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Towards a global regionally varying allowance for sea-level rise

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ABSTRACT

Allowances have been developed for future rise of relative sea-level (i.e. sea level relative to the land) based on the projections of regional sea-level rise, its uncertainty, and the statistics of tides and storm surges (storm tides). An 'allowance' is, in this case, the vertical distance that an asset needs to be raised under a rising sea level, so that the present likelihood of flooding does not increase. This continues the work of Hunter (2012), which presented allowances based on global-average sea level and local storm tides. The inclusion of regional variations of sea-level rise (and its uncertainty) significantly increases the global spread of allowances. For the period 1990–2100 and the A1FI emission scenario (which the world is broadly following at present), these range from negative allowances caused by land uplift (in the northern regions of North America and Europe) to the upper 5-percentile which is greater than about 1 m (e.g. on the eastern coastline of North America).

1. Introduction

A major effect of climate change is a present and continuing increase in sea level, caused mainly by thermal expansion of seawater and the addition of water to the oceans from melted land ice (e.g. Meehl et al., 2007, as reported in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC)). Over the last two decades, the rate of global-average sea-level rise was about 3.2 mm yr^{-1} (Church and White, 2011). At the time of AR4 in 2007, sea level was projected to rise at a maximum rate of about 10 mm yr^{-1} and to a maximum level of about 0.8 m (relative to 1990) by the last decade of the 21st century, in the absence of significant mitigation of greenhouse-gas emissions (Meehl et al., 2007, Table 10.7, including 'scaled-up ice sheet discharge').

Sea-level rise, like the change of many other climate variables, will be experienced mainly as an increase in the frequency or likelihood (probability) of extreme events, rather than simply as a steady increase in an otherwise constant state. One of the most obvious adaptations to sea-level rise is to raise an asset (or its protection) by an amount that is sufficient to achieve a required level of precaution. The selection of such an allowance has often, unfortunately, been quite subjective and qualitative, involving concepts such as 'plausible' or 'high-end' projections. Hunter (2012) described a simple technique for estimating an allowance for sea-level rise using extreme-value theory. This allowance ensures that the expected, or average, number of extreme (flooding) events in a given period is preserved. In other words, any asset raised by this allowance would experience the same frequency of flooding events under sea-level rise as it would without the allowance and without sea-level rise. It is important to note that this allowance only relates to the effect of sea-level rise on *inundation* and *not* on the recession of soft (e.g. sandy) shorelines or on other impacts.

Under conditions of uncertain sea-level rise, the 'expected number of flooding events in a given period' is here defined in the following way. It is supposed that there are n possible futures, each with a probability, P_i, of being realised. For each of these futures, the expected number of flooding events in a given period is given by N_i. The effective, or overall, expected number of flooding events (considering all possible futures) is then considered to be $\sum_{i=1}^{n} P_i N_i$, where $\sum_{i=1}^{n} P_i = 1$.

In the terminology of risk assessment (e.g. ISO, 2009), the expected number of flooding events in a given period is known as the *likelihood*. If a specific cost may be attributed to one flooding event, then this cost is termed the *consequence*, and the combined effect (generally the product) of the likelihood and the consequence is the *risk* (i.e. the total effective cost of damage from flooding over the given period). The allowance is the height that an asset needs to be raised under sea-level rise in order to keep the flooding likelihood the same. If the cost, or consequence, of a single flooding event is constant than this also preserves the flooding risk.

An important property of the allowance is that it is *independent of the required level of precaution* (when measured in terms of *likelihood* of flooding). In the case of coastal infrastructure, an appropriate

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height should first be selected, based on *present* conditions and an acceptable degree of precaution (e.g. an average of one flooding event in 100 years). If this height is then raised by the allowance calculated for a specific period, the required level of precaution will be sustained until the end of this period.

The method assumes that there is no change in the variability of the extremes (specifically, the scale parameter of the Gumbel distribution; see Section 2). In other words, the statistics of tides and storm surges (storm tides) relative to mean sea level are assumed to be unchanged. It is also assumed that there is no change in wave climate (and therefore in wave setup and runup). The allowance derived from this method depends also on the distribution function of the uncertainty in the rise in mean sea level at some future time. However, once this distribution and the Gumbel scale parameter has been chosen, the remaining derivation of the allowance is entirely objective.

If the future sea-level rise were known exactly (i.e. the uncertainty was zero), then the allowance would be equal to the central value of the estimated rise. However, because of the exponential nature of the Gumbel distribution (which means that overestimates of sea-level rise more than compensate for underestimates of the same magnitude), uncertainties in the projected rise *increase* the allowance above the central value.

Hunter (2012) combined the Gumbel scale parameters derived from 198 tide-gauge records in the *GESLA* (Global Extremes Sea-Level Analysis) database (see Menéndez and Woodworth, 2010) with projections of global-average sea-level rise, in order to derive estimates of the allowance around much of the world's coastlines. The spatial variation of this allowance therefore depended only on variations of the Gumbel scale parameter. We here derive improved estimates of the allowance using the same *GESLA* tide-gauge records, but spatially varying projections of sea level from the IPCC AR4 (Meehl et al., 2007) with enhancements to account for glacial isostatic adjustment (GIA), and ongoing changes in the Earth's loading and gravitational field (Church et al., 2011). We use projections for the A1FI emission scenario (which the world is broadly following at present; Le Quéré et al., 2009).

The results presented here relate to an approximation of *relative sea level* (i.e. sea level relative to the land). They include the effects of vertical land motion due to changes in the Earth's loading and gravitational field caused by past and ongoing changes in land ice. They do not include effects due to local land subsidence produced, for example, by deltaic processes or groundwater withdrawal; *separate allowances should be applied to account for these latter effects*.

A fundamental problem with existing sea-level rise projections is a lack of information on the upper bound for sea-level rise during the 21st century, in part because of our poor knowledge of the contribution from ice sheets (IPCC, 2007). This effectively means that the likelihood of an extreme high sea-level rise (the upper tail of the distribution function of the sea-level rise uncertainty) is poorly known. The results described here are based on relatively thin-tailed distributions (normal and raised cosine) and may therefore not be appropriate if the distribution is fat-tailed (Section 6). For cases where consequence of flooding would be 'dire' (in the sense that the consequence of flooding would be unbearable, no matter how low the likelihood), a more appropriate allowance would be based on the best estimate of the maximum possible rise.

2. Theory

Extremes are generally described by *exceedance events* which are events which occur when some variable exceeds a given level. Two statistics are conventionally used to describe the likelihood of extreme events such as flooding from the ocean. These are the *average recurrence interval* (or *ARI*), R, and the *exceedance probability*, E, for a given period, T. The ARI is the average period between extreme events (observed over a long period with many events), while the exceedance probability is the probability of at least one exceedance event happening during the period T. Exceedance distributions are often expressed in terms of the *cumulative distribution function*, F, where $F=1-E$. F is just the probability that there will be *no* exceedances during the prescribed period, T. These statistics are related by (e.g. Pugh, 1996)

$$F = 1-E = \exp\left(-\frac{T}{R}\right) = \exp(-N) \tag{1}$$

where N is the expected, or average, number of exceedances during the period T.

Eq. (1) involves the assumption (made throughout this paper) that exceedance events are independent; their occurrence therefore follows a Poisson distribution. This requires a further assumption about the relevant time scale of an event. If multiple closely spaced events have a single cause (e.g. flooding events caused by one particular storm), they are generally combined into a single event using a declustering algorithm.

The occurrence of sea-level extremes, and therefore, the ARI and the exceedance probability, will be modified by sea-level rise, the future of which has considerable uncertainty. For example, the projected sea-level rise for 2090–2099 relative to 1980–1999, for the A1FI emission scenario (which the world is broadly following at present; Le Quéré et al., 2009), is 0.50 ± 0.26 m (5–95% range, including scaled-up ice sheet discharge; Meehl et al., 2007), the range being larger than the central value.

The expected number of exceedances above a given level and over a given period may, in general, be described by

$$N = \mathcal{N}\left(\frac{\mu - z_P}{\lambda}\right) \tag{2}$$

where $\mathcal{N}$ is some general dimensionless function, z_P is the physical height (e.g. the height of a critical part of the asset), μ is a 'location parameter' and λ is a 'scale parameter'. As noted in Section 1, it is assumed that there is no change in the variability of the extremes, which implies that the scale parameter, λ, does not change with a rise in sea level.

Mean sea level is now raised by an amount $\Delta z + z'$, where Δz is the central value of the estimated rise and z' is a random variable with zero mean and a distribution function, $P(z')$, to be chosen below. This effectively increases the location parameter, μ, by $\Delta z + z'$. At the same time, the asset is raised by an allowance, a, so that it is now located at a height $z_P + a$. Under these conditions of (uncertain) sea-level rise and raising of the asset, the overall (or effective) expected number, N_{ov}, of exceedances ($> z_P + a$) during the period T, becomes

$$N_{ov} = \int_{-\infty}^{\infty} P(z')\mathcal{N}\left(\frac{\mu - z_P + \Delta z + z' - a}{\lambda}\right) dz' \tag{3}$$

The function, $\mathcal{N}$, is often well-fitted by a *generalised extreme-value distribution* (*GEV*). The simplest of these, the *Gumbel* distribution, fits most sea-level extremes quite well (e.g. van den Brink and Können, 2011). The Gumbel distribution may be expressed as (e.g. Coles, 2001, p. 47)

$$F = \exp\left(-\exp\left(\frac{\mu - z_P}{\lambda}\right)\right) \tag{4}$$

where F is the probability that there will be no exceedances $> z_P$ during the prescribed period, T.

From Eqs. (1), (2) and (4)

$$N = \mathcal{N}\left(\frac{\mu - z_P}{\lambda}\right) = \exp\left(\frac{\mu - z_P}{\lambda}\right) \tag{5}$$

μ is therefore the value of z_P for which $N=1$ during the period T, and λ, the 'scale parameter', is an e-folding distance in the vertical. Globally, the scale parameter has a quite narrow range;