Compound flooding (CF) is an extreme event taking place in low-lying coastal areas as a result of co-occurring high sea level and large amounts of runoff, caused by precipitation. The impact from the two hazards occurring individually can be significantly lower than the result of their interaction\textsuperscript{1,2,3,4}. Both the risk of storm surges and heavy precipitation, as well as their interplay is likely to change in response to anthropogenic global warming. Despite their relevance, a comprehensive risk assessment beyond individual locations at the country scale is missing. In particular, no studies have examined possible future CF risk. Here we estimate the potential CF risk along the European coasts both for present and future climate according to the business-as-usual (RCP8.5) scenario. Under current climate conditions, the locations experiencing the highest risk are mostly located along the Mediterranean Sea. However, future climate projections show emerging risk along parts of the Atlantic coast and the North Sea. The increase of the risk is mostly driven by an intensification of precipitation extremes. In several European regions, increasing CF risk should be considered as a potential hazard aggravating the risk caused by mean sea level rise (SLR).
CF is a coastal hazard and may cause damages and fatalities. Prominent examples from Europe are the Thames flood in London, 1928; the flash flood in Lisbon, 1967; the Avon flood in Bristol, 2014; and the Ravenna flood in 2015. In 2012, the Netherlands almost experienced a flooding of the water board Noorderzijlvest, which led to precautionary evacuation. The recently released pan-European (though not fully comprehensive) HANZE database lists 24 co-occurrences of storm surges and river floods along the Irish, UK, Belgian and Polish coasts, the French Atlantic and Mediterranean coast, and the Italian Adriatic coast. The risk of CF is in particular increased if storm surge and river flood do not occur independently. Ignoring this dependence may substantially underestimate the resulting risk.

Co-occurring storm surge and heavy rainfall are driven by deep low pressure systems. Whereas precipitation extremes alone can be caused by convection without intense cyclonic activity, the latter is a precondition for extreme surges. Intense cyclones drive storm surges through strong winds pushing water towards the coast, and the barometric pressure effect. CF can be caused by several mechanisms. A storm surge can block or slow down the precipitation drainage into the sea, causing flooding along the coast. Runoff from a river may require a certain time to drain into the sea such that precipitation may have to occur well before the storm surge. Similarly, flood levels of a storm surge may be amplified by any significant amount of precipitation. Finally, a flood may occur when precipitation falls on wet soil that is saturated by a preceding storm surge. The relative importance of these mechanisms in a particular location depends both on the local climate and topography.

Several studies have demonstrated the importance and damaging nature of CF for selected locations. Comprehensive studies, however, exist only for the UK, Australia and the US coast. The latter study detected an increasing risk of CF during the past decades, although it was not possible to attribute the changing risk to anthropogenic climate change. But given that extreme precipitation, river flooding, and extreme sea levels are expected to increase under future climate change, it is likely that also the risk of CF will increase along with these driving processes. Yet even though coastal cities are expected to further grow in the coming decades and more and more people will be exposed to CF, no studies have investigated future CF risk.

Our study aims to close this research gap. We analyse present and future potential CF risk along the European coastlines. A precise CF risk assessment can in practice only be site-specific because the actual risk depends strongly on local conditions such as the shape of the coastline, the orography and land surface of the surrounding land area where precipitation is collected, the existing flood protection, and the exposed population and assets. Modelling such local detail would, however, preclude a continental scale analysis. Thus we limit ourselves to modelling potential CF risk: we follow the approach of previous studies and model the probability of a co-occurrence of extreme sea levels and heavy precipitation. For the sake of brevity, however, we will write of CF risk only. At the end of the 21st century, SLR will be the primary threat for
Figure 1: **Synoptic weather conditions driving extreme events.** Composite maps of sea level pressure (hPa, in white) and total column water fields computed over days where extreme events (> 99.5\textsuperscript{th} percentile) occurred in Plymouth (UK, top) and Ancona (Italy, bottom) indicated by the red dots (based on ERA-Interim data, 1980-2014). Here, the astronomical tide component of the sea level is not considered to focus only on the meteorological driven part. Extreme events type: (a,d) compound flooding (CF), (b,e) storm surge but not extreme precipitation, (c,f) extreme precipitation but not storm surge. The total number of extreme events considered for computing the composite maps is shown at the bottom-left corner of the panels. Storm surges include the wave setup contribution (see text).
ERA-Interim reanalysis data\textsuperscript{24} for present climate (1970-2004) and with six selected CMIP5 models\textsuperscript{25} for future climate (2070-2099). Precipitation is directly taken from the reanalysis and the climate models. On each day, we consider accumulated precipitation within a time range of ±1 days, which allows us to account for the mentioned mechanisms responsible for CF, and precipitation occurring just before and after midnight of the storm surge day\textsuperscript{26}. We define univariate extremes of the individual hazards as events occurring on average every 200 days for sea level, and every 200 wet days for precipitation respectively. CF return periods are defined as the average waiting time between the co-occurrence of these extreme events\textsuperscript{27,28,29} (Supplementary Fig. S4). We model the dependence of sea level and precipitation extremes by a copula-based multivariate probability model. For details refer to the Methods section, and for an evaluation of the simulated CF risk see the supplementary information (Supplementary Fig. S2, S3 and S5).

The highest CF risk in present climate is experienced mostly along the Mediterranean Sea (Fig. 2a). The Atlantic coast appears to be particularly exposed to co-occurring storm surges and extreme precipitation (Fig. 2b). But here the effective risk is slightly reduced because of the high tidal range (compare Fig. 2a and 2b): no CF occurs when the peak of the storm surge occurs during low astronomical tide\textsuperscript{30}. The Gulf of Valencia (Spain), the Gulf of Lion (France), south- and northeastern Italy, the northwest Aegean coast, southern Turkey, the Levante region and the Eastern black sea coast are among the upper \(\sim 2\%\) most prone to CF with return periods of less than four years (Fig. 2a). The statistical dependence between sea level and precipitation greatly enhances the risk of CF along the European coasts: the CF return period increases by up to two orders of magnitude when ignoring the dependence (Fig. 2c).

In a warmer future climate, the risk of CF is projected to robustly increase particularly along the coast of Ireland, the west coast of Great Britain, northern France, the east coast of the North Sea, Italy and the eastern half of the Black Sea (Fig. 3a, Supplementary Fig. S6). Hotspot regions of emerging compound risk where return periods will decrease to less than 4 years are the Bristol Channel and the Devon and Cornwall coast in the UK, the Frisian coast of the Netherlands and Germany (Fig. 3b). The forced climate change signal appears to emerge from the uncertainty about present risk mostly along the Western British Isles, the North and Baltic Sea (regions 3, 4, and 5 in Fig. 3c). Along the Noorderzijlvest water board, which also faces the greatest SLR, the probability of potential CF occurrence will double. The Norwegian West coast around Bergen will see a fourfold increase in potential CF frequency. Along much of the Mediterranean coast, climate models do not agree about the direction of future changes in CF risk, along the Strait of Gibraltar CF risk is even expected to decrease (Fig. 3a, Supplementary Fig. S6).

Changes in CF risk can in principle be caused by changes in the risk of extreme sea levels, in the risk of extreme precipitation, or in the dependence between both hazards\textsuperscript{6,3,4,9}. For Europe and the Mediterranean, the main driver of future changes in CF risk appears to be changes in precipitation (Fig. 4). Changes in risk due to changes in the dependence between precipitation and extreme sea levels are minor (panel a, see also Methods), and can only explain the overall decrease in CF.
Figure 2: **Present potential compound flood (CF) risk.** Return periods of CF (co-occurring sea level and precipitation extremes, i.e. $>99.5^{th}$ percentiles) based on ERA-Interim data. In panel (a), sea level includes surge and astronomical tides. To isolate the effect of tides on the resulting potential CF risk, panel (b) shows sea level without including astronomical tides. In panel (c), sea level and precipitation are assumed to be independent.

A warmer atmosphere will allow storms to carry more moisture resulting in heavier precipitation. This thermodynamic effect dominates along the North Atlantic storm track in Northern Europe, and the Mediterranean storm track. But weaker upward winds will reduce or balance the thermodynamic increases of extreme precipitation along the North African coast, and will even reverse the full precipitation response over north-western Africa (panel c, also Supplementary Fig. S7).

In a future climate, sea level rise will be the primary threat along coastal areas, and societies will likely adapt to this risk. Here we have shown that CF may pose a severe additional hazard that has to be taken into account for a full risk assessment. In particular Northern Europe will experience an increased risk of CF. There it is key to consider increasing precipitation intensities when planning adaptation measures against coastal flooding. The overall risk of CF is strongly aggravated by the dependence between surges and precipitation.

To enable a continental scale assessment, we have considered potential flood risk without accounting for the individual local conditions. Users interested in CF risk at a specific site will know their local setting and should put our findings into perspective accordingly. If the particular site is not prone to surges and fluvial or pluvial flooding, the real CF may be negligible even where we identified a high potential risk. In locations, where surges and pluvial flooding are real hazards, our study will provide an initial guess of future changes in CF risk. As a basis for local adaptation planning, a full site-specific understanding of CF is necessary. To this end, a complex modelling chain is required which can simultaneously integrate

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**Figure 2:**

(a) CF risk (1980-2014)
(b) CF risk (1980-2014) (No tide)
(c) CF risk (1980-2014) (No dependence)
Figure 3: **Future potential compound flood (CF) risk.** (a) Multi-model mean of projected change (%) of CF return periods, between future (2070-2099) and present (1970-2004) climate. (b) Return periods for the future (2070-2099). Grey points indicate locations where less than 80% of the models (five out of six) agree on the sign of the risk change (four out of five models in the Black Sea). Grey points in (a) and (b) are slightly different, as the former are computed taking into account the past period (1970-2004) and the latter the period (1980-2004) (see delta change approach in Methods). (c) Median value of CF return periods over regions defined in (b) for past (1980-2014, based on ERA-Interim (Fig. 2a)) and future (2070-2099) climate, separately for individual models. For ERA-Interim, grey shading illustrates the sampling uncertainty 95% range.

information about precipitation, discharge, surges, topography and land-use, relative sea level rise and available or planned flood protections.

### Methods

**Data.** Storm surges were simulated with the DFLOW FM model using a flexible mesh setup (forced with 6-hourly wind and atmospheric pressure fields)\[22,23,20,21\]. Waves were simulated with the model Wavewatch III\[22,23,17\] (forced with 6-hourly wind field). Astronomical tides were simulated every six hours using the FES2012 model\[31,32,20\], which makes use of satellite altimetry data. The resulting sea level data are available every ~25 km along the coastline. Comprehensive validation and detailed information of the models can be found in refs.\[17,22,23,20,21\]. Our analysis is based on quantile values, therefore we do not bias correct simulated data. Sea level and precipitation data are based on ERA-Interim and six selected models from the CMIP5 multi-model ensemble (Supplementary Table 1). Precipitation was taken from the grid point nearest to each coastal location. CMIP5 models were selected based on the skill in representing the synoptic climatologies and inter-annual
Figure 4: Attribution of potential compound flood (CF) risk change to changes in dependence and marginal distribution. Multi-model mean of projected change (%) of CF return periods between future (2070-2099) and present (1970-2004) when only taking into account future changes of: the overall (a) dependence (Spearman and tail dependence [3]) between sea level and precipitation, (b) sea level distribution, and (c) precipitation distribution (Methods). The total projected risk variation (Fig. 3a) is not given by the sum of these three cases (a, b, c), as the overall dependencies and marginal distributions do not contribute linearly to the CF return periods. SLR is not considered in the definition of future sea levels (see text). Grey points indicate locations where less than 80% of the models (five out of six) agree on the sign of the risk change (four out of five models in the Black Sea).
estimate and the bootstrap-based estimate was small. As this procedure is computationally expensive, we therefore refrained from applying it to the CMIP5-based data.

**Return periods.** We define the bivariate CF return periods as the mean waiting time between events where sea level and precipitation simultaneously exceed the individual 99.5\textsuperscript{th} percentiles \(s_{99.5}\) and \(p_{99.5}\), respectively. To allow for a robust estimation, we apply a parametric copula-based bivariate probability distribution. Applying a parametric model for the full range of values, one would run the risk of biasing the representation of the extreme tail by the bulk of the bivariate distribution where most data occur. Therefore we apply the model only to pairs of high values. We select pairs where, simultaneously, sea level values exceed the individual 95\textsuperscript{th} percentile \((s_{sel})\), and precipitation values exceed the individual 95\textsuperscript{th} percentile of wet days \((p_{sel})\). In a few locations with very low wet day probabilities, one might end up with selecting few pairs only. Here we reduce the selection threshold 0.95 to ensure that at least 20 pairs of values are selected (never below 0.9). Clusters of selected event pairs separated by less than three days are replaced by a unique event which assumes the maximum sea level \(S\) and precipitation \(P\) observed in the cluster (see Supplementary Fig. S8).

The bivariate return period is thus given as

\[
T(s_{99.5}, p_{99.5}) = \frac{\mu}{P(s > s_{99.5} \text{ and } p > p_{99.5}) | (s > s_{sel} \text{ and } p > p_{sel})} = \frac{\mu}{1 - u_{S99.5} - u_{P99.5} + C_{SP}(u_{S99.5}, u_{P99.5})}
\]

where \(\mu\) is the average time elapsing between the selected pairs, \(u_{S99.5} = F_S(s_{99.5})\), \(F_S\) is the marginal cumulative distribution of the excesses over the selection threshold (accordingly for precipitation), and \(C_{SP}\) is the copula modelling the dependence between the selected pairs.

The marginal distributions of sea level and precipitation beyond the selection thresholds are modelled by a Generalised Pareto Distribution (GPD). Copulas were fitted to \((u_S, u_P)\) (obtained via empirical marginal cumulative distribution function (CDF)), and selected via Akaike information criterion from the families: Gaussian, t, Clayton, Gumbel, Frank, Joe, BB1, BB6, BB7, BB8. Marginal distributions and copulas were fitted through a maximum likelihood estimator (via the ismev\textsuperscript{35} and VineCopula\textsuperscript{36} R-packages). Goodness of fit of marginals and copulas was tested based on the Cramer-von-Mises criterion \(\text{Mises}\) (one-tailed; \(N_{\text{boot}} = 100\) for copulas) (via the eva\textsuperscript{35} and VineCopula\textsuperscript{36} R-packages respectively). The projected change (%) of the return period \(T\) (Fig. 3a) is estimated as \(\Delta T(\%) = 100 \cdot \left(\frac{T_{2070-2099} - T_{1970-2004}}{T_{1970-2004}}\right)\) for the individual CMIP5 models.

**Sampling uncertainty of ERA-Interim based CF return periods.** To obtain the 95% sampling uncertainty range of the ERA-Interim based CF return periods, we apply a resampling procedure (for eleven representative locations where the median regional return periods are found; see Fig. 3b). We base our estimate of sampling uncertainty on the previously
generated 240 bivariate sea level/precipitation time series (where surge and precipitation is identical, only astronomical tides have been resampled). Each of these 240 bivariate time series are used for a further resampling procedure by combining bootstrapped numerator and denominator values of the return period expression (equation (1)). The numerator bootstrapped \( \mu \) values are obtained based on resampling of the observed times elapsing between the selected pairs \((s_i, p_i)\) employed for fitting the parametric probability density function (pdf); the denominator bootstrapped values are obtained based on resampling of the observed pairs \((s_i, p_i)\) used for the fit of the pdf. The final return period sampling uncertainty range is defined as the 2.5\(^{th}\) - 97.5\(^{th}\) percentile interval of the 240-240 return period estimates. This procedure is preferred to a classic resampling of all of the pairs, which - here - would overestimate the obtained median return period due to the serial correlation of the sea level time series. Based on a large sample of data without any serial correlation, we estimated that our procedure overestimates by 30\% the 95\% sampling uncertainty range (with respect to a classic resampling procedure). Thus, conclusions about the detection of a climate change signal in the future (Fig. 3c) are conservative.

**Delta change approach.** We computed CF return period for future via the delta change approach\(^{39}\), i.e. multiplying the ERA-Interim based historical return period \(T_{Era}^{1980-2004}\) by the individual CMIP5 model \(i\) variation of the risk \(T_{Model \, i}^{2070-2099} / T_{Model \, i}^{1980-2004}\). The present day reference period is the intersection of the ERA-Interim and the historical CMIP5 data, for which sea level simulations are available. See Supplementary: (Fig. S5) for comparing return periods based on ERA-Interim and individual CMIP5 models, and (Fig. S9) for CMPI5 model-mean return periods in present and future.

**Return period for independent drivers.** We estimated the CF return period assuming independence between precipitation and sea level via shuffling (500 times) the cumulated precipitation time series (during 1980-2014), and plugging an independent copula in equation (1). Then, we extracted the median of the 500 return periods associated with the shuffled time series.

**Attribution of return period variation.** We carried out three experiments\(^{41}\) to assess how the CF risk would change in future when only considering variation - with respect to the present - of: (a) the dependence between sea level and precipitation, (b) the sea level and (c) precipitation overall marginal distributions (i.e. the distribution of the sea level without reference to precipitation, and vice versa). We estimated the relative change of the risk that would have occurred for experiment (i) as \(\Delta_{exp \, i} = 100 \cdot (T_{exp \, i}^{fut} - T_{exp \, i}^{pres}) / T_{exp \, i}^{pres}\) (Fig. 4), where \(T_{exp \, i}^{pres}\) is the return period for the present period and \(T_{exp \, i}^{fut}\) is computed as follows. Experiment (a): given the variables \((S_{fut}, P_{fut})\), we got the associated empirical cumulative distribution \((U_{S_{fut}}, U_{P_{fut}})\). From the variables \(S_{pres}\) and \(P_{pres}\) we defined the empirical CDFs \(F_{S_{pres}}\) and \(F_{P_{pres}}\), through which we defined \(S_{a} = F_{S_{pres}}^{-1}(U_{S_{fut}})\) and \(P_{a} = F_{P_{pres}}^{-1}(U_{P_{fut}})\). The variables \((S_{a}, P_{a})\) have the same Spearman correlation and tail dependence\(^{4}\) as \((S_{fut}, P_{fut})\), but marginal distributions as in the present period. We computed the return period \(T_{exp \, a}^{fut}\) based on \((S_{a}, P_{a})\).
Experiment (b): given the variable $S_{pres}$, we got the associated empirical cumulative distribution $U_{S_{pres}}$. From the variable $S_{fut}$ we defined the empirical CDFs $F_{S_{fut}}$, through which we defined $S_b = F_{S_{fut}}^{-1}(U_{S_{pres}})$. The variables $(S_b, P_{pres})$ have the same Spearman correlation and tail dependence as during the present, but the marginal distribution of $S_b$ is that of the future. We computed the return period $T_{exp b}^{fut}$ based on $(S_b, P_{pres})$. Experiment (c): as experiment (b), exchanging precipitation and sea level variables.

Data availability

Precipitation data from CMIP5 models are available from the Earth System Grid Federation (ESGF) Peer-to-Peer system (https://esgf-node.llnl.gov/projects/cmip5). Precipitation data from ERA-Interim are available from the ECMWF Public Datasets web interface (http://apps.ecmwf.int/datasets). The model FES2012, used for the astronomical tides simulations was produced by Noveltis, Legos and CLS Space Oceanography Division and distributed by Aviso, with support from Cnes (http://www.aviso.altimetry.fr/). Sea level data can be found in the LISCOAST data collection (http://data.jrc.ec.europa.eu/collection/LISCOAST).

Acknowledgements

We acknowledge the World Climate Research Programs Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP the U.S. Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu). E.B. received funding from the Volkswagen Foundations CE:LLO project (Az.: 88468), and M.V. from the "EUPHEME" ERA4CS project.

Author Contributions

E.B. and D.M. had the idea of the study and designed the work. E.B. carried out the data analysis. E.B. wrote the paper with D.M., and with contributions from M.I.V. E.B. performed the astronomical tide simulations, M.I.V. and E.V. performed storm surge runs, and L.M. performed the wave runs. E.V., L.M., and M.I.V. collected the observed sea level data and derived the observed astronomical tides. M.V. gave conceptual inputs during the data analysis. All authors discussed the results and commented on the manuscript.
Competing Financial Interests statement

The authors declare no competing financial interest.
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