Initial mapping of global climate hotspot areas in WP3-7 contexts

Deliverable 2.2

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Deliverable title	Initial mapping of global climate hotspot areas in WP3-7 contexts
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Lead beneficiary	URead
Authors	Rohit Ghosh, Ted Shepherd
Contributors	Ertug Ercin (WP3), Alessio Ciullo (WP4), Jaroslav Mysiak (WP5), Anders Levermann (WP6), Elco Koks (WP7), Dewi Le Bars (WP7)
Reviewers	Suraje Dessai, Bart van den Hurk, Karin van der Wiel
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Dissemination level of the document

X	PU	Public
	PP	Restricted to other programme participants
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RECEIPT builds climate risk storylines in which climate hotspots play an important role. Climate hotspots are defined by RECEIPT to be "areas outside Europe where extreme climatic features may lead to a strong European socio-economic impact". During the first year of the project, the different sectoral work packages (WP 3-7) have been engaged in a process of identifying candidate climate hotspots. They have been selected on the basis of expert knowledge of climate-related European socio-economic vulnerability, generally anchored in historical experience or current risk awareness, and are considered to be representative pictures rather than detailed descriptions of the extreme climatic features. The purpose of this deliverable is to document where the project stands at this point in time in terms of hotspot identification, acknowledging that this is a "moving target" and that some hotspots will inevitably be dropped, and new ones added, as the project develops.

1. Characterization of uncertainty

It is inherent in the nature of a climate risk storyline that it is a plausible cause-effect chain, or narrative, of what *could* happen, rather than a prediction of what *will* happen. In particular, there is no attempt to attach probabilities to climate risk storylines (Hazeleger et al., 2015; T. G. Shepherd et al., 2018). However, in order for our climate risk storylines to be useful for decision-making, there needs to be some kind of assessment of the uncertainty involved in determining the plausibility or likelihood of the events, or combination of events. Along with the hotspot mapping we therefore provide an indication of the nature of the uncertainty that would be involved in treating each of the climate hotspots, as this has implications for the modelling and analysis approaches that would be suitable for quantifying the climate component of the climate risk storylines.

There are a number of different ways in which uncertainty is characterized in the literature. Figure 1 shows the framework that has been used for the last 10 years in the IPCC Assessment Reports. It is used there in the context of a specific finding, and shows how the confidence one has in that finding depends on a combination of the nature of the evidence and the extent of agreement between the different lines of evidence. The lightest shading corresponds to Low Confidence, the medium shading to Medium Confidence, and the darkest shading to High Confidence. Generally, only the High Confidence findings are considered to be amenable to probabilistic quantification (such as 'likely').

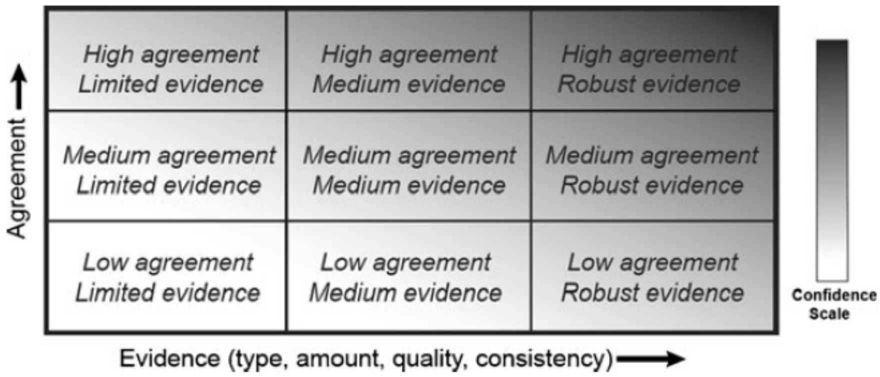

Figure 1. From Mastrandrea et al. (2011).

For RECEIPT we can use the framework shown in Figure 1 to characterize instead the state of knowledge that is relevant to a particular climate hotspot, which we describe as a "Level of Scientific Understanding" (LOSU) rather than a confidence level. The nature of the evidence will generally involve a combination of observations, models, and theory, with the extent and quality of each line of evidence varying, sometimes greatly, between different hotspots. We differentiate between the LOSU of the drivers of observed variability in the hotspot, and of their response to climate change.

Figure 2 shows a very general framework which provides examples of the different sorts of analysis methods that are suitable for characterizing uncertainty, depending on whether it is felt that the range of possible outcomes is well understood and it is only the probabilities of any particular outcome that are problematic, or that even articulating the range of possible outcomes is problematic. In the context of the physical climate system, it would generally be accepted that the possibilities are reasonably well understood, and that we are mainly concerned with the left-hand column of the matrix in Figure 2. However, for non-physical aspects of RECEIPT's climate risk storylines, it is expected that the right-hand column of the matrix would also be relevant.

For the current hotspot mapping exercise, the LOSU is purely concerned with the physical climate system. We consider that a High LOSU maps onto the upper-left corner of the matrix in Figure 2. In the context of storylines, that means that we can generally consider a single estimate. An example would be the regional mean temperature increase conditional on a global warming level. Medium and Low LOSUs map onto the lower-left corner of the matrix in Figure 2 and require methods that reflect 'plural, conditional' states of knowledge (in the language of Stirling, 2010).

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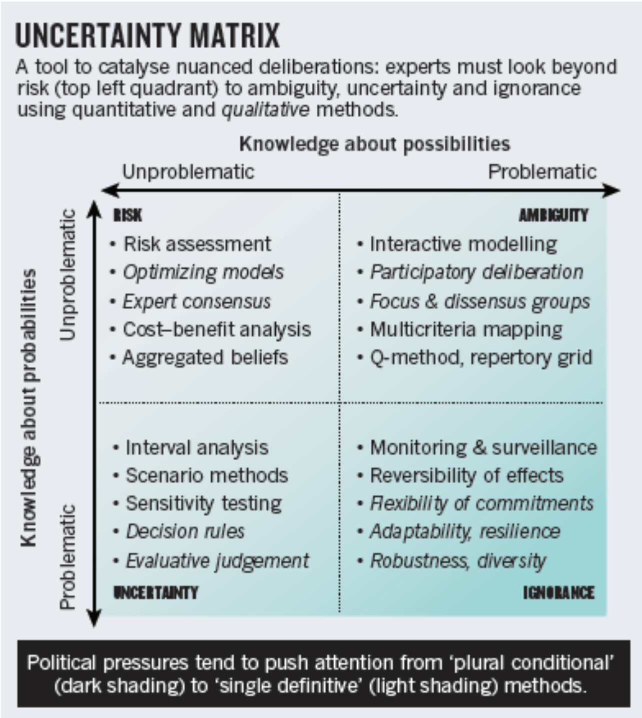

Figure 2. From Stirling (2010).

Based on the above frameworks, we use the following guide as an interpretation of the LOSUs:

For climate variability features under current climate conditions,

- **High** → clear idea of the drivers, consistent between observations, models and theory
- **Medium** → good idea of the drivers from observations, inconsistently reproduced in models
- **Low** → conflicting ideas of the drivers, non-robust results from models

For climate change features,

- **High** → good idea of what will happen under climate change due to a good idea of the drivers (hence conditional only on global warming level)
- **Medium** → sufficient idea to construct scientifically plausible storylines of regional aspects of change, without necessarily knowing which storyline will actually occur
- **Low** → no idea how conditions will evolve (hence requiring methods reflecting deep uncertainty)

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2. Table of global climate hotspots

We first provide a table, organized by sectoral WP, of the different climate hotspots so far identified by each WP. By climate hotspot is meant a geographical region, and associated climate condition (or 'stressor'), which can impact Europe through a climate risk storyline. Details of the climate risk storyline remain to be worked out by the sectoral WPs, so the description here is merely indicative, and as a consequence the stressor is rather generic. The main emphasis here is on the climatic component of the hotspots that can be deduced from our understanding of processes and interactions taking place in the present climate. We do not yet consider future storylines, but we provide a rough subjective indication of the level of scientific understanding (LOSU) of the climatic aspects, as described in Section 1 above, distinguishing between the drivers of current variability and the response to climate change. The LOSU is relevant to the modelling strategy that would be appropriate in each case, so is intended not as a definitive statement but rather as a guide to discussion of the modelling strategy. The asterisks indicate where the hotspot is a high priority for the sectoral WP.

WP	EU vul-nerability	Climate risk storyline	Hotspot	Stressor	LOSU (drivers of current variability)	LOSU (climate change)
3	Agri food economy	Cocoa supply reduction	West Africa (Ghana, Ivory Coast)	Drought, intermittent rainfall	Medium	Low
3	Food security	Soy production decline*	South America (Brazil, Argentina), midwest USA	Drought, suboptimal temperature climate	Medium	Low
3	Food supply chain	Palm oil supply reduction	Southeast Asia (Indonesia, Malaysia)	Drought	Medium	Low
4	Insurance and finance	Insurance premiums up; financial market shock	Southeast USA*	Tropical cyclones	Medium	Low (for frequency) High (for intensity)

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WP	EU vul-nerability	Climate risk storyline	Hotspot	Stressor	LOSU (drivers of variability)	LOSU (climate change)
4	Public finance	Risks to public insurance schemes (CCRIF, EUSF)	Caribbean*, Central America, EU outermost regions	Tropical cyclones	Medium	Low (for frequency) High (for intensity)
5	Foreign develop-ment and cooperation	Increase in humanitarian aid, internal migration	Sub-Saharan Africa*	Drought, flooding	Medium	Low
5	Foreign develop-ment and cooperation	Food security, internal displacement	Horn of Africa, East Africa*	Drought	Low	Low
5	Foreign develop-ment and cooperation	Food security, internal migration	Middle East and North Africa (Egypt*)	Drought	Medium	Medium
5	Foreign develop-ment and cooperation	Internal displacement and economic instability	Eastern border region of EU	Heat waves	Medium	High
5	Foreign develop-ment and cooperation	Increase in humanitarian aid, internal migration	Caribbean	Tropical cyclones	Medium	Low (for frequency) High (for intensity)
6	Manufactu-ring supply chain	Disruption to transport from USA	Northeast USA	Heavy snowfall	Medium	Low (for extreme snowfall) Medium (for mean snowfall)
6	Manufactu-ring supply chain	Computer parts capacity decline	Thailand*	Flooding	Medium	Low
6	Manufactu-ring supply chain	Disruption to transport from USA	New York City, Gulf of Mexico*	Tropical cyclones	Low	Low (for frequency) High (for intensity)

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WP	EU vul-nerability	Climate risk storyline	Hotspot	Stressor	LOSU (drivers of variability)	LOSU (climate change)
6	Manufactu-ring supply chain	Cotton production capacity	India, Pakistan	Drought, heat waves, flooding	Low	Low
6	Manufactu-ring supply chain	Coal production decline	Queensland, Australia	Flooding	Medium	Low
7	Coastal infrastruc-ture	West Antarctic Ice Sheet collapse*	West Antarctica	Sea level rise, coastal flooding	Medium	Low
7	Coastal infrastruc-ture	Arctic sea ice opening for new shipping routes (opportunity)	Arctic	Warming	Medium	Medium
7	Ports operation, food supply chain	Flooding of coastal infrastructure	Mid North Atlantic*	Warmer Atlantic SSTs, coastal flooding from TCs	Low	Medium

*High priority

3. Mapping of hotspots and identification of common hotspots

The image below presents a visual summary of the initial mapping of global climate hotspots.

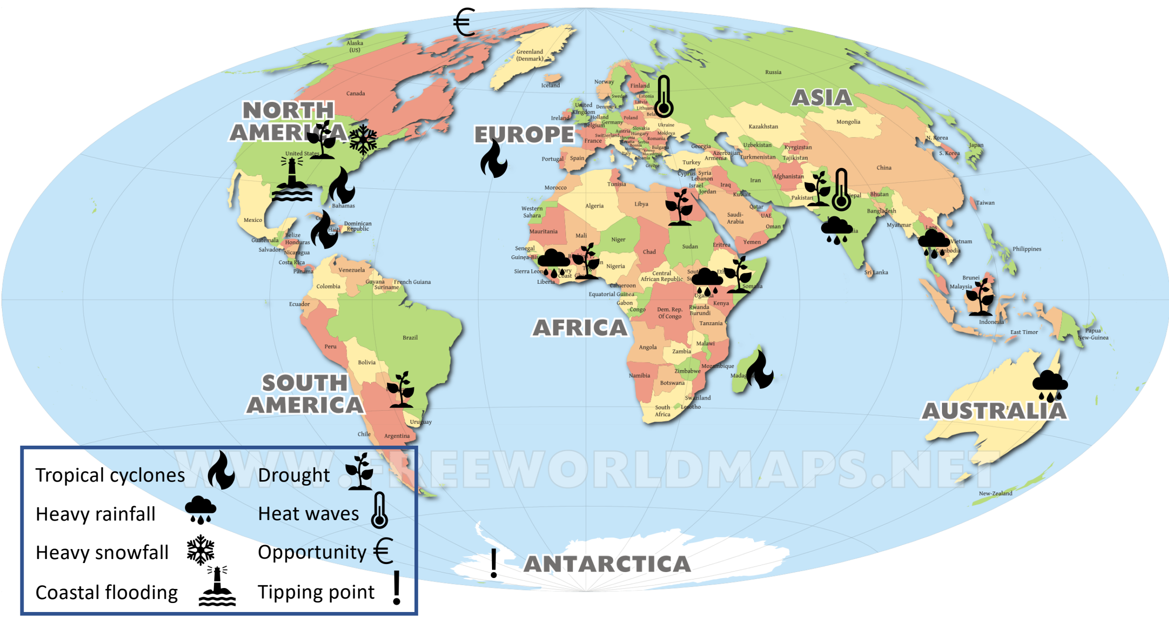

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Table of hotspots arranged by region, showing commonality between WPs:

Hotspot	**Stressor**	**WPs**		
Middle East and North Africa (Egypt)*	Drought	5 (int'l aid)		
West Africa*	Drought, heavy rain	3 (cocoa)	5 (int'l aid)	
Horn of Africa, East Africa*	Drought, flooding	5 (int'l aid)		
South America (Brazil, Argentina), midwest USA*	Drought	3 (soy)		
NE USA	Heavy snowfall	6 (transport)		
New York City*	Tropical cyclones	6 (transport)		
Southeast USA, Gulf of Mexico*	Tropical cyclones	4 (insurance, finance)	7 (coastal)	
Caribbean*	Tropical cyclones	4 (public insurance)	5(int'l aid)	
Other regions	Tropical cyclones	4 (public insurance)	5 (int'l aid)	7 (coastal)
Eastern border region of EU	Heat waves	5 (int'l aid)		
SE Asia (Indonesia, Malaysia)	Drought	3 (palm oil)		
Thailand*	Flooding	6 (computer parts)		
India, Pakistan	Drought, heat waves, flooding	6 (cotton)		
Queensland	Flooding	6 (coal)		
WAIS collapse*	Sea-level rise	7 (coastal)		
Arctic	Sea-ice melt	7 (coastal)		

*High priority

4. Additional details on selected hotspots

In the following we provide some additional details on a number of these hotspots, including historical analogues, relevant references to the published literature, and some comments on the state of understanding of drivers and the response to climate change.

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WP3: Food security and Agri food economy

For WP3, western sub-Saharan Africa, South America and Southeast Asia have emerged as three main hotspots of relevance for Europe with regard to agri-economy, food security and supply chain, respectively. Drought and water scarcity are identified as one of the key stress factors for all the sectors. Moreover, for cocoa, excessive heat and excessive rain could also affect production.

WP3.1: West Africa

Agri-economically, there is a major European dependence on cocoa from western sub-Saharan Africa, especially from Ivory Coast and Ghana. Western sub-Saharan Africa supplies 70% of world cocoa. Rainfall is mainly driven by the monsoon circulation and influenced by the tropical Indian, Atlantic and Pacific Ocean sea-surface temperature (SST) patterns (Rodríguez-Fonseca et al., 2015). In addition, local land surface processes seem to also play a key role in causing extreme conditions (Nicholson, 2000). This region has seen major droughts in the 1970s and 1980s, which made the high cocoa producing eastern forest belt of Ivory Coast unsuitable by the 1990s (Schroth, Läderach, Martinez-Valle, Bunn, & Jassogne, 2016). There was a partial recovery of the rainfall after the 1990's but the characteristic of the rainfall has changed, becoming more intense and intermittent away from the west coast (Biasutti, 2019). In particular, a recent study on western and central Ghana shows that farmers in the region perceive longer dry periods, unpredictable rainfall and higher temperatures in recent years as a noticeable change in climate, which could affect the suitability of their farming region for future cocoa plantation (Buxton, Lamptey, & Nyarko, 2018).

Northern hemispheric differential warming between the tropics and the extratropics is suggested to be the main driver of the declining rainfall over west Africa in the 1970s and 1980s (Biasutti, 2019; Park, Bader, & Matei, 2015). A colder extratropical SST compared to the tropical region restricted the northward movement of the intertropical convergence zone and led to reduced west African monsoon precipitation. By the end of the 1980s we find a recovery in rainfall which is suggested to be due to the comparatively warmer Mediterranean sea (Park, Bader, & Matei, 2016). In addition, aerosol is suggested to play an important role in west African monsoon precipitation variability (Dong, Sutton, Highwood, & Wilcox, 2014; Huang, Zhang, & Prospero, 2009; Undorf et al., 2018). Due to the interplay of these multiple driving factors, which led to the observed multidecadal variations in rainfall, and also due to the uncertainty in the dynamical response to global warming in the climate models (Monerie, Wainwright, Sidibe, & Akinsanola, 2020), the future trend of west African mean rainfall from climate change remains unclear.

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WP3.2: South America and Midwest USA

Regarding food security, Europe depends on the soy produced in Brazil and Argentina as being the largest source of feed for its dairy and meat production. Drought, associated with extreme temperature, is identified as one of the main climate stressors for soy production. The major droughts of 2014/15, 2011/12 and 2004-05 in Brazil have affected soy production and led to enhanced use of drought resilient variations of soy seeds (Engels, Rodrigues, Ferreira, Inagaki, & Nepomuceno, 2017). Although the soy growing area is expanding with time over Brazil, the central, southeastern (SE) Brazil and the La Plata basin is seen as the main soy growing region in South America. In addition, the midwest USA is also a hotspot for soybean production. The severe drought in central USA in 2011/12 caused a 27% reduction in production and led to simultaneous soybean crop failure both in South America and in the USA.

SE Brazil is mostly influenced by the south Atlantic convergence zone (SACZ) (Cavalcanti, 2012). There is also a high correlation of the precipitation extremes in the SE region with the SST anomalies in the central and eastern tropical Pacific (Liebmann, Jones, & de Carvalho, 2001). Further, a relation between the south Atlantic SST dipole and SE Brazil extreme wet/dry periods is also found. A north-south seesaw pattern of precipitation is seen in various studies, which is associated with the Pacific South American pattern (Cavalcanti, 2012). The northern part of the La Plata basin consists of SE Brazil and is mainly controlled by SACZ. For the rest of the La Plata basin, the rainfall is mainly governed by mesoscale convective systems (Cavalcanti, 2012) and also by ENSO episodes, where dry conditions occur during La Niña (Grimm, 2003; Grimm, Barros, & Doyle, 2000).

Previous observational studies generally found an increasing trend in extreme and heavy precipitation over SE Brazil and the La Plata basin and a decrease in precipitation over central to eastern Brazil over the last decades (Carvalho, 2020). This dipole pattern in precipitation trend is suggested to be due to the poleward migration of the SACZ (Zilli, Carvalho, Liebmann, & Silva Dias, 2017). In spite of an increasing heavy precipitation trend, the SE region of Brazil including the city of São Paolo shows periods of rainfall deficit from 2001 in austral summer (January-February-March), including remarkably dry conditions in 2001 and in 2014-2015 (Coelho et al., 2016). Hence the precipitation characteristic differs depending on the chosen area, especially over SE Brazil, and the time period of the year. However, a clear attribution to climate change either for increased heavy precipitation or for drought is not established due to the short record of observed data, in light of the prominent presence of low-frequency variability (Carvalho, 2020; Otto et al., 2016). Therefore, in

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spite of having a reasonable understanding of the main drivers of precipitation variability over this region, the role of climate change is yet to be determined.

The 2012 drought in central to southern USA is mainly associated with back-to-back La Niña events in 2010-11 and 2011-12 (Rippey, 2015). Under global warming, the chances of extremely hot droughts are projected to increase (Cheng, Hoerling, Liu, & Eischeid, 2019). In addition, the severity of the droughts and associated heat waves would be larger under future La-Niña like periods (Fasullo, Otto-Bliesner, & Stevenson, 2018). However, it has been suggested that under global warming, it would be harder to predict an El Niño or La Niña event due to its weakening relation with east Atlantic SSTs (Jia et al., 2019). Further study suggests that there will be a poleward shift in summer precipitation over the southern Great Plains, which could also play a role in determining the overall intensity of the droughts over the midwest USA (Bukovsky, McCrary, Seth, & Mearns, 2017).

WP3.3: Southeast Asia

Europe depends on southeast (SE) Asian countries, especially Indonesia and Malaysia, for the supply of palm oil, which is mainly used in manufacturing and agri-food processing. Drought is identified as the main stressor for this region. Due to the 2015 drought, SE Asian palm oil production fell the following year and prices rose from 2500 to over 3000 ringgit (800 USD) per metric ton. The precipitation extremes in these regions have a direct association with the summer monsoon rain (Aldrian, Gates, & Widodo, 2003; Kripalani & Kulkarni, 1997). ENSO has a significant influence on the SE Asian monsoon (Räsänen, Lindgren, Guillaume, Buckley, & Kummu, 2016; N Singhrattna, Rajagopalan, Krishna Kumar, & Clark, 2005). Further, the IOD has a negative correlation with SE Asian summer rainfall (Nkrintra Singhrattna, Rajagopalan, Clark, & Kumar, 2005). However, there is no emerging significant trend in monsoon rainfall over this region, which makes it hard to determine the possibility of further severe drought and the associated role of climate change.

WP4: Finance and Insurance

For WP4, the currently selected hotspots are all associated with tropical cyclones. The main focus is on the Atlantic basin (especially the Caribbean region and southeast USA), but consideration of EU outermost regions expands the areas of consideration to include the eastern Atlantic and the Indian Ocean. As an example, hurricane Katrina in 2005 turned out to be the costliest natural disaster of all time for the insurance sector with losses of $60B. This kind of major event leads to a spillover effect on European financial markets and causes a hard insurance market in Europe (Cambridge Centre for

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Risk Studies, 2018). Further, a major tropical cyclone in the European outermost regions could have an effect on the available capital of the European Solidarity Fund (Hochrainer-Stigler, Linnerooth-Bayer, & Lorant, 2017). For example, hurricanes Irma and Maria struck several Caribbean islands within two weeks in 2017. This incident brought moral liabilities to the EU, since the Caribbean Catastrophe Risk Insurance Facility is supported by the European Commission and EU member states. In addition, financial consequences on the public economy could lead to a decrease in European economic growth.

WP4.1: Caribbean Islands and Southeast USA

The year 2017 saw a particularly active Atlantic hurricane season. A crucial role of warmer tropical Atlantic SSTs has been identified, which combines the Atlantic multidecadal oscillation and Atlantic meridional mode (Murakami, Levin, Delworth, Gudgel, & Hsu, 2018). A role of SST anomalies in the Niño3 region is also found for the predictability of the Atlantic hurricane frequency (Smith et al., 2010). Further, the Atlantic meridional overturning circulation is also suggested to play a role in the observed long-term decline in Atlantic hurricane frequency (Yan, Zhang, & Knutson, 2017). Overall there is no clear trend in the frequency of hurricane development, but the predicted increasing trend in intensity with global warming is becoming apparent (Knutson et al., 2019).

WP5: Foreign development and cooperation

The three vulnerability topics in international development explored in RECEIPT are coping capacity, food security and internal displacement. Based on these factors, both West and East Africa/Horn of Africa are identified as crucial hotspots for EU's international relations. The severe drought of 1972-73 in West Africa was the worst since 1911-14 and required hundreds of thousands of tons of international food aid which even then could not alleviate the suffering. The 2019 spring drought in the Horn of Africa is among the top three driest on record, which required the EU to increase emergency humanitarian funding by €50 million making a total of €366 million since 2018. Further, in South East Africa, cyclone Idai in 2019 caused severe damage which affected 1.7 million people in Mozambique, and the EU has assisted with additional humanitarian support of €12 million in Mozambique, Zimbabwe and Malawi. It was the worst weather-related disaster ever to hit the Southern Hemisphere. In addition, the Caribbean islands remain a hotspot for foreign development due to some of the reasons already mentioned in the earlier discussion concerning WP4. In 2017, after hurricanes Irma and Maria hit the Caribbean islands, the EU commission gave 8 million Euros under European civil protection and humanitarian aid operations. Further, the eastern border region

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of the EU became a hotspot for foreign development after the 2010 Russian heat wave, which led to forest fires and large casualties with internal migration. Since West African drought and Caribbean tropical cyclones have already been and will be discussed in other work packages (WP3.1, WP4.1, WP7.3 and WP7.4 respectively), here we briefly discuss the climate aspects of the two additional hotspots from this WP, Horn of Africa and the eastern border region of the EU.

WP5.1: Horn of Africa

The Horn of Africa region has experienced major droughts in its 'long rain' period (March-April-May) in the last decades, with a substantial effect on its agricultural sector and economy (Lyon & Dewitt, 2012). However, climate models project an increase in rainfall over this region (Kent, Chadwick, & Rowell, 2015), leading to a dichotomy known as the 'East African climate paradox' (Rowell, Booth, Nicholson, & Good, 2015), which has only been exacerbated in the CMIP6 models (Zappa et al., 2020). Further studies suggest this dichotomy in precipitation could arise from competing influences of the key drivers, which are also a source of interannual rainfall predictability, such as the SST evolution over the southern and north-western Indian Ocean and also from the Pacific Ocean (MacLeod, 2019). Altogether our understanding of future extremes over this region and the effect of climate change remains highly uncertain.

WP5.2: Eastern border region of EU

The 2010 Russian heat wave was due to an unusually persistent atmospheric blocking, which started in mid-June and persisted for the entire summer (Grumm, 2011). Strong convection in the tropical Atlantic in the northern summer of 2010 led to a Rossby wave train that extended into Europe creating anomalous anticyclonic conditions over Russia, which then interacted with an anomalously strong Indian monsoon circulation (Lau & Kim, 2012) and supported a persistent atmospheric anticyclonic regime (Trenberth & Fasullo, 2012). Although it is still not clear if climate change would make such a situation more probable, and thus whether the 2010 event provides a useful analogue for future events, we can at least be certain that under global warming any such event in the future would be much stronger and highly damaging.

WP6: Manufacturing

In the case of the manufacturing supply chain, various hotspots are identified. Of these we focus on four key hotspots, which are Northeast USA, Thailand, New York-Texas and India-Pakistan. In 2018, heavy snowfall in the northeast USA led to complete production and transportation failure for a

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week. The major flood of 2011 in Thailand reduced the production of computer parts and disrupted the global electronic supply chain. Hurricane Sandy in 2012, which affected the New York area, and Hurricane Harvey in 2017, which affected the Houston area, caused major disruptions to manufacturing and the associated supply chain. Further, the 2019 erratic rainfall and drought in Pakistan led to shortage of 6 million cotton bales.

WP6.1: Northeast USA

Catastrophic winter storms often hit the northeast USA and account for around 74% of snowstorm related losses for the entire USA (Janoski, Broccoli, Kapnick, & Johnso, 2018). However, the recent storm in January 2018, a historic “Bomb Cyclone”, had severe impacts on transportation with an estimated damage of $1.1 billion. Previous studies suggest that mean snowfall over midlatitudes would reduce with global warming, but the changes in heavy snowfall events remain uncertain (O’Gorman, 2014). Although a warming Arctic has been suggested to be linked with extreme cold winters over the northeastern USA (Cohen, Pfeiffer, & Francis, 2018), this claim is highly contested.

WP6.2: Thailand

The 2011 Thailand flood is explained neither by anomalous monsoon rainfall nor by an anomalous frequency of tropical cyclones (Promchote, Wang, & Johnson, 2016). Instead, it was a collective result of a series of abnormal conditions. Contributing factors were the anomalously high rainfall in the pre-monsoon season (in March), record high soil moisture content throughout the year, elevated sea level in the Gulf of Thailand, and other water management issues. The pre-monsoon rainfall has increased from the 1980s onward due to strengthening northeasterly winds. Moreover, sea level is rising under climate change, which makes this kind of flooding more probable in the future. However, a clear attribution of the 2011 flooding to climate change was not unanimously supported due to a considerable role of infrastructure issues which led to the severity of the flooding (G. J. van Oldenborgh, Urk, & Allen, 2012).

WP6.3: New York and Texas

New York was hit by Hurricane Sandy in 2012 which significantly affected the manufacturing supply chain and caused an estimated damage of $50 billion (Blake et al., 2013). The landfall of Sandy was nearly perpendicular to the coastline, which is climatologically unusual for this region (Hall & Sobel, 2013). Regarding the contribution of a warmer climate for this storm, a previous study hypothesized that global warming increases the frequency of blocking patterns in the jet stream, which increases

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the likelihood of storm tracks similar to Sandy (Francis & Vavrus, 2012). Another study finds a decrease in the frequency of steering flows conducive to tracks similar to that of Sandy due to global warming, possibly making it less severe in a warmer climate (Barnes, Polvani, & Sobel, 2013). Hence there are different views regarding the changes in frequency of Sandy-like storms. However, regarding intensity, a study that simulated Sandy-like storms in a future warmer climate found an increase in intensity under climate change (Lackmann, 2015).

In 2017, Hurricane Harvey hit Texas and caused $125 billion in estimated damages reported by the National Hurricane Center, which is more than any other natural disaster in US history except Hurricane Katrina. In terms of size and wind speed, Harvey was a significant hurricane, though most of the damage related to Harvey was caused by the extreme flooding it brought in Houston and surrounding areas. It has been suggested that global warming made the rainfall 15% more intense (Van Oldenborgh et al., 2017). Another study indicated that human-induced climate change increased the precipitation accumulation from Hurricane Harvey in most affected areas of Houston by a factor of 3.5 (Risser & Wehner, 2017). Their study suggests a precipitation accumulation increase of at least 18.8%, which is larger than the estimate (6%-7%) attributable to a warming of 1°C in the Gulf of Mexico under Clausius-Clapeyron scaling. Another aspect of Harvey that could have led to a shorter response time was its faster development towards an intense storm. A study from satellite records has shown that in the Atlantic basin the intensification time has reduced by 20 hours compared to 25 years ago (Kishtawal, Jaiswal, Singh, & Niyogi, 2012). In addition, it has been suggested that urbanisation increased the probability of extreme flooding from Hurricane Harvey in Houston (Sebastian, Gori, Blessing, Van Der Wiel, & Bass, 2019; Zhang, Villarini, Vecchi, & Smith, 2018). Therefore, there could be multiple drivers of the extreme flooding that resulted from Hurricane Harvey, with human-induced climate change being just one of them.

WP6.4: India and Pakistan

The major cotton production and supply chain for Europe is in south Asia, from central India and Pakistan. The recent droughts in Pakistan are partly due to the rising temperature leading to extremely hot summers. In addition, irregularities in monsoon precipitation are also enhancing the severity of the droughts. Summer monsoon precipitation is mainly driven by the Indian Ocean SST pattern (Indian Ocean Dipole, IOD) (Ashok, Guan, Saji, & Yamagata, 2004; Ashok, Guan, & Yamagata, 2001; Rao, Chaudhari, Pokhrel, & Goswami, 2010) and the central to eastern Pacific SST or ENSO (Kumar, Rajagopalan, Hoerling, Bates, & Cane, 2006). The evolution of these SST patterns

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under global warming remains highly uncertain (Ma & Xie, 2013). Therefore, although global warming would favour extremely hot summers with a tendency toward severe droughts, the added effect from potential changes in the monsoon is yet to be determined. A narrative approach is used in a recent study on Southern Indian rainfall, which could be used for our analysis (Dessai et al., 2018).

WP7: Coastal Infrastructure

This WP has identified two hotspots regarding risks in coastal infrastructure, plus one risk/opportunity. The risks are mass loss from West Antarctica resulting in accelerated sea level rise, and an increased intensity of tropical cyclones forming in the mid North Atlantic leading to higher chances of coastal flooding, with the specific target area of coastal flooding yet to be determined. The risk/opportunity arises from the prospect of an ice-free Arctic, which would provide risks to certain European harbours but opportunities to others.

WP7.1: West Antarctica

A striking role of the West Antarctic ice sheet (WAIS) loss on global mean sea level (GMSL) is primarily implicated in paleo records of the last interglacial (LIG), when a higher polar temperature was accompanied by a 6 to 9 meter higher GMSL from the present day, which required a substantial (3.6 to 7.4 meter) contribution from WAIS loss (DeConto & Pollard, 2016; Dutton et al., 2015; Turney et al., 2020). By its nature, WAIS is supposed to be most vulnerable under warmer temperatures (Mercer, 1978). It indeed has melted at an alarming rate in the last decades, with ~2000-3000 billion tonnes of ice lost between 1992 and 2017 (A. Shepherd et al., 2018). This ice loss is driven by changes in ocean melting of ice shelves, similar to what was suggested from paleo records for the LIG (Shepherd et al., 2004; Turney et al., 2020). However, the observed ice melt shows decadal scale variations related to oceanic conditions (Dutrieux et al., 2016). A recent study with a combination of observations and multiple models has claimed a partial role of global warming for the increased WAIS melting (Holland, Bracegirdle, Dutrieux, Jenkins, & Steig, 2019). Nevertheless, due to the prominent nature of decadal scale variability and large uncertainty presented in the projected estimates (DeConto & Pollard, 2016; Ritz et al., 2015), this recent finding is yet to be evaluated and confirmed through further studies.

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WP7.2: Melting of Arctic sea ice

Future melting of the Arctic sea ice will lead to an opportunity for shorter shipping routes with potential reorganization of the ports and other coastal infrastructure location. In fact, the cumulative distance travelled by ships in Arctic Canada already nearly tripled during 1990-2015. Greater levels of Arctic ship-based transportation and tourism have socio-economic and political implications for global trade, northern nations, and economies linked to traditional shipping corridors. According to Meredith et al. (2019), for stabilised global warming of 1.5°C there is an approximately 1% chance of a given September being sea-ice-free at the end of century while for stabilised warming at a 2°C increase, this rises to 10-35%.

WP7.3: East coast of the USA, Gulf of Mexico

Coastal infrastructure in this region is primarily chosen as a focus due to linkages with other work packages (i.e. manufacturing; see WP6.3). Hurricanes such as Sandy or Harvey in a future warmer climate could hugely affect coastal infrastructure and disrupt the supply chain. Hence, the level of adaptation to these storms under climate change along the east coast of the United States and the Gulf of Mexico may influence the reliability of supply of chemical and manufacturing goods to Europe.

Common drivers of hotspots

Many of the major hotspots encompassing multiple WPs have common drivers of tropical SST anomalies. For example, precipitation over west and east Africa, South America, and south and south-east Asia have common drivers from SST anomalies in the tropical Atlantic, Indian and Pacific Oceans. This gives us a framework to assess simultaneous crop failure (Anderson, Seager, Baethgen, Cane, & You, 2019) or multi-sector disruption depending on the changes in their common drivers. We could use analysis such as event scaling procedures, mapping joint occurrence of strong winds/heavy precipitation or chasing analogues in climate simulations. We could also build storylines of the changes in precipitation depending on common SST drivers. Shown below is a schematic diagram of the major hotspots connected to the SST drivers.

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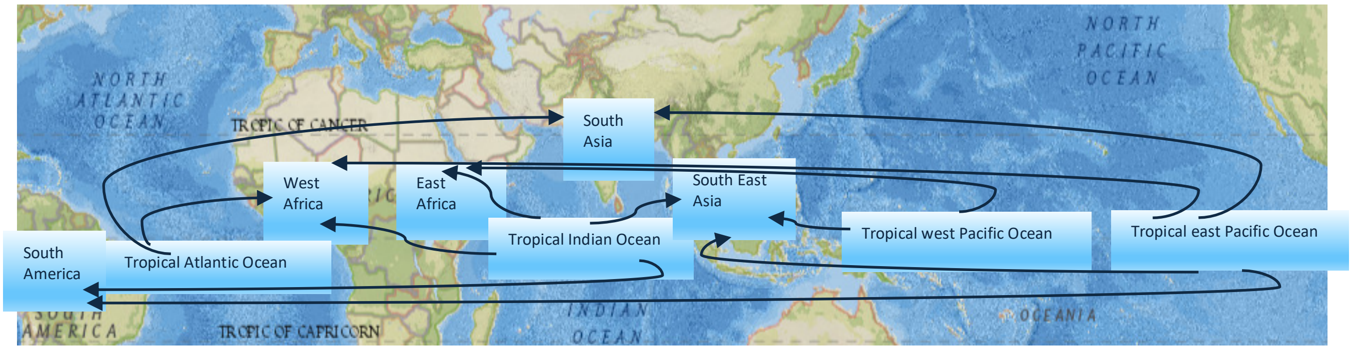

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Receipt

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