Sea Level Rise and Extreme Still High-Water Level

Mean Sea Level Rise

Although Global-mean sea-level rise scenarios are available, most coastal impact and adaptation assessments have ignored regional variations in sea-level scenarios, largely due to a lack of technical guidance and access to the necessary data in a useable format. In response to this, CLIMsystems followed IPCC guidance to construct sea level scenarios considering the different contributing factors (Nicholls *et al*., 2011).

In general, regional and local assessments benefit from considering the components of sea-level change on a more individual basis as regional and local contributions to local sea level change could be greater than that of global average sea level rise. The mean sea level rise for a selected location (*loc*) and year (*yr*) ($SLR_{loc,yr}$), is calculated as follows:

$$SLR_{loc,yr} = ZOS_{loc} * GSLR_{yr} - VLM_{loc} * (yr - 1995)$$

where $SLR_{loc,yr}$ is the mean sea level rise for the studied selected location and future year (after the baseline year of 1995); ZOS_{loc} is the normalized GCM sea level rise patterns for the studied location, which were estimated from the ensemble of 28 GCM and median value was applied; $GSLR_{yr}$ is the global mean sea level rise value for the selected RCP and future year under RCP8.5 and 2050 medium climate sensitivity; VLM_{loc} is the local vertical land movement values for the studied location (extracted from the global vertical land movement dataset). The grid cell value which covers the location was applied. Since VLM_{loc} is an annual rate, the difference between the selected year (2050) and 1995 had to be multiplied.

The methodologies for determining ZOS_{loc} and VLM_{loc} and $GSLR_{yr}$ are set out in the following three sub-sections.

GCM mean sea level rise (GSLR)

The local pattern of thermal expansion under RCP forcing can be approximated using a pattern-scaling method like that previously applied for other climate variables (e.g. Santer *et al*., 1990). In applying the pattern-scaling method to sea level, "standardised" (or "normalised") patterns of regional thermal expansion change, as produced by coupled AOGCMs, are derived by dividing the average spatial pattern of change for a future period (e.g. 2081-2100) by the corresponding global-mean value of thermal expansion for the same period. The resulting standardised sea-level pattern is thereby expressed per unit of global-mean sea level rise.

The following equation is employed to calculate the normalised sea surface elevation patterns, (or sea surface height above the geoid, ZOS), termed Δ *ZOS (unit: cm/cm ΔGSLR)*:

$$\Delta ZOS_{ij} = \{(ZOS_{ij2090} - ZOS_{ij1995}) - \Delta ZOS_{global} + \Delta GSLR\}/\Delta GSLR$$

where ΔZOS_{global} is the global mean annual sea level change calculated directly from GCM gridded ZOS data; $\Delta GSLR$ is the global mean annual sea level change from ZOSGA dataset.

$$\Delta GSLR = ZOSGA_{2090} - ZOSGA_{1995}$$

where, $ZOSGA_{2090}$ is the global sea level height at 2090, and $ZOSGA_{1995}$ is the global sea level height at 1995. 2090 is the average of 2080-2100; 1995 is the average of 1986-2005; and *i, j* denotes the latitude and longitude of the studied location.

Note: Theoretically, ΔZOS_{global} should equal to $\Delta GSLR$. However during data processing it was found that for some GCMs, these two variables are different, either owing to model drift or other unclear reasons, so these two variables were differentiated in the analysis, in order to remove the drifting error in the ZOS dataset.

Twenty-four GCM (RCP45) runs, which have both local *ZOS* and *ZOSGA* data, are applied. The variable 'zosga' is not available for four GCMs (CCSM4, HADGEM2-CC, HADGEM2-ES, INMCM4), so we applied 'zostoga' (global average thermosteric sea level change) instead. Given the multiple sources of uncertainty in sea level rise GCM data, these four GCMs are not outliers among other GCMs, so they can still be applied in an ensemble study thus forming the complement of 28 sea level rise patterns applied in Climate Insights.

Monthly Sea Level Rise Change Patterns (ZOS)

The monthly changes in SLR of 28 GCMs between 1986-2005 and 2081-2100 are calculated by the pattern-scaling method (see above). GCM data were retrieved from the Earth System Grid (ESG) data portal for CMIP5, including: the sea surface height (‘zos’), the global average thermosteric sea level change (‘zostoga’) and the global average sea level change (’zosga’) under a RCP4.5 scenario. For some GCMs, only ‘zosga’ was available and used instead of zostoga. The data availability was shown at the end of this document.

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The change in sea surface height was scaled by the change in global average thermal expansion by month following the pattern-scaling theory. The sea surface height from GCMs includes the regional variability of dynamic topography changes due to water mass advection, thermohaline circulation and to the wind-driven circulation, and did not include the tidal effects. The changes in global average thermal expansion were calculated by the changes in zostoga if it is available, or by the changes in zosga. The value X (m/m) in patterns is interpreted as “regional sea level may rise X m when the global average sea level rises 1 m”.

Vertical Land Movement (VLM)

VLM can be observed directly or inferred from related measurements. Direct observations are available through the SONEL initiative, whereby VLM is estimated from continuous GPS measurements at fixed locations, often coinciding with tidal observation stations. The latest set of “solutions” contains location (lat/lon) and estimates of VLM (mm/year). As there are requirements for determining the trend (length of the period, completeness, quality, stability of the solution), not all stations have an associated value.

Indirect observations have been extracted from the Permanent Service for Mean Sea Level (PSMSL), which maintains an archive of observed tides. An analysis of the data for these stations to estimate their trends (which are reflecting the rise in sea level), is also available. Note that not all stations meet the requirements of completeness, total number of observations and quality of measurements.

The local observed sea level rise and local vertical land movement have the following relation:

local observed SLR = local absolute SLR – local VLM

where VLM>0 means that land is rising, VLM<0 land is sinking, and

local absolute SLR = global SLR (over the observation period) * local normalized value

where local normalized value was extracted from an ensemble of GCMs, and *global SLR* was downloaded from the data restricted by Church and White (2011).

Note: The longest part of the global curve is based on tidal observations (up to 1992, after 1992 satellite observations are used). To do that, assumptions needed to be made about the local VLM at each tidal station. A global model (mostly for tectonic movements) was used to do this. This creates a “thinking loop” as we are trying to estimate local VLM from data that has been corrected with a modelled VLM. The assumption is that the averaging of the data around the globe minimizes this bias.

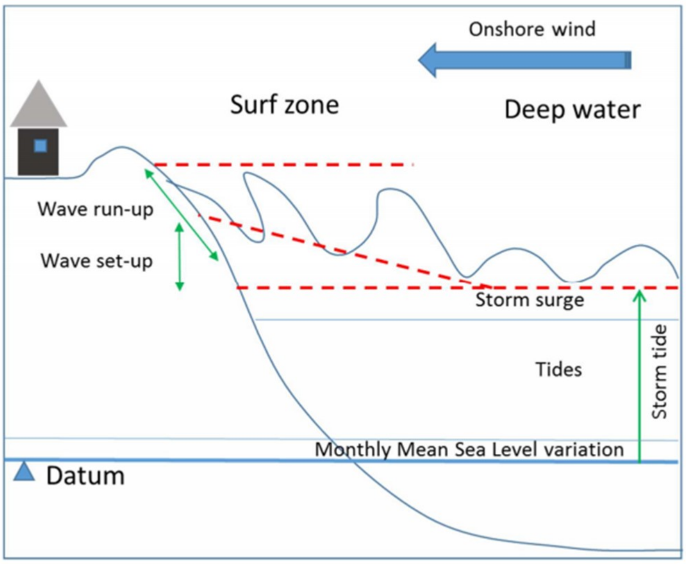
The VLM data were created based on tidal station data. To be able to use VLM in places where it has not been observed, the VLM values estimated from the (SONEL or PSMSL) point locations were interpolated spatially over the globe.

Extreme Still High-Water Level

Coastal extreme sea level elevations (in addition to sea level rise) often, but not exclusively, arise with a confluence of events such as exceptional seasonal high tides, wind and waves associated with tropical depressions or extra tropical low pressure systems, and coastal bathymetry.

In general, coastal extreme sea-level elevations are calculated mainly from storm-tides and wave setup for annual exceedance probabilities of 39%, 18%, 10%, 5%, 2%, 1% and 0.5% (corresponding to 2, 5, 10, 20, 50, 100 and 200-year average recurrence intervals, respectively). Storm-tide is defined as the sea-level peak reached during a storm event, from a combination of MMSL (monthly mean sea level) + tide + storm surge. Waves also raise the effective sea level at the coastline. Wave setup describes an average raised elevation of sea level when breaking waves are present. Wave run-up is the maximum vertical extent of wave “up-rush” on a beach or structure above the instantaneous still high-water level (that would occur without waves), and thus constitutes only a short-term fluctuation in water level relative to wave setup, tidal and storm-surge time scales.

The likelihoods associated with extreme storm-tides and/or waves, are reported in terms of their probability of occurrence. The annual exceedance probability (AEP) describes the chance of an event either reaching or exceeding a certain water level in any given year. Alongside AEP, the likelihood of extreme events can also be described in terms of their average recurrence interval (ARI), which is the average time interval between events of a specified magnitude (or larger), when averaged over many occurrences.



Schematic illustrating the various processes that contributes to coastal extreme sea level rise

CMIP5 GCM Data Availability for SLR

No.	GCM	zos	zostoga	zosga
1	ACCESS1-0	√		√
2	ACCESS1-3	√		√
3	bcc-csm1-1	√		√
4	bcc-csm1-1-m	√		√
5	CanESM2	√		√
6	CCSM4	√	√	√
7	CMCC-CM	√		√
8	CMCC-CMS	√		√
9	CNRM-CM5	√	√	√
10	CSIRO-Mk3-6-0	√	√	
11	GFDL-CM3	√	√	√
12	GFDL-ESM2G	√	√	√
13	GFDL-ESM2M	√	√	√
14	GISS-E2-R	√	√	√
15	GISS-E2-R-CC	√		√
16	HadGEM2-CC	√	√	
17	HadGEM2-ES	√	√	
18	inmcm4	√	√	
19	IPSL-CM5A-LR	√	√	√
20	IPSL-CM5A-MR	√		√
21	MIROC5	√		√
22	MIROC-ESM	√		√
23	MIROC-ESM-CHEM	√	√	√
24	MPI-ESM-LR	√	√	√
25	MPI-ESM-MR	√	√	√
26	MRI-CGCM3	√	√	√
27	NorESM1-M	√	√	√
28	NorESM1-ME	√		√