Changing risk of compound flooding over Europe under anthropogenic climate change

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Introduction

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[1,2]. Both the risk of storm surges and heavy precipitation, as well as their interplay is likely to change under anthropogenic global warming. Despite the relevance of CF, a comprehensive risk assessment beyond individual locations at the country scale is missing. In particular, no studies have examined the projected CF risk. A precise CF risk assessment can in practice only be site-specific because the actual risk depends strongly on local conditions such as the orography and land surface where precipitation is collected, the existing flood protection, and the exposed population and assets. Thus we limit ourselves to modelling *potential CF risk*, i.e. we model the probability of a co-occurrence of extreme sea levels and heavy precipitation. We estimate the potential CF risk along the European coasts both for present and future climate (RCP8.5 scenario).

Data & Methods

- Precipitation is accumulated within a time range of ±1 days.
- Daily maximum sea level is extracted from:

$$S = \underbrace{H_{\text{surge}}}_{\text{DFLOW FM}} + \underbrace{H_{\text{wave setup}}}_{\text{Wavewatch III}} + \underbrace{\eta_{\text{tide}}}_{\text{FES2012}}$$

  Surge and wave models are driven with atmospheric conditions from ERA-Interim and six selected CMIP5 models[3].
- In the future, sea level rise will be the primary threat along coastal areas, and societies will likely adapt to this risk. Here, we analyse the additional potential CF risk (→ focus on the meteorological-driven CF).

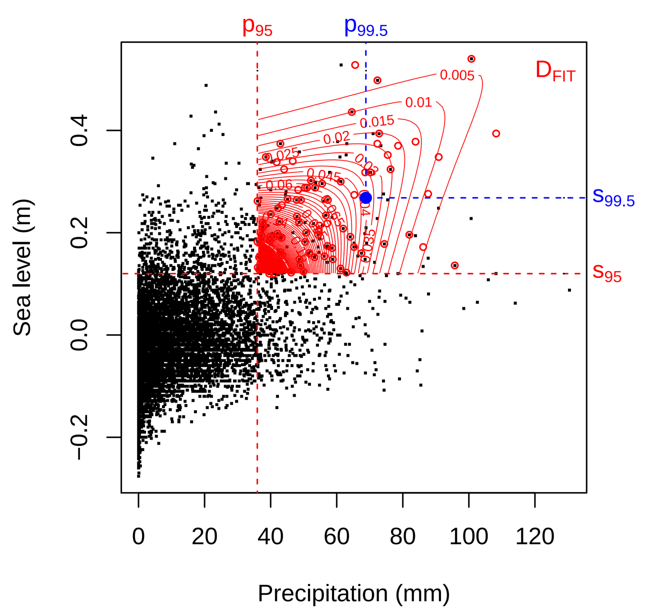

Figure 1: We compute return periods of potential CF (events where both sea level and precipitation exceed the individual present-day 99.5^{th} percentile (over wet days for precipitation)), based on a parametric pdf fitted (via copulas and Generalised Pareto Distributions) to simultaneously high values of precipitation and sea level.

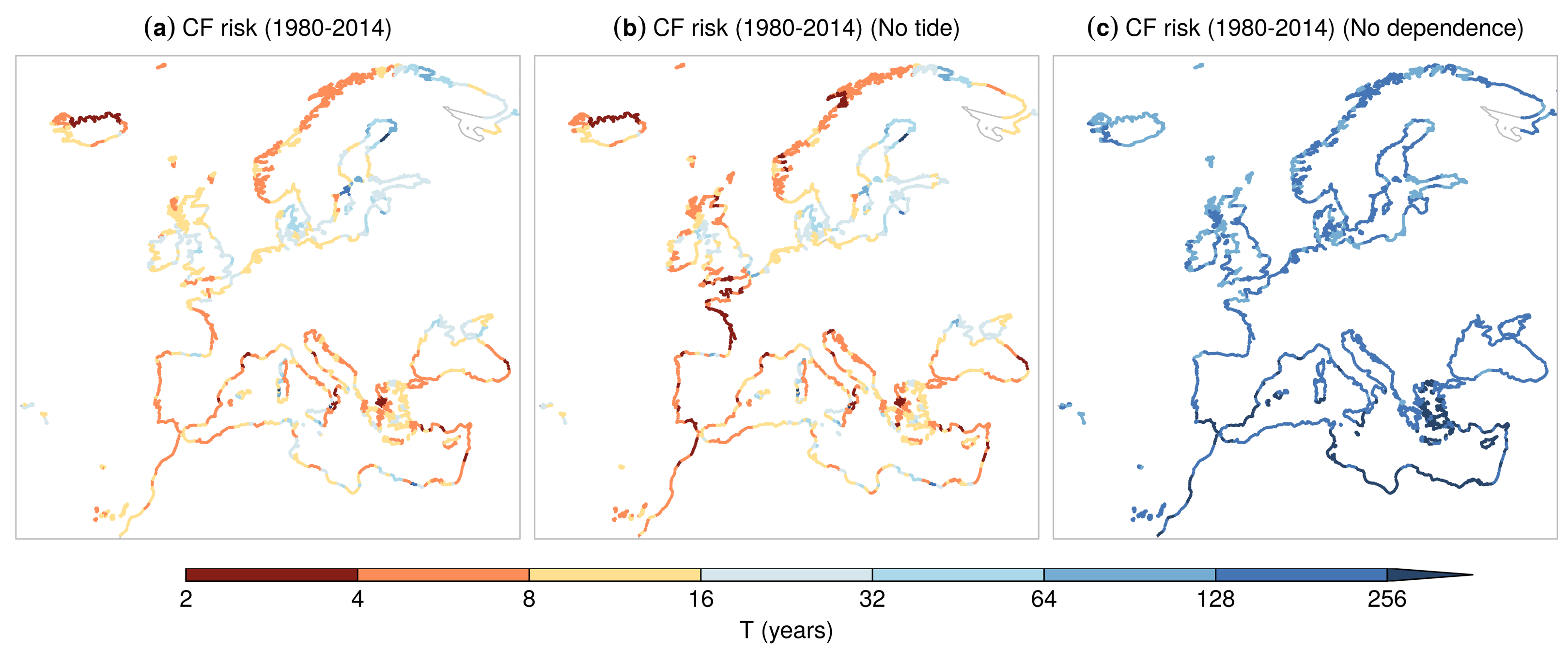

Figure 2: **Present potential CF risk.** Return periods of potential CF based on ERA-Interim data. In (**a**), sea level includes surges, waves, and astronomical tides. To isolate the effect of tides on the resulting potential CF risk, in (**b**) astronomical tides are not included. In (**c**), sea level and precipitation are assumed to be independent. In (**a**) and (**c**) the risk is underestimated.

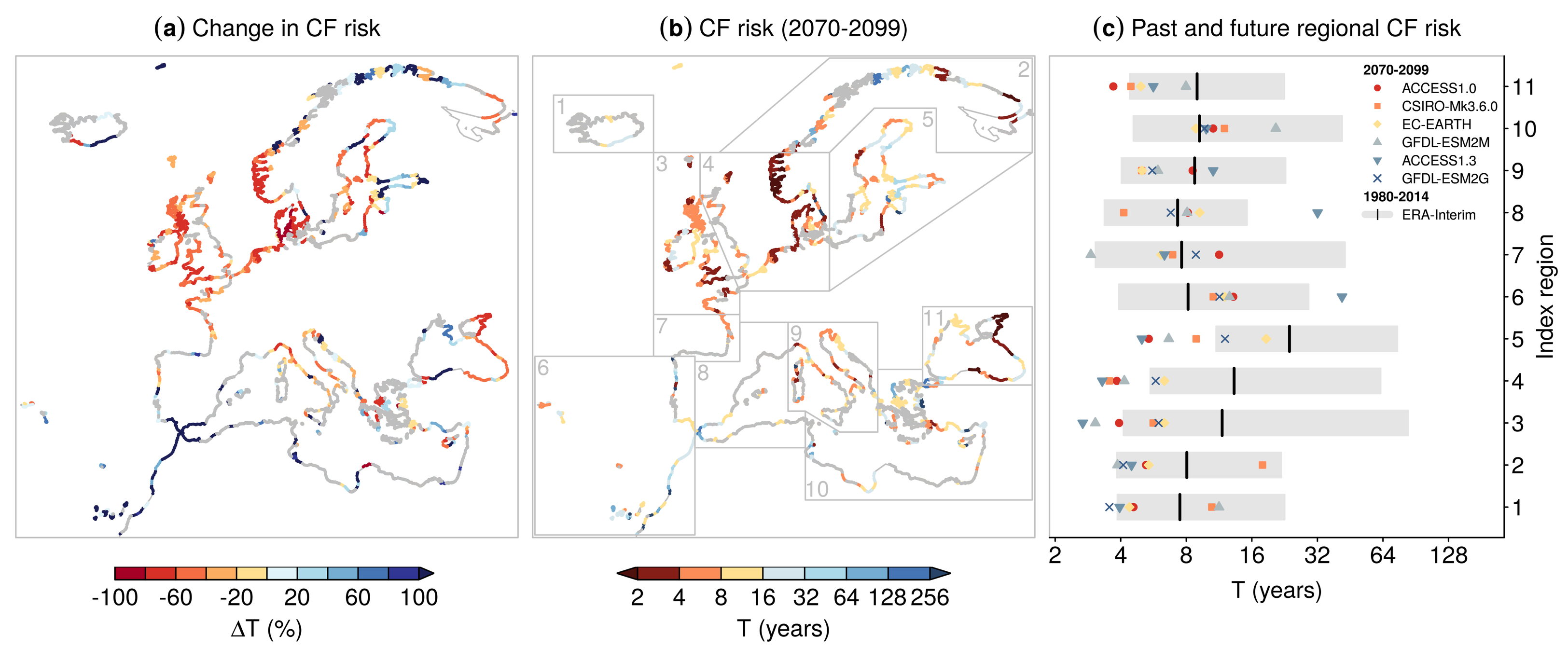

Figure 3: **Future potential CF risk.** (**a**) Multi-model mean of projected change (%) of CF return periods, between future (2070-2099) and present (1970-2004) climate. For each model, the projected change (%) of return periods is estimated as $100 \cdot (T^{\text{fut}} - T^{\text{pres}})/T^{\text{pres}}$ (negative values indicate increase of the risk). (**b**) Return periods for the future (2070-2099). Grey points indicate model disagreement on the sign of the risk change. (**c**) Regional median value of CF return periods for past (ERA-Interim, 1980-2014) and future (2070-2099) climate, separately for individual models. For ERA-Interim, the grey shading is the sampling uncertainty 95% range.

[1] Wahl, T., et al., Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nature Climate Change **5**, 1093–1097 (2015).

[2] Bevacqua, E., et al., Multivariate statistical modelling of compound events via pair-copula constructions: analysis of floods in ravenna (italy). Hydrology and Earth System Sciences **21**, 2701 (2017).

[3] Vousdoukas, M. I., et al., Extreme sea levels on the rise along Europe's coasts. Earth's Future **5**, 304–323 (2017).

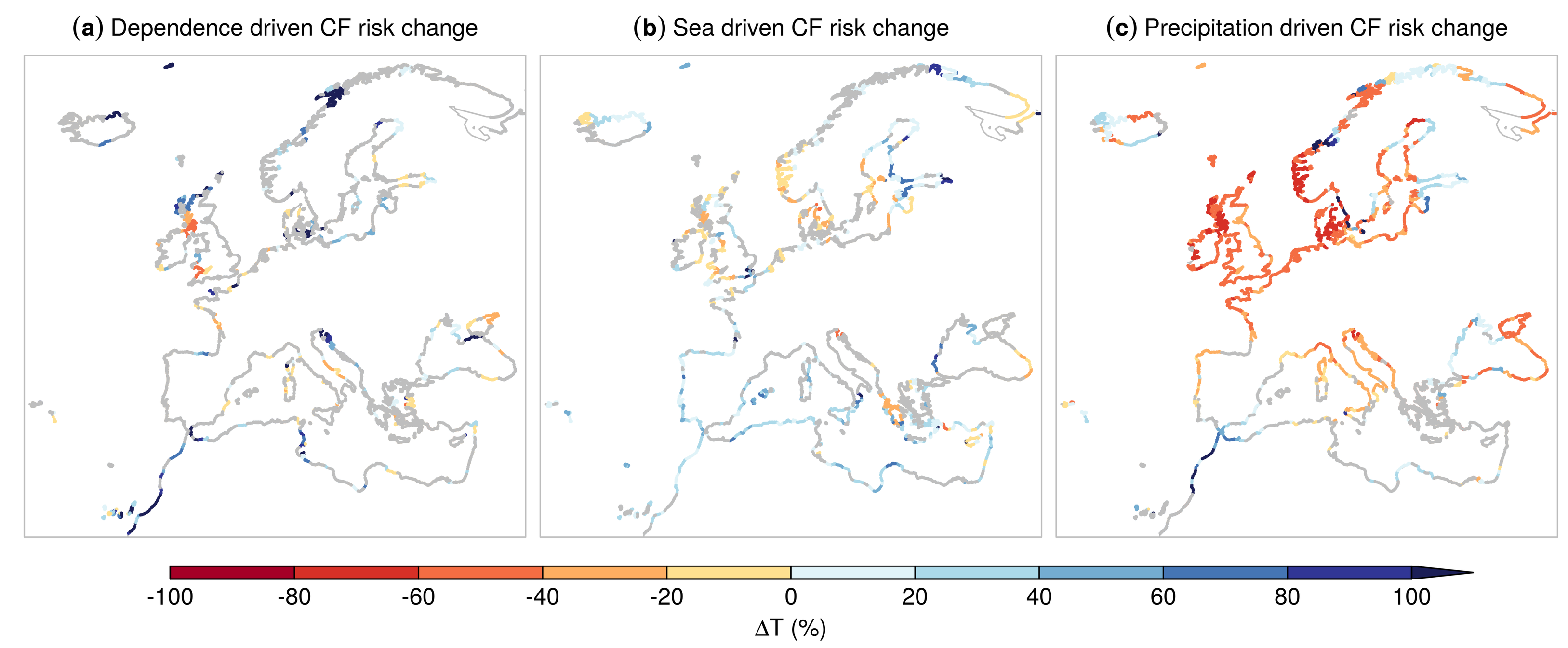

Figure 4: **Attribution of potential CF risk change.** Multi-model mean of projected change (%) of CF return periods between future (2070-2099) and present (1970-2004) when only taking into account future changes of: the overall (**a**) dependence between sea level and precipitation, (**b**) sea level distribution, and (**c**) precipitation distribution. Grey points indicate model disagreement on the sign of the risk change.

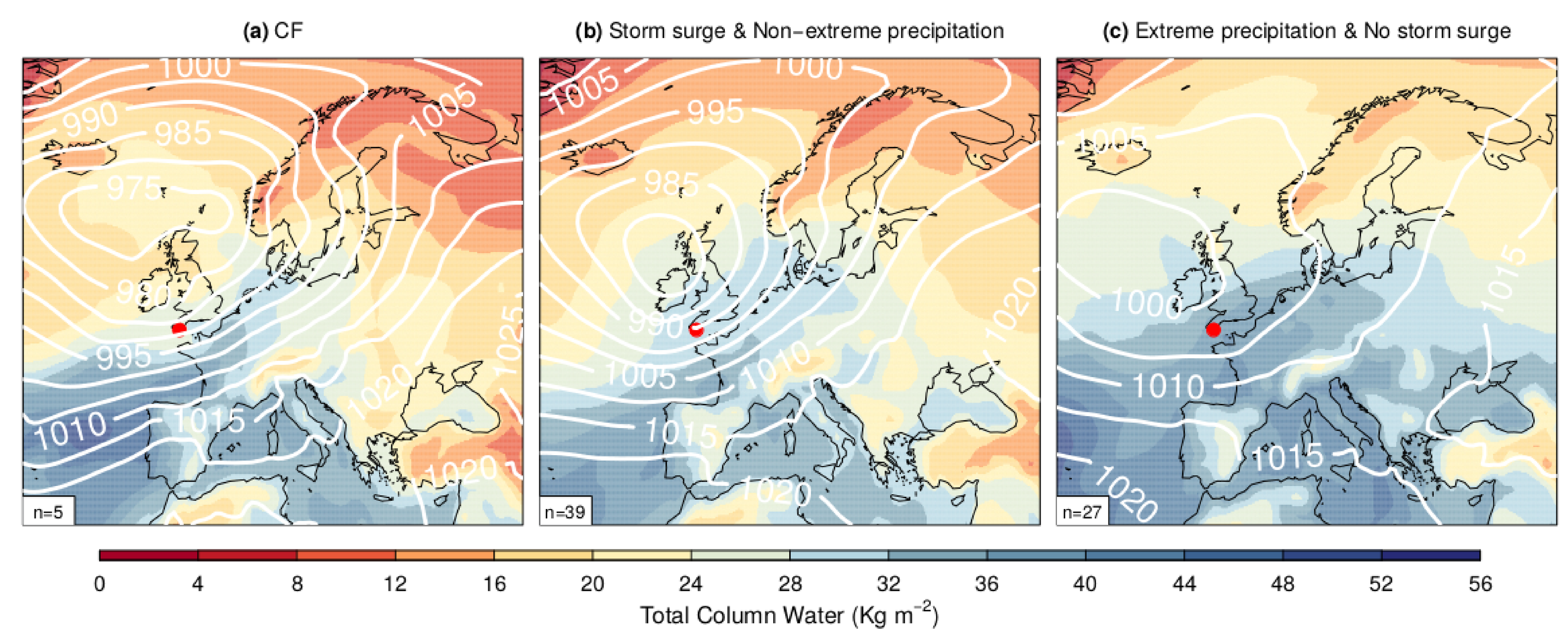

Figure 5: Composite maps of sea level pressure and total column water for events of (**a**) compound flooding, (**b**) storm surge but not extreme precipitation, (**c**) extreme precipitation but not storm surge, around Plymouth (England) marked as a red dot.

Conclusion

In the present, the locations experiencing the highest potential risk are mostly along the Mediterranean Sea.

In the future, sea level rise may be aggravated by CF, which has to be taken into account for a full risk assessment.

CF potential risk is projected to emerge along parts of the Atlantic and North Sea.

The main driver of future changes in CF risk appears to be changes in precipitation.