Manual. Climada Coastal Hazards Module

A tool to assess coastal hazards and risk of flooding globally.

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1. Introduction

'Climada' stands for 'climate adaptation' and is a probabilistic natural catastrophe damage model. Information on the core package can be found at <https://github.com/davidnbresch/climada/wiki>. This module add specific features for coastal zones.

This module adds specific functions to the climada suite that are particularly interesting for coastal areas and coastal risks. The functions and tools in this module work with the climada main core functions and applications (i.e. you need to have climada installed). Some functions have been modified from core climada original functions and adapted to more user specific needs and further customization.

This document provides a more theoretical background than the brief "README" guide that can be found in the github repository. It first describes the basis of probabilistic cat modeling and provides further insight in the equations and tools of the '*coastal hazards module'*. A final section describes some examples that can be found in the 'code' folder of the module and further functionalities.

2. Methodology for Probabilistic damage model

Risk is generally defined as a possible danger; which size can be expressed as loss potential multiplied by the occurrence frequency. An **event loss** or damage is the sum of all individual losses resulting from a single occurrence. In risk assessments, the risk depends on three basic sets of data, which configure different sections of the damage model:

- **Hazard** (or peril): Where, how often and with what intensity do events occur?
- **Damage function** (also called vulnerability or vulnerability curve): the extent of damage at a given event intensity
- **Assets** (also referred to as value distribution or portfolio of exposed assets): location and value of the various types of buildings and/or people

These three building blocks are quantified separately and are then combined to estimate the damaged generated by an event (Figure 1). This approach may generally be applied to all forms of natural hazard, whether storm, flood or any other type of peril.

Under this framework, adaptation takes play when we modify either the hazard, the damage functions or the assets, through actions that reduce each driver of risk (SwissRe 2011; ECA 2009). Coastal adaptation measures can include structural and non-structural interventions to attenuate or mitigate the hazard, for example, levees, flood walls or wetland restoration; but can also involve updated building codes, which would modify the original damage curves; or coastal management practices that influence the distribution of assets (e.g. coastal setbacks or other coastal development regulations).

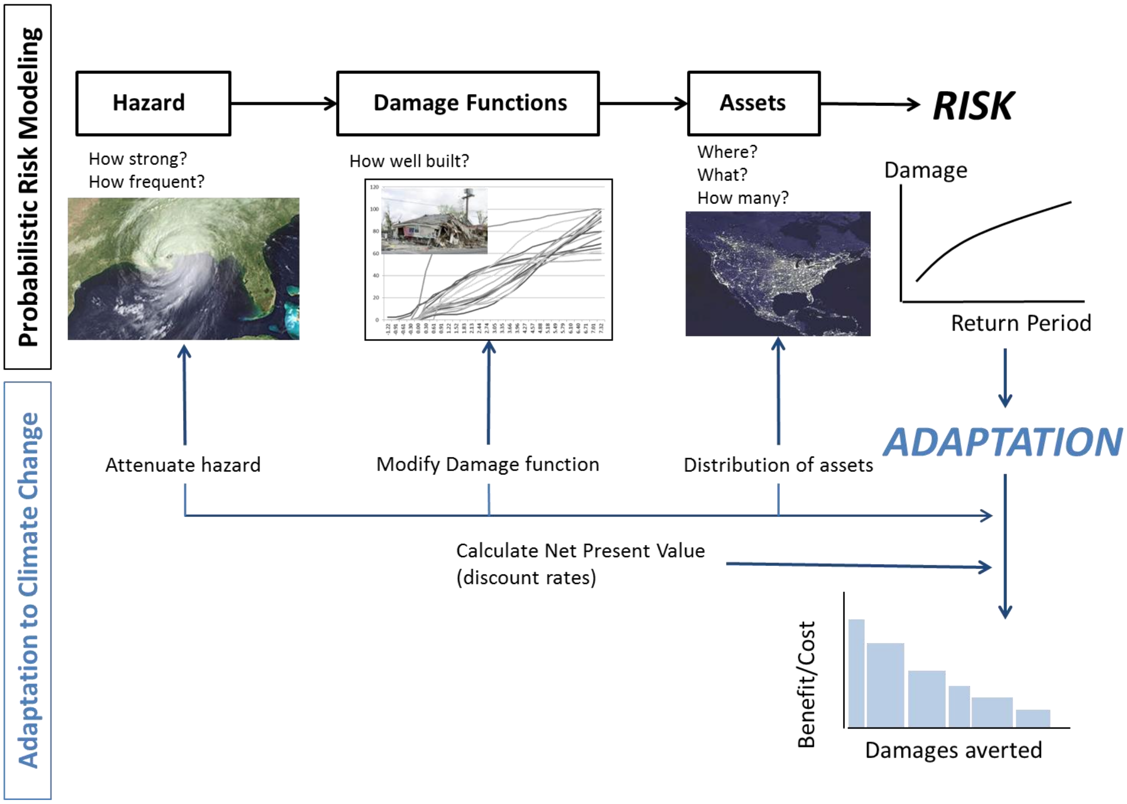


Figure 1. Sketch for quantitative risk assessment and assessing the economic benefit of adaptation

The simplest way to assess the damage is to simulate an individual natural catastrophe scenario. This is known as “deterministic” or “scenario-based” modeling. Such models often refer back to major historical damage events, applying these to the assets that exist now (“as-if analysis”). The disadvantage of this method is that, whilst it allows a single, extreme, individual event damage to be assessed, it fails to take account of all the other events that might occur. Therefore, it is not possible to calculate an expected annual damage for a portfolio of assets from a single event damage, and predictions of the occurrence frequency will remain uncertain.

However, a “probabilistic” or “stochastic” approach simulates a set of possible events that could unfold during a period of time (thousands of events), informed by the historical distribution of storms, rather than simply analyzing one individual event. This approach produces a “representative” list of event damages (i.e. that accurately reflects the risk). From this set of events, it is possible to understand the relationship between damage potential and frequency of occurrence, and hence the cost of average and extreme damage burdens.

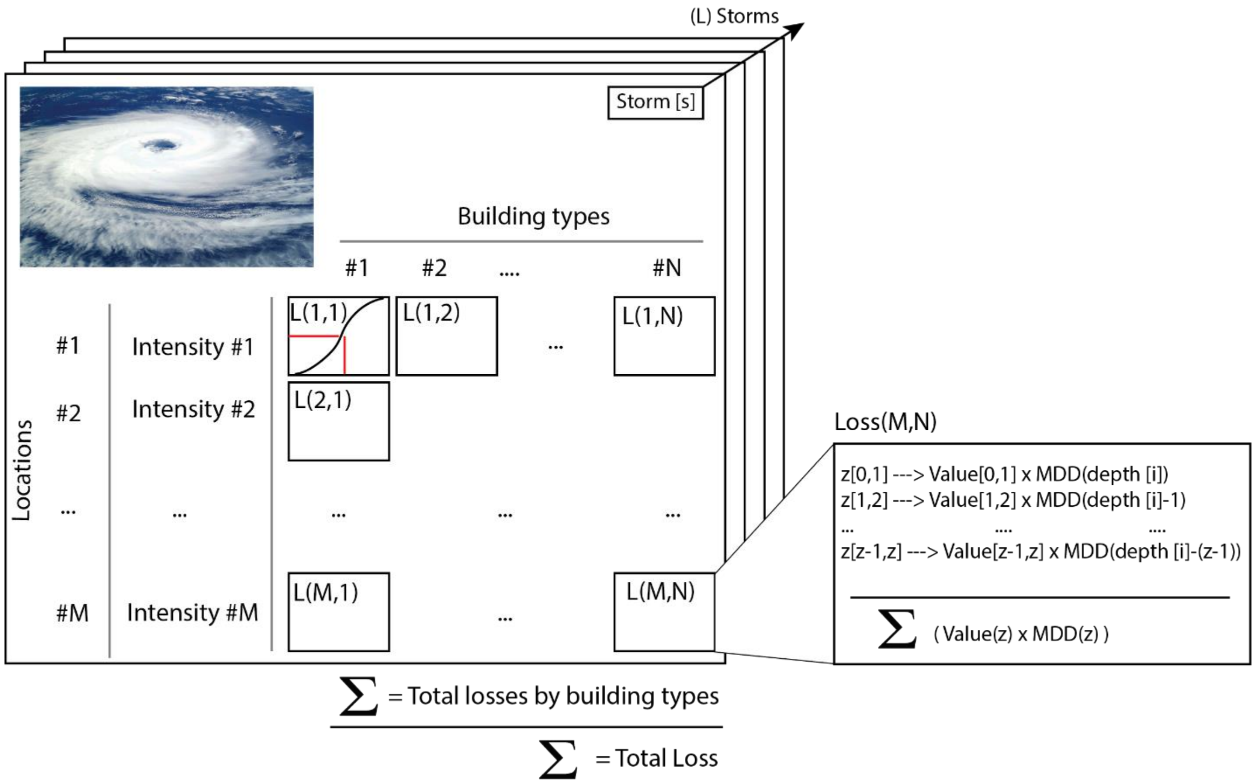


Figure 2. Methodological concept for probabilistic risk assessment.

Therefore, the **quantitative probabilistic risk assessment** is the statistical description of losses across events and scenarios. Losses from each individual storm are calculate across locations and types of assets as follow (Figure 2):

1) The hazard module generates L storms, based on the historical distribution of storms, from 1851 onwards from http://weather.unisys.com/hurricane. We use random walks with random origin and track pathway (Figure 3). More details can be found in the module dedicated to tropical cyclones in *climada* (Bresch and Mueller 2014).
2) For each storm or event (st), the expected intensity is calculated at each location (or centroid). For flooding, the intensity corresponds to the **total water level**, which is the combination of mean sea level, tides, surges and wave run up (Losada et al. 2013), while for wind is the wind gust. A specific section on hazard modules follows describing the models used to simulate each hazard component.
3) For each asset type, there is a **damage function** (also called vulnerability curve) that is specific to the asset type (e.g. type of building) and relates the intensity of the hazard (e.g. local water depth) with the damage degree (i.e. mean damage degree, MDD), which represents the damage inflicted by that intensity to the total value of the asset. The damage or loss is calculated by multiplying the MDD (e.g. 40%) and the value of the asset (e.g. 1,000,000), resulting in a (ground up) damage of 40,000.
4) In the case of flooding, the water depth at each asset location depends on the elevation. The model factors in this effect for each study unit or centroid, where the asset value at each elevation has been previously precomputed (e.g. value between elevation 0 and 1 meters, 1 and 2, etc.). The coastal exposure (i.e. value of assets for different ground elevations, i.e. *value(z)*) is then associated with the MDD for each specific relative depth (1, 2, …. meters) as indicated in Figure 2: loss at elevation z = [value(z) x MDD (z)]. Finally, the total loss at the location is the sum of relative losses of buildings across elevations (see description for loss at location m and asset n in the Figure).
5) This process runs for all the asset types and all locations, throughout storms. The result is a distribution of losses that can be aggregated and analyzed statistically. The sum of all damages produces the total damage from one event is the event damage. For example, in the figure, losses are aggregated by building types and the total loss associated from the storm is calculated.

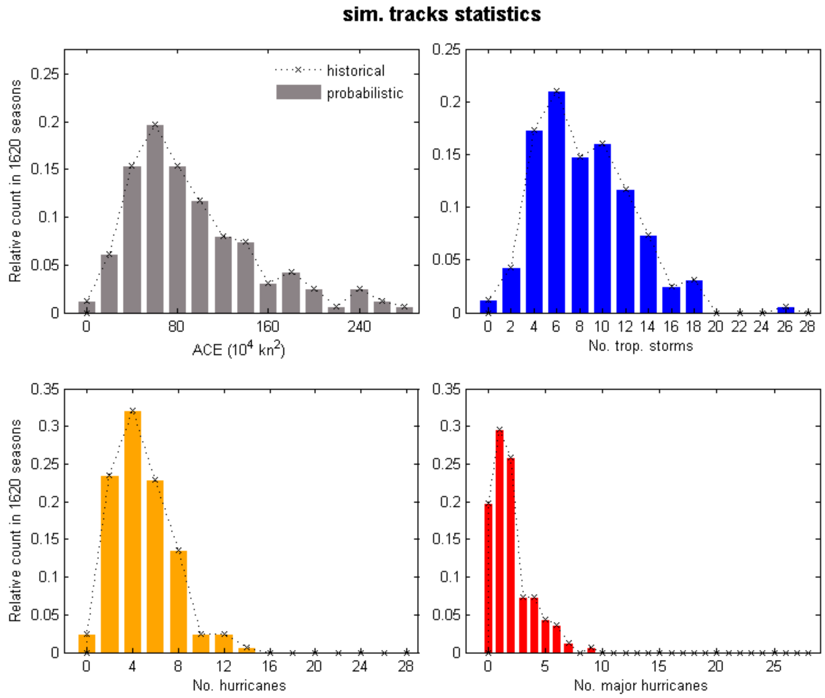


Figure 3. Statistics of simulated storms based on historical tracks. The simulation reproduces the statistical distribution of Accumulated Cyclone Energy (upper left panel), the number of tropical storms (upper right), total number of hurricanes (lower left) and major hurricanes, i.e. category of 3 or above (lower right).

The set of losses is then analyzed statistically, e.g. (Olsen et al. 2015), to define (1) expected annual damage, as the total sum of each event damage multiplied by the probability of each storm; and (2) extreme event loss, which corresponds to a certain return period. **Return period** describes the average time within which the magnitude of an event is reached or exceeded. The return period is inversely proportional to the occurrence frequency, i.e. a return period of 100 year corresponds to an occurrence frequency of 1 in 1,000 years, i.e. 0.01 per year.

3. Hazard Models

Part I. Storm simulation

This module uses as input the track information and stochastic simulation from the climada core functions. For example, Figure 4 and 5 show the historical distribution of storms reaching Quintana Roo, in Mexico, and simulates probabilistic pathways for hurricane Dean – see (Bresch and Mueller 2014) for more details.

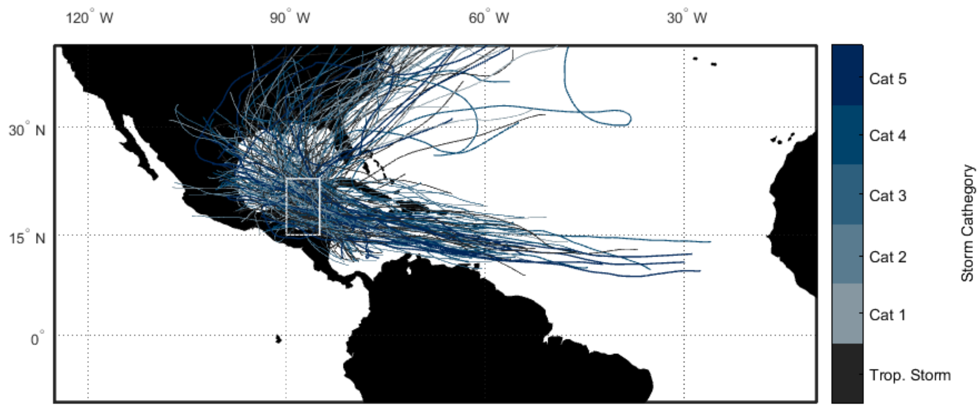


Figure. Historical tracks in the region

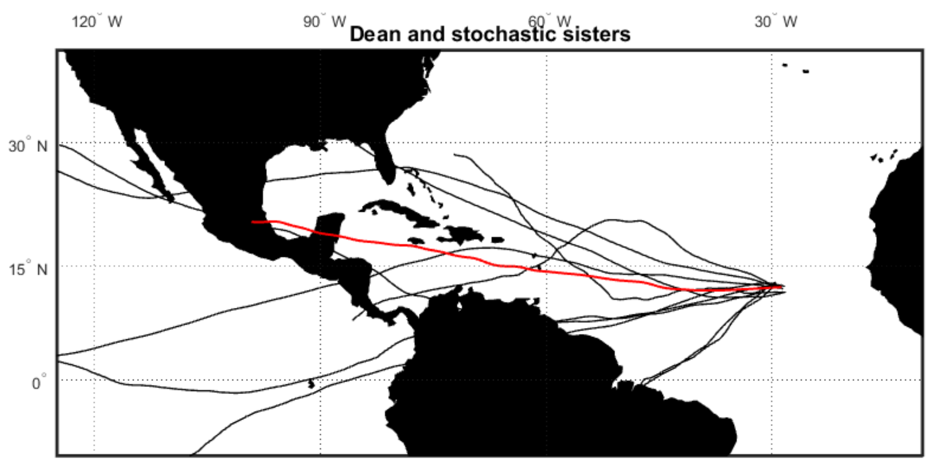


Figure. Example of synthetic storms

Part II. Defining the hazard from the storm tracks

From the information of the storm tracks, the module infers the spatial field of pressure and winds, and from them the effect on waves and surges. Additionally, the module includes information on other sea level components -such as sea level rise and tides- that are relevant for coastal assessments. The model includes a family of functions to help assessing different coastal hazards:

1) **Hurricane wind-waves**: generates wave fields (wave height and periods) for hurricanes using three different methods.
2) **Tropical Storm Surges**: simulates storm surge at coastal points. This module includes four different methods: two published relationships between surges and wind speeds; and one approximation of the shoaling of long waves for uniform and not uniform slopes (one assumes constant coastal shelf slope, another one uses a coastal transect with irregular bathymetry).
3) **Other sea level components:**

1. **Sea Level Rise**: calculates (i) historical sea level rise and subsidence, as used in (Losada et al. 2013) and (Reguero et al. 2015), as well as (ii) end of the century projections (see more detailed description below)
2. **Tides**: calculates astronomical tide for any location in the globe (based on TPXO database).

4) **Global wind Waves** –extratropical- (requires installing 'wave climate module' and additional data): calculates main statistics of global wave climate based on Reguero et al (2012) and (2015); and includes useful functions to analyze wave climate. – for more details, consult the specific module –

Hurricane wind-waves and Storm Surge

Tropical cyclone hazards are calculated in `climada_tc_hazard_surge`. The models implemented thus far are:

For waves: `climada_tc_wavefield`

- model(1) – (Bretschneider 1990)
- model(2) – (Young 1988)
- model(3) – Shore Protection Manual (USACE 1984)

For the wind component in surges:

- model(1) – Slosh regression in (Xu 2010)
- model(2) – CENAPRED formulation for Mexico
- model(3) – (Dean and Dalrymple 1991) with constant slope
- model(4) – (Dean and Dalrymple 1991) with variable bathymetry (non constant slope) - not implemented

Details on the specific models implemented follow can be found below.

1. Pressure field - `climada_tc_surgefield_barotropic`

To define the pressure field of each tropical storm, we use the Hydromet-Rankin Vortex model (Holland 1980):

$$P_r = P_0 + (P_N - P_0) \cdot e^{\left(-\frac{R}{r}\right)} \qquad (1.1)$$

where P_0 is the pressure at the center of the hurricane (mb), P_r is the pressure at a distance r from the center (km), P_N is the pressure outside the hurricane (usually1013 mb), and R is the radius of the maximum ciclostrofic winds (km), with $R = 0.4785 \cdot P_0 - 413.01$. These parameters can be obtained from the historical storms records and the climada storm simulation routines - see (Bresch 2014).

2. Wind field `climada_tc_windfield_HURAC`

For the wind field, the model uses a non-symmetric fields model (Bretschneider 1990), where the maximum gradient of winds U_R (km/h) can be obtained from:

$$U_R = 21.8 \cdot \sqrt{P_N - P_0} - 0.5 \cdot f \cdot R \qquad (1.3)$$

Where *f* is the Coriolis parameter $f = 2\omega \sin(\phi)$ and $\omega = 0.2618\, rad/h$ y ϕ is the latitude in degrees

The wind velocity (10 m; km/h) at a distance r from the center of the storm is:

$$W = 0.886(F_V \cdot U_R + 0.5 \cdot V_F \cos(\theta + \beta)) \qquad (1.4)$$

With $\theta + \beta$ being the angle between the hurricane moving speed V_F and the wind speed at distance R from its center, U_R.
F_V is a damping factor that depends on the relative location to the storm:

$$F_V = 1 - 0.971 \cdot \exp\left(-6.826\left(\frac{r}{R}\right)^{4.798}\right)$$ for $\frac{r}{R} < 1$ (inside the eye of the storm) (1.5)

$$F_V = \exp\left(A \cdot \ln^3\left(\frac{r}{R}\right) \cdot \exp\left(B \cdot \ln\left(\frac{r}{R}\right)\right)\right)$$ para $\frac{r}{R} \geq 1$ (outside the eye)

With A and B being:

$$A = -0.99 \cdot \left(1.066 - \exp\left(-1.936 \cdot \left(\frac{f \cdot R}{U_R}\right)\right)\right)$$ and $$B = -0.357 \cdot \left(1.4456 - \exp\left(-5.2388 \cdot \left(\frac{f \cdot R}{U_R}\right)\right)\right)$$

3. Tropical cyclone wind waves - `climada_tc_wavefield`

We then calculate wind waves generated by the wind field using three different models, for comparison purposes (Bretschneider 1990; Young 1988; USACE 1984):

(Bretschneider 1990), for Hs from a non-stationary cyclone at offshore depths

$$Hs = 0.2557 \cdot F_h \left(1 - \frac{6.69 \cdot N_C}{1 + 10.3 \cdot N_C - 3.25 \cdot N_C^{\,2}}\right) \cdot \sqrt{R \cdot (P_N - P_0)} \cdot \left(1 + \frac{V_F \cdot \cos(\theta + \beta)}{2 \cdot U_R \cdot F_V}\right)^2 \quad (1.6)$$

$$Ts = 12.1\sqrt{\frac{Hs}{g}}$$

(Young 1988), adjusting and calibrating the Hs max with numerical modeling at offshore depths.

$$\frac{g \cdot H_S^{\max}}{V_{\max}^{\,2}} = 0.0016\left(\frac{g \cdot x}{V_{\max}^{\,2}}\right)^{0.5} \quad (1.7)$$

$$\frac{g \cdot Tp^{\max}}{2\pi \cdot V_{\max}} = 0.045\left(\frac{g \cdot x}{V_{\max}^{\,2}}\right)^{0.33}$$

Shore Protection Manual (USACE 1984), modified to include some of the near-shore depth induced effects on the waves (Hs and Tp)

$$\frac{g \cdot Hs}{U_A^{\,2}} = 0.25 \cdot \tanh\left[0.6\left(\frac{g \cdot h}{U_A^{\,2}}\right)^{0.75}\right] \cdot \tanh^{0.5}\left\{\frac{4.3x10^{-5}\left(\frac{g \cdot 2F}{U_A^{\,2}}\right)}{\tanh^2\left[0.6\left(\frac{g \cdot h}{U_A^{\,2}}\right)^{0.75}\right]}\right\} \quad (1.8)$$

$$\frac{g \cdot Tp}{U_A} = 8.3 \cdot \tanh\left[0.76\left(\frac{g \cdot h}{U_A^{\,2}}\right)^{0.375}\right] \cdot \tanh^{1/3}\left\{\frac{4.1x10^{-5}\left(\frac{g \cdot 2F}{U_A^{\,2}}\right)}{\tanh^3\left[0.76\left(\frac{g \cdot h}{U_A^{\,2}}\right)^{0.375}\right]}\right\}$$

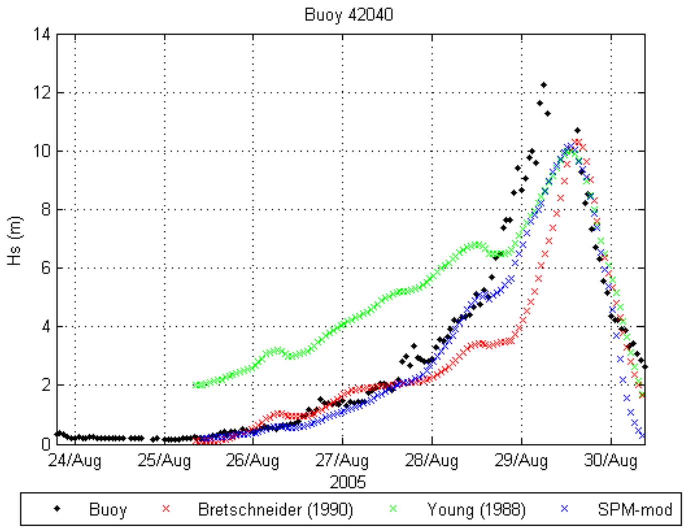


Figure 4. Significant wave height at NOAA buoy 42040 (29.212 North, 88.207 West, 164.6 m deep)

4. Tropical cyclone surges

`climada_tc_surgefield_barotropic`

'Storm Surge' refers to the water height above predicted astronomical tide level due to the inverse barometer effect and the wind stress over the sea surface (Losada et al. 2013).

Storm Surge is supposed to be the linear sum of two effects: (1) elevation due to the atmospheric pressure and (2) the wind shear stress over the sea surface. The storm surge sea level pressure effect spatial variation is supposed stationary and symmetric, only depending on the pressure gradient, and is calculated as (Dean and Dalrymple 1991)**:**

$$\eta_{vp} = \frac{(p_n - p_o)}{\rho g}\left(1 - e^{-\frac{(R-r)}{r}}\right)$$

Where η_{vp} sea level elevation; P_n pressure outside the storm (mbar); P_0 central pressure (mbar); ρ water density (1025 kg/m³) and R is the hurricane radius (km)

`climada_tc_hazard_surge_DD92_mslope`
`climada_tc_hazard_surge_DD92_variable_bathymetry (not yet implemented)`

The shear stress produced by the wind on the sea surface generates an elevation of the water level at the coastline, known as Storm Surge. Although its modeling is complex (Resio and Westerink 2008; Jacobsen 2013), the long wave equations can be used to described it on the continental shelf or a lagoon (Dean and Dalrymple 1991)**:**

The sea level surface induced by the wind stress (η_w ; SS) can be obtained from the following equation:

$$\frac{\partial \eta_w}{\partial x} = \frac{n \cdot \tau_{zx}(\eta_w)}{\rho \cdot g(h + \eta_w)}$$

Where h is the depth, n is a factor taken that varies between 1.15 and 1.30, and τ_W is the wind shear stress in the cross-shore direction.

The wind stress over the water surface is (USACE 1984):

$$\tau_W = \rho \cdot k \cdot U_{\max}\left|U_{\max}\right| \qquad (1.9)$$

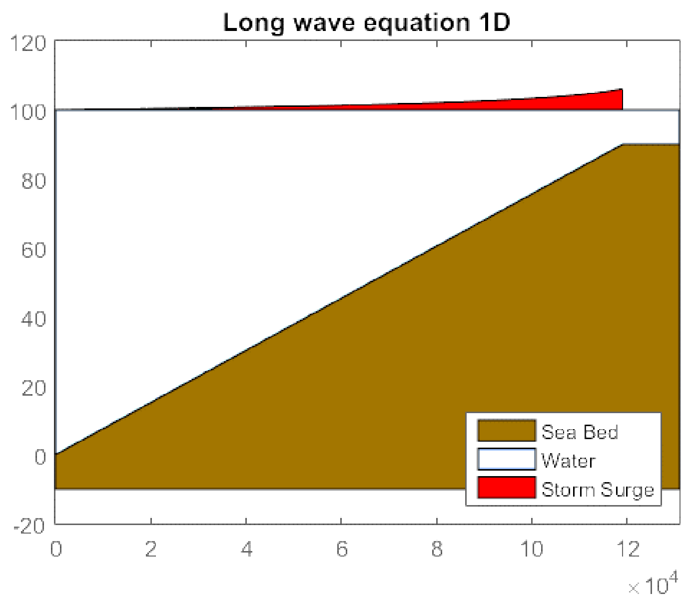
where ρ is the water density in kg/m³; $U_{\max}$ is the maximum wind speed (10 m over sea level), m/s; k is a friction factor, O(10⁶) , taken from (Van Dorn 1953):

$k = 1.2x10^{-6}$ for $|U_{\max}| \leq 5.6$ and $k = 1.2x10^{-6} + 2.25x10^{-6}\left(1 - \frac{5.6}{|U_{\max}|}\right)$ for $|U_{\max}| > 5.6$

The wind stress acting on the transect is $\tau_{wx} = |\tau_w| \cos\theta$. Although the wind shear stress is usually very small, when its effect is integrated over a large body of water, like the coastal shelf, it results in significant water levels onshore.

The approach assumes an orthogonal transect to the bathymetry and responds to an approximation of the long-wave shoaling on the continental shelf. Conditions are also assumed stationary for each storm position and the maximum wind speed acting on the coastal transect. The relative angle between the maximum wind speed and the bathymetric transect is considered to define the tangential stress and is taken at the beginning of the continental shelf (i.e. where shoaling starts having an effect), here assumed at 200 m deep. Bottom friction and 2D effects are neglected in this approach.

Example: `[surge]=fun_SurgeHeightFun(depth,u10,slope,check_plot);`

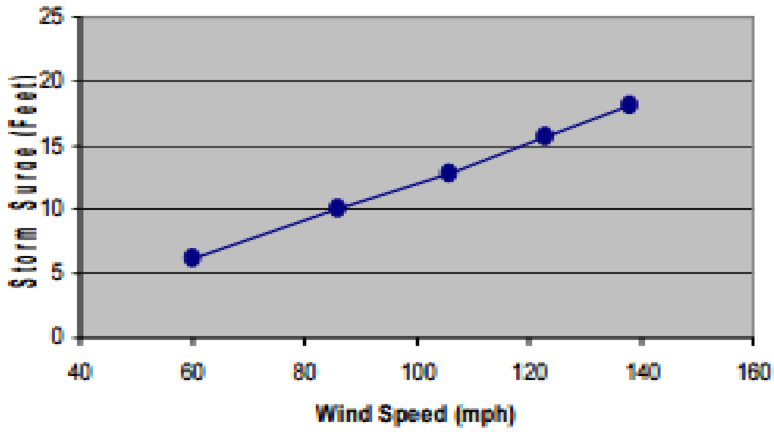


Other formulas implemented for storm surge:

Some studies have compiled regressions that provide storm surge based on storm parameters such as wind and radius. In this module, two of these regressions have been implemented.

`climada_tc_hazard_surge_SLOSH`

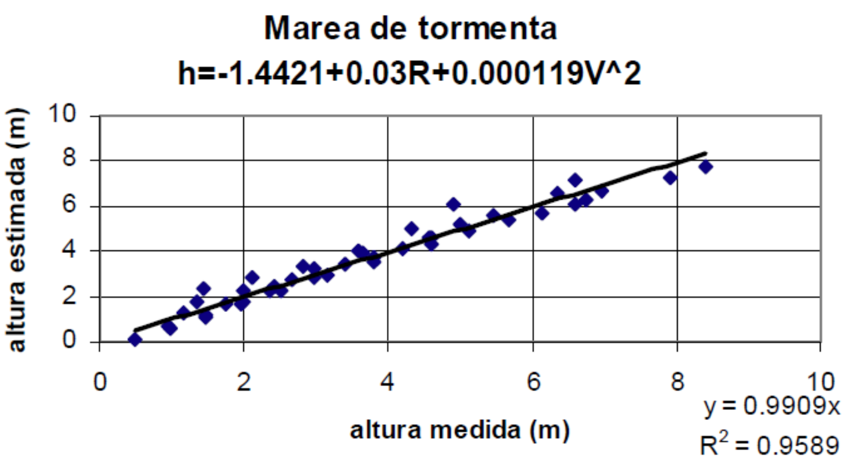
This function computes surge according to the regression line explained in (Xu 2010), from SLOSH simulations in the US Gulf Coast.



`climada_tc_hazard_surge_CENAPRED_field`

This is the formulation developed by CENAPRED for risk assessments in Mexico.

They provide maximum storm surge estimates as a function of storm radius and wind speed, and include a correction factor that depends on the landing angle. For more details and formulations, see *details_surge_models.ppt*



5. Astronomical tides

Astronomical tide (AT): sea level variation produced by the gravitational interactions of the earth, moon, and sun. In this work, the astronomical tide is calculated as the superposition of harmonic constituents provided by the TPXO database (i.e. eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf, Mm) and 3 non-linear (M4, MS4, MN4) harmonic constituents; long period constituents SA and SSA are not included).

Example:

```
tide71=climada_getTemporalSerie_AT(y0,x0,datenum(2000,1,1),datenum(2016,1,1),'TPXO7.1'
);  % extract tide time series for one single point
tide72=climada_getTemporalSerie_AT(y0,x0,datenum(2000,1,1),datenum(2016,1,1),'TPXO7.2'
);  % extract tide time series for one single point
```

6. Sea-Level Rise

Monthly mean sea-level (MSL) is the average height of the sea surface water level. It includes the seasonal cycle (monthly mean variations) and other anomalies in time scales that vary from months to longer-term changes. Sea level rise is the long-term changes in the mean sea level – see (Losada et al. 2013). The long term changes in the mean sea level is referred as sea level rise. Local factors such as land subsidence or uplift can cause relative displacements between the sea and land. The term relative sea level rise refers to the sea level rise signal where these geomorphic effects are discounted. This module provides information to calculate sea level rise and global land subsidence (note that local land uplift/subsidence may differ substantially from the global model).

To calculate the relative sea level rise, the module includes (1) historical mean sea level data, (2) IPCC projections for the end of the century, and (3) land subsidence to account for the relative movement between the land and the sea, i.e. relative sea level rise.

6.1. Historical sea-level rise

The model uses the data explained in (Losada et al. 2013) that provides global information on mean sea level from different sources, that include (John a Church et al. 2004) and satellite measurements.

Example:

```
SLR = climada_get_SLRhistorical(coastal_hazard_centroids.lon,coastal_hazard_centroids.lat);
```

The module additionally includes a function to calculate long-term trends from these time series (or others).

Example: `[trend]=climada_calculate_LTtrend(SLRhistorical.Time,timeseries)`

6.2. Dynamic Projections of sea-level rise

The modules uses information from the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (J.a. Church et al. 2013). It provides data on Regional Sea Level Change Projections[1], for different Representative Concentration Pathways. Representative Concentration Pathways (RCPs) are four greenhouse gas concentration (not emissions) trajectories adopted in AR5 and that supersedes the Special Report on Emissions Scenarios (SRES) projections published in 2000. The pathways are used for climate modeling and research. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs -RCP2.6, RCP4.5, RCP6, and RCP8.5- are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively)[2].

For each RCP, the tool provides information on the mean, high and low values of regional sea level change by the end of the 21st century.

Example:

```
SLRprojections  =
climada_get_SLRProjection(coastal_hazard_centroids.lon,coastal_hazard_centroids.lat);
% Values correspond to SLR for "2081-2100 20-yr mean minus 1986-2005 20-yr mean", in
meters (m)
SLRprojections =
    RCP26: [1x1 struct]
    RCP45: [1x1 struct]
    RCP60: [1x1 struct]
    RCP85: [1x1 struct]
```

6.3. Land subsidence

In addition to changes in the mean sea level, an assessment of coastal flooding should consider the contribution of the long-term vertical movement of the land, i.e., local subsidence, from either natural or anthropogenic causes, e.g. (Reguero et al.

[1] http://www.climatechange2013.org/images/report/WG1AR5_Chapter13_FINAL.pdf

[2] https://en.wikipedia.org/wiki/Representative_Concentration_Pathways

2015). In many areas, for example the deltas (e.g. Mississipi Delta), this component can well overcome the historical rates of sea level rise. Relative sea-level rise is calculated by adding to the regional sea-level rise data the local natural vertical land movements. This model uses the the global model of isostatic adjustment from (Peltier 2002). To account for the extra subsidence due to natural sediment compaction in deltas for example, studies usually assume an additional 2 mm/yr in these areas, following (Hinkel and Klein 2009). Also, note that additional contributions to subsidence due to human action or uplifts due to tsunamigenic events, for example, are not included in this database and should be factored in locally.

Example:

```
subsidence      =
climada_get_LandSubsidence(coastal_hazard_centroids.lon,coastal_hazard_centroids.lat);
```

4. Coastal flood and expected damages calculation

Once the hazards have been obtained at the hazard centroids units (see Figure 5), we need to calculate the economic impact of each flooding event inland. To calculate damages, the model uses two types of curves: (1) exposure and (2) damage curves.

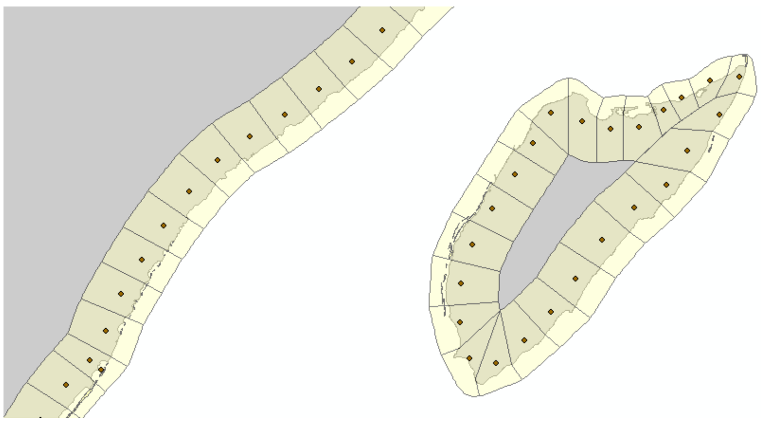


Figure 5. Example of spatial units where exposure is pre-processed and centroids where hazards and damages are computed.

Exposure curves.

The model works on reading exposure curves for different spatial units. These “exposure curves” represent the total value or number of people that fall at each ground elevation, for example: people from 0-1m, 0-2m, etc. Figure 6 gives an example of exposure curves for the region of Quintana Roo, in Mexico for people and three types of assets.

In the model, the process to calculate these curves is:

1) Pre-process assets at each elevation and by study units: this is previously computed outside the climada module, usually done with GIS routines.
2) Read entities: The distribution of assets is read from an xls table that provides information on the identification of each spatial unit and the different ground elevations. Example: Entities_QR_climada_2015.xls
3) Calculate differences between elevations: the damage computation works uses information between each elevation, i.e. 0-1, 1-2,2-3, etc. This is processed by `climada_entity_calc_diff`
4) Associate units and elevation array: each unique study unit id needs to be associated with a hazard point. This can be directly from the xls file or this association done independently.
5) Other corrections: socioeconomic exposure can also be given units, be corrected or calibrated externally and previously to calculating the damages.

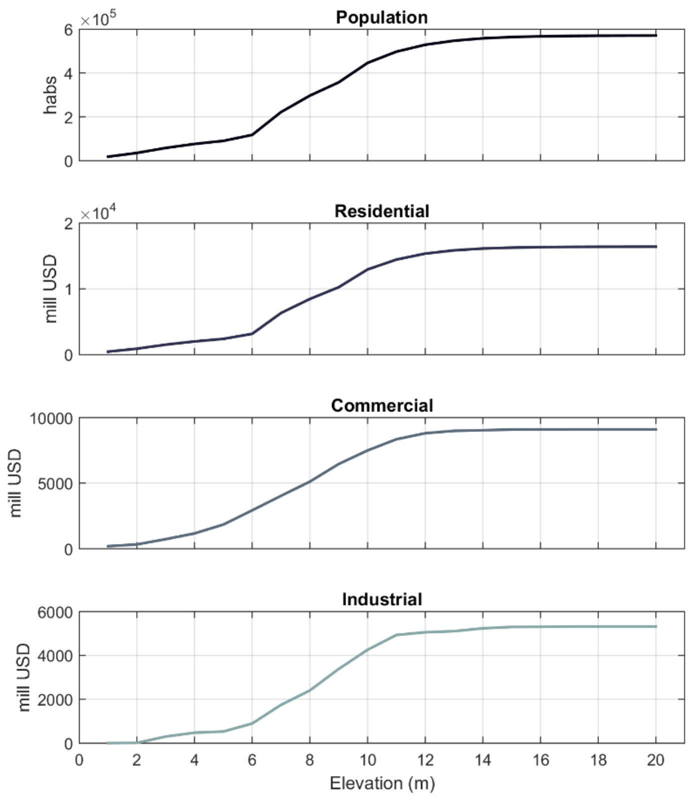


Figure 6. Example of exposure curves.

Example for reading exposure curves:

```
[entity,entity_save_file] = climada_entity_read_coastal(file_entities,'NOENCODE')

[entity] = climada_entity_calc_diff(entity);

entity.Population.units   = 'habs';
entity.elevation_array    = [1:20]; % correct here DEM elevations in case 0 is not the reference

%Note: the entities can be subjected to calibration internally in the model.
entity.Population.calibration_factor  = 1;
run('calibrate_entities.m')
```

Damage Curves for flood

The exposure curves (i.e. everything exposed in the flood plain) need to be affected by a certain amount of damage that depends on the water depth of each event. For this, we use “damage curves” that relate water depth to the Mean Damage Degree – see (Bresch 2014). Figure 8 represents some examples of damage curves for different types of assets. Note that these dmage curves can be expressed in different units but require to be consistent with the exposure curves, for example: sq meters exposed x $/sq. meter; people exposed x % people affected; or $ value exposed x % damage. Additionally, the ratio of assets affected by flooding can be adjusted through the PAA parameter (Percent of Assets Affected), which will be different to 1 (100% of units affected) depending on how the geospatial pre-processing is carried out and the exposure curves computed.

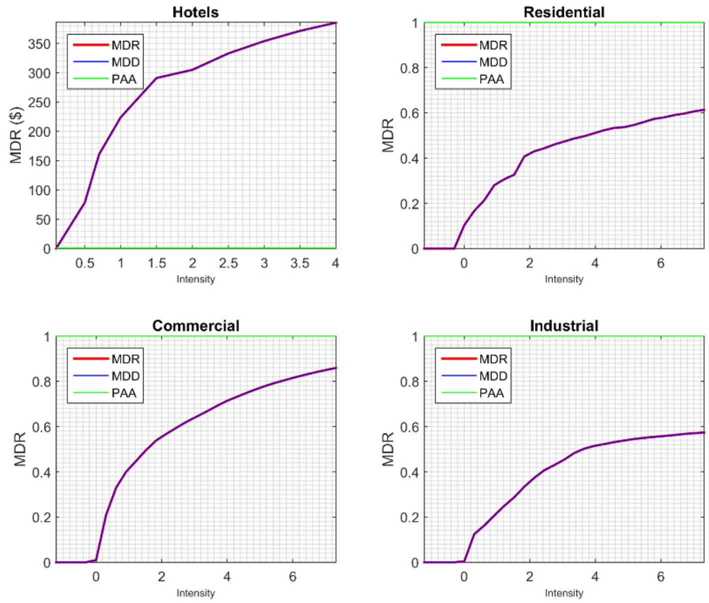


Figure 8. Damage curves for different assets.

Example to read damage curves:

```
% read damage curves
damagefunctions = climada_damagefunctions_read(damagefunction_filename)
% plot damage curves
climada_damagefunctions_plot_coastal(damagefunctions)
```

Finally, remember to associate the damage functions to the entity. The “entity” structure will include the information on the assets and the damage functions, as in the core climada model.

Example:

```
% remember to associate the damage functions to the entity structure
entity.damagefunctions = damagefunctions;
entity_field_names = {'Commercial','Industrial','Residential'};
```

Calculate damages in the flood zone

Damages are calculated from the intersection of the assets exposed in the coastal zone by a degree of damage that depends on the event flooding intensity, through `climada_EDS_calc_coastal`. The function returns an Expected damage sctructure (EDS) with the same structure as the climada root routines.

The algorithm calculates for each study unit and for each storm, at each elevation level the corresponding damage degree, see sketch in Figure 2, i.e. [damage between z and z-1] = [Value between z and z-1] x [Mean Damage Degree at the elevation relative depth: excess of water depth over z-1]:

Loss(M,N)

z[0,1] ---> Value[0,1] x MDD(depth [i])
z[1,2] ---> Value[1,2] x MDD(depth [i]-1)
... .
z[z-1,z] ---> Value[z-1,z] x MDD(depth [i]-(z-1))

$\sum$ (Value(z) x MDD(z))

Figure 9. Calculating damages for each unit and for each storm.

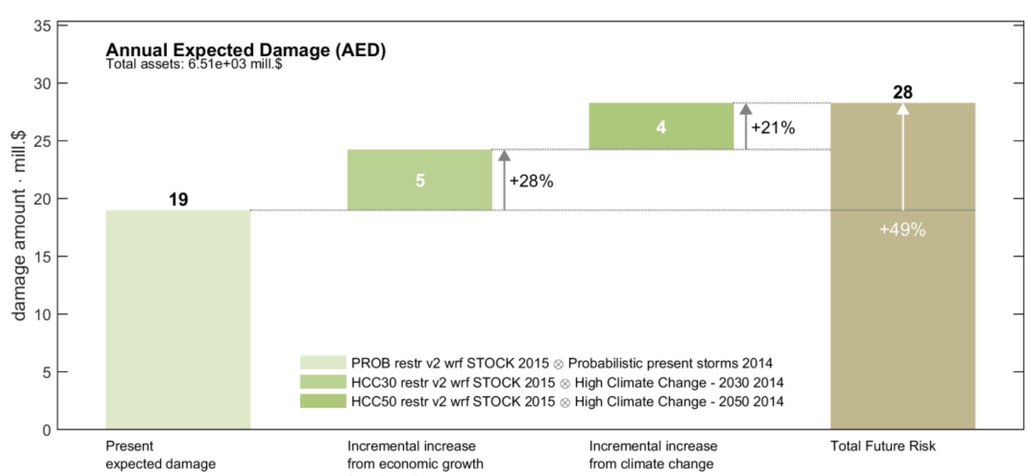
Example:

```
% Calculate the expected damage set
EDS=climada_EDS_calc_coastal(EDSentity,hazard,annotation_name,force_re_encode,silent_mode);

% give name to save
EDS_save_file = [climada_global.results_damages_dir,filesep,'EDS_',annotation_name];

% calculate statistics
return_period = [10 50 100 250 500];
EDS = climada_EDS_stats(EDS, EDS_save_file, return_period);

% save EDS data
climada_EDS_save(EDS,EDS_save_file)

% plot loss frequency curve
figure, hold on, plot(EDS.R_fit,EDS.damage_fit,'k')
```

The results can be plotted in a “risk waterfall graphic”, which allows to different EDS sets and compare them.

Example:

```
close all
Tr=100;
unit_scale = 1; % 1e3
units = 'mill.$'% thousands of mill$
xlabels_descrpt={{'Present';'expected damage'}, {'Incremental increase';'yr 2030'},...
                     {'Incremental increase';'yr 2050'},{'Total Future Risk'; 'yr 2050'}};
climada_waterfall_graph_coastal(EDS_all(1),EDS_all(2),EDS_all(3),Tr,unit_scale,units,xlabels_desc
rpt,0,'flood',[800 1000])

% plot Annual Expected damage
climada_waterfall_graph(EDS_2010,EDS_2030,EDS_2030_CC,['AED'])
```



5. Other auxiliary functions

- Compare statistics of tracks in a region – addition to the storm simulation module in the original climada - `climada_plot_compare_tc_tracks_inregion`

Example:

```
names_tracks = {'Historical','Probabilistic'};
[storms_stats.hist storms_stats.prob] =
climada_plot_compare_tc_tracks_inregion(tc_track,tc_track_prob,names_tracks,'stats_storms',
check_printplot,inregion);
```

- save figures with different output formats and resolution: `save_fig(handle,filename,resolution, varargin)`

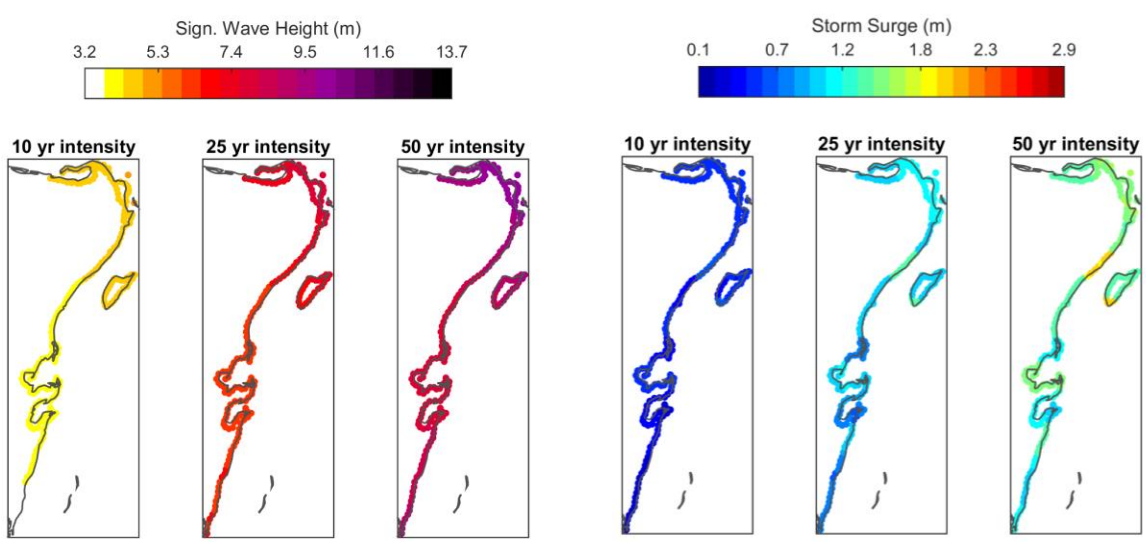
Example: `save_fig(gcf,[dirResults,filesep,filename],200)`

- plot hazard intensity maps for different return periods

This is a modification of the original climada `climada_hazard_stats` with advance functionality.

Example:

```
% height map
hazard_stats = climada_hazard_stats_coastal(hazard_tmp,return_periods,'Hs_intensity',...
save_fig(gcf,[dirResults,filesep,'RPmaps HS - ',comment],200)

% surge map
hazard_stats = climada_hazard_stats_coastal(hazard_stats,return_periods,'SS_intensity',...
save_fig(gcf,[dirResults,filesep,'RPmaps SS - ',comment],200)
```



- convert the damage frequency curves data into a shapefile `[S] = fun_DFC2struct(DFC_at_centroids,shp)`

Example:

```
% First, calculate DFC at centroids
```

```
run('aux_calc_EDS_at_centroids.m')

% this auxiliary script calls climada_EDS2DFC at each centroid:
%-----------------------------
       for cc = 1:Ncentroids
           EDS.damage = full(EDS.damage_at_centroid(cc,:));
           if any(EDS.damage)
               DFC                                     = climada_EDS2DFC(EDS,return_period);
               DFC_at_centroids.Value (cc,:)           = EDS.Value_at_centroid(cc,:);
               DFC_at_centroids.damage(cc,:)           = DFC.damage;
               DFC_at_centroids.damage_of_value(cc,:) =
                       DFC.damage./DFC_at_centroids.Value(cc,end);  % over the last elevation
                       value - 20m
           else
               continue
           end
       end
%-----------------------------

% save shps
 [S] = fun_DFC2struct(DFC_at_centroids,study_units);
fileout =  [dirout,filesep,'shp_dfc_',comment,'.shp'];
shapewrite(S,[fileout]);  % NOTE: REQUIRES MAPPING TOOLBOX.
```

6. Example of use

The module includes several example scripts to test the main functionalities. They are listed below:

1) Test for simulating hurricane and cyclone hazards: *TEST_surges_MEX.m*
2) Test to obtain the other sea level components: *TEST_sea_level_components_MEX.m*
3) Test to calculate damages: *TEST_damages _MEX.m*

7. References

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