-flows in the deepest parts of the northern region basin floor (prior to 8 ka before present (BP)); (2) how the fine balance between climate, sea-level, and margin physiography enabled coral reefs to thrive under limited shelf sedimentation rates after ~6 ka BP; and, (3) how since 3 ka BP, with the decrease of accommodation space, reduced of vertical growth led to the lateral extension of reefs consistent with available observational data.

4.3.2 Influence of carbonate platform on geomorphological development of the margin

Sedimentation regimes on the Great Barrier Reef margin often do not confine to more conventional sequence stratigraphic models, presenting difficulties when attempting to identify key processes that control the margin's geomorphological evolution.

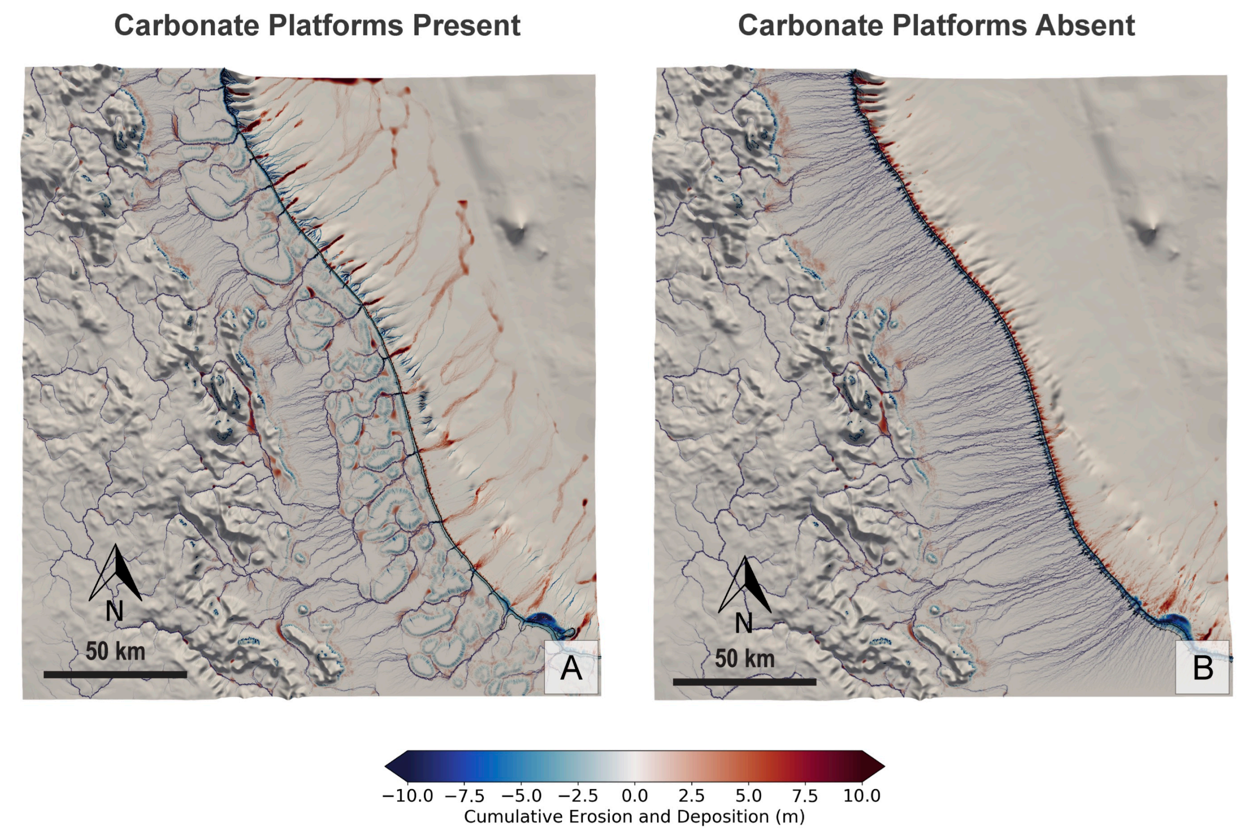
Note: By obstructing and modifying down-shelf and down-slope flows, carbonate platforms are thought to play a central role in altering the distribution and morphological presentation of common margin features.

Using badlands, we can test the role of the carbonate platforms in reproducing several features (*i.e.* paleochannels, shelf-confined fluvial sediment mounds, shelf-edge deltas, canyons, and surface gravity flows) that have been described from observational data (seismic sections, multibeam bathymetry, sediment cores, and backscatter imagery).

When carbonate platforms are present in model simulations, several notable geomorphological features appear, especially during lowstand. Upon exposure of the shelf, platforms reduce stream power, promoting mounding of fluvial sediments around platforms. On the outer shelf, rivers and streams are re-routed and coalesce between platforms, depositing shelf-edge deltas and incising paleochannels through knickpoint retreat.

Additionally, steep platform topography triggers incision of slope canyons by hyperpycnal flows, and platforms act as conduits for the delivery of land and shelf-derived sediments to the continental slope and basin. When platforms are absent from the topographic surface, the model is unable to reproduce many of these features.

Important: Results demonstrate the essential role of carbonate platform topography in modulating key bedload processes, and therefore exert direct control on the development of various geomorphological features within the shelf, slope, and basin environments.



4.4 Hands-on examples

4.4.1 1D model of coral assemblages evolution (not used from 2022)

Using **pyReef** model, we will simulate typical sequences of coral assemblages found in the GBR based on different initial conditions.

4.4.2 Carbonate platform evolution since the last LGM

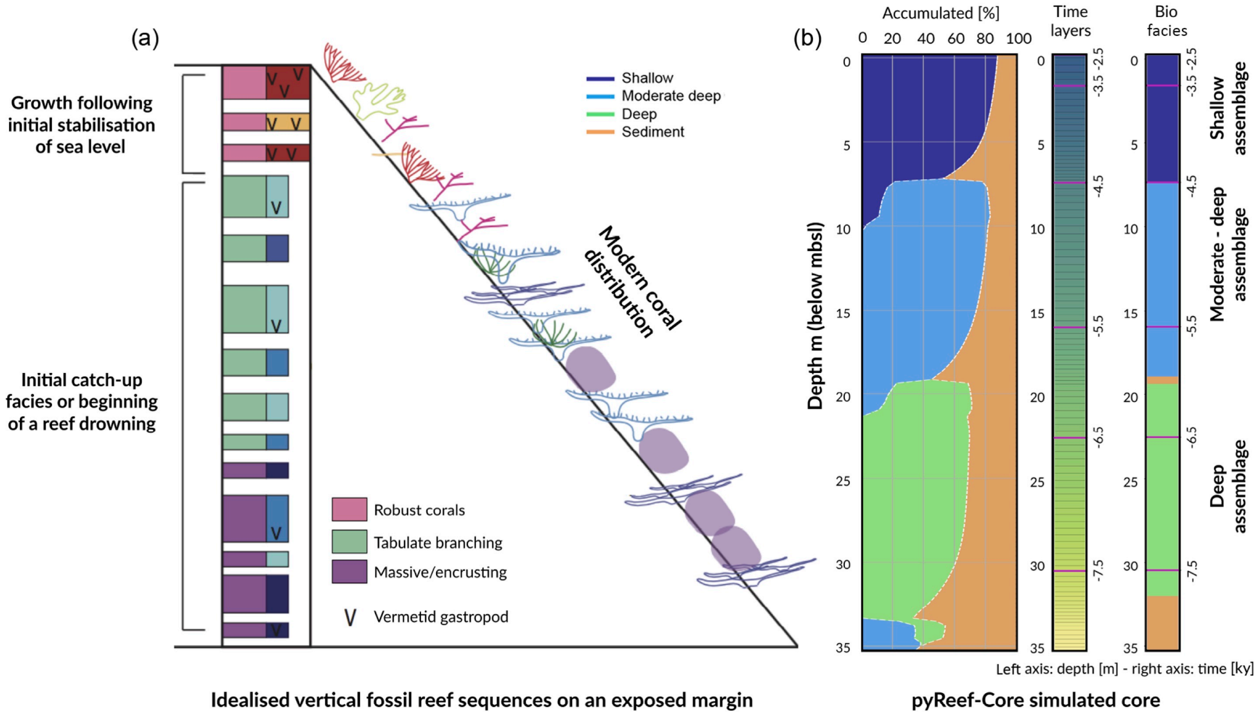
With badlands, you will simulate the evolution of a carbonate platform over the last 10,000 years accounting for the impact of waves, sediment transport and sea-level changes.

Click on the link above to start running the simulation in a **Jupyter Notebook**.

4.5 Miscellaneous

4.5.1 The Game of Life

Conway was interested in a problem presented in the 1940s by mathematician John von Neumann, who attempted to find a hypothetical machine that could build copies of itself. The Game of Life emerged as Conway's successful attempt to drastically simplify von Neumann's ideas. From a theoretical point of view, it is interesting because it has the power of a universal Turing machine: that is, anything that can be computed algorithmically can be computed within Conway's Game of Life.



Play with Conway's Game of Life here.