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Guidance Note on the Application of Coastal Modelling for Small Island Developing States

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Summary

Small Island Developing States (SIDS) are very diverse, but have something in common: they are all vulnerable to human-induced climate change, but have contributed very little to causing the problem, due to their small size and limited development. Much time has been spent in debating climate change and adaptation strategies for such countries, but little has been done in developing practical tools to assist them in managing the coastal zone. In this report we aim to address that.

In April 2017, some senior staff members from the National Oceanography Centre (NOC) visited St Vincent and the Grenadines, as part of the UK Foreign and Commonwealth Office-funded Neptune programme. At that time, some of the issues around coastal erosion on the east coast of St Vincent were identified, as well as some extreme events from which St Vincent and the Grenadines had suffered substantial losses of GDP. This was followed up by a workshop in January 2018 on 'Implementing and Monitoring the Sustainable Development Goals in the Caribbean: The Role of the Ocean', which was co-sponsored by the UK Government-funded Commonwealth Marine Economies Programme (CMEP) via the NOC (CMEP being the successor to Neptune).

During the period September 2017 to March 2020, the National Oceanography Centre, funded by the CMEP, has been working with St Vincent and the Grenadines to provide knowledge, data and training about data analysis application and software for the use of coastal managers, particularly in order to address the problem of coastal erosion. We held a stakeholder workshop in Kingstown, St Vincent, in March 2018 and a hands-on technical training workshop in January 2019. A final workshop is being held in March 2020. Here we present an overview of coastal modelling methodology for use by Small Island Developing States (SIDS), including references to previous model review studies and guidance on how to access and apply model outputs, which will be presented at the workshop, entitled 'Applying Knowledge of Coastal Processes for Coastal Zone Management into the Future'. This report seeks to collate the information on Coastal Modelling, which may be relevant to all SIDS, in order to support evidence-based decision-making. The case study is built around work done for St Vincent and the Grenadines.

It is not the intention to explain in detail the technical working and development of models, as it is envisaged that SIDS will not want or need to run complex models themselves, but if this is desired, information on further reading and training is provided. Some of the simpler and more accessible models, with particularly useful applications in the coastal zone, which do not require computer resources beyond a laptop computer, are described in more detail for in-house application and their use in decision-making is explained. The way forward in regional collaboration and capacity-building is discussed.

Glossary

Name (abbreviation)	**Definition**
Baroclinic model	Including density fields
Bathymetry	Underwater topography, depth of ocean
Boundary conditions	For models, these are supplied at the spatial limits of the model
Coastal model	Local area model, often nested within a regional model
Current	Flow of water
Depth-averaged current	Net transport due to current through depth, integrated over depth
Depth of Closure (DOC)	Offshore limit of beach profile, where no further change is observed
Forecast	Future state of system, atmosphere or ocean e.g. weather forecast
GEBCO	General Bathymetric Chart of the Oceans: latest version, GEBCO_19, is 15 arc-seconds resolution (about 0.5 km)
Global model	Numerical model covering the whole world ocean
Hind-cast	Past state of atmosphere-ocean system
Hurricane	A tropical cyclone in the Atlantic or western Pacific
Hydrodynamic model	Model for calculating surface elevation and currents in the ocean
Hydrography	the science of surveying and charting bodies of water, such as seas
Initial conditions	See boundary conditions, in this case initial conditions are the state of the model system at some initial time
LiDAR	Light Detection and Ranging, a laser system used for observing high-resolution nearshore bathymetry and coastal topography
Mean sea level (MSL)	Average level of the surface of the sea from which heights such as elevation may be measured. The global MSL is a type of vertical datum – a standardised geodetic datum – that is used, for example, as a chart datum in cartography and marine navigation
Mean wave period	Representative average wave period from the wave spectrum
Model dimensions	Models may be 1-D, 2-D or 3-D in space and also have a time dimension
Model resolution	The size of the discretisation of the sea for solution of the equations of motion
NEMO	Nucleus for European Modelling of the Ocean – a 3D baroclinic, hydrodynamic model
NOAA	US National Oceanic and Atmospheric Administration
Peak wave period	Most energetic wave period from the wave spectrum
Projection	A future forecast based on likely scenarios rather than short-term forecasts
Regional model	A limited-area model, often nested within a global model
Salinity	A measure of the saltiness of the sea, usually expressed in practical salinity units (psu)
Sea level rise (SLR)	Increase in mean sea level due to climate change/global warming
Sea surface elevation	Instantaneous sea level relative to MSL
Sea-level pressure	Atmospheric pressure at sea level
Significant wave height	The average height of the highest 1/3 of waves in a wave spectrum

Spectral wave model	Model based on calculating the statistical properties of a sea state (significant wave height, mean wave period, peak wave period, wave direction…) rather than individual waves
Storm surge	Raising or lowering of sea level due to a storm
Sea Surface Temperature (SST)	Temperature of the surface of the sea, usually measured in degrees Celsius
SWAN	Simulating WAves Nearshore – a spectral wave model intended primarily for near-shore applications, can be run in 1-G, 2-G or 3-G
Third-generation (3-G) spectral wave model	Third-generation means explicitly calculating the nonlinear wave-wave interaction effects, rather than using a parametric spectrum
Tides	The periodic rise and fall of the sea surface due to the gravitational attraction of the sun and moon on ocean waters
UNFCCC	United Nations Framework Convention on Climate Change
Water level	See sea surface elevation, relative to a vertical datum
Wave direction	By convention this is usually the direction from which waves are coming (like wind)
Waves (or wind waves)	The waves on the sea surface with periods between 1s and 20s
Wave spectrum	Usually defined as the distribution of energy among all the waves in a given sea state, at a given location, calculated over about 20 minutes
Wave model	Model for calculating surface wind waves
WAVEWATCH III®	3-G spectral wave model, used operationally at NOAA and UK Met Office
Wind direction	Direction from which wind is blowing e.g. NE Trade winds come from NE
Wind speed	Speed of wind, may be measured in m/s, km/h, mph, knots o
Wind-stress	Effect of wind on the sea surface
XBeach	Wave transformation and beach model

1. Introduction

Small Island Developing States (SIDS) are a distinctive group of 51 countries and territories, recognised at the United Nations Conference on Environment and Development (UNCED), or Earth Summit, held in Brazil in 1992 (see here for the current list https://sustainabledevelopment.un.org/topics/sids/list, although not all are islands and some are wealthy). These countries are disproportionately affected by anthropogenic climate change, while contributing least to its cause (Bush, 2018). Several countries have indicated that adaptation is their main priority in addressing climate change (UNFCCC, 2016); some adaptation actions also generate mitigation co-benefits, but the amount of emission reduction that can be achieved by SIDS will be relatively small in terms of the global budget, even with challenging local targets. Moving electricity generation away from the use of imported diesel to renewables such as photovoltaic electricity and wind power is a key action that will bring many important co-benefits, strengthening the resilience of island communities, and enabling them to cope better with the extreme weather that is a dominant feature of the changing climate. Preserving life and property in the coastal zone is very important, especially with the likelihood of more extreme events: strong winds and heavy rain, causing landslides, coastal flooding and erosion. Protecting coastal and marine ecosystems should be a top priority. Ecosystem-based adaptation needs to be implemented in collaboration with coastal communities. Preserving unique coastal ecosystems brings high quality tourism and sustains the health of the resident population.

In 2015, 189 countries filed communications with the UNFCCC secretariat in advance of the 21st Conference of Parties (COP 21) held in Paris in December of that year. 135 of those countries included information about their adaptation programmes, the climate change impacts they were already experiencing, and their assessment of their vulnerability to the way the climate is changing (UNFCCC, 2016). 165 countries submitted Intended Nationally Determined Contributions (INDCs). Those submitted by the island governments provide few tangible details about how they will cope with more violent storms, unpredictable rainfall, periods of drought, failing agriculture, and fisheries under increasing stress. There are ways that small islands can strengthen their resilience to these threats, but investing huge amounts of time in long-winded consultative meetings that produce yet more road maps, national strategies, policy documents, and wish-list action plans is not the way to go (Bush, 2018).

Overview of Coastal Hydrodynamics

The dynamic processes that occur in the nearshore region are generated by a number of different drivers e.g. tidal gravitational forces, atmospheric heating, winds and sea-level pressure. Under the influence of these external forces, the fluid motion of the water manifests itself as coastal currents, tides and tidal currents, internal and surface waves, storm surges, tsunamis and others (Horikawa, 1988).

The main difference between coastal waters and deep ocean waters is the presence of two physical boundaries i.e. the sea bottom, at a relatively shallow depth, and the coastline, which constrain the flow.

The nearshore zone is defined as the region extending from a landward limit associated with storm-wave phenomena (e.g., overwash), to a seaward limit beyond the point where incident waves break. Within this zone, several other regions may be distinguished, as shown in Figure 1 (a and b); the most important of these are the breaker zone, the breaking point, and the surf zone. The breaker zone is where incident irregular waves break; the breaking point is where the waves attain maximum height and breaking begins, and the surf zone is defined as the region between the seaward limit of the breaker zone and the area of high turbulence created by the collision of the back-rushing water mass and the incoming waves (Horikawa, 1988).

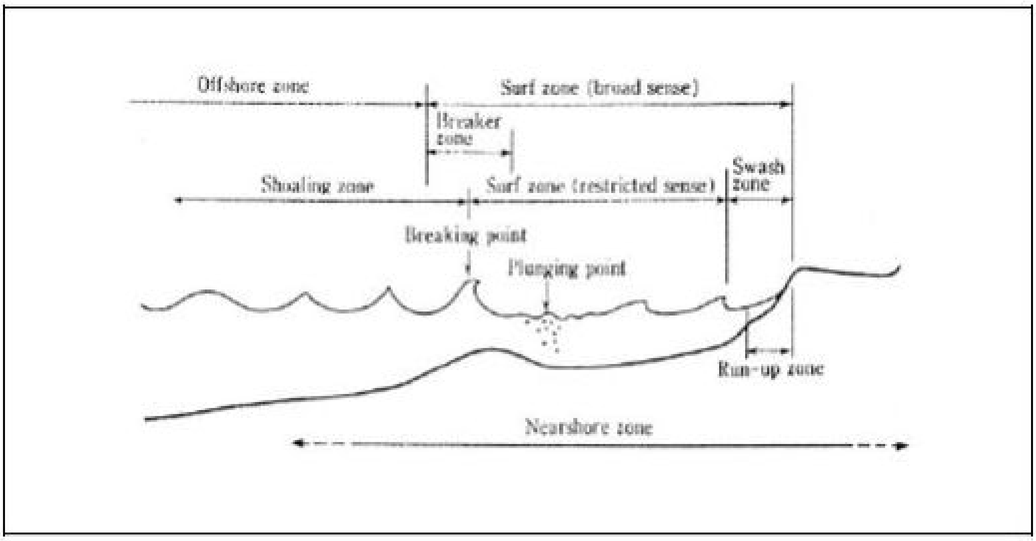


Figure 1a: Zone division in the nearshore region (Horikawa, 1988)

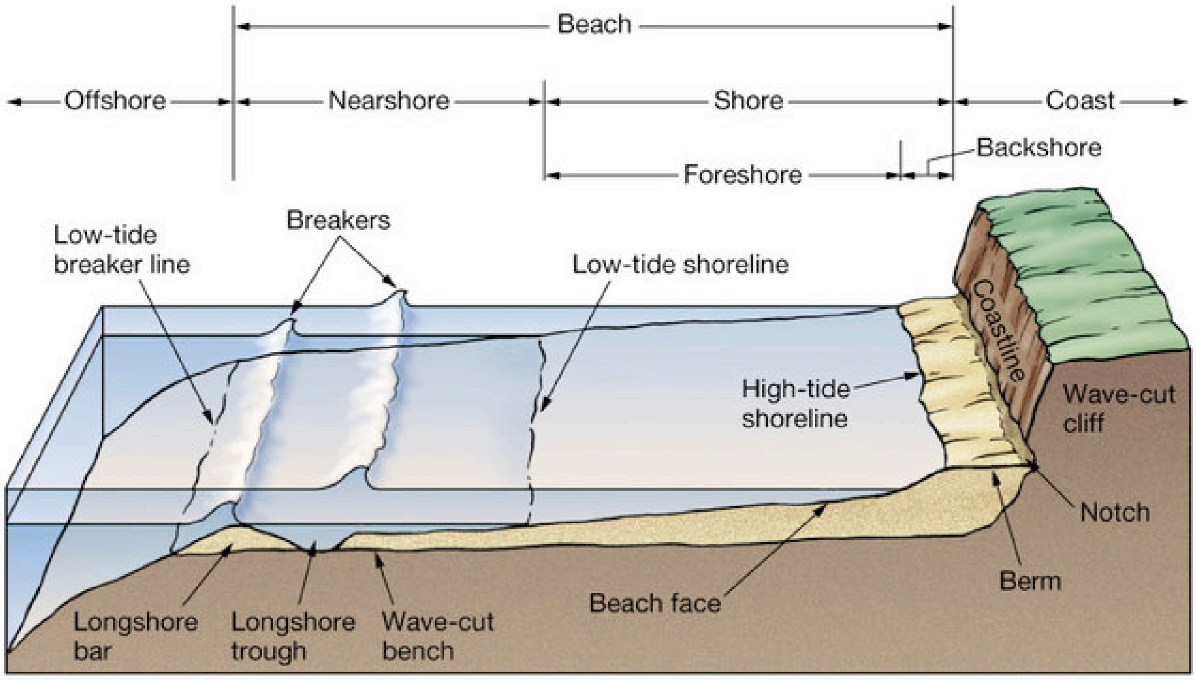


Figure 1b: Zone division in the nearshore region (Siry, 2007)

Introduction to Coastal Modelling

This report presents some practical recommendations for the application of numerical oceanographic models of the coastal zone for SIDS. Smaller nations may not have sufficient critical mass in scientific research and technical capability to carry out coastal modelling studies for themselves. Many rely on the use of external consultants, but these often produce reports that sit on shelves, as the capacity to implement recommendations is limited. We hope this is not one of those reports! Some models may be of use for in-house application, and the aspiration to carry out evidence-led decision-making is universal. We review the availability of various model datasets from work done by international organisations and then provide some basic guidance on the use of coastal models, which could be run without too much prior knowledge, like SWAN and XBeach. These models can give insight into coastal processes and provide a certain amount of independence from the use of external consultants and a level of expertise, which allows the use of such data for policy development, growing the maritime economy, coastal management and climate change resilience planning.

Numerical models are routinely used by engineering consultants in the USA, UK and Europe (and worldwide) for environmental assessment, including Environmental Impact Assessments (EIAs), Habitat Regulations Assessments (HRAs), and Water Framework Directive Assessments (WFDAs). The benefits of using models is that they can help interpret and extrapolate sparse observations, making the most use of available data. They cannot replace the need for observations altogether and in a complementary report (Becker et al., 2020) we discuss the need for coastal monitoring. Models can help to understand potential future changes to the hydrodynamic and sediment transport regime arising from a proposed development over a range of timescales, as well as likely changes due to climate change, which is of increasing urgency for coastal planners and managers. Models vary greatly in type and complexity: it is essential that the model chosen is (a) appropriate to the environment and situation to which it is being applied, and (b) capable of reproducing the range of processes identified as important to the study. The model must be able to represent the baseline environment as well as the potential impacts of any intervention scheme, such as coastal protection or infrastructure development.

This report contains a brief review of the types of numerical models currently available and most commonly used for short-, medium- and long-term modelling of coastal processes. These can be used to study near-field and far-field potential impacts of climate change, infrastructure development or a coastal intervention on the hydrodynamics (tides, waves, currents, wave/current interaction), sediment transport (cohesive and non-cohesive sediments) and water quality (salinity, temperature, suspended sediment concentrations, contaminants) in the coastal zone.

Some examples are given from a Case Study in St Vincent, where several regional and coastal models were applied. The CME Programme involves 3 delivery science organisations: the National Oceanography Centre (NOC), the Centre for Environment, Fisheries and Aquaculture Science (Cefas) and the UK Hydrographic Office (UKHO) and we worked together to produce these models. UKHO carried out a LiDAR survey, which was used to provide coastal bathymetry; Cefas carried out habitat surveys and implemented the TELEMAC/TOMAWAC models; NOC carried out regional modelling using NEMO and WAVEWATCH III® modelling, as well as coastal modelling using SWAN, XBeach and in collaboration with the University of Liverpool (funded through GCRF impact acceleration funds) LISFLOOD-FP.

It is not intended to provide a training course in the use of models, but to provide an overview of the capability of models and de-mystify the jargon used by technical experts, as well as allowing access to model outputs and guidance in the use of them for coastal decision-making.

2. Coastal Modelling

Coastal models generally require boundary conditions from global and regional models e.g. for tides and waves, and these can be supplied from pre-existing model outputs. Models also require observational data for calibration and validation. Where coastal observations are available it is possible to use observations to force the model boundaries, e.g. Prime et al. (2019) use the AWAC deployed for St Vincent by Wolf et al. (2019) to provide wave and water level boundary conditions to an XBeach model for a beach profile south of Georgetown. Figure 2 shows a schematic of the inter-relationship between models and monitoring, which is the overall focus of the project. It shows how climate scale atmospheric forcing and sea level are input into models and how validation is needed against observations. On the right-hand-side is the user interface where the questions to be addressed are formulated and model outputs are presented in various ways to decision-makers.

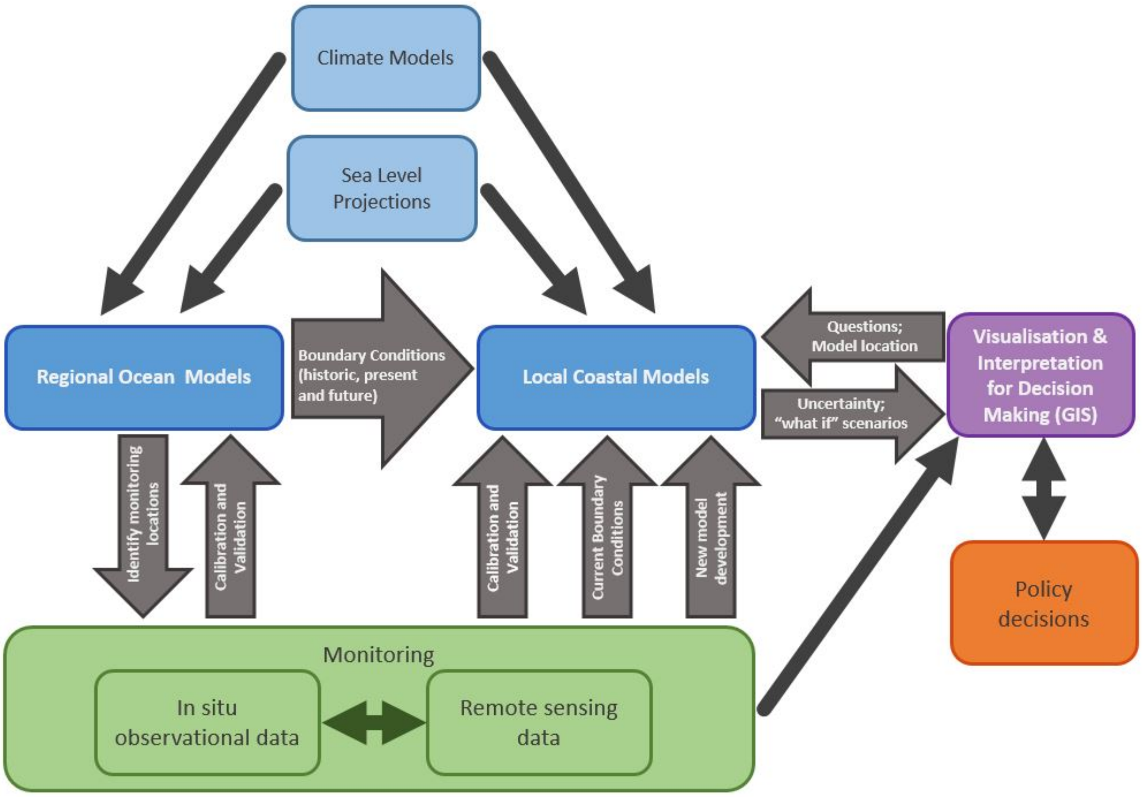


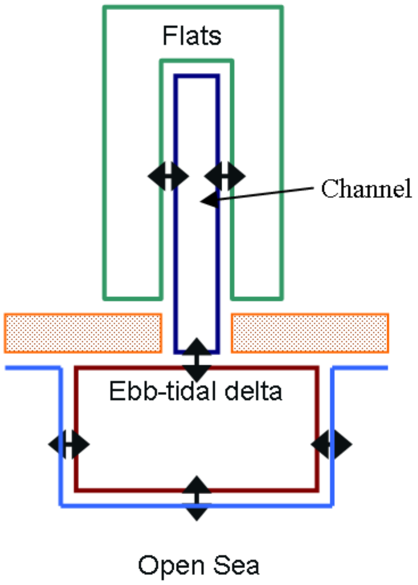
Figure 2: Different scales of model and their inter-relationship with monitoring (Becker et al., 2020)

Types of model

A model is generally described as a simplified representation of a real system, developed for a range of purposes, including real-time monitoring, forecasting, hind-casting (reconstruction of past events, often for validation purposes) or design. Models can be categorised in several different ways, including: physical, statistical, parametric (or equilibrium), analytical and numerical. It should be noted that there are overlaps in these model types and they can be used in combination in either composite (individual models are used separately) or functionally coupled modelling. Physical models are scale models of processes e.g. wave tanks or ship basin models. Here we will focus on numerical models (i.e. using quantitative calculations), using some discretization methods. These can be further divided into two sub-categories, process-based (or deterministic) and behavioural. There are also hybrid models, which combine some elements of process-based modelling with the systems-based/behavioural approach.

Process-based (sometimes known as ‘bottom-up’) numerical models are what we mainly focus on in this report. They start by solving Newton’s equations of motion applied for fluid dynamics, with various assumptions and approximations to make them tractable. Process-based oceanographic models are often separated into hydrodynamic and wave models because of the different scales required – the behaviour of tides, with wavelengths of 100’s of kilometres can be described on hourly time-scales, whereas surface wind waves have wavelengths of metres to 100’s of metres and vary on time-scales of seconds. The amount of computation needed to predict the free surface location and currents for individual waves is therefore orders of magnitude more than that needed for tides and storm surges (which have similar length and time-scales to tides). To limit the computational effort, we may treat waves using a statistical description of the wave energy at different frequencies – the spectral wave approach. Sometimes spectral wave and hydrodynamic models are coupled together to give a fully-coupled model system, which can also have additional functionality by coupling to an atmospheric model as well as sediment transport and ecosystem models. In general, these models work by solving a set of partial differential equations, which describe the evolution through time of various ocean parameters such as water level, currents or wave height, on a discrete spatial grid. The numerical solution methods are a specialist topic, which is not explained here, but can be grouped into finite difference, finite volume and finite element methods. Further information can be found on these topics e.g. in online courses such as https://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-950-atmospheric-and-oceanic-modeling-spring-2004/lecture-notes/.

Behavioural numerical models are a class of model that describe the expected behaviour of a whole system, using quasi-equilibrium methods. They are sometimes known as ‘top-down’ models, because they assume a particular form of solution, rather than allowing the behaviour of a system to ‘emerge’ from a ‘bottom-up’ model. Examples of this type of model are rule-based models, like the Bruun rule for beach behavior (which asserts a linear relationship between sea level rise and shoreline recession based on equilibrium profile theory: Bruun, 1962), and estuary models like ASMITA (Aggregated Scale Morphological Interaction between Tidal inlets and the Adjacent coast). ASMITA is a behaviour-oriented model for predicting the large-scale evolution of estuaries over decades to centuries. Within ASMITA the estuary must be schematised into morphological elements, such as channels, tidal flats and ebb-tidal deltas. For each element a morphological equilibrium is defined relating the morphology to the hydrodynamic forcing (usually tidal prism). The volumes of the schematised elements are predicted through time, based on sediment exchange between elements, which is driven by difference between current volume and equilibrium volume (Figure 3).



Element definitions

Flats: Water volume above flats, between mean low water and mean high water

Channel: Water volume below mean low water

Ebb-tidal delta: Excess sediment volume above a hypothetical, non-inlet shoreface

Figure 3: Typical three-element schematisation of an estuary as used in ASMITA

As well as these models, there are other types of models, which can be used to explore socio-economics or other applications. For example, models have been developed for the assessment of coastal vulnerability at the global to national level e.g. the DIVA model (Hinkel and Klein, 2009). The Delta Dynamic Integrated Emulator Model (ΔDIEM) model (Lazar et al., 2015) was developed during the ESPA Deltas project (Nicholls et al., 2016) to take the outputs of complex bio-physical models, including a coastal/estuarine model of the Ganges-Brahmaputra-Meghna (BGM) Delta, in Bangladesh, and apply emulators to provide simpler solutions. ΔDIEM was then integrated to project land use and livelihoods for the delta population over the 21st century, based on climate scenarios of temperature, rainfall and sea-level rise (SLR), aiming to assess ecosystem services and alleviate poverty.

This discussion has shown the range of application of quantifiable models, however, from here on we restrict ourselves to the discussion of dynamical models of hydrodynamics, waves, sediments and morphodynamics in the coastal zone.

Following Sánchez-Arcilla and Lemos (1990), the relevant phenomena in the nearshore zone can be classified into four different types:

(i) Sediment transport and corresponding changes in morphology, with a characteristic time scale of 1 day to 1 month, and a spatial scale between 100 m and 1000 m,
(ii) Currents (non-oscillatory flow), with time scales between 10 minutes and 1 hour, and spatial scales similar to those of sediment transport,
(iii) Organised oscillatory flows (i.e., wind waves, infra-gravity waves), with time scales ranging from 10^{-1} sec to 10 min, and space scales from 1 to 100 m.
(iv) Random oscillatory flow (turbulence), whose time scales are between 10^{-3} to 10^{1} sec , and with small (10^{-4} to 10^{-1} m) spatial scales.

In general, it can be said that the main active force in coastal hydrodynamics is wind waves, generated by the stress exerted on the ocean surface by the wind. As these waves travel from deep waters into shallower regions, they become more non-linear and dissipative. Eventually, the proximity of the sea bottom will induce the breaking of the waves, producing a large increase in turbulence and generating different types of currents, which may extend beyond the surf zone.

Wave, current and turbulence scales tend to overlap, thus giving rise to interactions between these three flow types, which can becomes quite complex. The usual procedure followed to derive and understand the governing equations is to decompose all the state variables into contributions from currents, waves and turbulence, and then use time-averaging operators to isolate the desired phenomenon.

Model dimensionality

The ocean is 3-dimensional (3D) in space, and also changes with time, so we need to represent this in our models. However, a lot of the physics can sometimes be reproduced in a 2D (depth-averaged) model, i.e. ignoring the vertical dimension and using only the horizontal spatial dimensions. This can be done for tides, surges and waves, for example, although when we need to understand the temperature and salinity (T-S) structure of the ocean and currents that vary through depth e.g. many ocean currents have deep counter-currents, we need to use the full 3D equations.

The proprietary MIKE 21 (2D) and MIKE 3 (3D) suites of models (which are not open-source) from the Danish Hydraulics Institute (DHI) are widely used by coastal consultancies and coastal engineering practitioners as are the open-source Delft3D suite from Deltares (Netherlands). The National Oceanography Centre, as an independent research institute, with in-house expertise in marine systems modelling, does not use commercial modelling software such as the MIKE suite of models, preferring to use the 3D baroclinic hydrodynamic model, NEMO, for which it is a co-developer, and open-source software like Delft3D and FVCOM.

In the following section we give some more details about the most relevant models needed for coastal studies. First we discuss the need for global and regional model to provide boundary conditions for local models.

Global and Regional models

Output from global models may be needed for some purposes e.g. to provide tidal boundary conditions, generated in the deep ocean, from the tidal gravitational forces, or waves generated by distant storms. These models then provide boundary conditions to more limited-area models. TPXO9 is the latest version of the Oregon State University inverse tidal model, which incorporates satellite observations, the data are freely available (https://www.tpxo.net/global, with acknowledgement to Egbert and Erofeeva, 2002).

Figure 4 shows an example of output from the global NEMO model, showing surface currents. Output from this model was used to drive the Caribbean regional 3D baroclinic model, with the addition of tides from TPXO9.

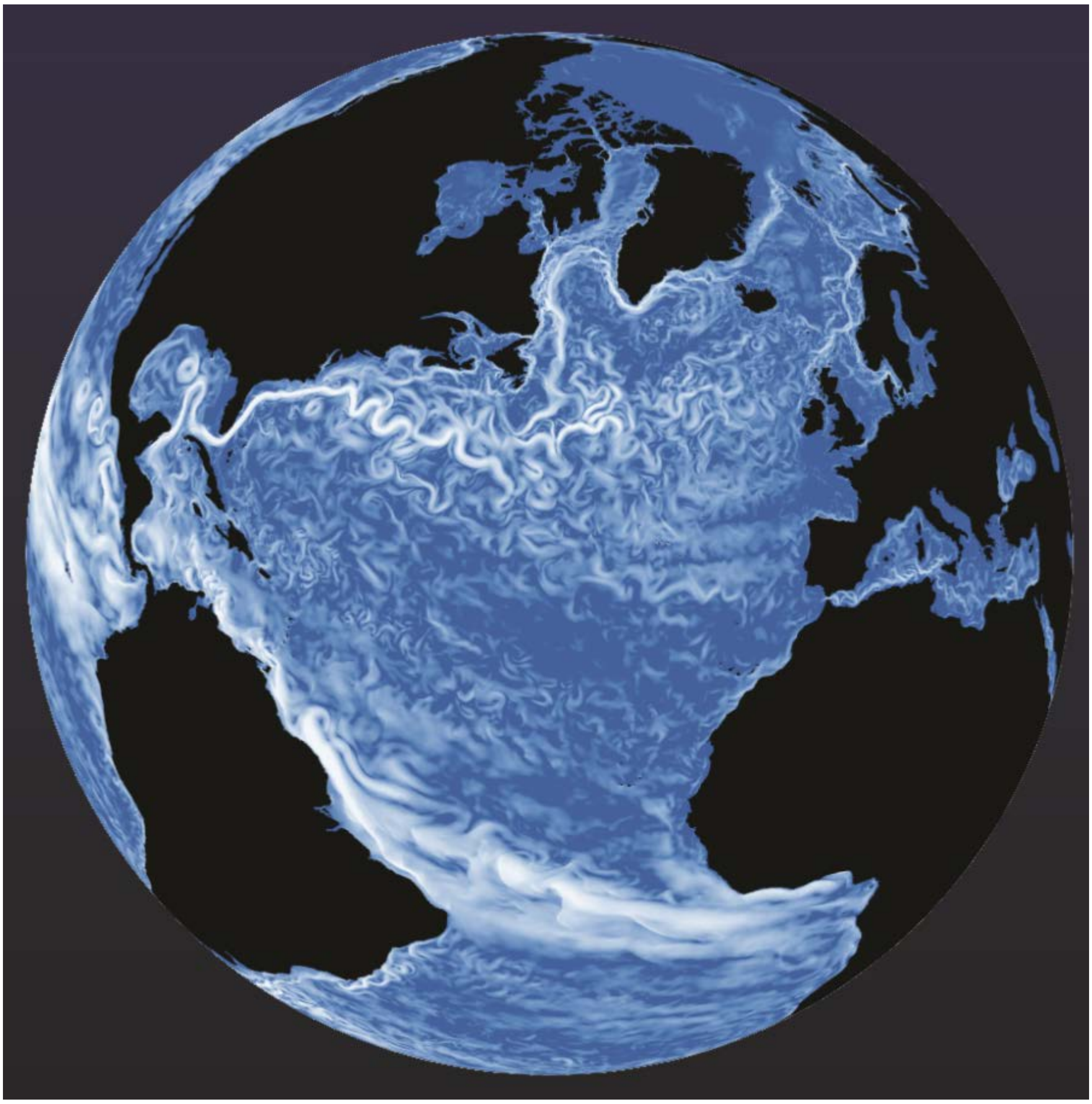


Figure 4: A snapshot of surface currents from the global NEMO model at 12km resolution

A different type of global and regional model is used to produce sea level projections, which are a very important component of coastal sea level and affect the dynamics of tide surge and wave models. These can be data-driven or semi-empirical. We refer to the work of Jevrejeva et al. (2012; 2016 and 2019). Estimates for future sea level rise for the Caribbean basin exceed the projections for global sea level rise (Jevrejeva et al., 2016). Sea level rise up to 2.2m would be due to a large contribution from ice mass loss from both ice sheets, which is very uncertain, but could not be excluded for the risk assessment in coastal area (Jevrejeva et al., 2019; van de Wal et al., 2019). The rate of sea level rise in the region will increase dramatically after 2050 and could be 12mm yr^{-1} (median) with up to 30mm yr^{-1} (95th percentile) by 2100 with RCP 8.5, compare to 1.7 -1.9mm yr^{-1} rate of sea level rise in the Caribbean region between 1950-2009 (Torres and Tsimplis, 2013). Outputs from previous studies have been used (Jackson and Jevrejeva, 2016; Jevrejeva et al., 2016), obtained by calculating spatial patterns of dynamic changes in sea surface height (SSH) and global average steric sea level change from 33 models in the Coupled Model Intercomparison Project Phase 5 (CMIP5).

What is a regional model?

A regional model is a model that covers a limited spatial area, usually selected because the area has some common characteristics that give it a unique identity: limiting the geographical extent can reduce computational costs. Ocean basins may be treated using a separate model, because they have some geographical or process-based identity e.g. the North Atlantic. Other sea areas can also be identified, for instance the Mediterranean Sea or the Caribbean Sea which are defined by land boundaries. The NW European continental shelf – a very large extent of water <200m deep, is an area with large tides, subject to extra-tropical storms, which is often treated as a homogeneous sea area for modelling purposes, although there are many local sub-areas with unique characteristics. The regional models, which we have used for the present project, are Caribbean-wide implementations of the NEMO model for hydrodynamics and WAVEWATCH III for waves.

NEMO

NEMO (Nucleus for European Modelling of the Ocean) is a primitive equation model adapted to regional and global ocean circulation problems. It is intended to be a flexible tool for studying the ocean and its interactions with the others components of the earth climate system over a wide range of space and time scales. Prognostic variables are the three-dimensional velocity field, a non-linear sea surface height, the Conservative Temperature and the Absolute Salinity. In the horizontal direction, the model uses a curvilinear orthogonal grid and in the vertical direction, a full or partial step z-coordinate, or s-coordinate, or a mixture of the two. The ocean is interfaced with a choice of sea-ice models, passive tracer and biogeochemical models, and with several atmospheric general circulation models. The manual is available at Madec et al. (2016), https://www.nemo-ocean.eu/wp-content/uploads/NEMO_book.pdf.

Figure 5 shows the extent of the Caribbean regional NEMO model. Two versions of the model were built, both with 1/12° latitude/longitude or ~12km horizontal resolution:

(i) Full 3D baroclinic model (Wilson et al. (2019): this model allows the simulation of the full 3D temperature, salinity and current fields. It includes tidal forcing and atmospheric forcing:

(ii) Tide-surge model (2D) (Jevrejeva et al., 2020): this model simulates sea surface height (SSH) and depth-averaged currents only and assumes constant density. It is forced by surface winds and sea level pressure as well as tides at the open boundary. It can be ruin quickly to model tides and storm surges. The atmospheric forcing can come from reanalysis datasets like ERA5 or from idealised scenarios e.g. constant wind or parametric hurricane model (Holland, 1980; Holland et al., 2010).

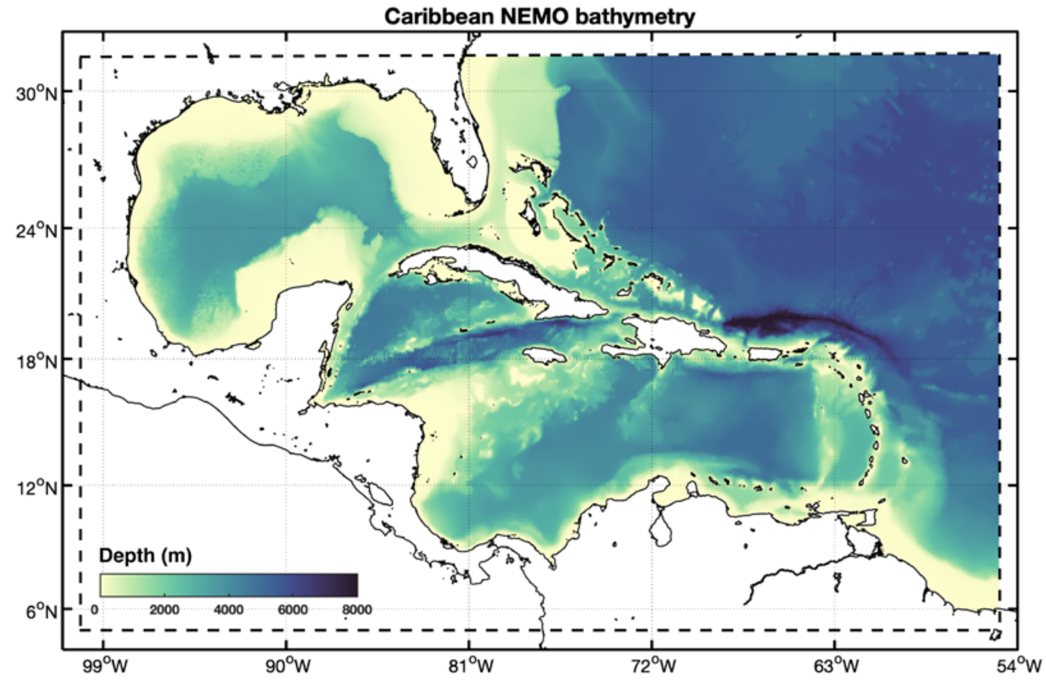


Figure 5: Bathymetry of the Caribbean Sea, showing regional model extent

Setup of NEMO model

Input requirements:

- Coastline locations
- Bathymetry (ocean depth)
- Tidal information at the open boundaries
- Reanalysis atmospheric pressure and wind information e.g. ERA5
- Idealised winds e.g. constant, Holland hurricane models

Outputs:

- Sea surface height (metres)
- Currents (m/s)
- Tidal harmonics
- netCDF file format

Figure 6 shows some results from the Caribbean regional 2D tide-surge model

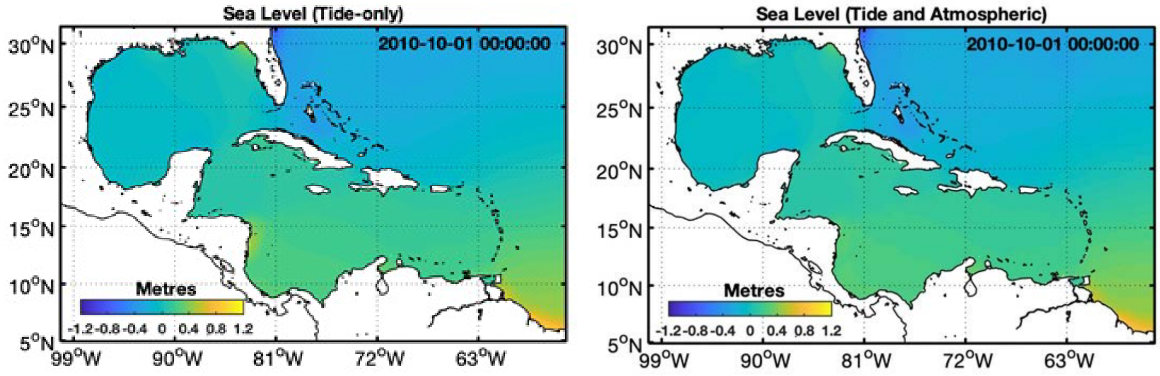


Figure 6: Tide-only (left) and tide + surge (right) instantaneous water level

WAVEWATCH III®

The WAVEWATCH III® model (hereafter WW3) is a 3rd-generation spectral wave model, widely used in operational forecasting centres worldwide (e.g. NOAA, UK Met Office). It is also open-source for model development and research purposes (see https://polar.ncep.noaa.gov/waves/wavewatch/). The model user guide is here: https://github.com/NOAA-EMC/WW3/wiki/WAVEWATCH-III-User-Guide, which explains how to set up and run the model, with access to code for developers if required. The Caribbean regional model was set up on the same model extent and resolution as the NEMO model (Fig. 5). It was forced at the open boundary by a global implementation of the same model (Bricheno and Wolf, 2018; Morim et al., 2019).

3. Local coastal models

Many different coastal models can be applied to answer management or research questions. Which one to choose may depend on the kind of outputs needed, price, open access to the model, the level of support required or familiarity. Each model will have slightly different data requirements (and file formats) for boundary and surface forcing. In order to set up the model it is first necessary to get the coastline and bathymetry data for the area of interest. Then, calibration of user-specified model parameters must be carried out, simulating a period of time for which data are available. Finally, model validation should be done, to assess the accuracy of outputs for the period of interest. Input data may be from observations or other numerical simulations, but must capture the required temporal and spatial variability. Observational data may be limited in time or space, depending, for example, on when a data-collection experiment (e.g. a scientific cruise or coastal fieldwork takes place) or where a mooring is deployed. Numerical simulations can be most useful for filling data gaps and/or to extend observational information, once the model is sufficiently well-validated. Good practice in coastal process modelling is discussed by Lambkin et al. (2009), Lawless et al., 2016) and Pye et al. (2015; 2017).

Coastal area models can be used to assess the contributions of different processes to the waves, hydrodynamics and sediment dynamics across a region. They are computationally expensive so simulations are often limited to a few months or years. These models are typically applied using a nested approach (where an outer, coarse-resolution model provides boundary conditions to an inner fine-resolution model) to provide good resolution at the coast. These models require large-scale datasets such as maps of bed characteristics to provide input data. National tide gauge and wave buoy networks are typically used to validate the wave-water level outputs. Additional information from satellites and observational campaigns can be used to validate temperature, salinity and velocity fields.

These numerical models represent tides, waves, currents and surges in coastal waters by solving equations that underlie their hydrodynamic processes. They calculate rates of change of water depth and extent across time and space that will result from different combinations of variables, for example, different meteorological and tidal conditions and varying coastal defence systems. The models are developed using observational data (see monitoring report, Becker et al., 2020) which allows them to be validated. Once validated a model can be used to simulate a number of “what if” scenarios including sea level rise, storm surges and sea defence failure. They can provide a forecast of what could happen in the future (Roelvink et al., 2009).

Coastal evolution models are used to simulate long-term changes in shoreline position. They require information about the nearshore wave climate (from an AWAC or Waverider buoy), to drive the model, and long-term shoreline position (from beach profiles, aerial photography or satellite imagery) for calibration of historical rates of evolution.

Cross-shore profile models are a computationally efficient way to assess storm impact. Outputs of interest are event driven erosion, wave run up and overwash values. They require beach profiles, combined wave and water levels offshore at the depth of closure (DOC, the seaward edge of the morphodynamically active shoreface, where there is no significant change in bottom elevation or sediment transport). These data are collected from beach and bathymetric surveys and joint probability analysis of closely positioned long-term tide gauge and wave buoy records.

Inundation models provide information about flood extent and depth. When combined with knowledge of the land use, an estimate of the potential economic cost of a severe event can be determined. Inundation models extend inland from a defence crest level or the low watermark. The boundary forcing requires information about the overtopping or overwashing volumes of a defence. A map of the topography and land use are also required, often these are determined from LiDAR and satellite data. Validation data can be difficult to obtain as it requires information on waterlines and driftlines which need to be collected soon after an event, before they are cleaned up.

Operational models and climate projections provide a useful long term data source over large national and regional scales. They enable simulation of past, present and a range of plausible future conditions to be explored. The data is often available at different resolutions. When using this information to force a model it is important to consider where the boundary is positioned relative to the data points available and if you are looking at changes in climatology, such as winter and summer conditions, or require the resolution of an event, such as a storm.

In selecting a suitable model it is first necessary to consider the question being asked. Once potential candidate models are identified, the data requirements and availability can be determined, to ensure a valid and meaningful simulation can be performed. In some cases, more than one model may be required to provide a detailed answer.

FVCOM

Many numerical ocean models have a regular (or structured, rectangular) grid. This can be fine fopr large ocean extents, but is not ideal for fitting complex coastal topography. FVCOM (Finite Volume Community Ocean Model, is an unstructured grid, finite-volume, three-dimensional (3D) hydrodynamic model The FVCOM horizontal grid comprises unstructured triangular cells, having variable horizontal resolution, typically varying from 10 to 20km offshore down to O(100 m) at the coast. This allows it to better fit the complexity of a real coastline.

SWAN

The Simulating WAves Nearshore (SWAN) model is a third-generation (3-G) spectral wave model, developed at Delft University of Technology, used to obtain realistic estimates of wave parameters in coastal areas, lakes, and estuaries from given wind, bottom, and current conditions. SWAN has user interface with a useful toolkit allowing it to be quickly applied in a given coastal region.

Delft3D

Delft3D is an open source numerical model, which can carry out simulations of flows, sediment transport, waves, water quality, morphological development and ecology. The programme is derived of several modules, including FLOW, for flows, MOR, for morphology and Wave, for waves. Each of these modules can be linked to another to create a model that can simulate a range of processes in coastal and estuarine environments. The model is multidimensional, 2D or 3D, and calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a curvilinear or flexible mesh boundary fitted grid. The model uses a Graphical User Interface (GUI), which can be set up to operate on a windows or linux system. The model requires an accurate bathymetry and can be forced at the boundary using observational or model data.

TELEMAC/TOMAWAC suite

This is a widely-used finite element unstructured grid model system, developed by Electricité de France (EDF) over many years and recently made open-source, which makes it much more accessible to the expert modelling community. TELEMAC is the hydrodynamic model and TOMAWAC the wave model. The unstructured grid means the mesh is formed of triangles of variable resolution (similar to FVCOM).

TELEMAC 2D is a finite volume hydrodynamic model, which applies mass and momentum conservation. TOMAWAC is a finite-element spectral wave model, using frequency and directional discretisation.

Why TELEMAC?

- Open source (can see and amend the model code)
- Strong consortium
    - 7 European institutions
    - Recurrent yearly meeting
    - User conference
    - Scientific committee meeting
    - Workshops
- Active (and really useful!) forum
- Growing user and developer community

Sediment transport and morphology modules are also available. The source code can be downloaded here: http://www.opentelemac.org/index.php/download.

The model suite was set up by Cefas over the area including Grenada and St Vincent and the Grenadines.

XBeach

XBeach is an open-source numerical model originally developed to assess hurricane impacts on sandy beaches. In its initial inception, it simulated hydrodynamic and morphodynamic processes and impacts on sandy coasts with a domain size of kilometres and on the time scale of storms. It has since been applied to other types of coast (e.g. coral fringing and atoll reefs) and purposes. The model includes the hydrodynamic processes of short and long wave transformation, wave-induced setup and unsteady currents, as well as overwash and inundation. Morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update and breaching. The model also includes effects of vegetation and hard structures. It can be used to simulate wave run-up, beach erosion and sediment transport. Whilst it has the capability of running in two dimensions (i.e. longshore and cross-shore), it can also be used in a basic one-dimensional cross-shore setup.

Further information on XBeach and guidance on its many functionalities, options and parameters can be found at https://xbeach.readthedocs.io/en/latest/xbeach_manual.html.

A demonstration of the XBeach model, presented at workshops in St. Vincent and Grenada in January 2019, is available online https://btphillips94.github.io/web_page/cmep-workshop-xbeach.html. This can be used to gain familiarity with how to setup and run a basic XBeach model, and how to use Python to plot wave run-up and changes in a beach profile during a storm.

LISFLOOD-FP

Flood inundation models can be used as a research tool to improve our understanding of flood inundation, prediction and risk assessment. They can be applied to simulate flood inundation in coastal, estuarine and fluvial environments. They simulate the movement of water over high-resolution topographic data of the land surface.

LISFLOOD-FP is a two-dimensional flood inundation model, which simulates local variation in the depth and extent of water level and depth averaged flow velocities. Outputs can be used to illustrate inundation as a series of maps and scenarios. The model has been successfully used in the coastal environment, e.g. to estimate a 1:1000 year flood event with varying degrees of sea level rise in the Thames Estuary, UK and flood extent in Fleetwood, UK, under a 1:250 year storm tide with sea level rise, river flow and wave overtopping. These examples show how LISFLOOD can be used in a sensitivity study context to simulate a number of different conditions which may occur in the coastal zone.

The increasing availability of high-resolution topographic surveys, using airborne remote sensing (e.g. Light Detection and Ranging, LiDAR) allows for accurate representation of flood inundation. LISFLOOD operates over a Raster grid of LiDAR data to predict the dynamic propagation of flood waves. Water moves across the grid from a user-defined boundary over floodplains. LISFLOOD simulates floodplain inundation in two-dimensions by solving the shallow water equations that describe water flow. The model assumes that the flow between two of the grid cells in the domain is a function of the surface height difference of the two cells and gravity.

Time varying boundary conditions define the hydrodynamic and meteorological inputs, which will operate across the model grid. Each of the time varying model conditions can be changed to simulate a range of scenarios e.g. progressively more severe storm surges or increasing sea levels over time.

The Digital Elevation Model (DEM) dictates how and where the water will move across the grid. Sea defences can be digitised into the model domain. A uniform or cell-by-cell floodplain friction coefficient is applied to the model grid to simulate the friction values of the land, which the water flows across. A uniform flow velocity can also be applied at the model boundary to determine how fast the water moves into the model domain.

4. Setting up a coastal model

The model extent and grid resolution must be selected. The model extent must be large enough to capture the processes of interest, while not being unnecessarily large. Ideally the boundary conditions are far enough away from the area of interest that errors do not dominate the solution, whereas this will usually be a compromise between the highest resolution wanted at the coast and the coarser resolution necessary for a large area model, which would require a long run-time if the finest resolution was used everywhere. Figure 7 shows the resolution of the Caribbean model around the Lesser Antilles. This model only represents islands as a few grid points so it will not give detailed results at the coast. The computational time for a model is determined by:

- Model grid size
- Number of grid-points
- Time step – this is limited by accuracy and stability requirements of the model solution
- Run duration – days, months, years, decades, centuries
- Complexity of the model – how many variables are included e.g. SSH, currents, T, S, other contaminants, sediments, biology
- Dimensionality (1D, 2D or 3D)

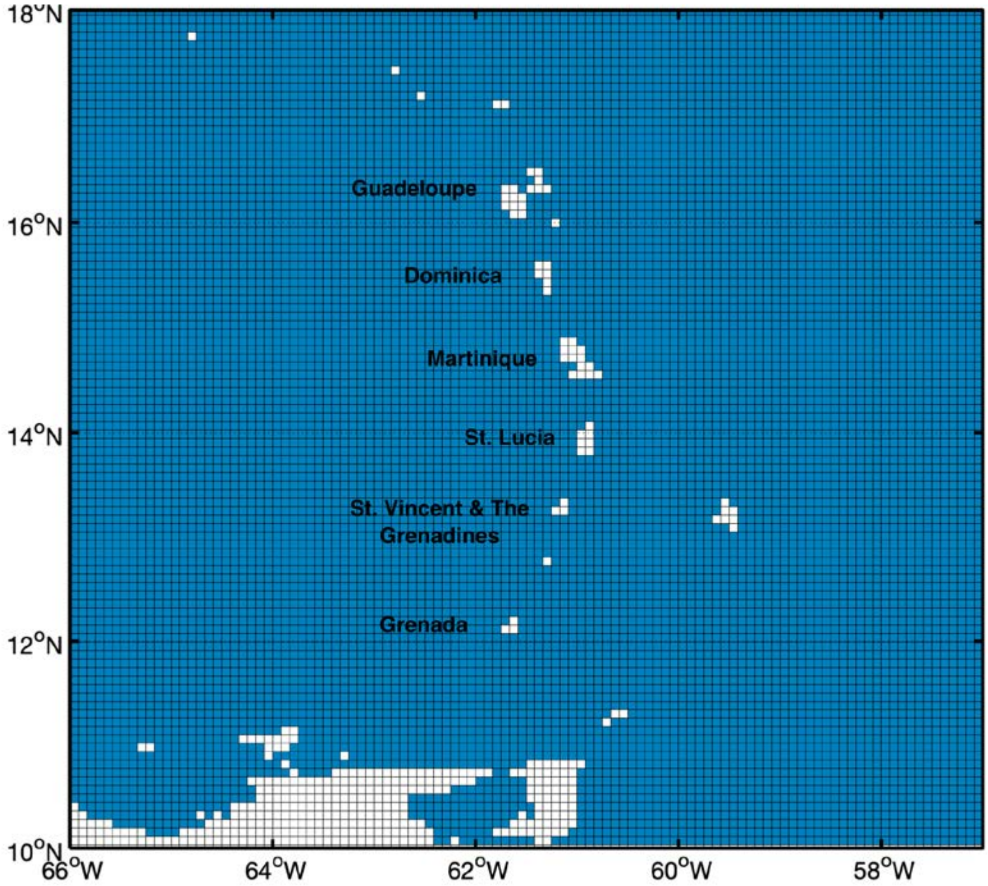


Figure 7: Zoom in of the Caribbean 12km model for the Lesser Antilles, showing land/sea mask

5. Sources of input data for coastal models

In order to run a model, the minimum requirements are usually water depth, coastal elevation data, offshore boundary conditions, initial conditions and forcing data.

Coastline

An accurate coastline may be freely obtained from the global dataset GSHHG (the Global Self-consistent, Hierarchical, High-resolution Geography database, formerly known as GSHHS) https://www.ngdc.noaa.gov/mgg/shorelines/.

Water depth/bathymetry

A quick source of data is the General Bathymetric Chart of the Ocean (GEBCO) atlas, which now has a resolution down to 15 arc-seconds of latitude/longitude globally (about 0.5 km), e.g. see

https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_2019/gebco_2019_info.html.

However, be aware that coastal bathymetry may still be inaccurate in some locations. Check the website for the latest information. If a local bathymetric survey is available, this should be used in preference.

An example of the GEBCO data (at 30 arc-seconds resolution) for the area around St Vincent is shown in Figure 8.

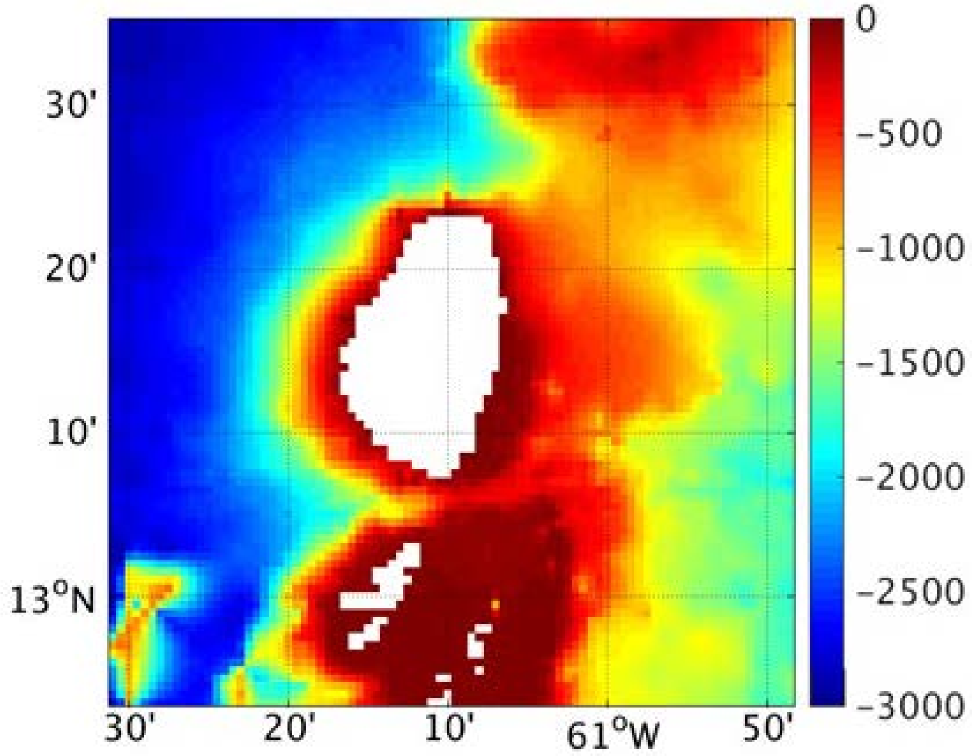


Figure 8: GEBCO 30 bathymetry around St Vincent. Colour bar shows water depth in metres, relative to mean sea level (MSL)

A LiDAR (**Li**ght **D**etection **A**nd **R**anging) survey was carried out by the UK Hydrographic Office (UKHO) in 2016, as part of the CME Programme, for Grenada and St Vincent and the Grenadines. This gives a Digital Elevation Map (DEM) of the coastal zone at much higher resolution (2m). Figure 9 shows the extent of this data for the island of St Vincent. It can be seen that there is only data in a narrow coastal strip because of the steep volcanic nature of the island. In the Grenadines, with shallow water between coral cays, there is more coverage.

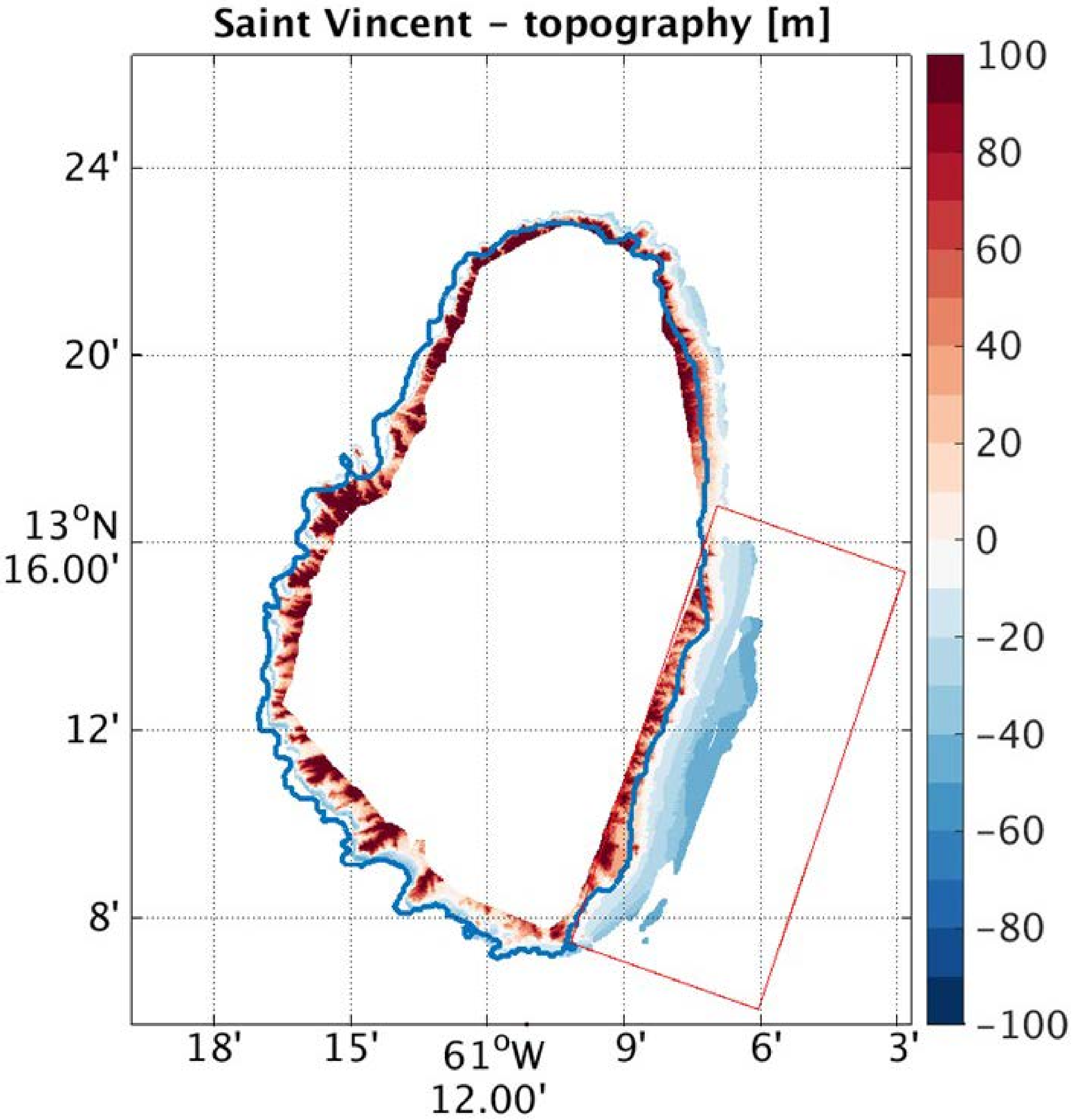


Figure 9: LiDAR survey of St Vincent, showing location of SWAN model

These data were used in the SWAN model setup (see Appendix 3) and experiments carried out between January-March 2018.

Offshore boundary conditions

For some processes, e.g. tides and waves, a limited-area local model will require boundary information either from a coarser-resolution e.g. NEMO/WW3 or TELEMAC/TOMAWAC. Alternatively, there are data on tides available from TPXO and for waves from ERA5.

Initial conditions

Sometimes, models may be run from an initial condition where all variables are set to zero. This can be done for dynamical variables like currents and sea level but is not viable for state variables like temperature and salinity, where it is more realistic to set a mean temperature and salinity e.g. from a climatological atlas of the world ocean, or larger area model run. It takes a long time (thousands of years of real time) to spin up these variables from zero. Even to follow seasonal changes, it is better to start from a realistic initial condition.

Forcing data

Forcing data includes atmospheric variables like sea level pressure (SLP), winds, precipitation and surface heat flux. It may include river run-off data, if available. Sometimes, idealised forcing can be generated e.g. blowing a steady wind over the model, or using an idealised tropical model. For real (past) events, hind-cast atmospheric data are available e.g. ERA5.

6. Visualisation and interpretation of model outputs

Usually model outputs can be visualised using special software tool such as GIS systems e.g. ARC-GIS and QGIS (free software). These provide horizontal spatial maps and overlays of different types of data (e.g. Lichtman et al., 2018). In general, they cannot handle 3D or time-series data, such as time-varying water levels, or 3D currents, so other tools can be used to visualise animations of successive snapshots. Data manipulation, analysis and plotting may be carried out using Excel (Microsoft Office). More sophisticated analysis and plotting can be done in Matlab or Python (the latter is free software), which can be run on a laptop or mainframe computer, but requires some specialised knowledge of programming.

7. Case Study – St Vincent

St Vincent and the Grenadines is an archipelagic state that forms part of the Windward Islands in the south-eastern part of the Caribbean. Located at 13°15’ N and 61°15’ W, it is neighboured by St Lucia to the north, Barbados to the east and Grenada to the south (Figure 1). Although St Vincent and the Grenadines lies to the south of the main hurricane storm track, the islands are occasionally impacted by tropical storms, hurricanes and heavy rainfall events. Most recently, heavy rainfall during April 11-12, 2011 caused rivers to overflow and landslides in the north-eastern section of St Vincent. An assessment by the National Emergency Management Office of St Vincent and the Grenadines revealed that the sectors most affected were water and agriculture. Accelerated sea level rise is expected to increase the likelihood of the inundation of low-lying coastal areas, increase the salinity of surface and ground water and result in higher water tables. The impact of sea level rise is likely to exacerbate the damage caused by existing anthropogenic impacts, such as coastal pollution and over-fishing. Improving the management of biodiversity and fisheries will become increasingly important to the welfare of Vincentians and to the sustainability of the country’s main economic activities – fishing, tourism and agriculture.

Regional modelling of storm surges and waves using NEMO and WAVEWATCH III

Some case studies of hurricanes that have impacted the eastern Caribbean were selected for detailed modelling. The storm tracks for the hurricanes of interest - Ivan (2004), Tomas (2010), Harvey (2017) and Maria (2017) - are shown in Figure 10.

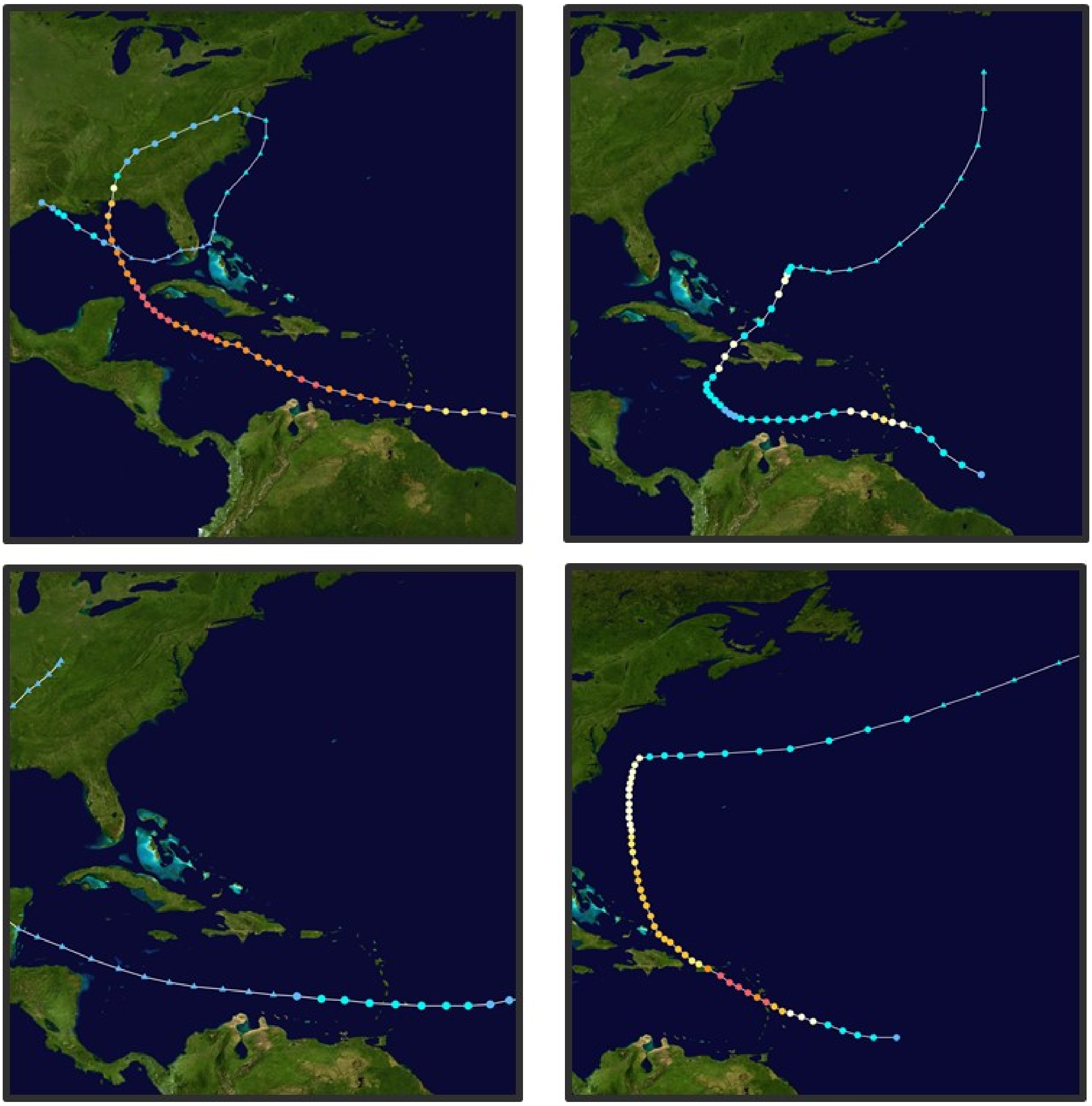


Figure 10: Top left – Hurricane Ivan (2004), top right – Hurricane Tomas (2010), bottom left – Hurricane Harvey (2017), bottom right – Hurricane Maria (2017)

These hurricanes were used to force the Caribbean regional NEMO 2D tide-surge model and the WW3 regional wave model. A local SWAN model was implemented for a rectangular domain centred on the Argyle International Airport (Appendix 4) and driven by steady winds and hurricane Tomas winds.

TELEMAC/TOMAWAC model

Cefas implemented TELEMAC/TOMAWAC for St Vincent, Grenada and the Grenadines. The extent of the model is shown in Figure 11, as well as the mesh resolution.

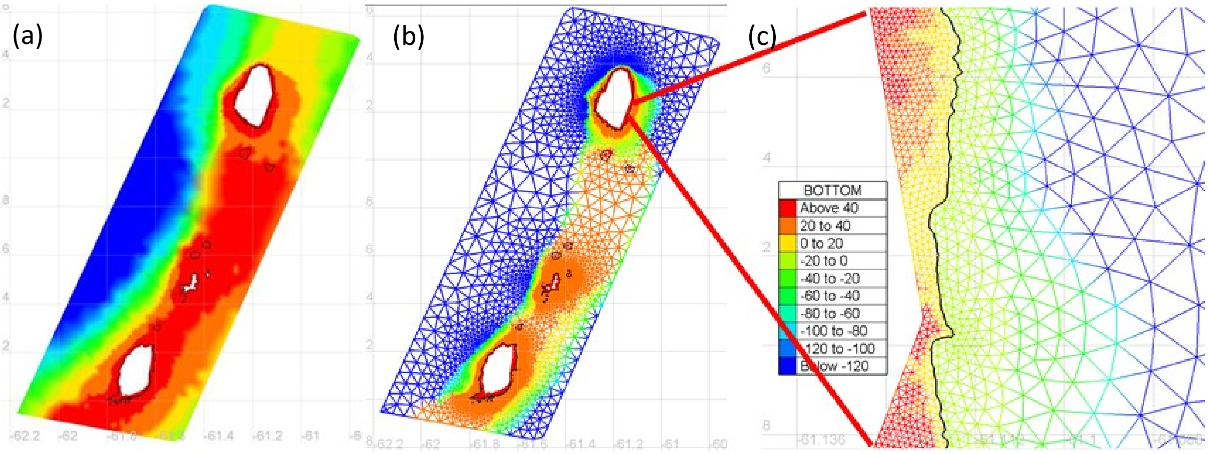


Figure 11: Extent of the TELEMAC/TOMAWAC model (a) bathymetry (b) mesh (c) zoom into east coast of St Vincent

Some examples of model output are shown in Figures 12 and 13. Details of how to access the model outputs are given in Appendix 2.

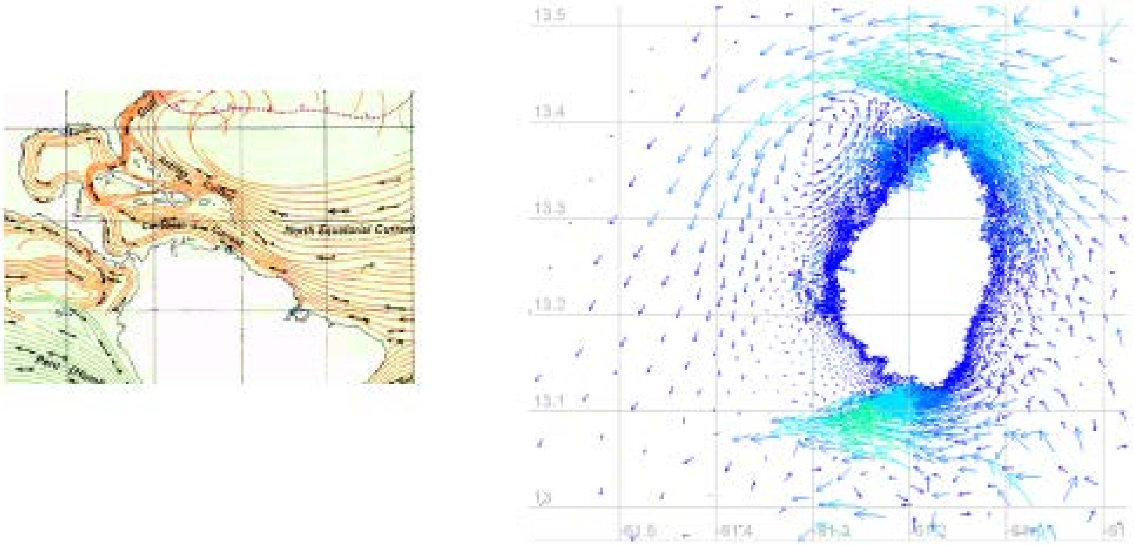


Figure 12: Simulation of westerly current (compare with current atlas for the North Guiana Current)

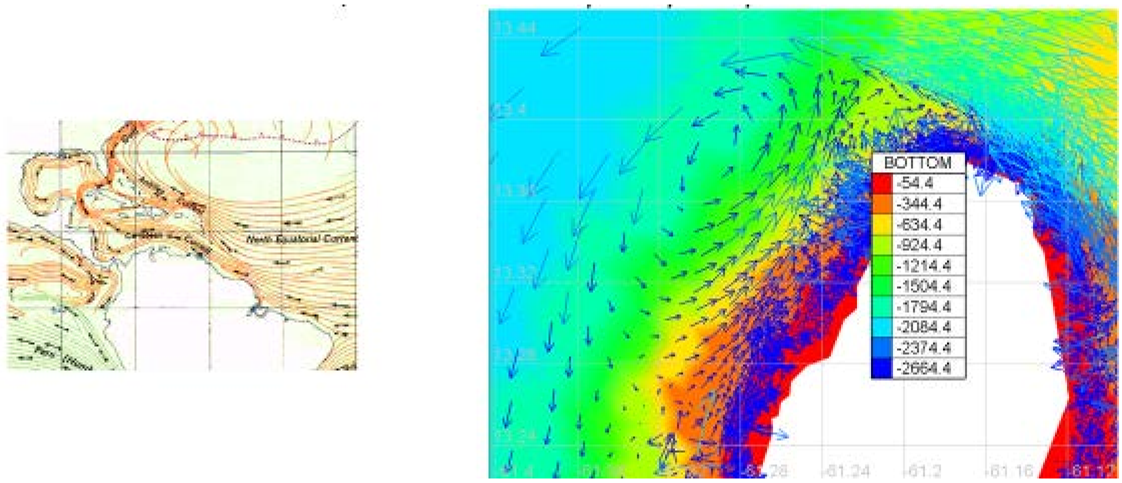


Figure 13: simulation of westerly current – note recirculation/eddies caused by bathymetry, behind the northerly point of the island

8. Application of model outputs for coastal management

In order to make evidence-based decisions some key datasets are needed. “Systematic, frequent and broad-scale monitoring of coastal drivers (forcing) and shoreline response is a fundamental task in planning for long-term coastal change” (Nicholls et al., 2013). Once the response of the shoreline to the drivers has been analysed, future change can be predicted from models.

Models can be used to generate data on extreme events, beyond the limited data which may have been observed. There are 2 main types of data which can be obtained. In the first case, we may want to plan a new development or coastal protection scheme for present day conditions, where the lifetime of the development has a lifetime of less than 10-20 years. Then we just need to know the probability distribution of water levels, currents and waves for the present day, to design resilient infrastructure. However, increasingly we are seeing the effects of climate change, so we need to also factor in climate change effects for design purposes.

Coastal Infrastructure

For coastal engineering design purposes it is often necessary to provide the 50-year (or 100-year) return period wave height and water level. It is not possible to observe waves and water levels for 100 years or more. There are two ways of obtaining these values, from shorter datasets:

1. Observe waves and water levels for a lesser period of time (at least a year but ideally for several years), carry out an extreme level analysis and extrapolate to the required return period. The limitations of this method is that the extrapolated water level/wave height may not be accurate.
2. Use a numerical wave and hydrodynamic model to run some extreme events, which have been observed, then validate the results against observations. Then use idealised storm forcing to generate more extreme events. For this we need to know the probability distribution of the storms rather than the waves. Understanding the mechanisms behind storms allows us to model future storms.

It may be necessary to resort to empirical parameterisation for some variables e.g. wave setup, swash and runup (e.g. Stockdon et al., 2006).

Climate Change

In order to understand the likely impacts of climate change, the main parameters required are future mean sea level, as well as future tides, storm surges and waves, i.e. to extrapolate extreme water levels. Sea level is increasing, due to global warming, but also the rate of change is accelerating. In turn these increased sea levels have an effect on tides and the frequency of return of extreme water levels. Models are the only way we can project future sea level and storms. Understanding present-day processes gives some confidence in future projections.

9. Conclusions

This report has given a brief introduction to coastal modelling, which hopefully can aid coastal managers in understanding coastal processes and allow some critical assessment of consultancy reports, even if there is no scope to run models themselves.

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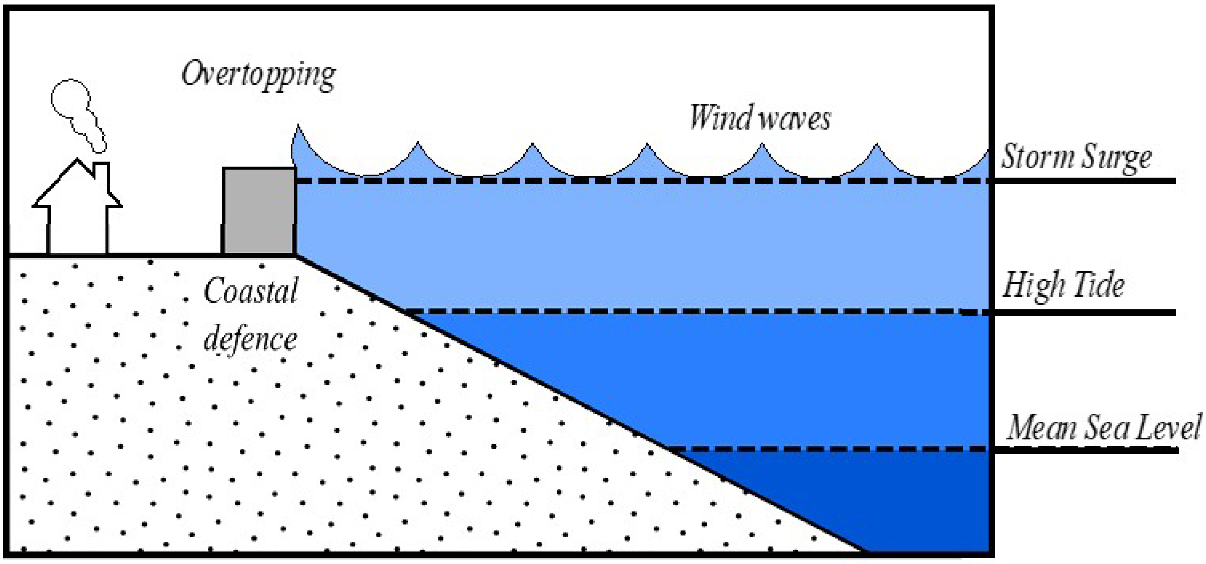
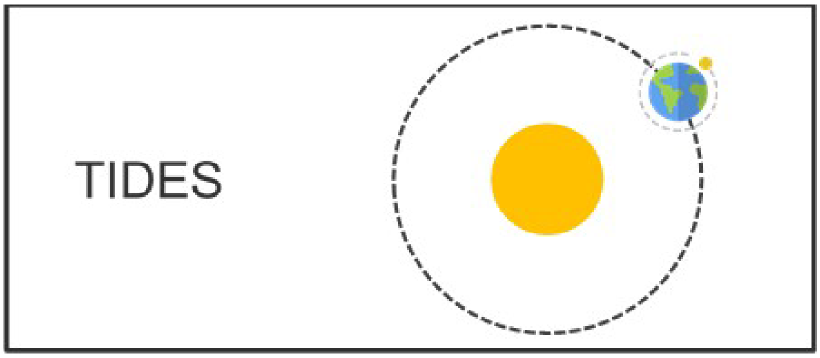
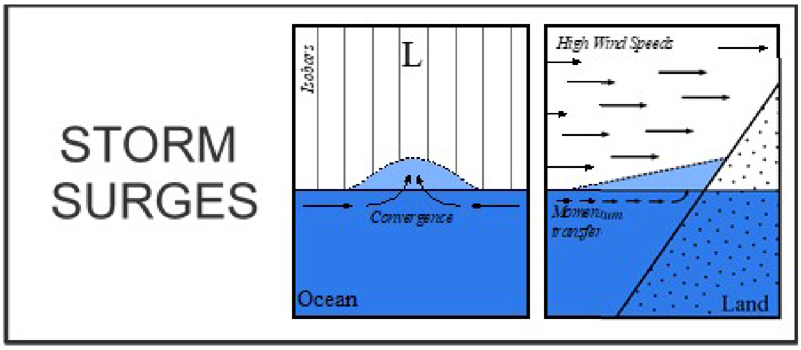
Appendix 1: Definitions of coastal sea level





Tides are driven by the gravitational attraction of the Moon and Sun on the Earth and hence are related to their predictable periodic movements. The actual tide at a particular position on the Earth is modified by the geometry of coastlines, varying water depth and the rotation of the Earth.



Storm surges are caused by storm winds and low atmospheric pressures. Strong winds are most effective at piling up water against the coast in shallow water, low pressure centres raise sea levels by the inverse barometer effect – one cm sea level for every 1mb (100 Pascals) of atmospheric pressure drop.

Appendix 2: Further reading and access to models

If there is interest in getting more training on coastal modelling, there are various ways of doing this. There are textbooks and online courses for self-education, or courses run by DHI (Denmark), Deltares (Netherlands) or HR Wallingford (UK). The National Oceanography Centre modelling staff would be pleased to have a dialogue about this – please contact the lead author of this document.

Table A1 shows a number of model in common use, with their application and source. Various reviews of models have been carried pout e.g. Smallman et al. (1994).

Table A1: Examples of process-based dynamical coastal models

Model	Organ-isation	Website	Dimensions	Wave forcing	Sediment	Morphology	Particle tracking	Water quality
Hydrodynamic Models								
Delft3D[#]	Deltares	oss.deltares.nl/web/delft3d	3D	SWAN	C, NC	Y, ST	Y	Y
POM	Princeton University	www.ccpo.odu.edu/POMWEB	3D	Y	N	N	N	N
NEMO[*]	Nemo System Team	www.nemo-ocean.eu	3D	Y	N	N	Y	Y
DIVAST	Cardiff University		2D	N	Y	N	N	Y
EFDC	US Environ-mental Protection Agency	www.epa.gov/exposure-assessment-models/efdc	3D	Y	C, NC	Y, ST	Y	Y
TELEMAC-2D[#]	EDF	www.opentelemac.org	2DH	TOMA-WAC	C, NC	Y, ST	Y	Y
TELEMAC-3D[#]	EDF	www.opentelemac.org	3D	TOMA-WAC	C, NC	Y, ST	Y	Y
OpenFOAM	OpenCDF Ltd	www.ansys.com	3D	Y	C, NC	Y, ST	Y	N
FVCOM								
MIKE 21[#]	Danish Hydraulics Institute	https://www.mikepoweredbydhi.com/products/mike-21	2D	MIKE 21 SW	C, NC	Y, ST	Y	Y
MIKE 3[#]	Danish Hydraulics Institute	https://www.mikepoweredbydhi.com/products/mike-3	3D	MIKE 3 SW	C, NC	Y, ST	Y	Y
ADCIRC			2D, 3D					
Wave Models								
SWAN	Delft University of Technology	www.swan.tudelft.nl	2DH	Y	N	N	N	N
WAVEWATCH III[*]	NOAA	Polar.ncep.noaa.gov/waves/wavewatch	2DH	Y	N	N	N	N
TOMAWAC	EDF	www.opentelemac.org	2DH	Y	N	N	N	N
WAM	Helmholtz-Zentrum	Mywave.github.io/WAM/	2DH	Y	N	N	N	N

	Geesthacht (HZG), Germany							
Inundation & Overtopping Models								
Lisflood_FP	University of Bristol	www.bristol.ac.uk/geography/research/hydrology/models/lisflood	2DH	N	N	N	N	N
SWASH	Delft University of Technology	swash.sourceforge.net	2DH	Y	N	N	N	N
EurOtop	HR Wallingford	www.overtopping-manual.com	1DH	Y	N	N	N	N
Short-term process-based morphological evolution models								
XBeach	Deltares	oss.deltares.nl/web/xbeach/	1DH 2DH	Y	NC	Y	N	N
XBeach-G	Deltares	oss.deltares.nl/web/ xbeach/	1DH	Y	NC	Y	N	N
CSHORE	US Army Corps of Engineers	sites.google.com/site/cshorecode	1DH 2DH	Y	NC	Y	N	N
Long-term process-based morphological evolution models								
SCAPE+	Mike Walkden, University of Bristol	www.channelcoast.org/iCOASST/SCAPE/	Q3D		NC, C	Y	N	N
COVE	BGS & University of Glasgow	github.com/COVE-Model	1DH, 2 Line		NC, C	Y	N	N
CEM	Duke University	csdms.colorado.edu/wiki/Model:CEM	1DH, 1 Line		NC, C	Y	N	N
UnaLinea	HR Wallingford	www.channelcoast.org/iCOASST/UNALINEA/	1DH, 1 Line		NC, C	Y	N	N
ASMITA	Delft University of Technology	www.coastalsea.uk/download-page/asmitaoo	Q2D		NC, C	Y	N	N
ESTEEM	University College London	www.channelcoast.org/iCOASST/ESTEEM/	1D 2D		NC, C	Y	N	
COASTAL ME	Southampton University	www.channelcoast.org/iCOASST/COASTAL_ME/	2DH, 1-line		NC, C	Y	N	
MESO i	Southampton University	www.channelcoast.org/iCOASST/MESO_i/	Q2D		NC, C	Y	N	

*denotes restricted open source, # denotes widely used commercial software, all other models are open source. Sediment: NC = Non-cohesive, C = Cohesive. Morphology: ST = Short-term (adapted from Pye et al. 2017)

A very useful portal for accessing coastal models is via the University of Colorado Community Surface Dynamics Modelling System (CSDMS) https://csdms.colorado.edu/wiki/Coastal_models.

Other useful websites:

http://www.coastalwiki.org/wiki/Modelling_coastal_hydrodynamics

https://www.mottmac.com/coastal/coastal-processes-modeling-analysis#

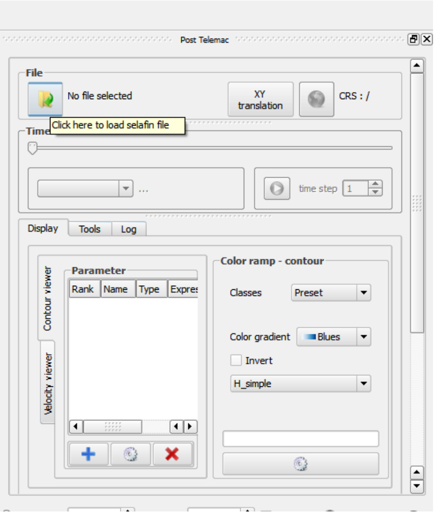
For those who want to access the latest research articles there are Special Issues/Article Collections e.g. in the journal Ocean Modelling https://www.sciencedirect.com/journal/ocean-modelling/special-issue/1055D2WFDJ9 but these may require subscription to the journal. Some papers are published as Open Access which means they are freely available online to any reader.

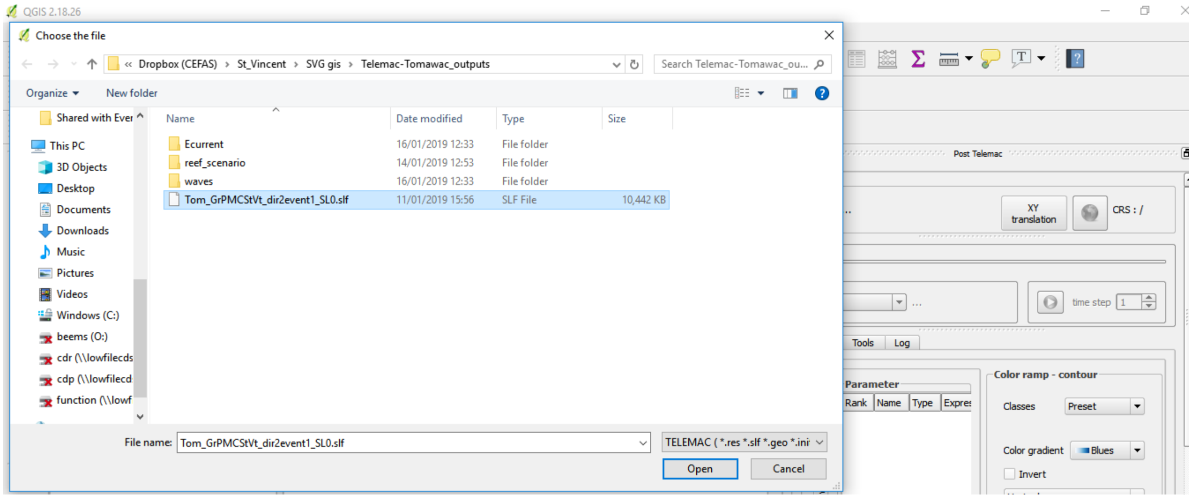
Appendix 3: How to input TELEMAC/TOMAWAC model data into QGIS

In the following steps, it is assumed that all the required plugins have been installed in QGIS. We do not go through the different steps of their installation. Hereafter, the **bold** words are referring to QGIS options.

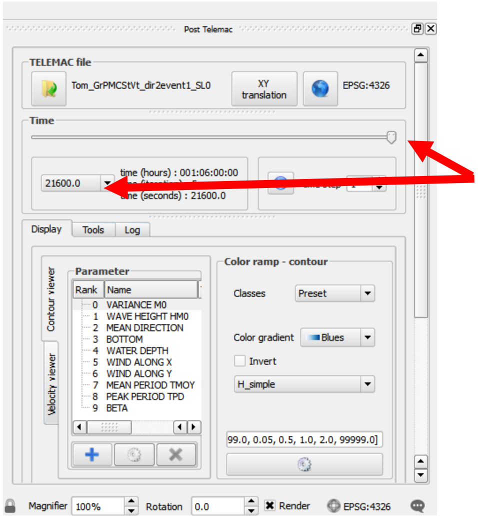
Open Telemac file:

Open the plugin "PostTelemac" (**Plugins→PostTelemac→PostTelemac**)





Select the last time-step, which is the final results of the simulation (the model has converged to the final results). You can do that in different way: more the cursor along the time line OR select the final time directly



21600.0

time (hours) : 001:06:00:00

time (seconds) : 21600.0

Rank	Name
0	VARIANCE M0
1	WAVE HEIGHT HM0
2	MEAN DIRECTION
3	BOTTOM
4	WATER DEPTH
5	WIND ALONG X
6	WIND ALONG Y
7	MEAN PERIOD TMOY
8	PEAK PERIOD TPD
9	BETA

Classes: Preset

Color gradient: Blues

☐ Invert

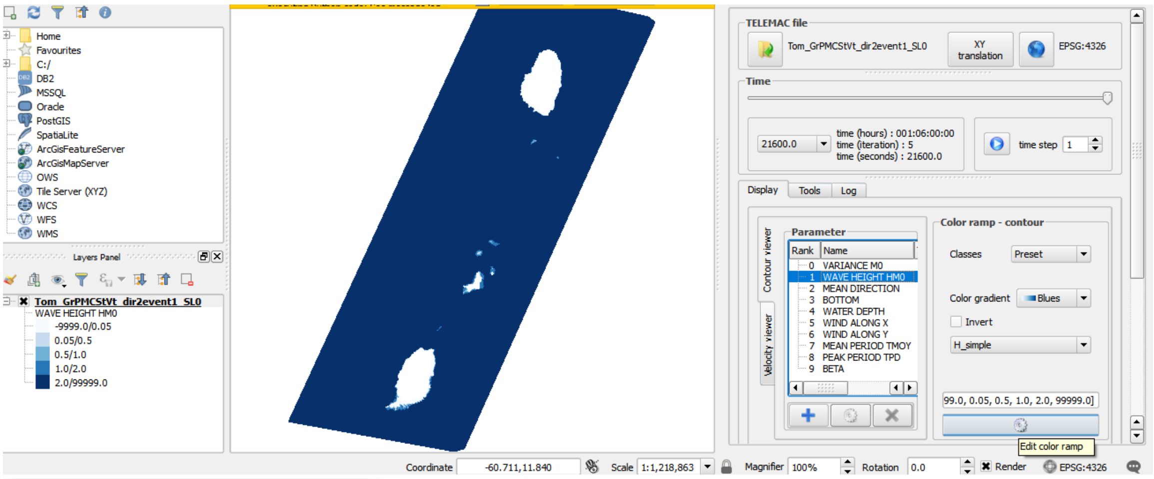
H_simple

99.0, 0.05, 0.5, 1.0, 2.0, 99999.0]

Magnifier 100% Rotation 0.0 ☒ Render EPSG:4326

Select the **wave height HMO** variable

The colour scale is not suitable, as we cannot see the variation in wave height for large waves. Change the colour scale by clicking on the **nut icon -Edit color ramp** (for example, linear scale, incremented by one, up to 15m wave height):



☒ Tom_GrPMCStVt_dir2event1_SL0

WAVE HEIGHT HM0
- -9999.0/0.05
- 0.05/0.5
- 0.5/1.0
- 1.0/2.0
- 2.0/99999.0

Tom_GrPMCStVt_dir2event1_SL0 EPSG:4326

21600.0

time (hours) : 001:06:00:00
time (iteration) : 5
time (seconds) : 21600.0

time step 1

Rank	Name
0	VARIANCE M0
1	WAVE HEIGHT HM0
2	MEAN DIRECTION
3	BOTTOM
4	WATER DEPTH
5	WIND ALONG X
6	WIND ALONG Y
7	MEAN PERIOD TMOY
8	PEAK PERIOD TPD
9	BETA

Classes: Preset

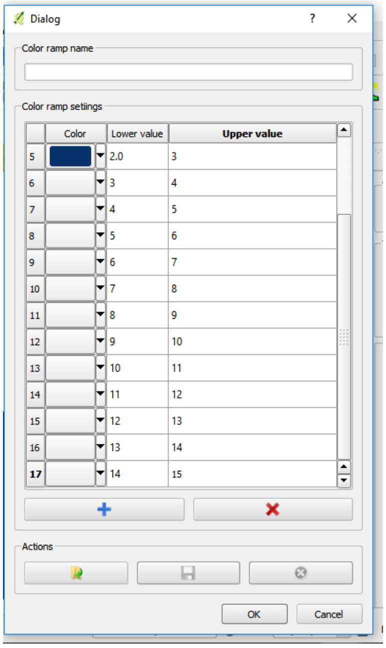
Color gradient: Blues

☐ Invert

H_simple

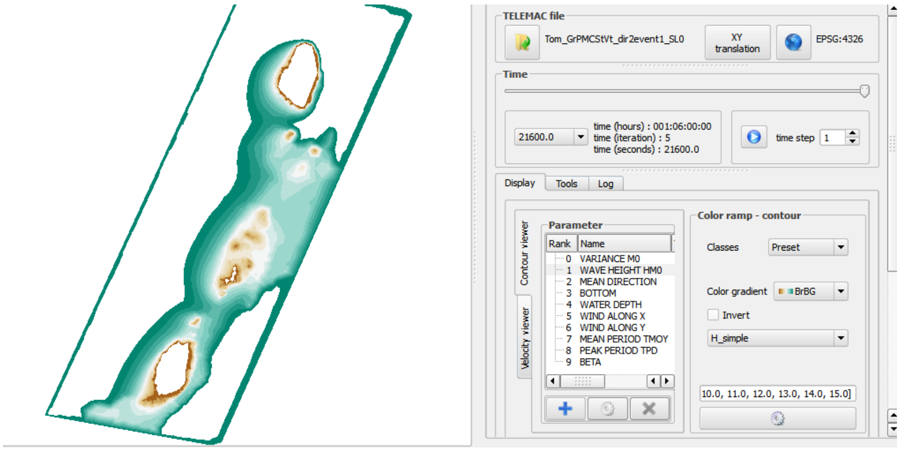
99.0, 0.05, 0.5, 1.0, 2.0, 99999.0]

Coordinate -60.711,11.840 Scale 1:1,218,863 Magnifier 100% Rotation 0.0 ☒ Render EPSG:4326



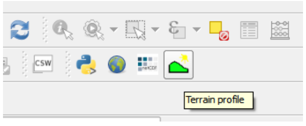
	Color	Lower value	Upper value
5	■	2.0	3
6		3	4
7		4	5
8		5	6
9		6	7
10		7	8
11		8	9
12		9	10
13		10	11
14		11	12
15		12	13
16		13	14
17		14	15

Change the **colour gradient** to BrBG:

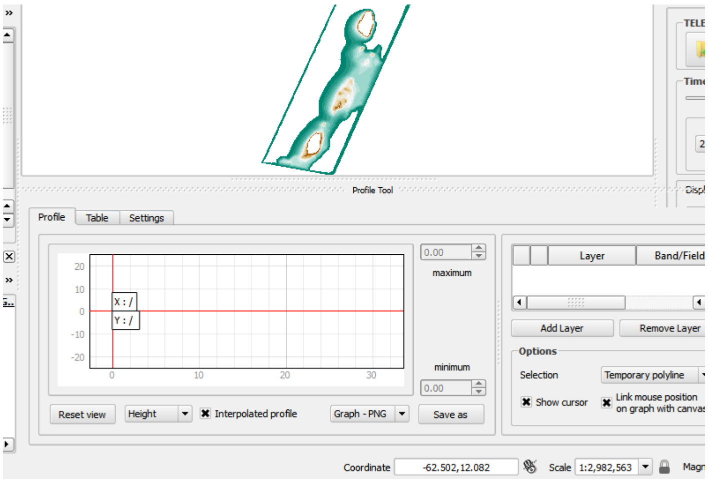


Draw a cross-shore profile of Telemac results

Open the profile tool by choosing **Plugins→Profile Tool→Terrain profile** or by clicking on this icon:

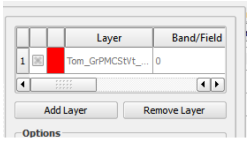


It opens the following sub-windows, and the mouse is transformed into a cross in the active window:

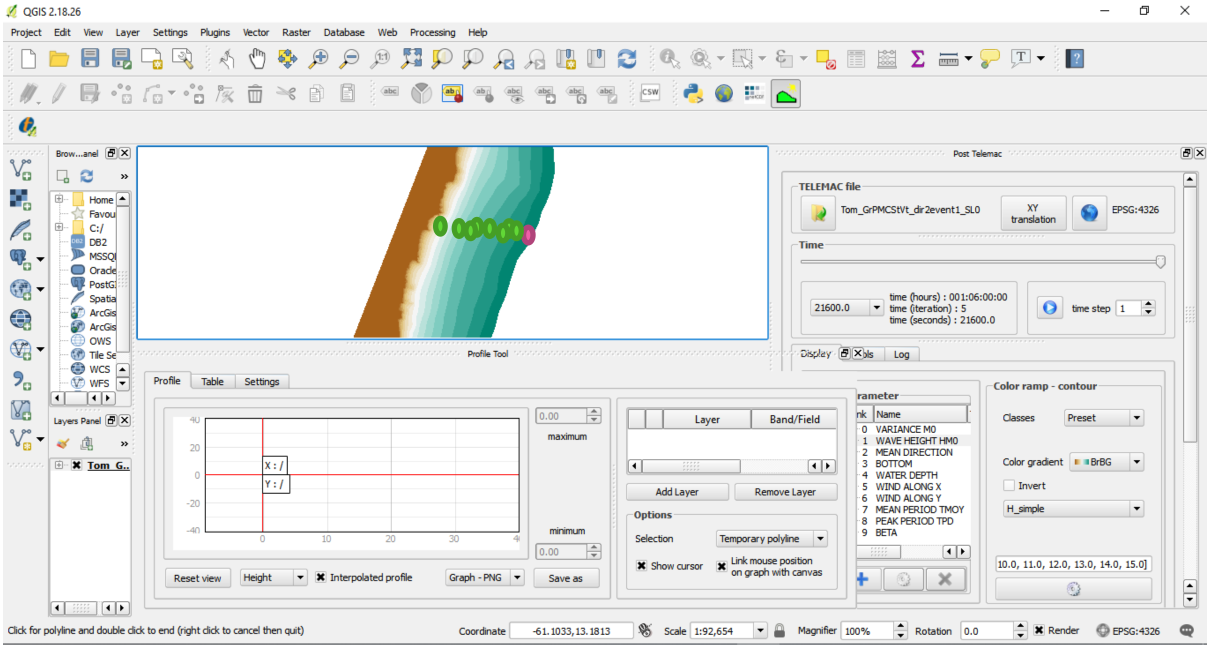


Select the layer you want to create a cross-shore profile of in the layer panel, and make sure the layer is highlighted. If necessary make the profile tool subwindow larger and click "**add layer**".

The layer you have selected should appear. Here the results file Tom_GrPMCStVt_dir2event1_SL0.slf



Zoom in, in the windows displaying Telemac data:



TELEMAC file: Tom_GrPMCStVt_dir2event1_SL0 — XY translation — EPSG:4326

Time: 21600.0 — time (hours) : 001:06:00:00 — time (iteration) : 5 — time (seconds) : 21600.0 — time step 1

Selection: Temporary polyline

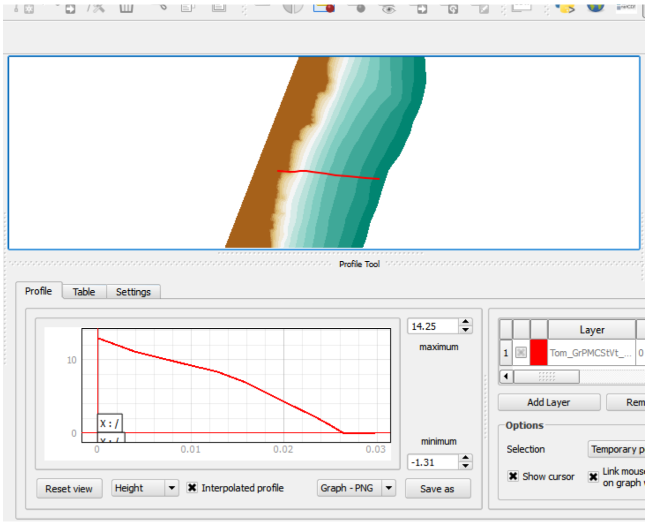
Parameter:
0 VARIANCE M0
1 WAVE HEIGHT HM0
2 MEAN DIRECTION
3 BOTTOM
4 WATER DEPTH
5 WIND ALONG X
6 WIND ALONG Y
7 MEAN PERIOD TMOY
8 PEAK PERIOD TPD
9 BETA

Classes: Preset — Color gradient: BrBG — ☐ Invert — H_simple — 10.0, 11.0, 12.0, 13.0, 14.0, 15.0]

Click for polyline and double click to end (right click to cancel then quit) — Coordinate -61.1033,13.1813 — Scale 1:92,654 — Magnifier 100% — Rotation 0.0 — EPSG:4326

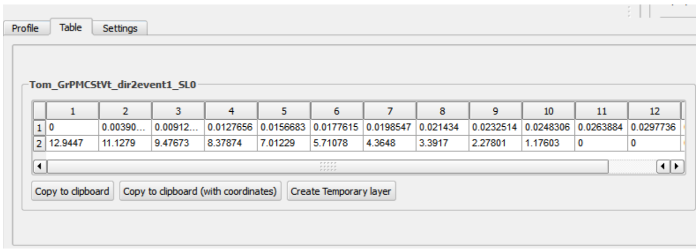
Select the profile tool, and begin drawing a cross-shore section, by selecting a point offshore (green dot)

Keep on building the cross-shore profile by adding additional points, clicking each time you want to extract the data (purple points…) and double click for the last point of the profile. This will end the cross-shore profile. The cross-shore section is updated gradually in the plugin window:



maximum: 14.25 — minimum: -1.31 — Layer 1: Tom_GrPMCStVt_…

You can save the picture as a png file, and/or look at the extracted data by choosing “table” in the sub-window. You can also save those variables.

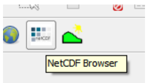


Tom_GrPMCStVt_dir2event1_SL0

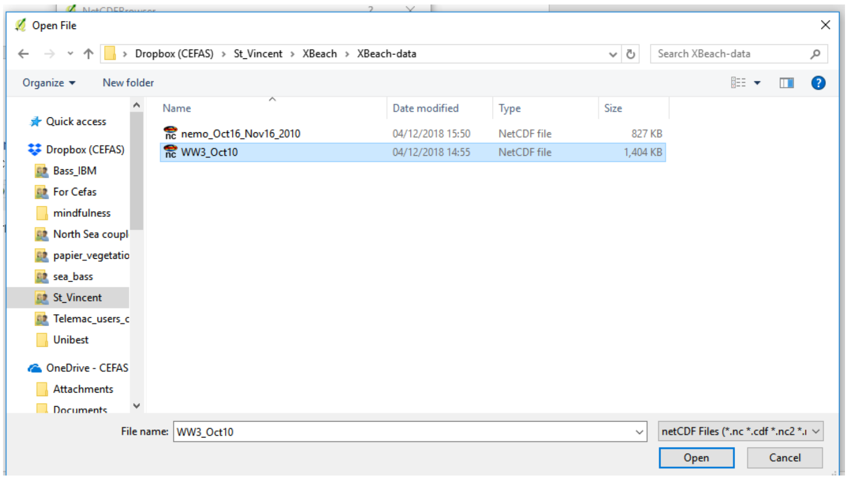
	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0.00390…	0.00912…	0.0127656	0.0156683	0.0177615	0.0198547	0.021434	0.0232514	0.0248306	0.0263884	0.0297736
2	12.9447	11.1279	9.47673	8.37874	7.01229	5.71078	4.3648	3.3917	2.27801	1.17603	0	0

Import netcdf data

Import the plugin **netCDF Browser** by going **Plugins→netCDF Browser → netCDF Browser** or by clicking on the following icon:



This will open a new window for you to find the netCDF data you want to open:

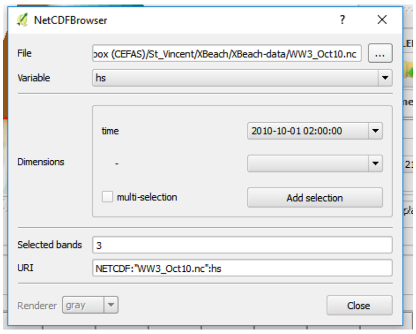


Name	Date modified	Type	Size
nemo_Oct16_Nov16_2010	04/12/2018 15:50	NetCDF file	827 KB
WW3_Oct10	04/12/2018 14:55	NetCDF file	1,404 KB

File name: WW3_Oct10

netCDF Files (*.nc *.cdf *.nc2 *.

Then select the wave height variable (**Variable→hs**), un-click the multiple selection and select a time different from the first time (in which we do not have data). Click “add selection”



File: oox (CEFAS)/St_Vincent/XBeach/XBeach-data/WW3_Oct10.nc

Variable: hs

time: 2010-10-01 02:00:00

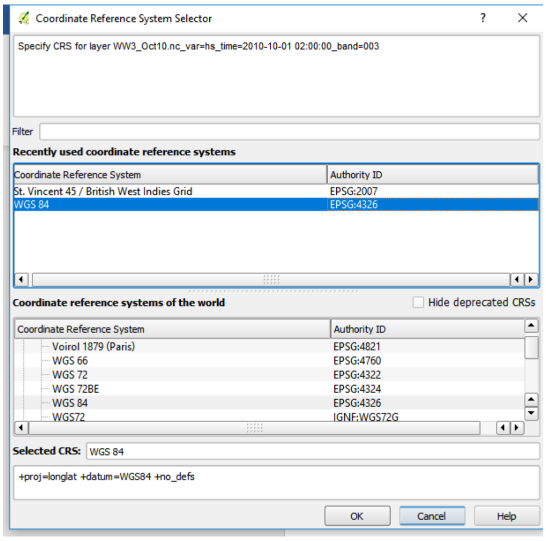
☐ multi-selection

Selected bands: 3

URI: NETCDF:"WW3_Oct10.nc":hs

Renderer: gray

If necessary, select the correct projection (here WGS84)



Specify CRS for layer WW3_Oct10.nc_var=hs_time=2010-10-01 02:00:00_band=003

Coordinate Reference System	Authority ID
St. Vincent 45 / British West Indies Grid	EPSG:2007
WGS 84	EPSG:4326

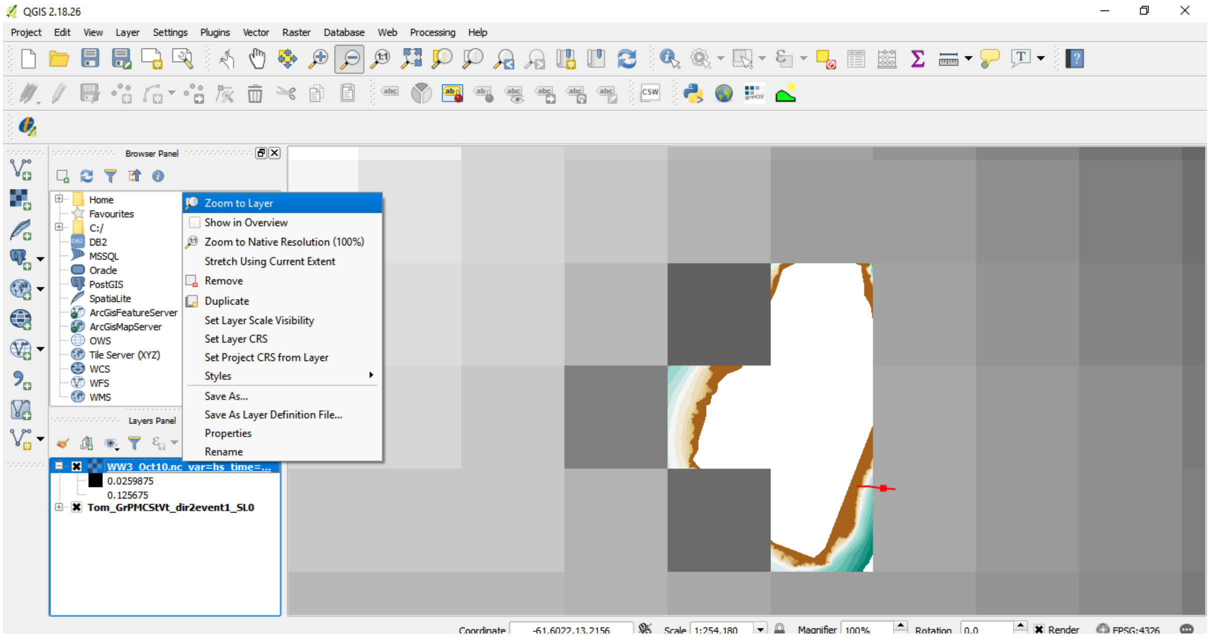
Coordinate Reference System	Authority ID
Voirol 1879 (Paris)	EPSG:4821
WGS 66	EPSG:4760
WGS 72	EPSG:4322
WGS 72BE	EPSG:4324
WGS 84	EPSG:4326
WGS72	IGNF:WGS72G

Selected CRS: WGS 84

+proj=longlat +datum=WGS84 +no_defs

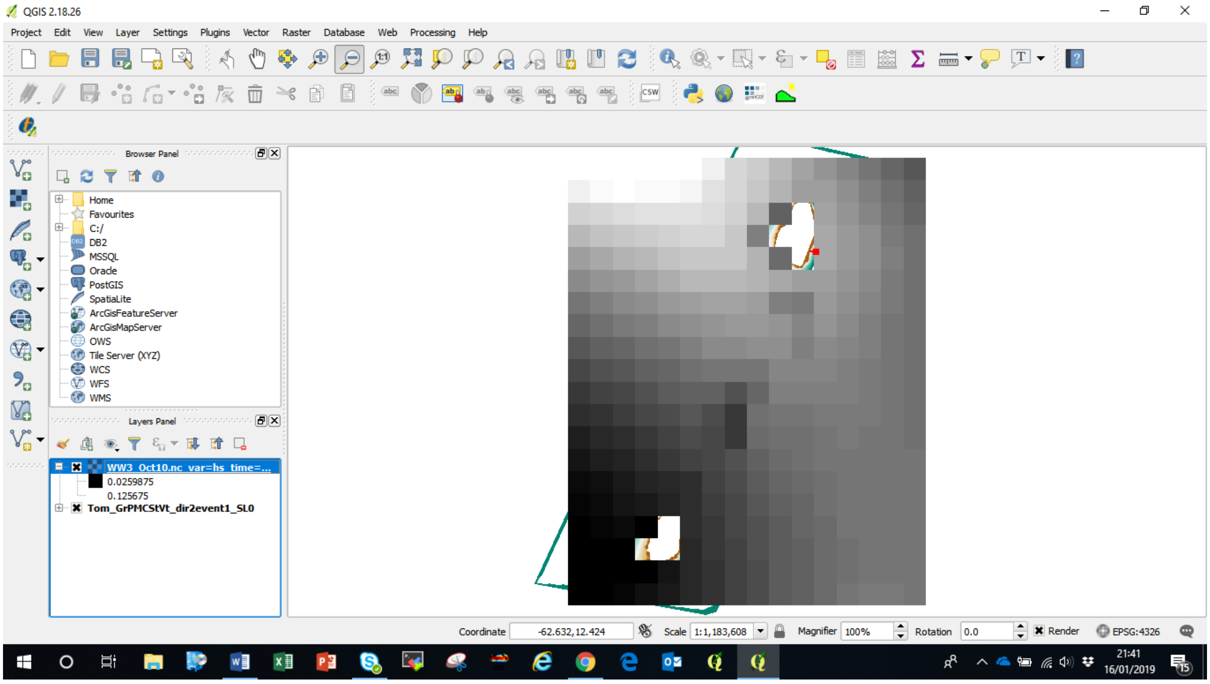
The new data is listed in the layer panel.

Click “zoom to layer”



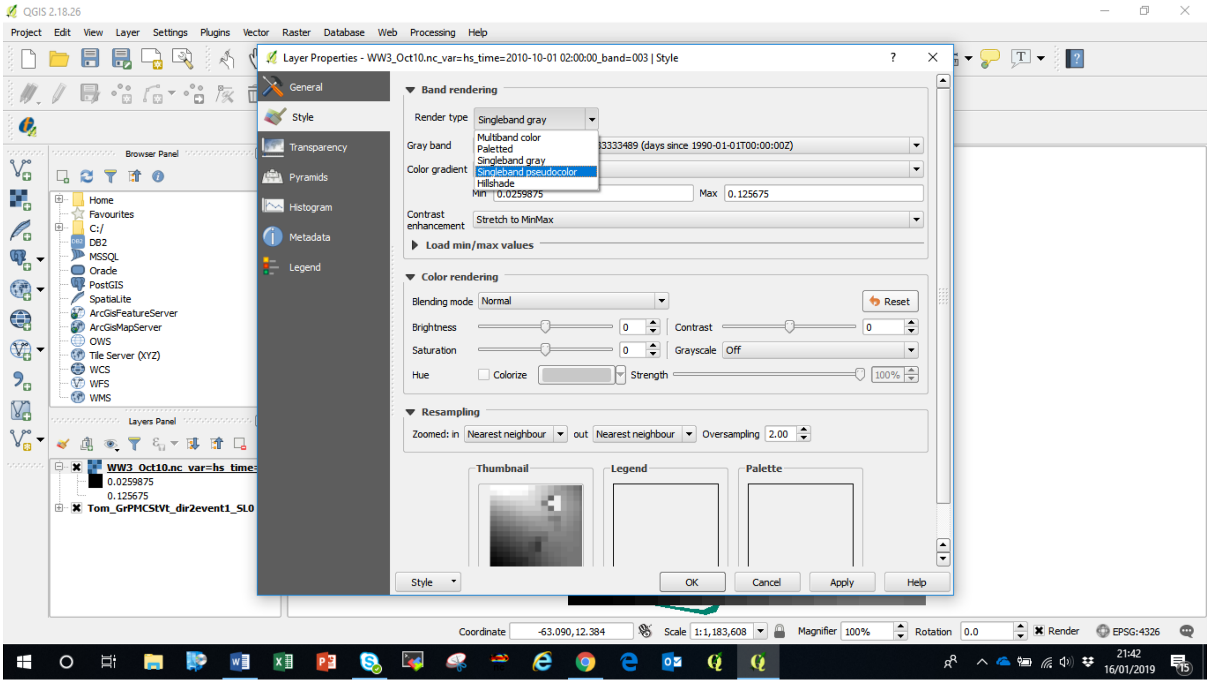
☒ WW3_Oct10.nc_var=hs_time=...
0.0259875
0.125675
☒ Tom_GrPMCStVt_dir2event1_SL0

Coordinate -61.6022,13.2156 Scale 1:254,180 Magnifier 100% Rotation 0.0 ☒ Render EPSG:4326

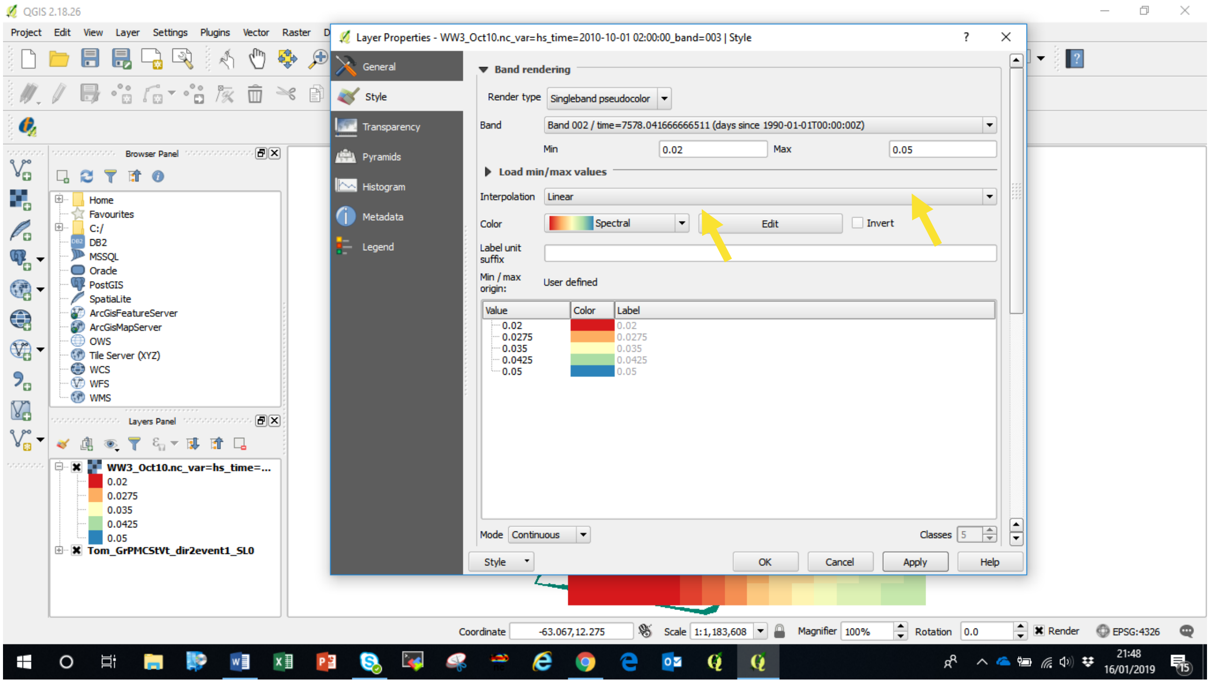


This displays the entire dataset extent.

In the properties of the layer (right click→properties), change the colour scale into a single band pseudo-colour scale.



Play with the scale (the minimum and maximum of the scale) so as to have a sensible colour scale for the data selected.



Layer Properties - WW3_Oct10.nc_var=hs_time=2010-10-01 02:00:00_band=003 | Style

Band rendering

Render type: Singleband pseudocolor

Band: Band 002 / time=7578.041666666511 (days since 1990-01-01T00:00:00Z)

Min: 0.02 Max: 0.05

Interpolation: Linear

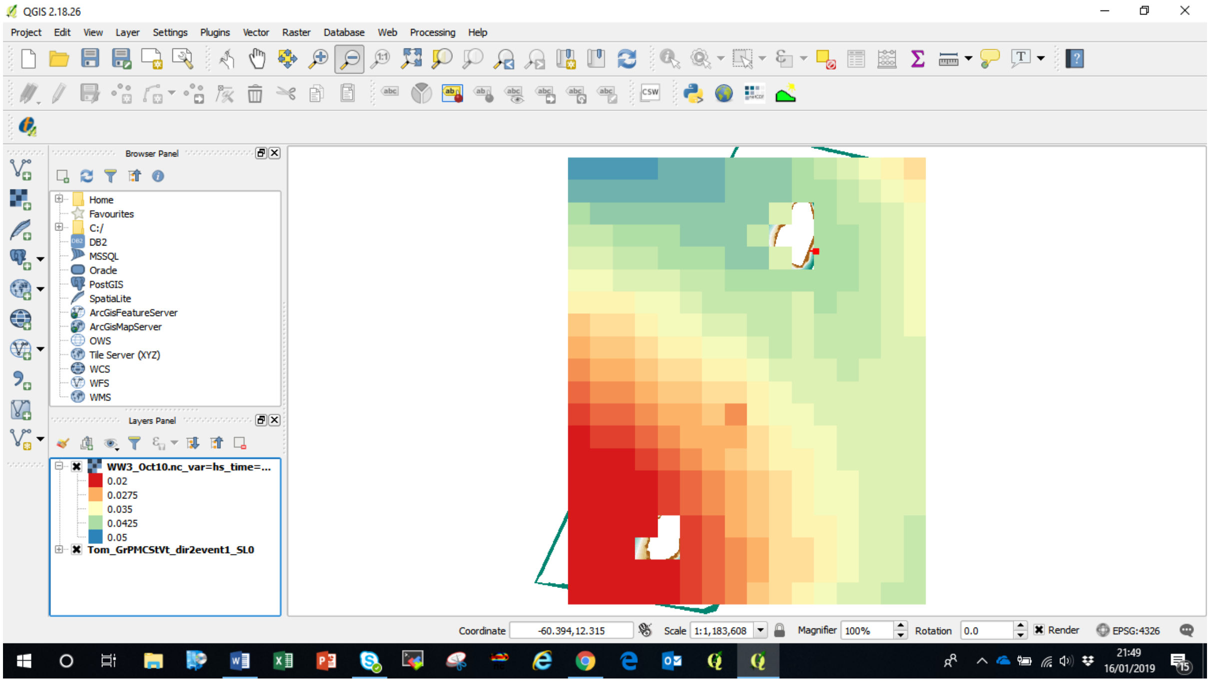
Color: Spectral

Label unit suffix:

Min / max origin: User defined

Value	Color	Label
0.02	🟥	0.02
0.0275	🟧	0.0275
0.035	🟨	0.035
0.0425	🟩	0.0425
0.05	🟦	0.05

Mode: Continuous   Classes: 5



Appendix 4: Using the SWAN coastal wave model

The SWAN wave model is a 3G wave model, which may be used in default mode or using various user options. There is very good documentation for this model. It can be downloaded from https://www.tudelft.nl/en/ceg/about-faculty/departments/hydraulic-engineering/sections/environmental-fluid-mechanics/research/swan/ or http://swanmodel.sourceforge.net/download/download.htm or https://sourceforge.net/projects/swanmodel/files/swan/. The latter gives most information. At the time of writing (March 2020) the latest version of the code is 41.31 (May 2019). This was the version used to implement a local area model for the SE coast of St Vincent (including location of Argyle International Airport (AIA).

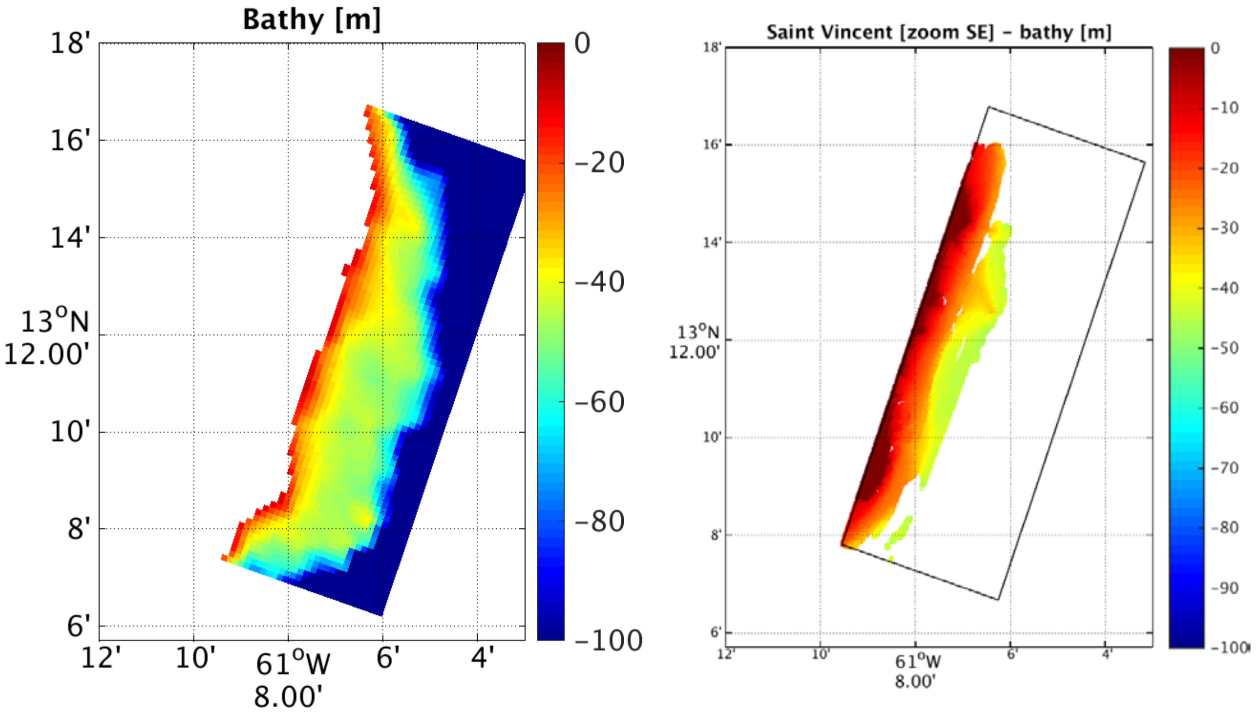


Figure A3.1: (left) GEBCO 30 bathymetry (1km); (right) UKHO bathymetry from Lidar survey

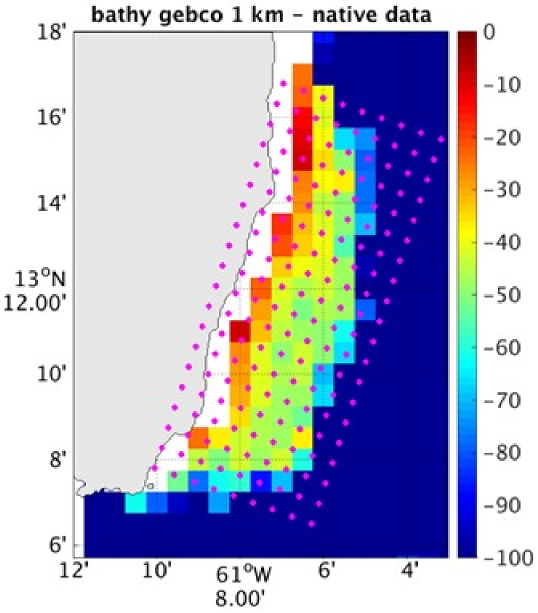


Figure A3.2: Showing model resolution (1km) grid points extracted from GEBCO data