Grant agreement no. 776479

COACCH

CO-designing the Assessment of Climate CHange costs

H2020-SC5-2016-2017/H2020-SC5-2017-OneStageB

D3.1 Operationalizing socio-economic and climate tipping points

Work Package:	3
Due date of deliverable:	M 8 (JUL/2018)
Actual submission date:	30/JUL/2018
Start date of project: 01/DEC/2017	Duration: 42 months
Lead beneficiary for this deliverable:	Deltares
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Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	
CI	Classified, as referred to in Commission Decision 2001/844/EC	

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

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Suggested citation:

van Ginkel, K, Jeuken, A., Haasnoot M., Botzen, W., Tesselaar, M., Hunt, A., Watkiss, P., Cimato, F., Steininger, K., Bachner, G., Troeltzsch, J., Lincke, D., Hinkel, J., Boere, E., Sainz de Murieta, E., Scoccimarro, E., Bosello, F. (2018). D3.1 Operationalizing socio-economic and climate tipping points. Deliverable of the H2020 COACCH project.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

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Version log

Version	Date	Released by	Nature of Change
0.6	4/July/18	Kees van Ginkel (Deltares)	Early draft for Graz-meeting
0.9	17/July/18	Kees van Ginkel (Deltares)	Full draft after Graz-meeting
1.0	22/July/18	Ad Jeuken (Deltares)	Final draft
1.1	30/July/18	Francesco Bosello (CMCC)	Final check by the coordinator
1.2	16/May/20	Ad Jeuken (Deltares)	Version incorporating reviewers comments

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1. Introduction and method

Tipping points are an important notion in climate change research and communication. Tipping of large elements of the climate system may cause rapid change in the biophysical system (e.g. accelerated sea level rise) which has profound consequences for the socio-economic structure of Europe. However, also gradual changes in climatic conditions may significantly and abruptly alter socio-economic structures in Europe. COACCH therefore set out to significantly advance the knowledge on climate tipping elements and socio-economic tipping points induced by climate change.

The objective of this deliverable is to operationalize the concept of tipping points within COACCH. During the co-design process in WP1, stakeholders proposed a series of candidate tipping points which are of key concern for Europe. In this deliverable, we analyse these examples and process them into a set of inputs which are suitable for analysis by the modelling tools and investigation approaches in the COACCH portfolio (Figure 1).

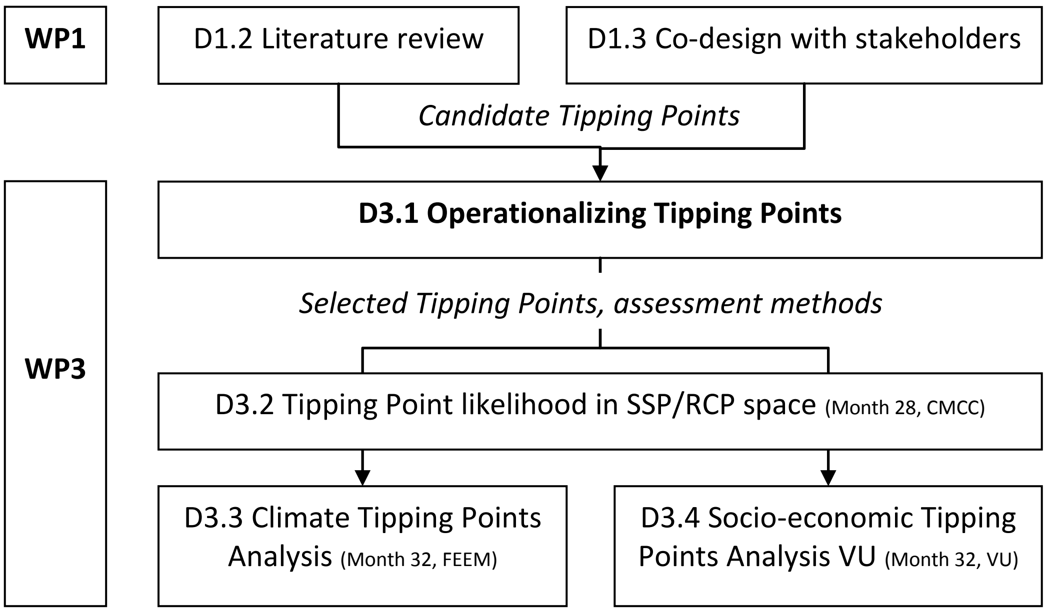

Figure 1 Relations with other COACCH deliverables

1.1 Method and structure of deliverable

Chapter 2 starts with an overview of the literature on tipping points, from which we derive definitions of tipping points and develop criteria for their selection.

Chapter 3 presents the candidate tipping points derived from the COACCH project co-design process and the final selection based upon the criteria specified in chapter 2.

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Chapter 4 discusses how the impacts and economic costs of chosen climate tipping points will be studied using COACCH sector-specific and macro-economic models.

Chapter 5 discusses how the likelihood and potential impacts of chosen socio-economic tipping will be studied using COACCH sector-specific and macro-economic models.

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2. Review and typology of tipping points

In this chapter, a short recap of tipping point literature in climate change discourse is given (section 2.1), from which definitions and a typology of tipping points are derived (section 2.2) to conclude with a set of criteria to select candidate tipping points (section 2.3) for further analysis in COACCH.

2.1 Literature review

An in-depth review of tipping point literature is presented in COACCH D1.2 *Knowledge synthesis and gap analysis.* Here, we restrict ourselves to a short recap of main bodies of scientific research, to prepare the reader for the tipping point definitions in section 2.2. This recap is not meant to give a full overview of the diverse literature and debate on definitions of tipping points.

The term “tipping points” stems from the English verb “to tip”, meaning “falling” or “turning over” as a result of imbalance in the system of interest (Oxford Dictionary, 2018) and received more widespread use after Gladwell (2000). Usage of the term is diverse, varying from loose and metaphorical (small cause, large effects) to very strict (bifurcation theory). On the one hand, its usage is a trend, re-describing phenomena that previously went under other headings. On the other hand, it is recognized as a constructive metaphor to communicate the severity of climate change impacts and bridge the gap between science and a wider audience (Russill and Nyssa, 2009, Van der Hel et al., 2018).

Climate tipping points

Climate tipping points concern abrupt state changes of so-called ‘tipping elements’ of the climate system. Tipping elements are large components (minimum scale 1000 km) of the earth system, and changes in their state may have profound consequences on the environmental and socio-economic system (Lenton, 2008). The classic example is a substantial weakening of the Atlantic Thermohaline Circulation: the ‘conveyer-belt’ mechanism transporting heat to Europe. Currently, winter temperatures in Europe are up to 10 ^{0}C higher than expected without this circulation. Levermann et al. (2012) identified the following potential tipping elements with direct impacts on Europe:

- Melting of arctic sea-ice: with profound consequences on Europe’s climate
- Melting of the Greenland Ice-Sheet: causing rapid sea level rise
- Melting of West Antarctic Ice-Sheet: causing rapid sea level rise
- Weakening of the Atlantic Thermohaline Circulation: see above
- Melting of Alpine glaciers: changing river flow timing and volumes
- Arctic ozone depletion: increasing UV exposure to humans and ecosystems

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Several other examples have been proposed, and the likelihood of their occurrence and potential impacts are still subject of scientific debate. For example, recently two studies presenting opposite results on the weakening of the Atlantic Thermohaline Circulation were presented in *Nature* (Thornalley et al., 2018; Caesar et al., 2018).

Ecological tipping points

Turning to ecological systems (usually with smaller scales than the above climate tipping elements), tipping points indicate ‘regime shifts’ or ‘critical transitions’ between multiple stable system states (Scheffer, 2003). The classic example is the hypothetical lake-town problem: when too much pollution from the town enters a lake, the lake will suddenly shift from an eutrophic to a trophic state, with profound adverse consequences (Quinn et al., 2017). Comparable state shifts are found in countless ecological systems. Changes in climatic conditions such as temperature and precipitation may be an important cause of these state shifts. For example, arid grasslands may ‘tip’ to deserts; coral reefs may suddenly disappear; and forest diebacks may occur under droughts (Moore, 2018; Camarero et al., 2015).

Socio-economic tipping points

In the social sciences, the tipping point metaphor originated, to indicate shifts from predominantly white neighbourhoods to predominantly black neighbourhoods (Russil, 2015, referring to the work of Thomas Schelling from 1960-1970). The bestseller on tipping points by Gladwell (2000) also focussed on socio-economic phenomena. In climate change discourse however, tipping point literature left climate induced social and economic tipping points mostly unexplored (Kopp et al., 2016). COACCH seeks to fills this gap by exploring climate induced socio-economic tipping points.

Adaptation tipping points

Adaptation tipping points denote the crossing of formal (e.g. standard) or informal acceptability thresholds (Haasnoot et al., 2013) at some point in the future, triggering a change in current actions or policies. Other authors use ‘turning points’ (Werners et al., 2015) or ‘trigger points’ (Buurman and Babovic, 2016; Walker et al., 2015) to indicate more or less the same. The key notion behind the approach is bottom up formulation of acceptability thresholds and studying the likelihood of their exceedance in an uncertainty space spanning climate and socio-economic scenarios. The classic example is from the Dutch Delta Programma, with its clearly defined flood safety thresholds (Kwadijk et al., 2010).

Transformation tipping points

In literature on social transformations towards a sustainable world, tipping points indicate the point where the transformation is not only adopted by a few early adaptors, but rapidly spreads over the majority of actors. For example, Moser and Dilling (2007) refer to the prototypical S-curve of social change towards a sustainable world where sound mitigation and adaptation strategies are incorporated in policies,

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where there is widespread political engagement and where climate friendly technologies are widely adopted by population and the industry.

2.2 Definitions and typology

Based on the above exploration of the literature we propose the following definitions for use within COACCH:

1. Climate tipping point: **a critical point at which the future state of a tipping element (a large component of the earth system, minimum scale ~1000 km) is switched into a qualitatively different state by a small perturbation** (Lenton et al., 2008)
2. Ecological tipping point: **a point indicating a (climate-induced) regime shift or critical transition between different stable ecological states of a system**. (Scheffer and Carpenter, 2003)
3. Socio-economic tipping point: **a climate change induced, abrupt change of an established socio-economic system's functioning into a new functioning of fundamentally different quality (beyond a certain threshold that stakeholders perceive as critical)**
4. Policy tipping point: **a fundamental change in policies or implied actions in response to climate change to continue to achieve societal objectives under changing conditions.** This can for example reflect a change in transformation measures, because a) one foresees a crossing of a formal (e.g. standard) or informal acceptability threshold: 'adaptation tipping point' (Haasnoot et al., 2013), b) opportunities arise for implementation of specific adaptation or development measures (e.g. due to change in cost/benefit ratio resulting from changes in climate risk) (Bouwer et al. under review), c) or a social change where climate friendly technologies and policies are widely adopted by diverse actors (Moser and Dilling, 2007).

Within COACCH the focus is on type 1 climate tipping points and type 3 socio economic tipping points. As there is already a whole body of literature and relative consensus on the climate tipping points the remainder of this chapter is dedicated to socio economic tipping points.

2.3 COACCH criteria for socio economic tipping points definition and selection

In the previous section, we proposed four definitions of tipping points. Here, a set of criteria to guide the selection of relevant socio-economic tipping points is proposed. Developing criteria to determine which tipping points are 'true tipping points' is however challenging. First of all, there is no consensus about a definition among scholars. Definitions range from very strict (for example by equating tipping points to bifurcations in dynamic systems theory) to a more metaphorical use (small cause, large effect). Others prefer definitions that stay close to the examples provided by Gladwell (2000). Second, criteria that are useful and easily applicable in one scientific field are hard to transfer to a different discipline. For example, the strict mathematical

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definitions applied to climate and ecological systems are hard to express in socio-economic terms, and even harder to be used to describe policy shifts or societal change.

For the purpose of COACCH research, we are therefore looking for a set of criteria that while safeguarding the scientific rigor (Kopp et al., 2016; Werners et al., 2013) of the definition still recognizes some broader breadth than the narrow mathematical meaning (Van Nes et al., 2016; Russil and Nyssa, 2009; Russil, 2015).

Additionally, we seek a definition in which tipping points can be expressed in economic terms, because economic evaluation of climate change impacts is of key relevance to our society and thus a key aspect of COACCH.

Eventually tipping points in COACCH should at least meet the following three criteria:

C1. Small causes with (disproportional) large effects (i.e. a non-linear response to a gradual change in conditions). In economic terms, the latter could be reflected by a significant percentage change in economic indicators, e.g. of GDP.

C2. Rapid change (i.e. quickly occurring, abrupt change)

C3. Structural reconfiguration or transformation of a system (in a mathematical sense: multiple stable states)

In addition, many tipping points may share the following characteristics, but these are not as necessary as the first 3:

C4. Irreversibility: this could mean hard to reverse, limited reversibility on a human time-scale or unattractive to reverse from a societal or economic point of view. This could also imply that the path to the original state is different from the path to the altered state (hysteresis).

C5. Feedbacks as system-internal drivers for further feedback as well as state stabilizers.

Coherence with other criteria for tipping points

The above set of criteria clearly meets the metaphorical use of tipping points: small causes with large effects. They are a direct derivation from Milkoreit et al. (2018) who states the following four core criteria for tipping points in coupled socio-ecological systems:

M1. Multiple stable states (implying a certain magnitude of change and a structural reconfiguration of the system)

M2. Abruptness (also: non-linearity or disproportionality between cause and effect)

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M3. Feedbacks as system-internal drivers of change between the two system states as well as state stabilizers

M4. Irreversibility, or at least: limited reversibility on a timescale relevant for humans

We take M4 as an optional requirement (Milkoreit et al. also hint at doing so), because for many systems, some degree of reversibility is possible. The point is mainly that it is either beyond human ability to do so within a reasonable timescale (for climate tipping points), very hard to do so (for example to reverse lake eutrophication) or undesirable to do so (from an economic point of view).

Furthermore, they are also consistent with the ‘Gladwellion characteristics’, after Gladwell (2000) and Kopp et al. (2016):

G1. Contagious spreading of a phenomenon (Gladwell showed how ideas and trends can spread like infectious diseases)

G2. Little cause can have disproportional large effects

G3. Rapid (quickly occurring) change

Obviously, G2 and G3 are directly represented by C1 and C2. Concerning G1, we recognize that contagious spreading (through network effects) can be the cause for the state shift/structural reconfiguration, but there might be also other mechanisms causing a tipping point. We elaborate on these mechanisms in section 5.1.

2.4 Additional requirements

A final set of criteria follows directly from COACCH aims to analyse and discuss policy relevant tipping points. Policy relevance of tipping points is determined by:

- Extent of economic impact. Case studies with significant EU-wide economic impacts are prioritized over case studies with smaller economic impacts.
- Large impact, even though hard to express in monetary terms (e.g. large impact on ecosystem services, reputational damage, requiring large shifts in policies or social transformations)
- Large priority for COACCH stakeholders (key concern for a particular group)
- highly representative and scalable to different contexts in many EU-regions even though local

As a final general remark, it is important to stress that many of the criteria identified cannot be determined ex ante, but only ex post as a result of the investigation. Therefore, some initial candidate tipping points, may eventually fail to meet the chosen criteria and be dropped.

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3. Candidate tipping points

This chapter summarizes outcome of the COACCH co-design process on tipping points. In section 3.1, the tipping points discussions during the first co-design meeting are described. In section 3.2, a list of candidate tipping points per sector is presented and a final selection is made using the criteria presented in section 2.3.

3.1 Group discussions co-design workshop

On May 17, 2018, the COACCH project organized a co-design stakeholder workshop in Brussel. It gathered 29 European stakeholders representative of 5 different areas: national policymakers (2x); policymakers on EU and international level; non-governmental stakeholders; industry and business. One of the objectives was to make an inventory of tipping points of key concern for Europe. This section gives an overview of the candidate tipping points that were brought up in the stakeholder meeting.

3.1.1 National policymakers

Climate tipping points

The occurrence of climate tipping points is rather distant from the perspective of policy makers. They are not so much interested in the exact scientific causes and system dynamics of natural processes, but rather in their effects and impacts. For example, with regard to the melting of the West Antarctic and Greenland ice-sheets, they want to be informed about the amount of sea level rise they can expect and the rate of change. The question for government policy makers is - how can we adapt to such changes? They also wonder if there may be any effects on marine life and ocean food chains due to warming of water and acidification. They recommend to focus on smaller scale biophysical tipping points such as melting of the Alpine glaciers and its impact on water availability, ecosystems, migration of species and impacts on tourism – all things that they see as having direct implications for their society and economy.

Socio-economic tipping points

Policy makers are concerned about the impacts of sea level rise: at country level, they are worried about the viability (e.g. possibility to continue to exist and operate) of coastal communities and damage to roads and railways along the coast; at a regional/European level, they fear mass migration towards Europe induced by climate change in other continents.

Southern countries are very concerned about the impacts of droughts and extreme heat, at both local and national level. In several coastal areas in Italy for example, water saving policies prohibit the use of water for showering on beach facilities. This is a large nuisance for tourists that in the future might contribute to reducing tourism in those areas.

In general, droughts threaten a large variety of ecosystem services in southern Europe. Glacier melts in Alpine regions pose a threat to ecosystem services, which are currently

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not included in economic analysis. In central Spain (Castillia) a collapse of rain fed agriculture is feared. A drought of one or two years can still be backed by insurance companies, but more recurring droughts are unlikely to be covered by insurance. This would most likely lead to irreversible abandonment of rain fed agriculture and migratory flows towards cities. It was reported that several attempts of the Spanish Government to urge people to return to rural areas have so far failed.
On the contrary, in northern Europe, higher temperatures are likely to create opportunities for agriculture where this formerly was not possible. For example, in parts of Russia and Greenland, a gradual temperature increase may involve a tipping point - from no agriculture to new opportunities for agriculture.
Higher temperatures also have proven to negatively affect labour productivity. At temperatures above 26 degrees, there is a sudden drop in labour productivity.

3.1.2 National policymakers 2

Climate tipping points
This group of policy makers recommends focussing on joint occurrence of tipping points and interactions across climatic tipping points. According to them, the climatic tipping point cannot be seen as standalone events and need to be considered as a whole. Some of the tipping points seem to have contradictory impacts, for example, weakening of the thermohaline circulation will decrease the temperature in Europe, whereas the climate change in general will lead to higher temperatures. What will be the overall impact on temperatures in Europe?

Socio-economic tipping points

The national policy makers indicate that migration from the South (Middle East and Africa) to Europe can change societal structures and possibly entail high impacts. Research could focus on how many refugees would come, what the causes of migration are (political instability, wars, large droughts), and which security implications the refugee flows might have on Europe. Another concern is changes in tourism flows in the Mediterranean and Alpine areas. Heat waves may change the peak of the tourism season towards less warm parts of the year and may also cause a shift towards northern countries. A very specific problem in Alpine regions is the economic viability of low-lying ski resorts. Local authorities confirm the 100-day rule (amount of days with good snow conditions) to determine the economic viability of individual resorts. A recurring number of years with fewer days with good snow would mean the collapse of many resorts, many of which are currently already highly subsidized.
Disruptions of international supply chains can also impact national or regional policies; do these mechanisms pose a threat for national security? Macro-economic shifts in trade can also be considered a tipping point in the opinion of the policy makers. The need for mitigation may also require large socio-economic shifts in Europe. For example, in Germany, the shift towards to renewable energy requires a large reconfiguration of the energy network.
Policy makers responsible for transport networks mention candidate tipping points at

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different scales. In the UK, several railway lines and roads are threatened by coastal erosion. On the urban scale, intensive rainfall can cause large disruptions, which increase due to latent heat release. Many elements of road and rail infrastructures are designed for rainfall quantities far below the projected rainfall under certain climate scenarios. This may cause large disruption of national highway networks with profound economic consequences. In the EU-accession country Albania, wash-away of rural roads caused a severe economic shock.

3.1.3 Policy makers on EU and international level

Climate tipping points

The EU and international policy makers are mainly interested in the consequences of climate tipping points in terms of hazards: how does a tipping point translate into frequency of droughts, extreme heat, extreme precipitation etc.? They also wonder if the occurrence of rapid sea level rise may induce large migration towards Europe. On the other hand, will the need for adaptation and mitigation provide new opportunities to invest? Also, another tipping point in the biophysical system was mentioned: there is a clear non-linear relation between temperature increase and the amount of rainfall to be expected during extreme rainfall events. This might have profound impact on the extent of flood events. However, it seems that this non-linearity is already accounted for in several climate models.

Socio-economic tipping points

The international policy makers expect that socio-economic tipping points will occur earlier than climate tipping points and therefore have higher policy relevance. Given the general trend that climate change hits the southern member states hardest, the group expressed concerns about the financial ratings of these countries. They noticed that banks will not be eager to transfer money to Southern Europe to offset the impacts of climate change, because they rather have a tendency to move out of areas exposed to high risks. At the moment, the European investment bank has 16% of its portfolio in Spain, followed by Italy. Concerns may arise about the exposure of these investments to climate hazards well before the hazards actually occur, leading to less financial capital for already vulnerable regions. Here, there seems to be some tension between the EU solidarity principle and the natural behaviour of financial institutions. In addition, there is a risk of stranded assets when state or regional budgets are insufficient to maintain earlier investments.

3.1.4 Non-governmental stakeholders

Climate tipping points

The Non-governmental stakeholders consider all climate tipping points as important, as long as their occurrence can be expressed in terms of hazards. They are concerned about the impact of accelerating sea level rise on coastal ecosystems such as the Wadden Sea. This unique ecosystem may severely suffer or even disappear from rapid sea level rise due to melting of the Greenland and West-Antarctic ice sheets.

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In addition, they noted that problems may occur with urban heat and forest fires in areas where we have not seen these problems before. Climate may also impact soil diversity and lead to migration of species. With respect to deforestation in other parts of the world (Amazon, East Asia) they mentioned that forest diebacks can have large implications for industry that uses wood as input in their production processes. This implies they have to switch to using other raw materials.

Socio-economic tipping points

Despite examples that are already mentioned in other groups, this group expressed concerns about the dominance of climate-sensitive sectors in certain areas of Europe such as mono-culture agriculture, regions fully dependent of tourism (some parts of Greece, the Alps). In Southern Europe, high temperatures, droughts and desertification may cause collapse of these sectors. A particular issue mentioned for agriculture was the risk of disappearance of insects, that could disturb pollination. For the energy sector, structurally limited cooling capacity for power stations may lead to transformations. On a global scale socio-economic tipping points included migration issues, deforestation (specifically in the Amazon and East Asia), and the potential to move from the niche of sustainable finance into the general investment and finance sector. The latter can be seen as a positive tipping point.

3.1.5 Business, industry and business organizations

Climate tipping points

Businesses constantly adapt to changes in the market and supply chains. The potential introduction of new vectors would require major adaptation of the health care industry. Road operators are interested in the consequence of tipping points in terms of weather extreme: how much intense precipitation and heat waves can we expect? The paper industry is concerned about forest diebacks. These may cause major alterations in the supply chain to find new raw materials. However, the sector is also interested in new opportunities posed by major climate tipping points: shipping via the poles can be facilitated when more ice melts and new oil fields can be explored.

Socio-economic tipping points

Infrastructure impacts can cause large changes and impacts on businesses, like shutdown of ports or roads, and also of electricity systems. A long disturbance in logistical systems is in general a tipping point for businesses.

A tipping point is when parts of the supply chain of businesses disappear because of climate impacts or regulations. It is a combination of climate and socio-economic events which can cause such impacts.

Migration from the South (Middle East and Africa) to Europe can change societal structures and possibly entail high impacts. From research it is important to know how many refugees would come and what the causes are (political instability, wars, large droughts) and implications in terms of security for Europe.

Insurance industry: Tipping points can be reached through extreme weather as well as gradual changes. At one point the insured damage can become too high and then at

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one point it cannot be insured anymore under the standard conditions. An example is the extreme hail storms that caused substantial damage in the Netherlands in 2016 when the damage reached between € 300 and 500 million. Greenhouses afterwards had to be rebuilt with stronger glass to remain to be insurable. If the damage would have been in a year about 1 billion euro, insurance coverage would probably be restricted. This can be done by increasing the prices to such a degree that demand is low; that way insurance can limit its exposure to extreme climate change risks. The sector cannot cope with two large events like this hail damage if these events occur in a short time period after each other.
Renewable energy generation: if the marginal costs for renewable energy become lower than the marginal costs of fossil fuel energy (e.g. due to regulation or taxes) then the renewable energy market will get a boost which is a tipping point.
Large changes in vector borne diseases would be relevant for the health care sector.
Can global or regional epidemics be caused by climate change?

However, from the perspective of businesses, there also are several opportunities that arise from tipping points. In the project a SWOT analysis can be made for the different tipping points, so also positive business opportunities become clear.
Examples of opportunities could be the following:

- Consumer acceptance of green products can boost such markets. This can be caused by taxes or regulation.
- Green investments by companies.
- New oil fields can be explored after ice melts.
- Agriculture conditions can improve in Russia due to climate change. Also for Greenland.
- Shipping at poles can be facilitated due to ice melting.
- A taking off of the circular economy can create new business opportunities.

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3.2 Long list tipping points tested on criteria

Table 1 gives an overview of the candidate socio-economic tipping points from the co-design process. Each candidate tipping point has been tested on the three necessary requirements, two optional properties, and on compliance with the objectives and impact focus of COACCH.

Table 1. Candidate non-climate tipping points tested on five criteria for tipping points
Shaded rows indicate selected case studies by [consortium partner] for further investigation in this work package; §-symbol indicating corresponding section

	Necessary requirements			Optional requirements		Focus of COACCH
Examples\criteria	**C1. Small cause large effect (non-linear)**	**C2. Rapid change**	**C3. Structural reconfiguration**	**C4. Irreversibility**	**C5. System feedbacks**	**Policy relevance**
Health						
Extreme Heat mortality urban areas (HWMI[1]>8 every 2 -3 years [PWA] **§5.2**	Yes: non-linear increase of mortality with rising temperatures	Yes: Individual heat events can have a rapid onset rapid	Temporal reconfiguration: from state A (no heat; low mortality) to B (heat wave, high mortality)	No: Events one off, but could lead to systemic change from trigger of event	No: mortality does not feedback to heat wave	Large numbers of heat related mortality cases (serious non-monetary impact)
Introduction new vectors [PWA] **§5.2**	Yes: threshold effect when conditions are such that diseases take hold in EU region	Uncertain; likely to occur when distinct weather pattern results in a few years in a row	Significant impacts on healthcare sector; from state A (no vectors of certain species) to B (many vectors)	No: May die out but only after outbreak has occurred	Unclear: Unknown consequences	Significant welfare, productivity and treatment costs
Impacts of Migration [PWA] **§5.2**	Yes: threshold effect as populations make decision to take action (migration/conflict)	As changing annual weather patterns are recognised or single event (e.g. persistent drought)	Significant impacts on healthcare sector	More-or-less: passing of time likely to make reversal less likely; often people don't migrate back to country of origin	Not in the sense that the migration impacts the climate driver. However, once migration starts, this might cause a lot of other migration	Significant welfare, productivity and treatment costs; currently a large issue in the EU
High labour productivity impacts through to exceedance of health limits of WBGT[2]	Yes: Linear effects initially but then thresholds	See heat mortality	See heat mortality	Likely associated with short periods of exceedance	No	Rising labour productivity losses, then exceedance of occupational limits
Tourism						
Disappearance low-lying ski resorts	Yes: A small increase of temperature may cause the collapse of several low-lying ski resorts	Yes: a number of recurring unfavourable years may cause a sudden bankruptcy of a resort	Yes: From A: exploitation to the resort to B: abandonment of the resort	Yes: Unattractive to reverse (from economic point of view)	No: the abandonment of resorts does not influence the temperatures	Iconic example to illustrate the concept of socio-economic tipping points; but also problematic for certain alpine regions
Coastal areas become unattractive due to water shortages/forced rationing during the summer (e.g. southern Italy)	Uncertain: drought is already a large change at boundary condition	No: droughts are already present	Possibly: from top tourist destination to less attractive destination	Yes: can only be reversed if expensive new water resources become available	No.	Very dependent on scale: research required

[1] HWMI: Heat Wave Magnitude Index (Russo, S., A. Dosio, R. G. Graversen, J. Sillmann, H. Carrao, M. B. Dunbar, A. Singleton, P. Montagna, P. Barbola, and J. V. Vogt (2014), Magnitude of extreme heat waves in present climate and their projection in a warming world, J. Geophys. Res. Atmos., 119, 12,500–12,512, doi:10.1002/2014JD022098.
[2] WBGT: Wet Bulb Global Temperature

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	Necessary requirements			Optional requirements		Focus of COACCH
Examples\criteria	**C1. Small cause large effect (non-linear)**	**C2. Rapid change**	**C3. Structural reconfiguration**	**C4. Irreversibility**	**C5. System feedbacks**	**Policy relevance**
Ecosystem services						
Glacier melts in Alpine regions pose threats to ecosystem services	Yes: results from gradual increases in temperature	Uncertain: review needed	Yes: ecosystems could completely disappear	Yes: like climate tipping points	No: the ecosystem change is not likely to have impact on glacier melts	Iconic example
Accelerated SLR may cause disappearance of the Wadden Sea ecosystem	Yes: non-linearity between ecosystem service and SLR, especially for rate of change	Uncertain: review needed	Yes: unique ecosystem could completely disappear	Yes: on a human timescale irreversible	No: disappearance does not impact climate change	Non-monetary impact (but UNESCO heritage)
Agriculture/forestry						
Plant-pollination mismatch	Yes: Climate change affects both the ability of plants and pollinators to thrive in a certain area, as well as the interaction between them. A small increase in temperature may lead to a rapid decline in pollinators in a certain area.	Yes: Population extinction or the reduction of their services to plants	Yes: Large crop yield losses or the inability of certain crops to be produced at certain locations. Relocation of plants based on a geographical shift in pollinators. Chemical solutions that may take over part of the services of pollinators.	Yes: Population extinction, land abandonment	Yes: in terms of influence on biodiversity and plant-species interactions	Loss of biodiversity. Significant economic losses along the supply chain. Significant land abandonment that result from farm exit and result in landscape losses.
Food supply shocks in Europe, leading to e.g. desertification in Southern Europe [IIASA] **§5.4**	Yes: The increased occurance of extreme weather events impact yields and lead to drastic changes in food production in Europe	Potentially: Large yield losses lead to the inability to grow certain crops in certain locations. Sequential losses of yields will lead to the depletion of the 'buffer' provided by storage facilities, leading to large price surges.	Yes: Switch from exporting to importing region by reallocation of crop cultivation to other regions	Land abandonment, leading to e.g. desertification in Southern Europe Loss of economic activities in a certain region Change in farm management. Structural change in trade relationships.	Influence on water / energy use.	Significant economic losses along the supply chain. Significant land abandonment that results from farm exit and results in landscape losses. Food crises Food security issues
Food supply shock outside Europe [IIASA] **§5.4**	Climate change will lead to relatively larger crop losses outside Europe compared to inside Europe	Yes: Large losses in other regions will lead to a surge in the demand for food production in Europe, leading to large increases in prices and market instabilities	Possibly: switch towards more intensive cropping systems. Dietary change. Land abandonment in other regions, structural change in trade relationships.		Influence on water / energy use.	Large policy relevance: large increases in prices and market instabilities, food insecurities, social unrest
Food market crisis [IIASA] **§5.4**	Yes: Increased risk / uncertainty perceived on the producer side will lead to a rapid increase in the speculation aspect on food prices	Yes: Increase in (perceived) variability of revenues / yields leads to rapid increases in prices	Yes: Change to an alternative crop portfolio which may hedge for part of the producer risk. Disappearance of crops that are vulnerable to climate change in certain locations Policy options that aim at market stabilization	Yes: Structural change in farm management, unlikely to turn back to the original situation. Risk of feedbacks, where increased risk will lead to more market disturbance	To some degree: farming practices impact water and energy use which in turns impacts agriculture.	Significant economic losses along the supply chain. Importance of market stabilization policies.
Water scarcity	Yes: gradual global temperatures lead to a rapid increase in water needs in	Yes: In the agricultural sector, irrigation is often mentioned as a	Yes: Impossible for the agricultural sector to expand irrigation or to irrigate areas that were	Yes: Land abandonment. Loss of economic activities in a certain	See above: influence on water / energy use	Significant economic losses along the supply chain.

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	Necessary requirements			Optional requirements		Focus of COACCH
Examples\criteria	**C1. Small cause large effect (non-linear)**	**C2. Rapid change**	**C3. Structural reconfiguration**	**C4. Irreversibility**	**C5. System feedbacks**	**Policy relevance**
	many sectors.	solution to the increased frequency of drought spells under climate change. However, with the increased demand from other sectors, competition for water rapidly increases.	previously irrigatable. Shift in cultivation to areas where the pressure on water demand is lower, or a disappearance of cultivation in certain areas.	region		Significant land abandonment that result from farm exit and result in landscape losses. Water scarcity.
Impossibility to meet mitigation challenge due to the loss of forests	Yes: 1) Frequency of extreme droughts will increase under climate change, which will pose threads to the increased frequency of forest fires, as well as the size of the areas impacted by them. (2) Deforestation due to land use change, specifically in the Amazon and South-East Asia.	Yes: Forest fires significantly increase GHG emissions. Forest losses lead to a large reduction in negative emissions and impact above-ground and below-ground biomass pools.	Temperature increase, loss of mitigation options.	Burned and degraded areas are hard to restore	Influence on biodiversity and tree-species	Loss of climate mitigation options Loss of biodiversity
Infrastructure						
Trade impacts of failure of critical infrastructures due to flooding [Deltares] **§5.5**	Yes: Failure of a major harbour (or several during one large event) may have profound economic impacts	Yes: During and after a flood: sudden stop of the flow of commodities	Yes, but temporarily. After the event, some suppliers may return but other may structurally avoid the risky harbour in the future	No: harbour operation can be restored; but certain harbours may be abandoned	No	Could have a significant impact on EU economy
Failure of critical coastal infrastructures [GCF] **§5.7**	Yes: small scale failure of protection infrastructure can cause large effects of flooding. (Example: New Orleans – small breaches in dikes caused large scale flooding in the city).	Yes: failure of protection infrastructure can cause rapid inundation in areas behind.	Depends: If the failure of protection infrastructure leads to reactive retreat (see below): yes. Otherwise: no.	Can be. If the failure of protection infrastructure leads to reactive retreat (see below), this can be irreversible.	No: the flood will hardly impact the sea level	Seems to be one of the largest threats for Europe Direct damage cost (flood damages). Indirect follow up cost (migration cost or protection update cost).
Restructuring of the energy network induced by need for mitigation						
Limited cooling capacity for power stations						
Structural reconfiguration of flood protection policies due to accelerated sea level rise [Deltares] **§5.6**	Yes: Sea level rise may require a large reconfiguration of existing flood protection infrastructure and policies	Yes: Very rapid compared to the time it takes to develop new flood protection infrastructure	Yes: From one flood protection policy to a very different one	More-or-less: Probably it is unattractive to turn back to the original policy	No, the new policy does not influence the sea level rise	The Dutch situation is representative for many low-lying Deltas in the world
Transport						
Large-scale road damage	Yes: At increasing	Yes: During one	Yes but temporal:	No, can be restored	No	EU accession

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	Necessary requirements			Optional requirements		Focus of COACCH
Examples\criteria	**C1. Small cause large effect (non-linear)**	**C2. Rapid change**	**C3. Structural reconfiguration**	**C4. Irreversibility**	**C5. System feedbacks**	**Policy relevance**
due to pluvial flooding (Albania)	rates of precipitation, the road starts to disintegrate	extreme rainfall event: rapid reduction of road capacity	rerouting of transport flows through the country	after some time, probably better (creative destruction)		country; a significant percentage of GDP is lost in these countries
Road disruptions due to intense rainfall in Western Europe	Yes: Road transport capacity show clear non-linear behaviour with the amount of precipitation	Yes: During one extreme rainfall event, rapid decrease of road capacity	Only temporarily, but may require a reconfiguration of the design criteria (large costs involved to upgrade existing assets)	No	No	In terms of GDP not very large, but very troublesome during the event
Large disruptions of supply chains	Yes: Just one crucial ingredient missing means no supply of final demand and investment goods. Lacking crucial supply may cause sector troubles (supply of crucial goods for production)	Could be for some suppliers: If no other supply chains are prepared	Yes, in any case temporal: for the time that the former supply chain is interrupted (which may mean many months), may remain in the new way or switch back upon re-established availability later again	No: could be reversed after some time	To some degree: if production reduces, income declines and consequently also further demand decline. Can especially hit hard if production is geographically concentrated.	Supply chains disruptions could pose a significant threat for critical production in Europe.
Migration						
Climate related migration towards Europa	Unclear: is the cause for migration small? Often, migration seems to be induced by large conflicts combined with unfavourable environmental conditions					Large policy relevance in Europe
Proactive coastal retreat (from local to national scale) [GCF] **§5.7**	No. Effects are large, but not caused by a small cause. Empirical work (M. Esteban) shows that retreat generally is a last resort response. Small causes will trigger no retreat.	No. Proactive retreat would have a much slower pace than reactive retreat. Given to limited rate of sea-level rise, it would be a rather slow process.	Yes. If (large scale) retreat occurs, this is a structural change for a country or a region. Potentially, large number of people have to be resettled. For the Netherlands, the UK or the Maldives a huge structural change, for Germany not.	Probably. Once areas are retreated it is not very likely that they will be elevated and resettled again. Although political considerations could reverse retreat	No.	Large direct costs for EU member states
Reactive coastal retreat (from local to national scale) [GCF] **§5.7**	Maybe. Reactive retreat could be caused by single events (floods), but also by a sequence of events.	Yes. Reactive retreat occurs on much faster pace than proactive retreat as it react to a certain event.	Yes. See above.	Even more probably then in the proactive case. But still possible. (Example: New Orleans – pump the water out, rebuild dikes, rebuild city). However, the new state is different from the old one.	No.	Direct cost (migration cost).
Finance						
The green investments become the mainstream investments	More-or-less: the increased initiatives and requirements for sustainable finance will accelerate a transition	Yes: at some point this will go fast	Structurally there will be much less investment in fossil fuelled development	Probably no way back		Major impact on mitigation and adaptation

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	Necessary requirements			Optional requirements		Focus of COACCH
Examples\criteria	**C1. Small cause large effect (non-linear)**	**C2. Rapid change**	**C3. Structural reconfiguration**	**C4. Irreversibility**	**C5. System feedbacks**	**Policy relevance**
Renewable energy becomes more attractive investment than fossil fuels [GRAZ] **§5.8**	Yes, financial viability is a tipping point – policies on top of current cost decline of renewables can move them there	Yes, with tipping point investment redirected to new energy source capacities	Yes, energy system (and sectors linked) switches to variable and intermittent supply sources	Reversibility increasingly difficult over time, given both the long life time of investment and the increasing share of the new energy sources, but theoretically possible	Yes, due to learning by doing in the production of the new technologies and thereby cheaper renewable energy supply	Energy transition has high policy relevance (e.g. GDP and welfare implications of this switch for the case of Photo-Voltaic)
Drop in financial rating of southern member states [PWA] **§5.3**	Yes: Uncertainty about climate change impacts may impact financial ratings, which has significant impact on national economies	Yes: at a certain point, the financial rating is suddenly lowered	Yes: but temporal	No: can be reversed	Yes: rating reduction negatively impacts economy which again could reduce financial rating	Large concern for Southern EU Member states
Unwillingness to invest in areas exposed to higher risks or high cost of capital (higher risk premium required) [PWA] **§5.3**	Depends: Gradual shift of IFIs and FDI towards less risky projects, or increasing cost of capital for some projects – the latter might be more difficult to reverse	Depends: Unwillingness to invest is more likely to fluctuate over time due to a wider range of factors determining the attractiveness of investments. Cost of capital might increase more suddenly – perhaps after a series of close extreme events.	Yes: Need to find alternative sources of finances. Debt financing carries risks (see above)	Can be reversed when the hazard decreases in a certain area, but this seems to be unlikely	Yes: increased cost of capital may in turn reduce the capacity to adapt which increases vulnerability	Large concern for certain vulnerable regions
Stranded assets	Yes, on both the adaptation and mitigation side: e.g. higher SLR may induce an adaptation policy switch to retreat from some region – turning the assets there to stranded ones. On the mitigation side: a small further cost decline e.g. in renewables will switch profitability (and could turn fossil structures into stranded assest	Yes, with tipping point reached, a significant amount of assets turns into stranded assets	The structural reconfiguration mainly arises directly form the process that also turns assets into stranded assets, but to some degree also the stranded asset manifestation may trigger additional structural reconfiguration (by reduced economic potential of firms and households affected)	For some cases: in practical terms: Yes (e.g. the SLR-adaptation by retreat); for others: could be more easily reversed (e.g. in mitigation), but unlikely	Yes, that agents (firms, households) loose economic potential does reduce their spending (consumption, investment, operating expenses) implying larger economic effects	Stranded assets due to shifts in adaptation policy, and due to climate change mitigation could pose significant economic impacts in Europe, their distribution is of particular interest.
Insurance						
Collapse of insurance markets for extreme weather risks. This can be illustrated with case study narratives for agriculture hailstorm insurance	Yes: Increased extreme weather risk, due to climate and socioeconomic change causes certain insurance	Yes: Once several extreme weather events (hailstorm, flood, or drought) occur consecutively that cause large	Yes: The structural change is that the insurance product is no longer available under reasonable prices.	Yes: It is unattractive for insurance companies to reverse back to the original state (offer the insurance again	Yes: Increase in price of the insurance, lowers demand for the insurance, which lowers the risk pool and can lead to a	Unavailability of insurance products against extreme weather risks implies that recovery after

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	Necessary requirements			Optional requirements		Focus of COACCH
Examples\criteria	**C1. Small cause large effect (non-linear)**	**C2. Rapid change**	**C3. Structural reconfiguration**	**C4. Irreversibility**	**C5. System feedbacks**	**Policy relevance**
(Netherlands), flood risk insurance (EU), and agriculture crop insurance (Southern Europe) [VU] **§5.9**	systems to be unsustainable. Excessive premiums can cause unaffordability of insurance and underinsurance, and a collapse of specific insurance markets.	insurance claim payments, then insurance prices can rapidly increase making purchasing coverage unattractive.		at reasonable prices).	collapse of the market.	future disasters is hampered due to a lack of adequate compensation. Moreover, there can be indirect impacts on economic activity and investments (e.g. financial institutions may not lend to farmers who cannot insure their greenhouses, lowering investments in the agriculture sector).
Other						
Climate-induced economic shocks [VU] **§5.9**	High economic damages at the local level can be caused by small additional temperature changes which trigger larger scale temperature changes (positive feedback mechanisms arising from rapid melting of permafrost which releases methane emissions that add to global warming).	Economic shocks can occur rapidly when damage functions are highly non-linear and economic persistence of shocks is taken into account	Large shocks can change the economic equilibrium and lower welfare and trigger different adaptation or mitigation policy responses.	Large losses can cause fundamental changes in economic equilibrium, e.g. permanently lower GDP levels, or trigger fundamental changes in adaptation policy	Consequences in economic shocks can reinforce each other through persistence in GDP	High monetary losses at the local level (e.g. 5% of GDP or more)

The selection of SETPs as indicated by the grey shaded areas in Table 1 is the result of a team effort in which the input from the stakeholders plus own ideas were weighted against the tipping point criteria as mentioned above. Feasibility of an analytical approach to analyse the SETP's is another implicit criterion that played a role. In Chapter 5 the analytical approach for the selected SETPs is further elaborated.

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4. Modelling climate tipping points

This chapter presents more in detail the selected climate tipping points and discusses how the associated impacts and economic costs of can be studied using the sector-specific and macro-economic models in the COACCH portfolio.

Table 2 selected climate tipping points

Climate tipping point	**Consortium partner**	**Short description of model approach**
Global Sea Level Rise	BC3/GCF	Definition of tipping point timing based on existing literature/ sectorial impact evaluation/ impacts on the overall economic systems
Alpine glaciers melting	CMCC	Definition of tipping point timing and uncertainty based on EURO-CORDEX data/ sectorial impact evaluation/ impacts on the overall economic systems
Disappearance of Arctic summer ice	CMCC	Definition of tipping point timing and uncertainty based on CMIP5 data/ sectorial impact evaluation/ impacts on the overall economic systems
Slowdown of Thermohaline circulation	PWA	Definition of tipping point timing based on existing literature/ sectorial impact evaluation/ impacts on the overall economic systems

4.1 Global Sea Level Rise

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) projects that it is likely that global mean sea-level will rise by 0.5-1m from 1986-2005 to 2100 under RCP8.5 (Church et al., 2013). AR5 also acknowledges that sea-levels could rise significantly above the likely range due to accelerating dynamic contribution of the Antarctic Ice Sheet, which is the component of sea level rise (SLR) contributing most to the tail-end uncertainty. Due to a lack of robust data and process-based modelling evidence on the dynamic contribution of the Antarctic Ice Sheet, Church et al. (2013) concluded that the current state-of-knowledge does not allow to quantify probabilities beyond the likely range. In an attempt to address this limitation, expert elicitation has been used. For example, Bamber and Aspinall (BA13) asked 13 experts on the 21st century contribution of ice sheets to global mean SLR and found the 95th percentile to be 0.84m (Bamber and Aspinall, 2013). To compare, the 95th percentile of the process-model based ranges reported upon in AR5 are 0.21m for the Greenland Ice Sheet and 0.12m for the Antarctic Ice Sheet (Church et al., 2013). The results of BA13 have also been used in combination with ensemble model runs for the other components of SLR to come up with 95th to 99.9th percentiles of global mean sea-level rise by 2100 (Grinsted et al., 2015; Jackson and Jevrejeva, 2016; Jevrejeva et al., 2014; Kopp et al., 2014). Expert elicitation has also been criticized in that the higher percentiles attained are very sensitive to the method used for combining individual expert opinions (Bakker et al., 2017; Vries and Wal, 2015). More recent work (Bars et al., 2017; Kopp et al., 2017) have used results from the new ice sheet model of DeConto and Pollard (DeConto and Pollard, 2016) to estimate higher percentiles of 21st century SLR. The projections of DP16 for the Antarctic ice sheet mass loss are much

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higher than those of other recent studies (Golledge et al., 2015; Levermann et al., 2014; Ritz et al., 2015) because their model produces widespread early surface melting of ice shelves, which are then destroyed by hydrofracture, and includes a process called "marine ice cliff instability" which has not previously been considered relevant for the majority of the Antarctic ice sheet. This chain of processes make the ice sheet response strongly dependent on atmospheric temperature increase, but the confidence in these results are still low due to a lack of robust observational data that could be used to better constrain ice sheet models. Existent literature will be used to define the projected SLR for different dates along the current century and to estimate the relative uncertainty. The derived SLR values for different decades along the current century will be used as input for the impact chain described in 4.5.

4.2 Alpine glaciers melting

Across the Alps, glaciers have lost half their volume since 1900. And melting has accelerated since 1980. Most Alpine glaciers could be gone by the end of this century. Models project that at 2°C of global warming (+3–4◦C locally) there could be an almost complete loss of glacier ice volume in the Alps. This will affect for instance water availability in the region, especially as glaciers sink (with increased short-term flows from melt water) affecting hydropower and stability/ landslides.
Based on EURO-CORDEX (Jacob et al. 2014) simulation under all of the available scenarios (RCP2.6, RCP4.5, RCP8.5) we will verify the timing of conditions leading to irreversible ice melting over Alpine regions, based on available parameters (within the ESGF EURO-CORDEX data base) for the definition of the glaciers cover and/or relative proxies such as surface temperature. Depending on data availability the analysis will be based on daily or monthly values. A multimodel (no more than 4 models will be considered) approach will provide an evaluation of the relative probability of the tipping point occurrence within each 10-y window for the current century. The timing of alpine glacier vanishing will be the input for the impact chain described in 4.5

4.3 Disappearance of Arctic summer ice

Arctic sea ice, the layer of frozen seawater covering much of the Arctic Ocean modulates the Earth albedo thus the amount of solar energy sent back to space, having a cooling effect on our planet, thus the reduction of sea ice cover strongly impact the radiative balance at the surface. Also the melting of sea ice across the Arctic, might open shipping routes— including directly over the North Pole — by mid-century. The sea ice cap changes with the season, growing in the autumn and winter and shrinking in the spring and summer. Its minimum summertime extent, which typically occurs in September, has been decreasing, overall, at a rapid pace since the late 1970s due to warming temperatures.
We will consider a Arctic Sea Ice Extent (SIE) lower than $10^6 km_2$ as free ice conditions, and we will verify the occurrence of such condition for September within at least 10 CMIP5 fully coupled General Circulation Models, based on monthly time series covering the current century over RCP2.6 RCP4.5 RCP6 and RCP8.5. Due to the high SIE interannual variability we will consider 10 years windows over the current century

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verifying the ice free conditions for more than 5 years in the windows. Also the expected consequential widening of the annual window of the ice-free season will be investigated.

The timing of free ice conditions and the relative uncertainty will be the input for the impact chain described in 4.5.

4.4 Slowdown of Thermohaline circulation

The Atlantic Meridional Overturning Circulation (AMOC) plays an important role in the climate system by transporting heat northwards in the Atlantic (Bryden and Imawaki, 2001). Large and rapid reorganisations of the ocean currents may have occurred in the past (Rahmstorf 2002; Clement and Peterson 2008), and this circulation is predicted to weaken as the climate warms and the surface waters of the North Atlantic become less dense. The IPCC 5th Assessment Report (Stocker et al, 2013) report that although many more model simulations have been conducted since AR4, under a wide range of future forcing scenarios, projections of the AMOC behaviour have not changed. They report that it remains very likely that the AMOC will weaken over the 21st century. Best estimates and ranges for the reduction from CMIP5 are 11% (1 to 24%) for the Representative Concentration Pathway RCP2.6 and 34% (12 to 54%) for RCP8.5, but there is low confidence on the magnitude of weakening. It also remains very unlikely that the AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered (high confidence). For an abrupt transition of the AMOC to occur, the sensitivity of the AMOC to forcing would have to be far greater than seen in current models, or would require meltwater flux from the Greenland ice sheet greatly exceeding even the highest of current projections. Although it cannot be excluded entirely, it is unlikely that the AMOC will therefore collapse. There is low confidence in assessing the evolution of AMOC beyond the 21st century because of limited number of analyses and equivocal results.

However more recently, and in sharp contrast to the IPCC, a recent paper (Sgubin et al, 2017) has estimated the probability of rapid North Atlantic cooling (subpolar North Atlantic (SPG)) to be much higher: this cooling might significantly affect the climate of the Northern Europe. The implication is the chance of an NA abrupt cooling in the coming century is not negligible while the chance of a complete AMOC collapse is negligible. Since the local SPG convection is part of the large-scale overturning circulation system, an interruption of SPG deep-water formation does weaken the AMOC. A convection collapse in the SPG would have impacts on the surrounding regions, with temperature and precipitation representing an important hazard for many economic sectors. The derived information (from literature) on the chance to have a SPG abrupt cooling will be indicated for different dates and used as an input for the impact chain described in 4.5.

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4.5 Impact assessment methodology

The methodology that will be applied for the study of 4.1-4.4 climate tipping points will follow closely that used in WP 2 to assess the sectoral, smooth, impacts of climate change and to get finally to their overall, integrated evaluation.

An important distinction is however in order: climate tipping point will very likely imply impacts that are by far larger than those occurring under smooth climatic transitions. This has several consequences: Firstly it can be the case that some of the quantitative tools that in WP2 are used to assess economically climate change impacts are stressed beyond modelling capacity and are then not able to provide meaningful economic evaluations. The strategy in this case is to use the models up to their simulation limits and then to extrapolate results "out of sample" using support from expert judgments and learning from and comparing with past experiences (e.g. inspecting the literature on environmental disasters and disaster risk reduction, and on global and local economic crises, like e.g. sudden increases in key resource prices, as in the 80's oil shock or in the 2008 food price spikes).

Secondly, impacts can be so large than a purely economic assessment risks to provide a very partial picture of the consequences triggered. Therefore the quantitative information will be coupled with qualitative insights discussing the transformations that social and economic systems will undertake.

Thirdly, the policy implications, especially the prescriptions concerning the "optimal" or "acceptable" policy mix e.g. between mitigation and adaptation will be completely different. This has an implication also for the policy analysis conducted in WP4. The assessment models used there need to be tailored to perform analyses abandoning the framework of maximizing expected utility, to endorse different principles of robust decision making under deep uncertainty, like the min max or others.

This said, the starting point for the methodological set up is that provided by COACCH D2.1 that:

i) Establishes the protocol for the information exchange across COACCH modelling teams and sectoral studies which implies to,
ii) Identify the interactions and information channels linking the different sectorial studies and tools used by COACCH as well as the use of ISIMIP simulation results,
iii) Define respective output-input flows in order to enable model integration.

Figure 2 depicts model integration.

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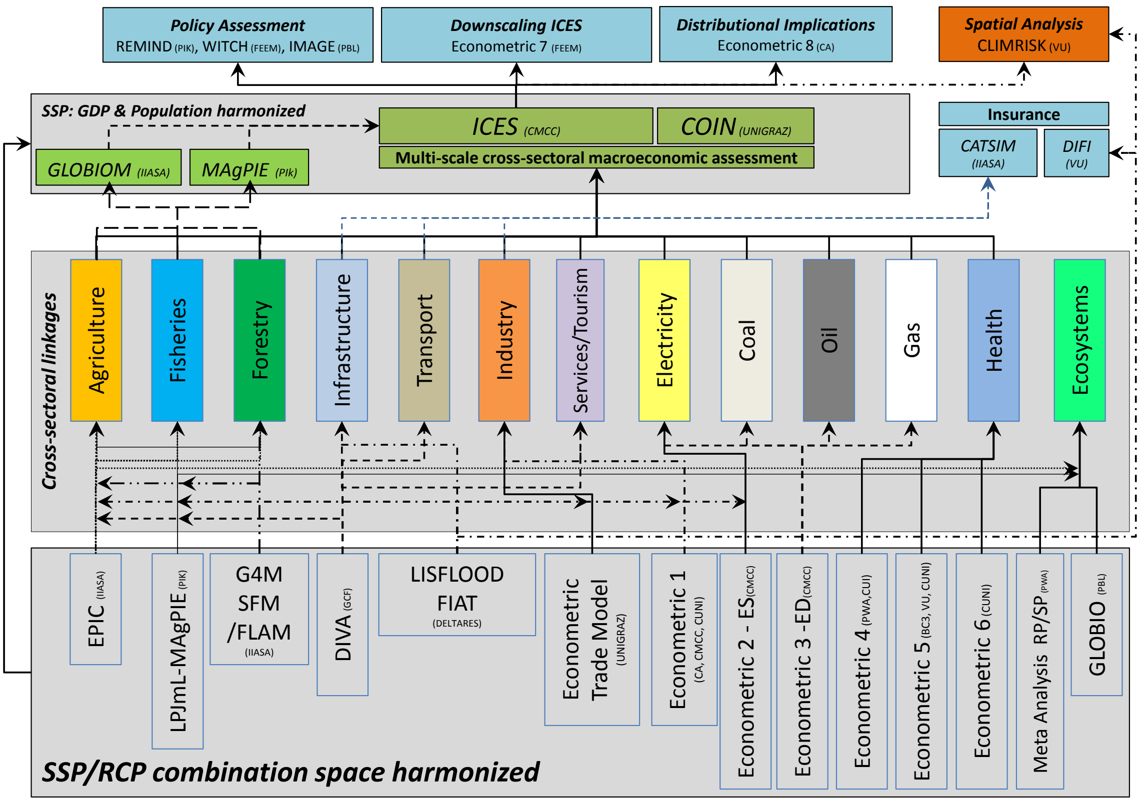

Figure 2 COACCH model suit and integration (source COACCH D2.1)

Taking the case of extreme sea-level rise, triggered by disappearing of West Antarctic ice sheet, for instance the sequential evaluation chain is the following:

Inspection for past modelling approaches that allow identifying when under different scenarios a tipping point (in terms of Sea Level High anomaly with present conditions) will be reached and the uncertainty associated.
Then: the DIVA (GCF) model will assess the impact on land lost, capital and infrastructure direct damages, people at risk of forced migration. Impacts on agricultural land lost will be transformed into lost agricultural and forestry production and impacts on the agricultural markets by EPIC (IIASA), GLOBIOM (IIASA), MAGPIE/LPJML (PIK), G4M (IIASA). Physical capital loss will be the input to evaluate the stress on the insurance sector with the CATSIM (IIASA) and DIF (VU) models. Finally the macro-economic models ICES and COIN will evaluate the consequences of these sectorial impacts on the overall economic systems of the EU countries and regions.
Such approach will be similar for the evaluation of the other climate tipping points listed in table 1, with the usage of appropriate different models for the impact phase, as for instance the usage of LISFLOOD model instead of DIVA in the 4.2 case, for the evaluation of glacier melting effects.

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5. Modelling socio-economic tipping points

This chapter discusses how the potential impacts of relevant socio-economic tipping points can be studied using the available modelling approaches. Plausible mechanisms leading to tipping points are described and impacts of their occurrence are indicated. A key step in the approach is the identification of performance thresholds, indicating the boundary between acceptable and unacceptable performance of the socio-economic system of interest. This threshold should be formulated in metrics that can be assessed by the models in the COACCH portfolio.

Table 2: selected socio-economic tipping points

Socio-economic tipping point	**Consortium partner**	**Name of the model**	**Short description of model approach**
Health	PWA (5.2)	To be developed	Partial equilibrium models to be constructed utilising existing data.
Finance	PWA (5.3)	With EIB	Partial equilibrium model to be constructed utilising existing data.
Agriculture	IIASA (5.4)	GLOBIOM-X	Bottom-up, recursive-dynamic partial-equilibrium model that runs in annual time-steps. The model focuses on the agricultural sector and separates the production decision of producers based on expected prices and yields, from the market clearance after yields are known. The model can therefore take stock of both the climate-induced deviations between expected and observed prices and yields, the impacts on the food commodity market, and analyse different adaptation mechanisms, such as storage. The model integrates these elements to analyse the impact of different market stabilization measures on agricultural production and consumption, resource use and trade.
Adaptation to accelerating sea level rise	Deltares (5.5)	Method: adaptive policy pathways	Application of adaptive policy pathways: are current ways of protecting the Netherlands sufficient, or is a large reconfiguration required: different infrastructure; risk approach or even retreat from certain areas?
Trade disruptions due to flooding of critical hubs in the EU infra system (indirect flood impacts)	Deltares (5.6)	MRIO coupled with existing river flood and coastal storm surge maps	We create an explicit link between EU-scale economic trade data, the EU transport network and two climate hazards: river and coastal flooding. We study how failure of individual trade hubs (major ports and other freight transfer points) may impact the European economy (via a multi-regional input-output model) under a large number of climate scenarios.
Coastal migration	GCF (5.7)	DIVA	Coastal impact model including protection and migration modelling. Can be used to analyse CBA-based protection/retreat decisions. These decisions can depend on slr-rate-thresholds.
Energy supply system switches	UNIGRAZ (5.8)	WEGDYN Econometric	Indicator-based analysis of system design and financial viability of renewable energy supply, indicating potential trigger points for large scale restructuring of the energy system (i.e. for switches in major segments of energy supply) and according economic implications. Methodologically the direction of the latter is explored employing both an econometric approach (CMCC) and computable general equilibrium modelling (UniGraz).

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Collapse of insurance markets for extreme weather risks	VU (5.9)	DIFI and CLIMRISK	*Case study flood risk insurance:* The DIFI model of the VU assesses the impact of rising flood risk on insurance penetration rate, unaffordability of premiums and incentivized risk mitigation by households under various insurance structures and behavioural scenarios. This model enables the projection of under which conditions prices of flood insurance increase to such a degree that demand declines and a private (voluntary) insurance market becomes unviable. This can trigger "adaptation tipping" points because insurance reforms are needed to keep premiums affordable. Such required reforms can be identified with the DIFI model. Input data: changes in flood risk under climate change scenarios Output: changes in insurance premiums, demand, and desirable set of reforms. *Case study crop insurance:* Examine using the CLIMRISK model of the VU when, where and under which conditions thresholds of temperature increase and precipitation decline are reached which can trigger collapse of crop production and related crop insurance against drought risk. Input data: climate change scenarios Output: when and where thresholds of temperature increase and precipitation decline are reached
Climate-induced economic shocks	VU (5.10)	CLIMRISK	Examine using the CLIMRISK model of the VU when, where, and under which conditions thresholds of local high economic damages from climate change (e.g. 5% of GDP or more) are reached.

5.1 Mechanisms leading to the occurrence of SETPs

To be able to model the SETPs in conjunction with their input scenarios models should be able to simulate the mechanisms leading to SETPs.
We recognize the following mechanisms that might lead to the occurrence of socio-economic tipping points.

1. **Non-linear effects between system variables.** For some systems, there are clear non-linear relations between system variables which can also be described for models. For example, a clear non-linearity is observed between temperature increase and the intensity of heavy rainfall. For temperatures below 10^0 Celsius, extreme rainfall will increase by 7% per degree, whereas for temperatures above 10^0 C, extreme rainfall will increase by 14% per degree Lenderink, G., & van Meijgaard, E. (2008). Many biophysical systems display such non-linear behaviours (see section 2.1). When there is linear connection between the biophysical and the socio-economic system, a non-linearity in the biophysical system will directly lead to a non-linearity in the socio-economic system as well.
2. **Network effects.** Contagious spreading is the first 'Gladwellion' criterion for tipping points (see G1, section 2.3). Gladwell (2000) gives examples of how ideas and behaviours spread over a population like a virus. Indeed, network effects (cascading or domino-effects) can meet the three criteria for tipping

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points: C1) small cause, large effect; C2) rapid change and C3) structural reconfiguration of systems. Applications for COACCH can be found in: collapse of financial markets; impact of failure of critical infrastructures; impact of hazards on multi-modal transport networks.

3. **Cost-benefit rationality.** Many decisions made by governments and business are based on systematically comparing costs and benefits of alternatives. Climate change may significantly alter the costs and benefits of these alternatives, leading to different decisions. This might cause a structural reconfiguration of the socio-economic system, and therefore can be a considered a tipping point under certain conditions. When referring to a change in cost-benefit as a tipping point, one has to show that there is a structural reconfiguration of the system (C3), rapid change (C2) and that the effect is relatively large compared to the cause (C1).
4. **Stock-depletion mechanism.** In many cases, stock depletion mechanisms lay behind structural reconfiguration of systems. For example, the systematic depletion of an aquifer can lead to a collapse of agriculture in a certain area. Stock depletion as a result of recurring crop failures may lead to a rapid increase in prices. Similar examples can be found for insurance. One stakeholder feared that rainfed agriculture in Spain may disappear as a result of recurring droughts: insurance may cover one or two dry years, but after that the stocks are depleted and insurance is no longer possible.

5.2 Health

Coupled Migration-Health case study

The stakeholder workshop identified that the consequences of migration - in which climate change is a potential contributory factor - was a dominant concern. A significant consequence is the health consequences for a) the migrant population; b) the population of the migrant host region, and; c) the population in the region of origin. Using historical evidence on the potential population-health relationships; we will make first estimates of the potential scale of such health impacts. Impacts include a range of primarily non-communicable diseases, encompassing mental health. The scope will consider non-SLR as well as SLR-induced migration and include extra-EU to EU, as well as intra-EU, population movements.

Vector-borne diseases

The stakeholder workshop also identified that vector-borne diseases are a potentially significant concern, particularly if outbreaks of different diseases occurred at the same time, thereby imposing change of public health service priorities. At the scoping stage, we would consider tick-borne diseases and their link with Myalgic Encephalopathy (ME), as well as arboviral diseases (e.g. dengue and chikunguna). The focus will be on the EU as a whole.

Heat mortality

Global climate change will increase average temperatures, as well as shift the distribution of daily extreme temperatures and high relative humidity – so that heat

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episodes will become more frequent and more extreme. In order to cope with heat, an instinctive adaptive action by a worker is to reduce work intensity or increase the frequency of short breaks. One direct effect of a higher number of very hot days is therefore likely to be the “slowing down” of work and other daily activities. This occurs through “self-pacing” (which reduces output) or occupational health management interventions (which increases costs), but the end result is lower labour productivity. A critical issue is that climate change affects labour productivity in terms of both outdoor as well as indoor employment, though these tend to be higher for developing countries. Indeed, most of the literature has focused on outdoor labour productivity because of the dominance of agriculture in the employment and GDP of these countries. Recent studies have analysed both outdoor and indoor labour productivity for future climate and socio-economic scenarios (Lloyd et al, 2016). This uses the latest RCP and SSP scenarios of the IPCC 5th Assessment Report. This follows the method of Kjellstrom et al (2014) to estimate labour loss in the working population. This is primarily associated with slow onset change, but above certain thresholds, this could have major effects, e.g. with outdoor work in certain regions, or with exceedance of occupational health standards.

A more extreme related impact is the exceedance of biophysical limits for humans (wet bulb temperature), building on work of Huber and Sherwood et al. However, these are not expected to occur in Europe, and not globally until the long term for very high future scenarios.

There is also a major issue with extreme heat waves, such as the extreme heat waves identified in recent EEA CAA-DRR report. This identified that there have only been two extreme heat waves HWMI (heat wave magnitude index over 8), one in 2003 and one in 2010 (though latter was mostly Russia). It projects this will increase to one every 5 – 10 years by mid and by end of century, one every 2 – 3 years. These events are different to the standard increase in heat related mortality (i.e. the estimates from Kendrovski et al (2017), because they lead to large indirect effects and emergency health response. Recent studies have found these effects could happen at low temperatures in other parts of the world that might also lead to indirect impacts in Europe (Matthews et al. 2017). These extreme heat episodes will also impact more strongly on labour productivity, because they could mean a cessation of outdoor (and even indoor) activity during the period more generally. This would have large economic costs. These events would also trigger other economic costs, notably the rise in electricity for cooling demand, water demand, etc. as well as damage (heat extremes on infrastructure), disruption of production chains etc. These events will have large political effects and might trigger high cost adaptation responses.

The final area considered is the emergence of major new disease outbreaks, where climate change is a factor in vector transmission and disease outbreaks. This follows the large health issues from e.g. the SARS virus/avian flu.

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5.3 Finance for high-risk EU regions

Case description

The stakeholder workshop discussed the possibility of bank credit crunch to businesses in regions featuring high climate risk for assets (e.g. floods) or significant disruption/transformation of economic circumstances (e.g. out-migration from an area as a result of repeated droughts). The focus will be finalised in discussion with EIB but is likely to focus on the Southern and Eastern regions in the EU.

Drop the financial rating of southern member states

The world today invests some $2.5 trillion a year on transportation, power, water, and telecommunications systems. Looking ahead, McKinsey Global Institute finds that the world needs to invest an average of $3.3 trillion annually just to support currently expected rates of growth.

If on one side there is an increasing need for infrastructure investment, on the other, this has actually declined as a share of GDP in 11 of the G20 economies since the global financial crisis. Cutbacks have occurred in the European Union, the United States, Russia, and Mexico. By contrast, Canada, Turkey, and South Africa increased investment.

Governments around the world have clamped down on infrastructure investment, giving precedence to fiscal concerns and debt fears. Many face years of fiscal consolidation and deleveraging to bring public debt down to manageable levels (McKinsey Global Institute, 2016).

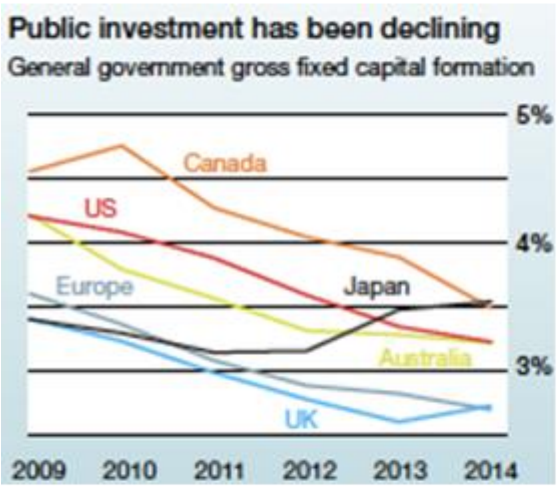

Figure 3: Public investment development (Source: McKinsey Global Institute, 2016)

Climate change risks are likely to worsen this situation even further: infrastructure will need to be built in a way that is climate resilient, in some case requiring additional (above BAU) costs; also, more frequent extreme events will most likely eat into already strained fiscal budgets, which are suppliers of first resort. Unfunded losses, such as

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post-Katrina repairs in the Gulf region, that ultimately get picked up by tax payers have the consequence of raising sovereign risk (McKinsey 2016).

Many countries in the Eurozone already have low credit ratings, and some of these countries (e.g. Spain, Greece, Italy) are also greatly exposed to climate change risks such as sea level rise, droughts, and floods. Governments' decisions on infrastructure investment affects the level of public borrowing (unless other mechanisms are in place for funding infrastructure, such as user fees) as well as their prospects of economic growth. Since public finance is still the primary source of funding for infrastructure building and restoration costs, it becomes clear that unless the countries most exposed to climate risks will find efficient ways to fund their infrastructure investment needs and support their economic growth, higher adaptation/restoration costs could result in even worse credit ratings. This in turn would increase the cost of borrowing – that is, the interest rate that will have to be paid by the issuer to attract buyers – and make t-bonds unattractive to some investors.

Unwillingness to invest in high-risk zones or high cost of capital

International Finance Instituions with the mandate of supporting infrastructure investment in European countries -such as the EIB- will need fulfil their mandate while ensuring their own (high) credit rating will be preserved. This might, at least in the short term, result in favouring investment in countries with a pipeline of bankable projects with relatively higher financial returns, and whose ability to re-pay debt is less likely to be compromised by uncertain future climate events. Access to capital might become an issue for some institutional borrowers also due to negative credit rating, as explained above.

If climate-related events are perceived as adding risk to investment, this will be included in the risk-adjusted financial return required by both multilateral and commercial banks. As a result, the cost of accessing finance could increase for certain borrowers based on e.g. project location, regional exposure and vulnerability to climate risks, and low adaptive capacity of the borrower. Such increase in the cost of capital could be hard to reverse.

The cost of insurance could also increase in the future if the frequency and scale of extreme events will continue to increase. Even though insurance represents for many a form of adaptation, in the long-term insurance premiums might increase in value, and become unavailable or unaffordable to many.

Note one other issue might be the break-down of insurance, i.e. what happens what return periods change and this affects the viability of insurance products (premiums) (see also section 5.9).

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5.4 Agriculture

Climate change and the increased occurrence of extreme weather events will impact yields and therefore food production both inside and outside of Europe. As indicated by stakeholders, this may lead to a collapse of rainfed agriculture, for example in Southern Spain.

Case description

Selected case: Food supply shock inside and outside Europe

It is our hypothesis that food supply shocks due to crop losses inside and outside Europe may lead to socio-economic tipping points that can be measured both on the producer, as well as on the consumer side.

On the producer side, crop losses may become of such a magnitude and frequency that farms structurally experience that their costs are larger than their benefits of production. In case this happens, several producer-related tipping points may arise. The extreme droughts may eliminate the possibility of rain-fed agriculture, leading to a shift in crop management from rain fed to irrigated agriculture *(measured in rain fed and irrigated hectares by crop in a certain location)*. It may also be that irrigation is not a possibility due to the available water or not the most profitable option in the specific location. In this case, the crop may disappear from the location altogether and may be replaced by a more profitable crop that is more resistant to the extreme weather events *(measured in hectares by crop in a certain location)*. In case both a shift in cultivation practices and a change of crops may not be a viable option, producers may be forced to leave a certain area, leading to farm exit and land abandonment *(measured by the number of hectares by land cover in a certain location).* In all three of these producer-related tipping points, we are not looking for certain thresholds to be passed, but looking for a substantial area of land cover/production by crop/management that existed before the shock took place, and does not exist anymore (or vice versa).

On the consumer side, a significant reduction in the supply of key crops does not necessarily lead to a direct reduction of consumption, as there may be some buffer capacity provided by storage facilities. However, an increased frequency of shocks may lead to the inability to re-stock the depleted storage facilities *(measured as the tons of a crop in stock; stocks are depleted if there is nothing left in stock of a crop).* In case of shocks on top of a situation with depleted stocks, food scarcity and food insecurity may arise *(measured as production falling below the 2500 kcal per person per day line).* Food insecurity issues may especially arise outside Europe, leading to increased pressures on food produced within Europe, causing prices to rapidly increase and the risk of hysteresis on the market *(measured in terms of a continued increase in prices over a sequence of years).* The increased speculation caused by hysteresis may lead to more market disturbance and significant economic losses along the supply chain.

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Analytical approach

The aforementioned tipping points on the producer and consumer side occur only with substantive yield drops. We will determine the likelihood of the tipping points to occur through backward induction. We first investigate under what magnitude and frequency of yield shocks the socio economic tipping points mentioned in columns 5 and 6 of Table 3 are likely to occur using the bio-economic model GLOBIOM-X. Second, we assess what combination of climatic variables (e.g. temperature increase, drought spells) would lead to these yield shocks using the process-based crop model EPIC (column 3 of Table 3). Third, we analyse the likelihood of these climatic / weather events to occur using the EURO-CORDEX data (column 2 of Table 3).

Table 3 Flow, indicators and methods used to analyse tipping points due to food supply shocks inside and outside Europe

	Climatic / weather event	**Input indicators: Agriculture**	**Input indicators: Water**	**Output indicators: Producer related**	**Output indicators: Consumer related**	**COACCH impact**
Indicator	Multiple sequential droughts Impact of drought Probability of drought Sequence of droughts	Yield impact, depending on management system Yield impact on irrigated land Yield impact on rain-fed land	Ability to irrigate Monthly flow of irrigation Competition from other sectors	Shift in management systems Shift in crop cultivation Land abandonment / farm exit	Storage depletion Food scarcity Food insecurity Hysteresis and speculation	Large increases in prices Landscape losses and farm exit Economic losses along the supply chain Market instabilities
Tool	Climate model projections	Process-based crop-model EPIC	Bio-economic model GLOBIOM-X	Bio-economic model GLOBIOM-X	Bio-economic model GLOBIOM-X	

5.5 Economic impact of flood hazards to major hubs in the EU-transport infrastructure

Case description

COACCH stakeholders have shown strong interest in the failure of critical infrastructures, in particular in the wider economic consequences of such failures through network effects. In this study, we elaborate on this modelling cascade: climate hazards -> network effects -> economic impacts. Our application is on flood impacts on major hubs in the EU transport infrastructure network, but the modelling approach can be applied to other climatic hazards (e.g. landslides in Alpine regions) or other types of networks (e.g. electricity, drinking water, internet) as well. Ultimately, one could overlay multi-hazard maps with multi-network representations: the so-called 'system of systems' (Hall et al., 2016).

Climate hazard: floods

Up till date, EU-scale flood modelling has mainly focussed on improving direct damage estimates from flood events, for which several models have been developed. With

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regard to river flooding, state-of-the-art models are GLOFRIS (VU/Deltares) and LISFLOOD (JRC), with corresponding damage mapping routines. With regard to coastal flooding, the state-of-the-art models are DIVA (GCF) and GTSR (VU/Deltares) with corresponding damage models. Flood hazard maps from these studies will be used as a starting point for the assessment of *indirect* economic effects.

Network effects: the EU transport network
We will study critical elements (links and hubs) in the EU transport network, and the likelihood of their disruption given a certain flood. Where direct impact studies only have focussed on the direct damages of infrastructure assets, the connection to the transport network enables studying wider economic impacts which might reach far beyond the region where the flood takes place. Initially, the focus will be on individual trade hubs (major ports and other freight transfer points) which are crucial for the European economy.

Economic impacts: MRIO
Economic impacts of network disruptions will be studied using a Multi-Regional-Input-Output (MRIO)-model on the NUTS-2 level, after Koks (2016). For groups of commodities, this model explicitly states the mode and route of transport through Europe. This data will be aggregated through main commodities in Europe and then attributed to a simplified model of the EU-transport network.

Model approach

Around the three model blocks: hazard – network effects – economic impacts, we might build an EMA-workbench environment (Kwakkel, 2017). This would enable us to randomly sample from flood hazard event sets (under different climate scenarios) and hub probability failure distributions to create plausible failure combinations of hubs. A tipping point (measured in terms of % GDP losses) could occur when several hubs fail as a result of a climate-related disaster.

Besides this novel approach to climate change impact modelling, the study will provide insight in an important conceptual question underlying the COACCH project: how do individual hub failures (which clearly are tipping points on a local scale) relate to EU-scale economic losses (larger scale tipping points)?

Table 4 Indicators and models to assess economic impacts of hub disruptions in EU transport network

	Climatic / weather event	Input indicators	Output indicators	COACCH impact
Indicator	Coastal storm surges River floods	Disruptions of critical elements in the transport network as a function of water levels	Losses per NUTS-2 region	Identify critical points in EU transport network Understand relation between local tipping points and EU-wide tipping points
Tool	DIVA/GTSR GLOFRIS/LISFLOOD	MRIO of European Transport network		

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5.6 Tipping points for adaptation of Dutch flood protection infrastructure

Case description

Some recent studies on ice sheet melting dynamics have suggested that melting processes may go much faster than earlier expected (e.g. DeConto and Pollard, 2016). This has not been accounted for in the current Dutch Delta management plans, which anticipate a sea level rise of 1.0 m by 2100 (compared to the 1995 level), whereas the more extreme melting scenarios suggest a sea level rise of 1.0 – 4.0 m by 2100 (Le Bars et al., 2017). It seems that especially the rate by which the sea level can change gives problems for adaptation, given that it took decades to develop the flood protection infrastructure currently in place. Moreover, there are limits to the adaptation strategies that have been followed in the past. In this case study, we explore whether accelerated sea level rise may require a structural reconfiguration of the Dutch flood protection strategy, for example towards a retreat scenario. This is an important story to tell, because Europe has several comparable low-lying Deltas and vulnerable cities (e.g. London - Thames Delta; Gothenburg - Gothen River; Glasgow - Clyde River; Hamburg – Elbe River; Antwerp – Scheldt River; Venice). These areas may face similar issues under accelerating sea level rise scenarios. In developing countries, limits to adaptation may be even larger, making them potentially unable to adapt (Hinkel et al., 2018).

Analytical approach

Starting point of the analysis is the literature in which the accelerated sea level rise scenarios are described. Using the site-specific model instruments, the impact on storm surge levels and river floods is studied. Then, the different adaptation strategies and limits of these strategies will be explored. This includes the best-before dates of the infrastructure in place and the time it would take to replace this infrastructure. Following this model approach, we explore how fast the socio-economic system has proved to adapt in the past and relate this to the policy challenges faced. Socio-economic tipping points may occur when adaptation strategies have to be adopted that are societal unacceptable, such as managed retreat scenarios or giving up the Wadden Sea area. Other tipping points may arise from large budget shifts or devaluation of assets in the Randstad region, with cascading economic effects.

Table 5 Indicators and models to assess tipping points for Dutch flood protection strategies

	Climatic / weather event	Input indicators	Output indicators	COACCH impact
Indicator	Extreme sea level rise scenarios and its impact on storm surge, river water levels, salt intrusion etc.	Storm surge and river water levels	Performance and limits of different adaptation strategies	Representative story for many urbanized low-lying Deltas in Europe
Tool	Site-specific model s	Site-specific models		

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5.7 Coastal socio-economic tipping points: 1) Local extreme events; 2) National cost of dealing with SLR

Case 1 description

Local extreme water levels are supposed to shift up with sea-level rise (Menéndez, 2010) causing potentially catastrophic impacts. Huge losses can occur in densely populated areas as in the 136 coastal megacities (Hallegatte, 2013). Extreme events in these location can lead to losses which might trigger a socio-economic tipping point, especially if the extreme event leads to a (partial) retreat from the location. There are two conditions necessary for a local extreme event to define a tipping-point in a bigger socio-economic system (country or subnational administrative unit):

- losses by the event must be significant in relative terms (GDP of the country/subnational administrative unit).
- migration as a result of (partial) retreat must be significant in relative terms (population of the country/subnational administrative unit).

Such a reactive (partial) retreat would fulfil the criteria of a tipping point as it is abrupt, has large effect although the cause is rather small and it would imply a structural irreversible change in the underlying system.

Analytical approach case 1

Within COACCH we will use the coastal impact model DIVA to analyse the impacts of an extreme flood event (i.e. 1-in-1000 year event) in the 136 coastal megacities and narrow down the potential of these events to trigger socio-economic tipping points. Sea-level rise and socio-economic tipping point will be taken into account to model the increased impacts over 21st century.

Table 6 Flow, indicators and methods used to analyse tipping points due to cost of local reactive retreat as a consequence of extreme events.

	Climatic / weather event	**Input indicators: Sea-level rise cost**	**Output indicators: Relative cost of sea-level rise**	**COACCH impact**
Indicator	Extreme water level event	Damage cost and migration implied.	Damages as proportion of total GDP, migration as proportion of total population	In addition to direct impact, extreme events might induce shocks to the economy that propagate through the whole system (country etc.).
Tool	Sea-level rise scenarios from Climate and ice-sheet models, storm surge levels from GTSR (Muis,2016)	Coastal Impact and adaptation model (DIVA)	Coastal Impact and adaptation model (DIVA) and SSP projections.	Economic models ICES/COIN to analyses further economic impacts.

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Case 2 description

Adapting livelihoods to the environmental conditions in coastal floodplain areas causes cost. While current cost of managing life in coastal areas are dominated by protection and damage cost, sea-level rise might lead to significant coastal migration and associated migration cost. Thus, there will be national cost of dealing with sea-level rise as the sum of:

- Protection cost (investment and maintenance of protection infrastructure)
- Damage cost (flood damages in unprotected areas or damages due to overtopping)
- Migration cost (cost of people migrating from unprotected coastal areas)

Kabat et al. (2015) estimate the annual cost of SLR in the Netherlands €3.1 billion per year in 2050, which is about 0.5% of the current Dutch gross national product. For poorer countries, the relative cost of SLR might be even higher. If the relative cost exceed a yet to be defined threshold this can be seen as a socio-economic tipping point, as the countries might no longer be able to capture the cost. In this situation the tipping-point criteria might apply:

- C1. Small causes with (disproportional) large effects (i.e. a non-linear response to a gradual change in conditions): Although the gradual sea-level rise might be small in general (less than a few centimeters/year), the costs are large and usually grow non-linearly. Socio-economic development increases the exposure behind protection structures and thus causing high potential cost in the case of overtopping.
- C2. Rapid change (i.e. quickly occurring, abrupt change): The GDP threshold can be exceeded rapidly.
- C3. Structural reconfiguration or transformation of a system (in a mathematical sense: multiple stable states): Once a society exceeds the GDP threshold for dealing with sea-level rise, the economic structure of the system might change significantly.
- C4. Irreversibility: Once a society exceeds the GDP threshold for dealing with sea-level rise, (at least) the economic structure of the system might change permanently.

Analytical approach case 2

In COACCH we will analyse the cost of sea-level rise on national level under the COACCH scenario-combinations. We will assume cost-benefit-optimal local decisions, analyse the implied cost of sea-level rise, and set them in relation to current and/or future GDP.

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Table 7 Flow, indicators and methods used to analyse tipping points due to cost of gradual sea-level rise.

	Climatic / weather event	Input indicators: Sea-level rise cost	Output indicators: Relative cost of sea-level rise	COACCH impact
Indicator	Gradual sea-level rise	Protection cost, Damage cost, Migration cost	Sea-level rise cost as proportion of GDP	Large relative cost of sea-level rise might act as a continuous shock of GDP.
Tool	Sea-level rise scenarios from Climate and ice-sheet models	Coastal Impact and adaptation model (DIVA)	Coastal Impact and adaptation model (DIVA) and SSP projections	Economic models ICES/COIN to analyses further economic impacts.

5.8 Energy supply system switches[3]

Case description

The economic viability of renewable energy employment can be characterized by tipping points that can turn into socioeconomic tipping points. For utilities to switch to large scale employment of renewables, or for industries to switch to renewable energy based low-carbon production processes, a certain stringency level of a policy (e.g. a minimum carbon price) or a sufficiently well designed renewable energy system (ensuring sufficiently low carbon-free energy cost) may be necessary. If so, each of these act as economic viability tipping points for employing the respective technology and switching in investment accordingly. For example, in the steel industry the economic viability of a switch to near-process-emission free production (such as substituting hydrogen for coke in the iron reduction) requires either a sufficiently high carbon price on coke or a sufficiently low renewable electricity price for the production of hydrogen (Schinko et al., 2014). Once such an economic viability tipping point is reached, the investment in a whole sector switches to the low-carbon technology and the production system and related socioeconomic system is restructuring (López Prol and Steininger, 2017, 2018), indicating a socioeconomic tipping point. As a small change in the cost ultimately triggers a full system switch, the COACCH SETP criterion C1 (small cause) is given, the change in the investment demand occurs rapidly (C2), and a structural reconfiguration is triggered (C3) as the energy system (and sectors linked) switch to variable and intermittent supply sources. The reversibility gets increasingly difficult over time, given both the long life time of investment and the increasing share of the new energy sources, but is theoretically possible (thus the additional criterion C4 is not met without restriction), but C5 (system feedback) usually

[3] This tipping point has been suggested by stakeholders, however it refers more to mitgation action rather than to climate change impacts and adaptation. The COACCH consortium is thus considering the possibility to define a tipping point more strictly linked to the impact in the energy/electricity sector.

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is fulfilled, as the start in employment of new low-carbon (energy) technologies will further reduce their costs (e.g. due to learning by doing in the production of the new technologies) and thus will re-enhance their employment.
We note that specific renewable energy system designs can reduce renewable energy costs substantially, and in this way contribute to reaching a tipping point. For photovoltaic (PV) electricity supply it has been shown in particular that geographic distributed generation can reduce overall unit supply costs by half (if locations are distributed across the same hemisphere) or by three quarters (if the distribution is inter-hemispherical) (Grossmann et al., 2013, 2014, 2015). Thus, the completion of such designs can function as a socioeconomic tipping point.

Analytical approach
Methodologically, in our COACCH analysis a business level oriented production cost analysis is employed, which for the case of PV solar electricity is also based on solar PV isolines (Grossmann et al., 2015). Input indicators are the respective cost positions and their dynamic development. For the socioeconomic implications, first a qualitative analysis is employed to get a comprehensive narrative. To seek the quantification of some core aspects the recursive dynamic CGE model WEGDYN and an energy related econometric approach will be employed.

Table 8 Indicators and models to assess energy supply system switches

	Socio-economic tipping point	**Input indicators: steel**	**Input indicators: PV**	**Output**	**COACCH impact**
Indicator	Switch to renewable energy/production processes profitable Candidate examples: - Low carbon process steel production - Photovoltaic electricity as reference technology	- Technology cost - Fossil prices - Steel demand scenarios - SPA (carbon price)	- Dynamic technology costs development - Solar influx - Energy system capital stock composition	- switch point in time - policy options - macro-economic impacts - budgetary impacts	- Parameters identified that govern switches - Economic impacts of switches - Distributional implications - Policy recommendations
Tool	technology production cost analysis; for PV Solar PV isolines	stakeholder dialogue	Solar PV Isolines	WEGDYN Econometric	

5.9 Collapse of insurance markets for extreme weather risks

Case description
Increased extreme weather risks, due to climate and socioeconomic change can cause certain insurance systems to become unsustainable. After several large natural disasters occur in an area, insurers may realize extreme weather risk is rising, which can lead to increases in premiums (Botzen et al., 2010a). For example, in the Netherlands an extreme hailstorm caused insured losses of about €500 million in 2016 mainly to the agricultural greenhouse sector. According to insurance experts, the occurrence of another similar hailstorm that year would have made the risk uninsurable in the sense that premiums would have risen considerably. Another example could be consecutive large flood events, which cause flood insurance

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premiums to rise, as has for example occurred in the Caribbean after an active hurricane season with large scale flooding.
Such a relatively small cause can have large economic consequences. Rapidly rising premiums can cause unaffordability of insurance and lower demand for coverage, which can lead to a collapse of specific insurance markets (Lamond & Penning-Rowsell, 2014). A feedback mechanism that reinforces the problem is that a lower demand for insurance lowers the risk pool of the policy, which increases the costs of insurance provision and premiums, lowering demand even further. Moreover, economic activities that depend on insurance coverage may be hampered if such insurance markets collapse (Klein et al., 2014). For example, unavailability of flood insurance can have adverse effects on financial institutions that provide mortgages, because after the next flood event uncovered properties may be left unrepaired and hence the mortgage provider can only sell the property at a lower price in case of a loan default.
The structural reconfiguration in the insurance market is that it is unattractive for the insurance company to again offer the insurance at lower prices. In order to preserve affordable coverage and, therefore, resilience against climate risk, a reform of insurance systems may be required (see for example Paudel et al., 2012). For example, purchase requirements should be strengthened to increase the pool of insurers, risk reduction effort should be stimulated to lower risk for the insurance company and hence reduce premiums, and the government may need to step in the market and cover (some) of the risk, e.g. in the form of public reinsurance.

Analytical approach:
The case study will be illustrated with narratives for hailstorm insurance in the Netherlands, agricultural insurance in Southern Europe and flood insurance in the EU. Descriptive and mostly qualitative storylines will be developed for the hailstorm and agricultural cases, which, where possible, will be supported with quantitative information about changing risk (empirical analysis in Botzen et al. 2010b for hailstorm risk under climate change and the GLOBIOM model of IIASA for agriculture) and expert knowledge from COACCH insurance stakeholders (Dutch Union of Insurers). For flood insurance, a more formal modelling approach will be taken based on the EU scale Dynamic Integrated Flood Insurance (DIFI) Model of VU-IVM (Hudson et al., 2018) as described in Table 9.

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Table 9 Flow, indicators and methods used to analyse tipping points due to EU flood- and agriculture insurance systems.

	Climatic / weather event	Input indicators:	Output indicators: Producer related	Output indicators: Consumer related	COACCH impact
Indicator	Flood events under climate change scenarios	Flood risk under climate change scenarios	Insurance premium Required reforms to prevent collapse of the market	Insurance demand. Affordability of insurance premiums. Risk mitigation effort by households.	Costs of insurance. Underinsurance, due to unaffordability, reduces resiliency to climate risk. Policy tipping points: which reforms are needed when to prevent a collapse of markets
Tool	Dynamic Integrated Flood Insurance (DIFI) model	DIFI model	DIFI model	DIFI model	DIFI model

5.10 Climate induced economic shocks

Case description

Extreme temperatures and climate hazards resulting from climate change can induce significant losses to economic output (van den Bergh and Botzen, 2015). Positive feedback mechanisms in the climate system can cause rapid increased levels of warming, for example when global warming results in a fast melting of permafrost which causes releases of methane emissions that accelerate warming (Koven et al., 2011). Moreover, global warming can lead to enhanced local warming at the city level due to the urban heat island effect, which exacerbates economic impacts (Estrada et al., 2015). This case study will examine the local economic shocks that can occur when high temperature increases are realized (95^{th} percentile of possible temperature increases). Since the damage functions of relations between temperature increases and economic impacts are non-linear (quadratic) (Botzen and van den Bergh, 2012), this could lead to the rapid approach to an economic tipping point whereby a high percentage (like 5%) of local GDP is lost. When a large economic shock is experienced, it could be irreversible due to structural changes in the economic equilibrium (e.g. supply/demand shocks, structural unemployment etc.) and it can trigger policy changes, like enhanced climate adaptation policies. Moreover, consequences in economic shocks can reinforce each other through persistence in GDP (Estrada et al., 2017).

Analytical approach

The economic shocks from climate change can be explored on a local, country and regional level with the Integrated Assessment Model CLIMRISK. This would allow to

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gain a better understanding of when, where, and under which conditions large local economic shocks can occur. The modelling flow in terms of model input and output is shown in Table 10.

Table 10 Flow, indicators and methods used to analyse tipping points due to climate induced economic-shocks

	Climatic / weather event	Input indicators: Temperature/Precipitation	Output indicators: Economic Damage	Output indicators: Date and location of realization	COACCH impact
Indicator	Extreme temperature realizations	Annual local temperature and precipitation (grid-cell), generated probabilistically	Percentage of annual GDP lost	Date and location of tipping point occurrence, allowing for assessment of window of mitigating action for each year	Integrated assessment model for exploring the local effects of extreme climate events (e.g. high temperature increase) expressed as loss as total annual output
Tool	Climate module in CLIMRISK	Climate module in CLIMRISK	Impact module in CLIMRISK	CLIMRISK	

5.11 Macro-economic assessment of SETPs

A final macro-economic assessment with ICES and COIN as part of task 3.4 is finally executed to evaluate the consequences of the sectorial impacts calculated as indicated in 5.1-5.10 on the overall economic systems of the EU countries and regions.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

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