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# Global assessment of impacts on migration and security issues

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# Executive Summary

This deliverable report presents findings from two studies under the D5.7 ‘Global assessment of impacts on migration and security issues’ section of the High-End cLimate Impacts and eXtremes (HELIX) project. The first study considers the impacts of climate change on food insecurity at the national level across the globe, and the second considers the impacts of climate change on migration.

## Assessment of the impacts of climate change on national level food insecurity using the Hunger and Climate Vulnerability Index

Climate change is a potential risk to all aspects of food security (Porter *et al.*, 2014). In addition, understanding how, when and where climate change will impact those that are most vulnerable to food insecurity is challenging. To gain insight to this challenge, the Hunger and Climate Vulnerability Index (HCVI; Krishnamurthy *et al,*2014; Richardson *et al.*, 2017) has been designed to assess the relative national-level vulnerability to food insecurity across developing and least developed countries, as a result of current and future climate-related hazards. Recent analysis with the HCVI concluded that both mitigation and adaptation are required to avoid the worst impacts of climate change and to make gains in tackling food insecurity (Richardson *et al.*, 2017).

The study presented here has investigated the impact of using a different climate model ensemble at a higher resolution than previous HCVI results. This new version of the HCVI was calculated using output from the high resolution ensemble of HadGEM3 simulations (from Work Package 3 of the High End cLimate Impacts and eXtremes (HELIX) project). The geographic pattern of results is broadly similar to that in Richardson *et al.* (2017); the highest vulnerability scores in the baseline are found in sub-Saharan Africa and South Asia, and the most vulnerable regions projected to see the largest increases in the future. The absolute values of the HCVI are increased in some regions and reduced in others as a result of using a different ensemble of climate models at a higher resolution. However, the application of scenarios of adaptation investment supports the requirement for both mitigation and adaptation, although this study highlights the dependence of the results on the models used and the limitations of the empirical approach to adaptation scenarios.

The results from this study suggest, in the absence of adaptation, that around 5.73 billion people could become more vulnerable to food insecurity in a 2°C warmer world compared to the present-day and 5.76 billion in a 4°C warmer world. In a 2°C warmer world, an estimated 189 million people could become more vulnerable to food insecurity than is currently experienced anywhere under the current climate. In a 4°C warmer world, this figure increases ten-fold to an estimated 1.8 billion people potentially reaching unprecedented levels of vulnerability to food insecurity.

The HCVI methodology was also adapted to account for food imports, which enables the inclusion of developed countries in the calculation. This trade-weighted index weights the HCVI values by the appropriate proportions of locally produced cereals and imports from the global market, taking into account relative wealth and the climate vulnerability of national GDP (via the fractions of agricultural and non-agricultural GDP). Applying the trade-weighting generally results in a small reduction in the vulnerability values, particularly in countries which have a high fraction of imported cereals (i.e. within the Middle East and North Africa region). This first iteration of an HCVI that accounts for food imports only considers the vulnerability of a country’s ability to import food. It does not currently consider the impact of climate and climate change on the production of cereals globally, the availability of cereals on the global market, nor the impact this has on global commodity prices or how these transmit to domestic prices paid; this is the subject of future developments of the HCVI.

## Assessment of climate change on migration

It is today widely acknowledged that climate change will induce significant population movements of different nature - forced and voluntary, temporary and permanent, internal and international (Foresight 2011). Logically, different studies have attempted to forecast the magnitude of future migration flows induced by climate change, but these have not proved conclusive so far. In this deliverable, we try and provide a more realistic approach to forecast migration futures under different climate scenarios. For this, we have built an approach based on case-studies representative of different contexts and different climate impacts, in Africa and South Asia. By studying how populations have reacted to climate shocks in the past, we were able to identify a series of key patterns that will determine migration flows under different levels of warming. Our key argument is that warmer temperatures will not just affect the amplitude of migration, but more importantly its patterns.

Indeed, there's no correlation between the magnitude of climate and social impacts: an accumulation of small climate impacts can lead to major transformations, while some migratory systems will be able to absorb important climate shocks. Furthermore, aggravated climate change will not necessarily result in an increase of migration, as more people will also find themselves unable to move and relocate to a safer place. This is the reason why the scale of migration resulting from climate change cannot only be understood in terms of alteration of volume, but rather of patterns and structures.

Mobility dynamics associated with extreme climate change will often be non-linear, and question our acception of the expected migration patterns. At the end of the day, such will come down to the issue of inhabitability, which is by itself a very subjective concept. These characteristics should help better anticipate the patterns of future migration flows associated with climate change. Three case-studies are presented here to illustrate these patterns: in Burkina Faso, Senegal and Bangladesh.

# 1. Introduction

This report presents findings from research undertaken as part of the 'High-End cLimate Impacts and eXtremes' (HELIX) project, which looks at climate change under a range of scenarios of future global average temperature rises. These scenarios are identified by Specific Warming Levels (SWLs) which are set at a global annual mean rise of 1.5, 2 and 4°C relative to the pre-industrial climate (1861-1880). These have been used to assess climate change impacts and adaptation, both globally and in three regional focus areas: Europe, sub-Saharan Africa and South Asia. The wider HELIX project aims to assess the impacts of these specific warming levels on food, water and energy security, flooding, infrastructure, ecosystems, health and human migration in order to provide tailored climate impact information to stakeholders, such as the European Commission (EC) and the World Food Programme (WFP), policy-makers and businesses. This report aims to assess the impacts of climate change on migration and food security and falls under the global-scale assessment of socio-economic impacts (Work Package (WP 5) section of HELIX.

The HELIX project frames the assessment of the impacts of future climate change in terms of SWLs, i.e. levels of global warming above a defined baseline. This framing is used because international climate policy generally uses such an approach, e.g. aiming to limit global warming to "well below 2°C". Furthermore, the use of SWLs places primary emphasis on the aspects of future climate change projections in which we have greater confidence – the fact that ongoing warming will lead to these levels being passed sooner or later. It gives secondary emphasis to an aspect about which we are much less certain, such as the rate of warming. This is important because stakeholders need to understand that these aspects of the predictions are less certain, to help reduce the risk of making inappropriate decisions on the basis of over-confidence in the predictive capability of climate models.

In HELIX, the climate states and associated climate impacts at the different SWLs are analysed. These are defined using new high-resolution transient climate simulations driven by the RCP8.5 scenario. This scenario is consistent with ongoing high emissions and hence features a rapid rate of warming. The climate model has been run with a number of different initial conditions based on the results of the large ensemble of models in the 5$^{th}$ Coupled Model Intercomparison Project (CMIP5; Taylor *et al.* 2012). Consequently, the model ensemble members show different geographical patterns of change at any given SWL and also warm at different rates meaning that the simulations each reach any given SWL at a different date in the future.

This report presents the findings from two studies. The impacts of climate change on national level food insecurity using the Hunger and Climate Vulnerability Index are presented in Section 2, followed by the results from assessments on the impacts of climate change on migration in a number of case study regions in Section 3.

# 2. Assessment of the impacts of climate change on national level food insecurity using the Hunger and Climate Vulnerability Index

This section of the report aims to assess the impacts of climate change on food security at the national level across the globe. Understanding the impacts of climate change on food security is challenging given the complex nature of the food system. Food security analysis is comprised of four components: availability, access, utilisation and stability, and all of these components of food security are at risk from the changing climate (Porter *et al.,* 2014). This analysis makes use of the previously published Hunger and Climate Vulnerability Index (HCVI; Krishnamurthy *et al.,* 2014; Richardson *et al.* 2017) which is designed to bring together both the socio-economic and climate change aspects of food security. It assesses national-level vulnerability to food insecurity as a result of climate-related hazards under a range of emissions and adaptation scenarios, and was developed in collaboration between the Met Office and World Food Programme.

As part of this project, the HCVI is updated to use the high-resolution HadGEM3 global climate model data from HELIX WP3 (HELIX D3.1, 2017) to assess the impacts of 1.5, 2 and 4°C of global warming, above pre-industrial levels, on food insecurity, using the HCVI. The sensitivity of the results to the spatial resolution of the input data is also examined and compared to previous results using the CMIP5 model ensemble, following the previous practice of simulating impacts at specific times in the future: the 2050s and 2080s, to allow a direct comparison. In addition, since the current HCVI methodology only accounts for in-country production of food, a proposed methodology to incorporate food imports into the HCVI is also presented, along with the initial results (hereafter referred to as the trade-weighted index).

The remainder of this chapter is structured as follows: the analysis begins with a review of the HCVI in Section 2.1, followed by the results from the index as driven by the high-resolution HELIX data in Section 2.2, and then the method and results from the trade-weighted index in Section 2.3. The results are summarised in Section 2.4 and references for this part of the report can be found in Section 2.5.

## *2.1 Overview of the Hunger and Climate Vulnerability Index (HCVI)*

The Hunger and Climate Vulnerability Index (HCVI; Krishnamurthy *et al.,* 2014) was developed to provide a country-level assessment of vulnerability to food insecurity as a result of climate-related events. The latest iteration of the HCVI makes use of gridded climate model projections to understand the impact of climate change on vulnerability to food insecurity, and also the benefits adaptation can bring via scenarios of adaptation investment (Richardson *et al.,* 2017). This iteration of the HCVI only considers in-country production of food and does not account for food trade. For this reason, the HCVI is only calculated for developing and least-developed countries[1].

The index provides quantification at the national level across the globe of the scale and direction of impact of climate change on food insecurity. As such, it aims to provide the following: 1) information to help policymakers understand the level of challenge to global food security that climate change presents; 2) information on the geography of the impacts and help to evaluate the relative benefits of mitigation and adaptation responses.

[1] Developing and least-developed countries are defined here are those that do not belong to the OECD or EU.

The index is not intended to be a detailed planning tool, but aims to help planners evaluate the nature of the top-level threat to food insecurity that climate change presents, thereby supporting prioritisation of effort.

The HCVI consists of three equally-weighted components: exposure to climate-related hazards, sensitivity of national agricultural production to climate-related hazards, and adaptive capacity – a measure of a country's ability to cope with climate-related food shocks. Each component is comprised of a number of indicators; these are listed in Table 1.

**Table 1 – Indicators used to make up the three components of the HCVI; exposure (analysis of climate data), sensitivity and adaptive capacity (country level statistics, representative of the year 2010 and all accessed in 2013).**

| **Component** | **Indicator** | **Data source** |
|---|---|---|
| Exposure | Average length of floods and droughts | WATCH (Weedon *et al.,* 2011) |
| Sensitivity | Forest cover (% of total area) | World Bank (2016) |
| | Rainfed agriculture (% of total agriculture) | World Resources Institute (2013) |
| | Cereal crop yield (tons/ha) | FAOSTAT (2016) |
| Adaptive capacity | Water access (rural population) (%) | World Bank (2016) |
| | Water access (urban population) (%) | World Bank (2016) |
| | Paved roads (% of all roads) | World Bank (2016) |
| | Government effectiveness (%) | World Bank (2016) |
| | Decadal population growth (2000-2010) (%) | UNFPA (2013) |
| | Total population below poverty line ($2 per day, PPP) (%) | UNDP (2013) |
| | Vulnerable employment (% of total labour force) | World Bank (2016) |
| | Rural population (% of total population) | World Bank (2016) |

The exposure component is comprised of proxies for the average length of flood and drought events calculated with daily precipitation data. The "WATCH Forcing Dataset" (Weedon *et al.,* 2011) was used for the baseline period (1981-2010)s used and an ensemble of twelve global climate models from the CMIP5 archive (Taylor *et al.* 2012) was used for the future projections (the 2050s and 2080s). Each of these datasets was first re-gridded to the lowest common grid; a global resolution of 90x144 grid cells.

Country level exposure values were constructed by masking the flood and drought proxies to only include grid cells where climate-related hazards would be most prominently felt. Values chosen were grid cells with a population density greater than 150 people per km$^2$ and grid cells with more than 1% of the grid cell given over to crop production. The median value of the remaining grid cells was selected as the country level value for each of the flood and drought proxies, and these were combined to produce a country-level measure of exposure. Each of the components of the HCVI were normalised to place the values on a relative scale (the exposure component was normalised across the country values, and the sensitivity and adaptive capacity components were normalised to plausible maximum and minimum limits), resulting in the HCVI measure of vulnerability to food insecurity on a 0-1 scale (Figure 1).

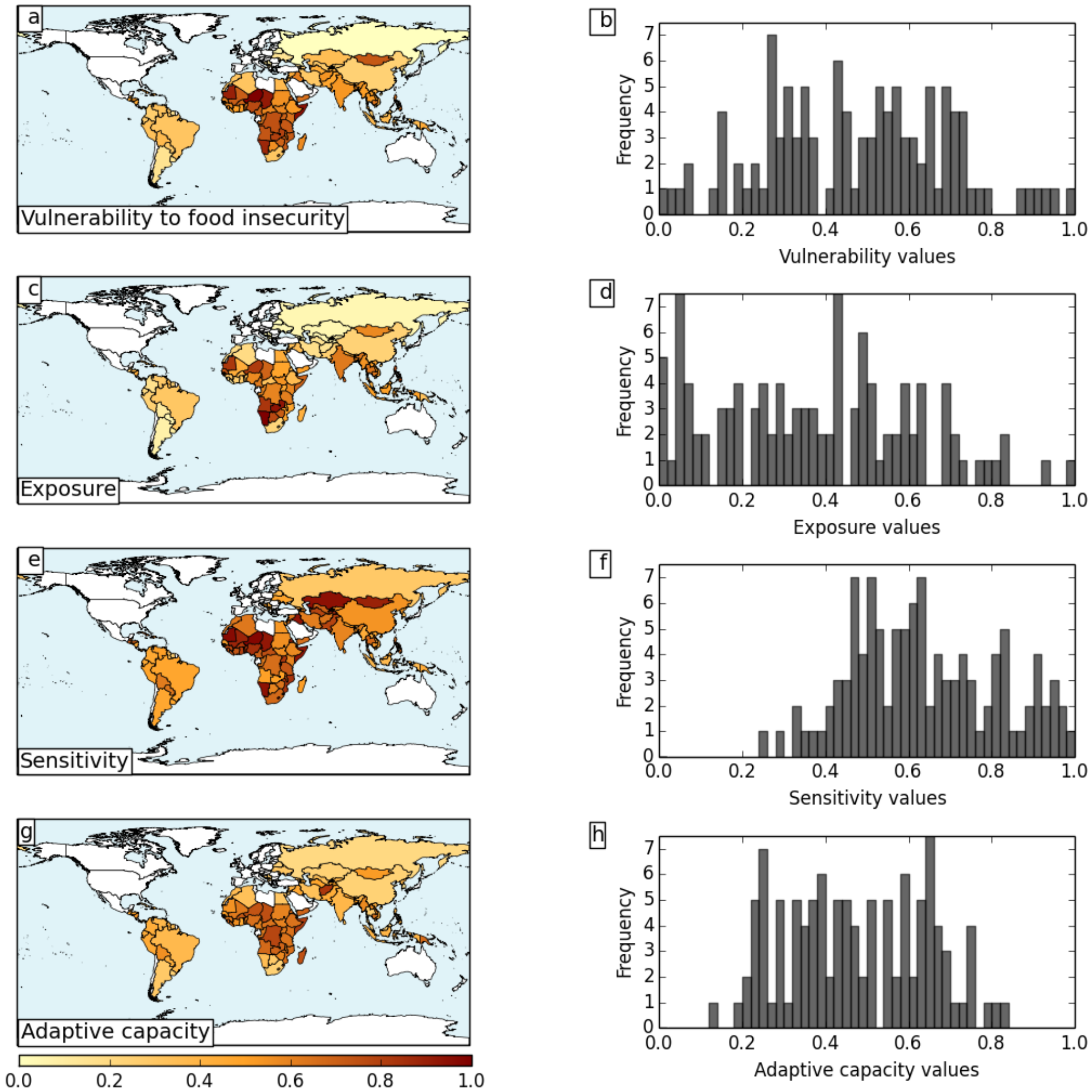


**Figure 1 – Maps and histograms of the national HCVI and the three components over the baseline period (1981-2010) as calculated in Richardson *et al.* (2017) using WATCH forcing data at a resolution of 90x144. Figure taken from Richardson *et al.* (2017).**

Future projections of the HCVI were calculated for a range of future greenhouse gas emissions and adaptation investment scenarios for both the 2050s and 2080s. The results showed the dual requirement for both mitigation and adaptation to avoid the worst impacts of climate change and to make gains in tackling food security. A summary of the results of the future projections is provided in Appendix A for completeness.

## 2.2 The HCVI with high-resolution HELIX data

This section of the report reassesses the future HCVI values using the new higher resolution global climate model simulations from HELIX WP3 at the SWLs and compares the results to the previous work presented in Richardson *et al.* (2017).

### 2.2.1 Data and methods

The climate data used for the HCVI reassessment comes from HadGEM3[2]; the Met Office's high resolution global climate model (HELIX D3.1, 2017). This model was run as a six-member ensemble in atmosphere-only mode at 0.5° resolution (corresponding to a grid spacing of about 50km by 50km at the equator). Each ensemble member takes sea surface temperatures from a different driving model run at a lower resolution (refer to
Table 2 for details of the driving models). The climate model data has been bias-corrected relative to the Princeton Global Forcings V2 reanalysis data product (Sheffield et al., 2006) according to the ISI-MIP bias correction protocol (Hempel et al., 2013). Note that only five ensemble members of the full six-member HadGEM3 ensemble available were used in this analysis as there were issues with the bias correction applied to one of the ensemble members[3].

The central year of SWL1.5, SWL2 and SWL4 for each ensemble member is defined as the year in which the 20-year running mean of the global annual mean temperature anomaly first passes the specific temperatures of 1.5, 2, and 4°C respectively (for more detail see HELIX D2.1, 2014). The temperature anomaly is calculated relative to the pre-industrial period: defined in HELIX as the mean of 1861-1880. In WP2 and WP3, the central SWL years are calculated using the raw data from the global climate model simulations and therefore do not account for the bias in the present day warming between simulations and the estimate derived from the instrumental record. The impact models in HELIX (and the present study) use bias corrected high-resolution simulations (Hempel et al., 2013) and therefore the central SWL years are different to those from WP2 and WP3. The bias-corrected central SWL years are calculated assuming the observed warming from pre-industrial period to the bias correction reference period (1861-1880 mean to 1981-2010 mean) is 0.61°C (Morice et al., 2012).

In accordance with the HELIX protocol, 20 years of data either side of the central year were used to calculate the HCVI for each SWL (Table 2). The 2050s and 2080s time slices use the standard 30-year climatologies (2041-2070 and 2071-2100 respectively).
For full details of the methodology for running the HELIX climate simulations see HELIX D3.1 (2017), and for details of the bias correction methodology see Hempel et al. (2013).

**Table 2 - The central years for specific warming levels 1.5°C, 2°C and 4°C for the high resolution simulations from WP3, and the 20 year range used for the analysis (in brackets). It is assumed that the observed warming from pre-industrial period to the reference period (1861-1880 mean to 1981-2010 mean) is 0.61°C (HadCRUT4, Morice et al., 2012)**

| SST Driving Model | SWL 1.5 | SWL2 | SWL4 |
|---|---|---|---|
| ACCESS1-0 | 2026 (2017-2036) | 2040 (2031-2050) | 2081 (2072-2091) |
| GFDL-ESM2M | 2036 (2027-2046) | 2051 (2042-2061) | - |
| IPSL-CM5A-LR | 2024 (2015-2034) | 2035 (2026-2045) | 2071 (2062-2081) |
| IPSL-CM5A-MR | 2023 (2014-2033) | 2036 (2027-2046) | 2069 (2060-2079) |
| MIROC-ESM-CHEM | 2020 (2011-2030) | 2032 (2023-2042) | 2068 (2059-2078) |

[2] The specific simulation of HadGEM3 was HadGEM3 GA6.0 N216 UM10.2 (Walters *et al.*, 2017; Williams *et al.*, 2015)

[3] The HadGEM3 model driven by HadGEM2-ES sea surface temperatures exhibited anomalous behaviour in the daily precipitation data after the bias correction process and is therefore excluded from this analysis.

As the GFDL-ESM2M model did not reach SWL4, this model has been excluded from all of our SWL ensemble mean analyses in order to produce a consistent assessment of the index. The SWL ensemble mean is therefore computed from four models and the 2050s and 2080s ensemble mean is computed from five models. Each ensemble member is given equal weighting in the derivation of the ensemble mean. The effect of excluding this model from the ensemble is to increase the standard error on the ensemble mean by an average of less than 0.01%[4]. The mean standard error is typically <0.003 of the ensemble mean for each country for the baseline and <0.03 for the 2080s, which builds confidence in the robustness of the ensemble mean values. A visual comparison of the difference between these two ensemble means for SWL2 is provided in Appendix B.

The baseline period used for comparison with the SWLs and the future time periods in all cases was 1981-2010 and was taken from each respective ensemble member's data, as opposed to the WATCH reanalysis data in previous work. This results in small differences between the baselines for each of the ensemble members because although each member's data has been bias corrected to the same reanalysis dataset, the bias correction methodology is applied at a lower temporal resolution than the daily time step of the model data.

Due to the increased resolution of the climate model data used in this study, it was necessary to recalculate the exposure component agricultural and population mask. This is applied at the new 0.5° resolution (Figure 2). The higher resolution of this mask results in additional countries being included in the HCVI calculation as compared to previous results from the CMIP5 iteration of the HCVI in Richardson *et al.* (2017). This is because the smaller grid cell size allows the calculation of more exposure values for each country. The new countries included are: Costa Rica, Equatorial Guinea, Gabon, Jamaica, Libya, Mauritius, Oman, Puerto Rico, Saudi Arabia, the Soloman Islands, Timor-Leste, Trinidad and Tobago, and Tunisia.

In addition, as part of this work package the HCVI has been re-written in the Python programming language in order to accommodate state-of-the-art functionality for handling the large datasets associated with the high-resolution climate model data. The baseline HCVI values computed with the WATCH data and the new technology are comparable to the values calculated using the same data with the original software (<0.06 in difference).

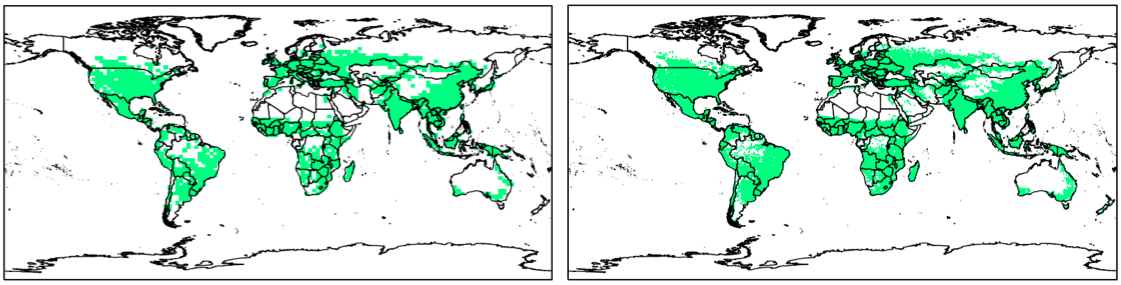

**Figure 2 - Masks resulting from thresholds of a population density greater than 150 people per km$^2$ (definition of rural population based on OECD (2011)) using an estimate of population density in the year 2000 (van Vuuren *et al*., 2007)) and with more than 1% of the grid cell given over to crop production (using cropland data representative of the year 2000 from Monfreda *et al*., 2008). Left panel: mask from previous HCVI analyses using CMIP5 climate models and the WATCH data at 1° resolution; right panel: mask from this HCVI analysis using the HadGEM3 base model at 0.5° resolution.**

[4] The standard error on the mean is given by $\sigma/\sqrt{n}$ where $n$ is the sample size, and $\sigma$ is the standard deviation of the ensemble member values.

### 2.2.2 Results and discussion

Results from the HCVI calculated with the high-resolution HadGEM3 global climate model data are presented in this section. Figures showing the average length of flood and drought events indicators calculated from the new HELIX data can be found in Appendix C. The HCVI for the baseline period (1981-2010) is presented in Section 2.2.2.1 and comparisons are made with the HCVI calculated with WATCH data at a lower resolution to identify the sensitivity of the results to resolution and different model results.

Results from the future projections of the HCVI under the SWLs are presented in Section 2.2.2.2. The adaptation investment scenarios applied in Richardson *et al.* (2017) were developed specifically for use with the 2050s and 2080s time periods. It was therefore not possible to apply these to the SWL time slices because the SWLs imply a different time period for each exposure scenario. The SWL results therefore show vulnerability to food insecurity at a global annual mean rise of 1.5, 2, and 4°C relative to the pre-industrial climate (1861-1880) in the absence of adaptation only.

Future projections of the HCVI using the new HELIX climate data for the 2050s and 2080s are presented in Section 2.2.2.3, both with and without adaptation and comparisons are made to the previous future climate HCVI results from Richardson *et al.* (2017).

#### 2.2.2.1 Baseline

The new high-resolution ensemble mean baseline HCVI values show a similar spatial pattern to the previously-derived baseline HCVI values (compare left panel of Figure 3, with top left panel of Figure 1). The highest levels of vulnerability to food insecurity currently experienced are in Africa and South Asia and lower levels are identified in South and Central America and wider Asia.

Compared to previous HCVI results using the CMIP5 multi-model ensemble and the WATCH data, the new baseline HCVI values show a slight reduction in vulnerability to food insecurity, particularly for sub-Saharan Africa (Figure 3, right panel). The differences are greater than the standard error on the ensemble mean for the baseline period in two-thirds of the countries. The highest values, though, are still found to be in West Africa.

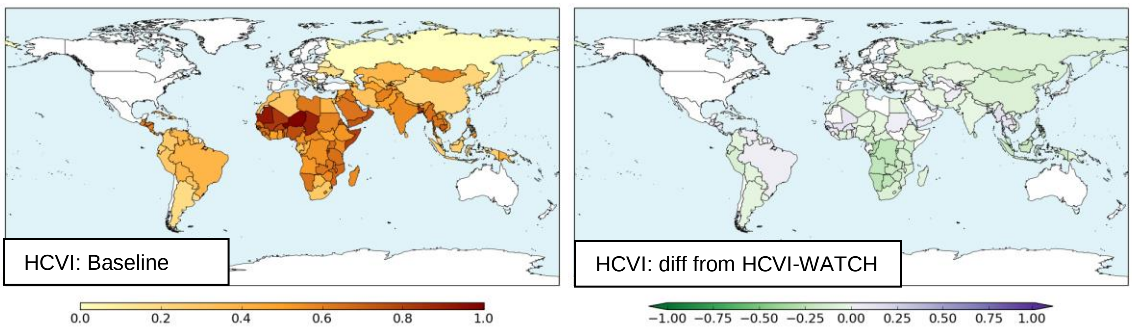


**Figure 3 - HCVI values for the HadGEM3 ensemble mean baseline period (1891-2010). Maps of the HadGEM3 ensemble mean HCVI for the baseline period (1981-2010; left panel) and the difference between the left hand map and the previously reported baseline HCVI values calculated from the WATCH data for the same period (Figure 1; right panel).**

There is a low spread in the HCVI values across the HELIX models themselves (see Appendix D, Figure D 1), as to be expected due to the bias-correction of the data to the common baseline (refer to Section 2.2.1). The reason for the small differences between the HadGEM3 baseline HCVI values and those presented previously derived from the WATCH data (Figure 3, right panel) is due to the difference in resolution between the datasets, the differences between the WATCH reanalysis data product and the Princeton Global Forcing V2 reanalysis product, and the differences found from the software rewrite (refer to Section 2.2.1).

#### 2.2.2.2 Vulnerability to food insecurity at 1.5, 2 and 4°C (HCVI)

Future projections of the HCVI at 1.5, 2 and 4°C were calculated using precipitation data from the specific years defined for each SWL for each model (Table 2) to assess the exposure component of the HCVI (see Appendix C for figures of the flood and drought indicators used to calculate the exposure components). The sensitivity and adaptive capacity components were kept at their present-day values.

The HCVI results driven by the climate at the SWLs indicate that vulnerability to food insecurity is projected to increase in almost all countries, with the magnitudes of the increases larger with higher levels of warming (Figure 4 - Figure 7). The pattern of vulnerability for all SWLs is similar to the pattern of the baseline period with the most vulnerable countries located in western Africa and the least vulnerable countries located in northern Eurasia. Consistent with previous findings (Richardson et al., 2017), the largest projected increases occur in the countries which currently experience the greatest vulnerability to food insecurity.

Results for each SWL are presented here for the HadGEM3 ensemble mean values, which are broadly representative of the ensemble spread despite each model passing the SWLs at different times in the future. Results from each individual ensemble member are also provided in Appendix D and an example of the ensemble spread is given in this section for SWL2.

#### a) Specific Warming Level 1.5 (SWL1.5)

The years in which the model simulations project the global mean temperature to increase to 1.5°C above pre-industrial levels are the early to mid-2020s (Table 2). The pattern of the model ensemble results for a 1.5°C warmer world is therefore quite similar to those for the baseline period (Figure 4 as compared to Figure 3). The magnitudes, however, are in general slightly higher than the baseline period, with the largest increases in South Asia. The smallest increases are seen across Central Africa, and a couple of countries may benefit slightly from the warmer climate, however these decreases are very small (<0.01, which is only marginally greater than the standard error on the SWL1.5 ensemble mean of 0.006 and therefore unlikely to be significant).

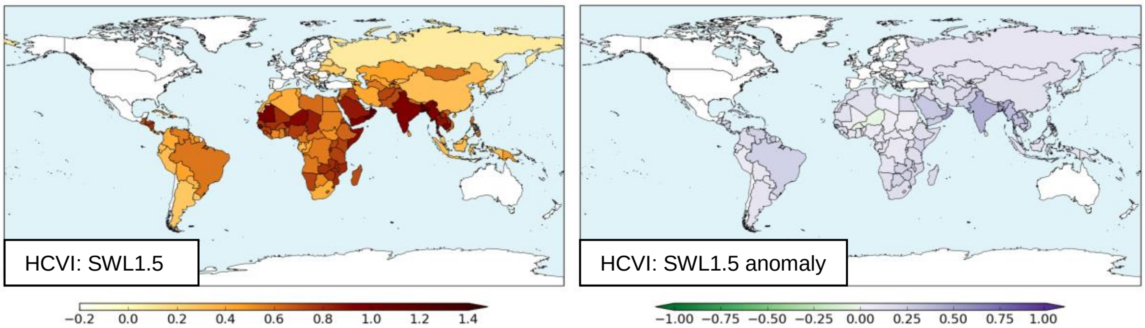


**Figure 4 - Maps of the HadGEM3 ensemble mean[5] HCVI SWL1.5 (left panel) and the anomaly from the baseline HCVI (as shown in Figure 3; right panel).**

[5] Note that only the four-member HadGEM3 ensemble was used for the SWL results as the GFDL-ESM2M driven HadGEM3 model did not reach an increase in global average temperature of 4°C above pre-industrial levels by 2100.

## b) Specific Warming Level 2 (SWL2)

The years in which the model simulations project the global mean temperature to increase to 2°C above pre-industrial levels are the early to mid-2030s (Table 2). At 2°C warmer than pre-industrial levels, vulnerability has generally increased, particularly in northern South America, Central America, West Africa and South Asia (Figure 5). Similarly to the SWL1.5 and future time slice results, a couple of countries in Central Africa are projected to experience modest improvements in their level of vulnerability to food insecurity as a result of the changing global climate, however, these decreases are small (between -0.007 and -0.04) and are similar to the size of the standard error on the SWL2 ensemble mean of 0.008 so may not be significant.

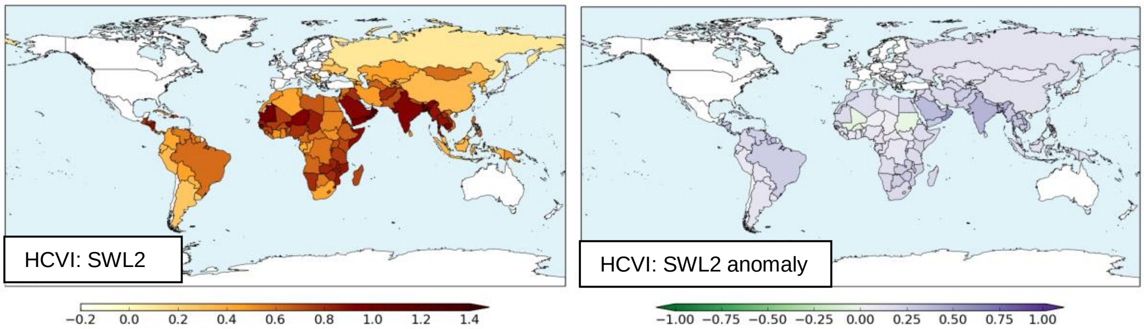


**Figure 5 - Maps of the HadGEM3 ensemble mean5 HCVI for SWL2 (left panel) and the anomaly from the baseline HCVI (as shown in Figure 3; right panel).**

The models each pass SWL2 at different times, however, the HCVI results are broadly similar for each model, with some small regional differences (Figure 6). For example, The MIROC-ESM-CHEM driven ensemble member passes SWL2 at the earliest time and shows larger increases in vulnerability in South Asia compared to other models.

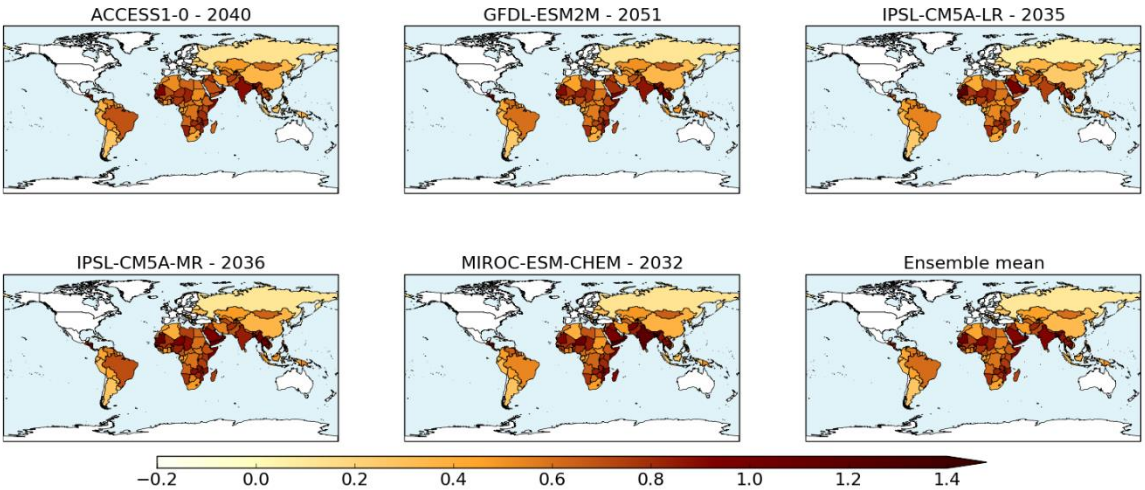


**Figure 6 - Maps of the HCVI for SWL2 for the individual ensemble members and the ensemble mean5 (bottom right panel). The central SWL year for each model is given in the panel title.**

## c) Specific Warming Level 4 (SWL4)

The years in which the model simulations project the global mean temperature to increase to 4°C above pre-industrial levels are the early to mid-2070s (Table 2). At 4°C warmer than pre-industrial levels, vulnerability has increased markedly relative to the baseline conditions, particularly across equatorial regions of Central and South America, Africa and South Asia (Figure 7). Some countries in Central Africa are projected to continue to experience modest improvements in their level of vulnerability to food insecurity as a result of the changing global climate, however, these decreases are small (<0.07) in relation to the size of the standard error on the SWL4 ensemble mean (0.02), so may not be significant.

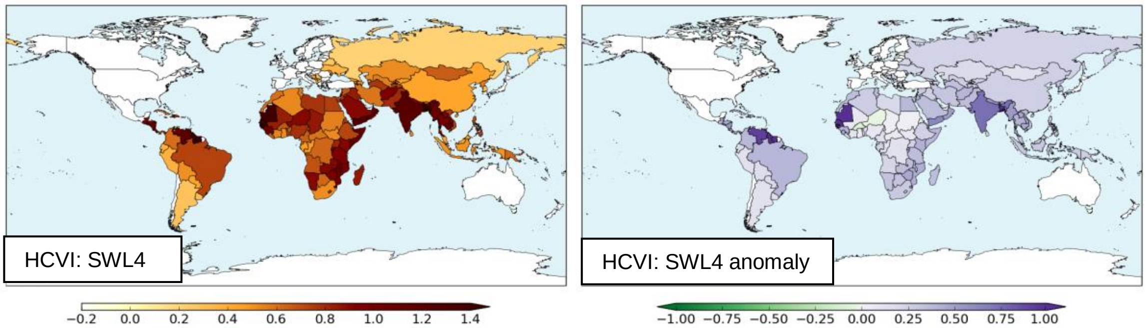


**Figure 7 - Maps of the HadGEM3 ensemble mean5 HCVI for SWL4 (left panel) and the anomaly from the baseline HCVI (as shown in Figure 3; right panel).**

### d) Projected population at risk of increased vulnerability

The HCVI results were converted into estimates of the potential number of people affected by climate change for each of the SWLs. This calculation was done using the average of 2010-2015 population data for each country from the World Bank (2016) dataset, and summing up the populations in the countries which see projected increases/decreases under the future projections of the HCVI. In addition, the populations are summed for any countries which exceed an HCVI value of 1 to indicate the number of people exposed to HCVI values that exceed that found in any country in the baseline climate. The HCVI values are based on assumptions made for the index itself, and are also model dependent. As a result, they provide only a rough guide to the scale and direction of change in vulnerability to food insecurity due to climate change.

Using this methodology, the model ensemble mean results equate to roughly 5.73 billion people (World Bank, 2016) potentially becoming more vulnerable to food insecurity in a 2°C warmer world and just 79 million people better off (Figure 8). In a 4°C warmer world, roughly 5.76 billion people are projected to become more vulnerable to food insecurity than they are in the baseline climate, with around 34 million projected to become less vulnerable. Of those countries projected to increase vulnerability to food insecurity levels at SWL2, three countries (equating to 189 million people) are projected to experience levels of vulnerability to food insecurity that exceed anything experienced in any country in the baseline climate. However, in a 4°C warmer world, the number of people who could be exposed to vulnerability to food insecurity levels unprecedented in the baseline climate increases 10-fold, to 1.8 billion people. There is quite a wide spread in the individual model ensemble member results for a 2°C warmer world (as shown in Figure 8), but there is a measure of broad consistency amongst the model ensemble members for a 4°C warmer world.

These numbers are likely to significantly overestimate the consequences of climate change on vulnerability to food insecurity since the assessment methodology adopted does not account for differing income levels within populations. Those most impacted in the future are likely to represent the poorest of society. Conversely, though, the assessment conducted here does not account for future population growth and this increase in demand could increase vulnerability to food insecurity levels further. Furthermore, no attempt has been made to remove potentially non-significant results from the analysis and so some of the changes in the HCVI values are small in relation to the standard error on the ensemble means. Nevertheless, these HCVI results highlight the need to assess adaptation options, which is considered in the next section.

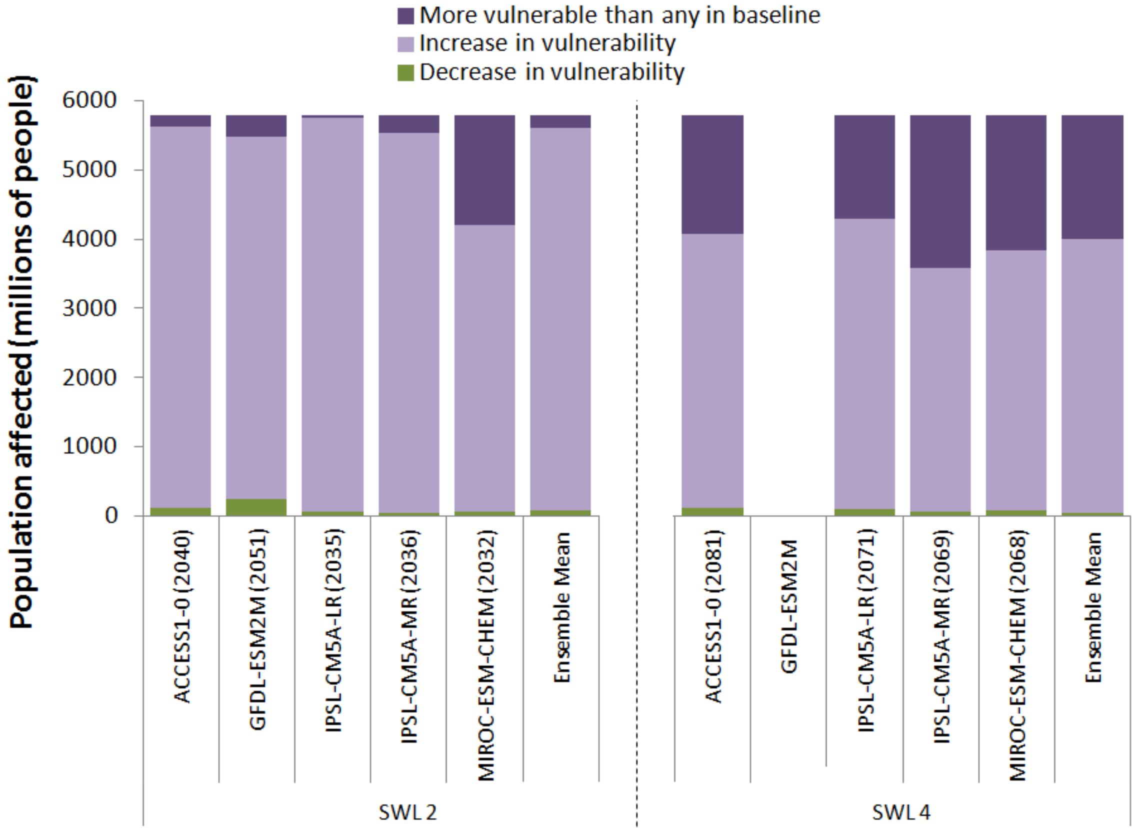


**Figure 8 - Change in vulnerability to food insecurity as compared to baseline conditions (1981-2010). Light purple bars show the number of people projected to reduce their levels of vulnerability to food insecurity as compared to the baseline climate, green bars show the number of people projected to reduce their levels of vulnerability as compared to their levels in the baseline climate, dark purple bars shows the number of people projected to experience levels of vulnerability that exceed that found in any country in the baseline climate. Results for each individual ensemble member come from the individual ensemble member specific warming level scenario compared to the individual ensemble member baseline. The central year for the given SWL for each model is given under each model label. Results for the ensemble mean come from the ensemble mean for each specific warming level scenario compared to the ensemble mean baseline but exclude the GFDL-ESM2M model in each case because it did not reach SWL4.**

### 2.2.2.3 Comparison with future projections from previous work

Future projections of the HCVI with the HadGEM3 ensemble for the 2050s and 2080s are presented in this section for comparison with results from the previous iteration with the lower resolution CMIP5 model ensemble (see Section 2.1 and Appendix A). These are calculated using precipitation data from fixed time periods for the 2050s (2041-20170) and 2080s (2071-2100) to assess the exposure component of the HCVI. As the HadGEM3 ensemble was only run for the highest greenhouse gas emissions scenario (RCP8.5), it was only possible to make comparisons with the RCP8.5 results from Richardson *et al.* (2017).

The 2050s and 2080s timeslice results also incorporate the adaptation scenarios used in Richardson *et al.* (2017) which change the sensitivity and adaptive capacity components of the HCVI results. This analysis enables us to understand how the new data impacts the messaging from Richardson *et al.* (2017).

### a) Response to climate change alone

Similarly to the SWL results, the HCVI results driven by the future climate in the 2050s and the 2080s indicate that vulnerability to food insecurity will increase compared to the present day in almost all countries (Figure 9 and Figure 10). Consistent with previous findings (Richardson et al., 2017), the largest projected increases occur in the countries which currently experience the greatest vulnerability to food insecurity. The largest increases in vulnerability to food insecurity by the 2050s are seen in South Asia. Larger increases are projected for the 2080s compared to the 2050s (compare Figure 10 with Figure 9), as expected since the highest greenhouse gas emissions pathway (RCP8.5) is used for these results which assumes no action is taken tackle the causes of climate change. The largest increases in vulnerability to food insecurity by the 2080s are seen in South Asia, northern South America and Central America (Figure 10). Although the baseline HCVI results showed a low spread between the ensemble members, the spread increases as the climate warms (see Appendix D).

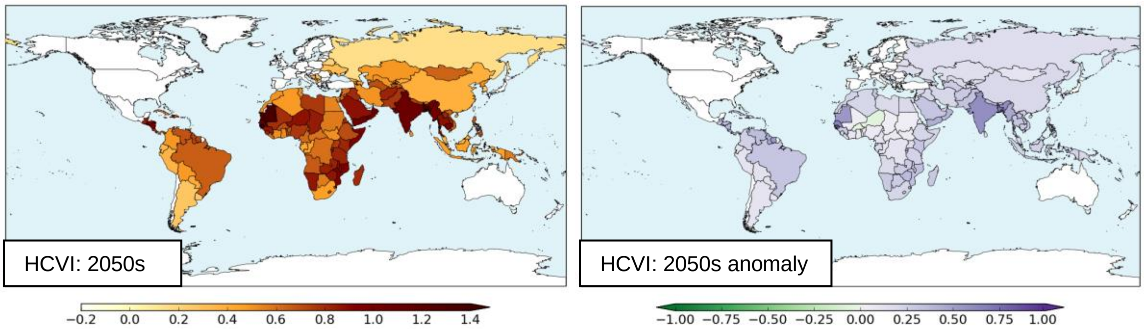


**Figure 9 - Maps of the HadGEM3 ensemble mean HCVI for the 2050s (left panel) and the anomaly from the baseline HCVI shown in Figure 3 (right panel).**

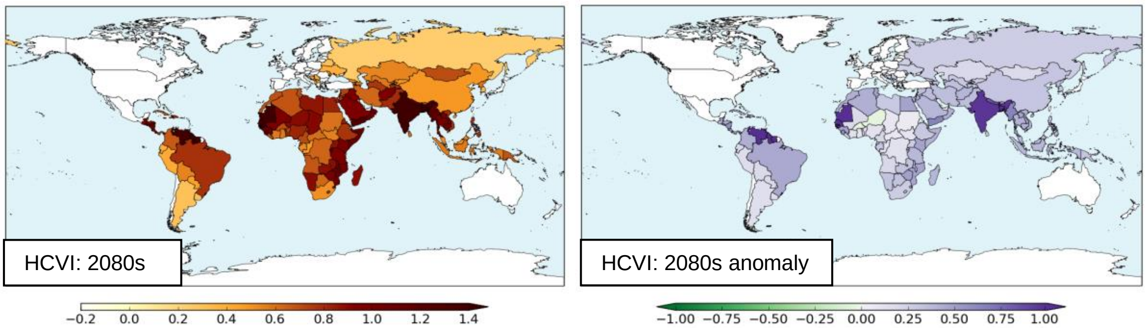


**Figure 10 - Maps of the HadGEM3 ensemble mean HCVI for the 2080s (left panel) and the anomaly from the baseline HCVI (as shown in Figure 3; right panel).**

In general, the HCVI values from the HadGEM3 ensemble are lower than the previous results projected by the CMIP5 ensemble (Richardson *et al.*, 2017; Figure 11). The HadGEM3 model is run at a much higher resolution than the CMIP5 models were and this reduction in grid cell size leads to an improved representation of small-scale processes such as precipitation. The impact of this has been to reduce the average length of floods and droughts. In addition to the model resolution, there are many other potential reasons for the differences between the HCVI values from these two ensembles. The CMIP5 ensemble consisted of 12 members as compared to only five with the HadGEM3 ensemble, and only two of the models are common to both ensembles (namely IPSL-CM5A-MR and GFDL-ESM2M). Furthermore, the HadGEM3 ensemble consists of just one atmosphere-only model for all of the ensemble members as compared to the 12 fully coupled and independent models in the CMIP5 ensemble. An atmosphere-only model is unable to fully capture ocean feedbacks to the climate system, which could affect climate variability.

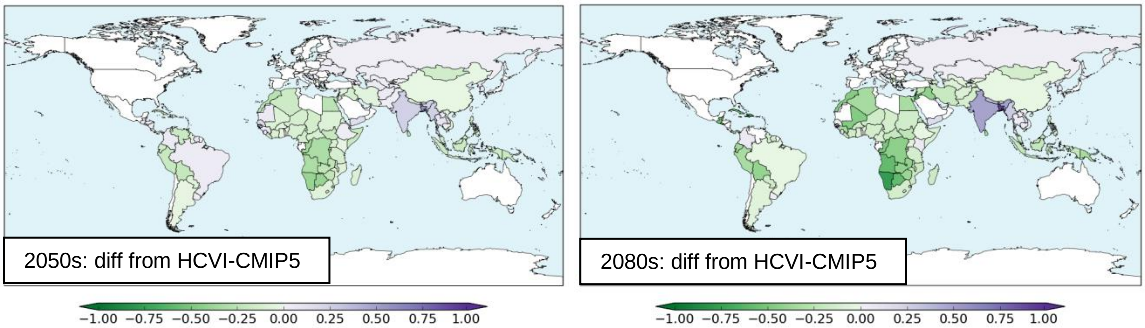


**Figure 11 – Maps of the difference between the HadGEM3 ensemble mean HCVI and the CMIP5 ensemble mean HCVI for the 2050s (left panel) and 2080s (right panel)).**

### b) Response to climate change with adaptation

To understand the impact of investment in adaptation on the HCVI results, the high adaptation scenario from Richardson *et al.* (2017) was applied to the 2050s and 2080s results from the HadGEM3 ensemble of results, as shown in above. The message from the Richardson *et al.* (2017) stated that the highest level of adaptation considered did not offset the increases in vulnerability as a result of climate change in the majority of countries, and that both adaptation and mitigation are required to avoid the worst impacts of climate change on food security.

By applying the high adaptation scenario from Richardson *et al.* (2017) to the HCVI HadGEM3 results for the 2050s, around 80% of the countries included in the HCVI are projected to still see increases in their vulnerability to food insecurity as compared to current conditions (Figure 12). For the 2080s, the application of the high adaptation scenario results in around 75% of the countries continuing to see increases in vulnerability compared to current conditions (Figure 13). The countries which do see a reduction in vulnerability compared to the present-day (around 20% in the 2050s and 25% in the 2080s) are located in Central Africa, southern South America and Central Asia.

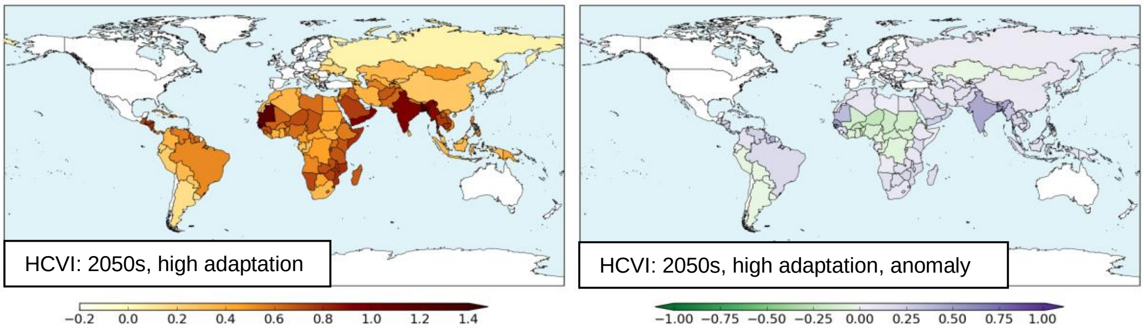


**Figure 12 - Maps of the HadGEM3 ensemble mean HCVI for the 2050s under the 'high adaptation' scenario (left panel) and the anomaly from the baseline HCVI (as shown in Figure 3; right panel).**

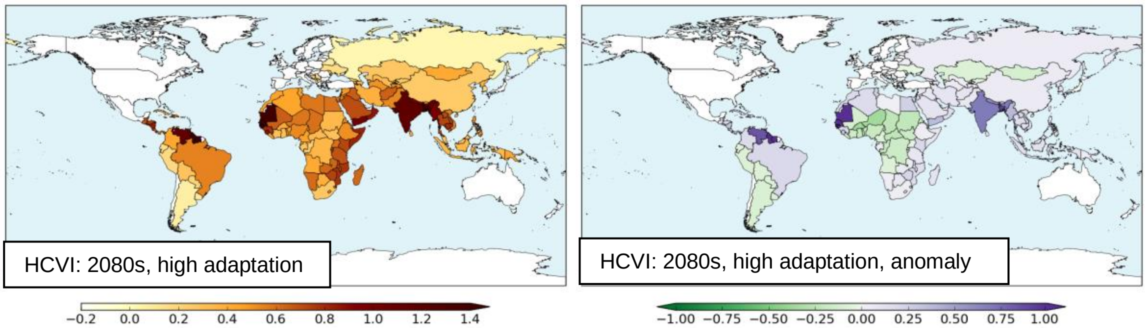


**Figure 13 - Maps of the HadGEM3 ensemble mean HCVI for the 2080s under the 'high adaptation' scenario (left panel) and the anomaly from the baseline HCVI (as shown in Figure 3; right panel).**

This means that the highest level of adaptation considered does not offset the impacts of climate change on vulnerability to food insecurity in the majority of countries. This result is consistent with the messaging from Richardson *et al.* (2017). However the proportion of countries projected to see reductions in vulnerability when adaptation is considered is larger here than compared to the results in Richardson *et al.* (2017). This is because the adaptation scenario applied is an empirical function designed to reduce sensitivity and improve adaptive capacity by a scaled amount which is dependent on the baseline values of these components. The adaptation scenarios are independent of the climate change projections (which only impact the exposure component of the HCVI), and therefore the results of applying the adaptation scenarios are indicative of improvements in the sensitivity and adaptive capacity components of the HCVI only. Since the HadGEM3 HCVI results show lower values of the HCVI on the whole compared to the results using the WATCH data and CMIP5 ensemble from Richardson *et al.* (2017; see Figure 3, right panel), and the application of the adaptation scenarios also results in slightly lower HCVI values on the whole, this results in more countries shifting from an increase to a decrease in vulnerability. This highlights the dependence of the results on the climate models and the resolution of the models used for the future projections as a result of climate, and the weaknesses of using an empirical function for the adaptation scenarios.

## 2.3 Adapting the HCVI to account for food imports

The HCVI methodology presented above is designed to only consider in-country production of food via the inclusion of the national cereal crop yield indicator and consideration of national level climate hazards. However, the food supply in many countries also includes imported food and, in some countries, food imports dominate the food supply as shown in Figure 14. This makes those countries vulnerable to the impacts of climate hazards in the regions where the imported food is produced, and the knock-on effects this has on agricultural trade and commodity prices (Bren d'Amour *et al.*, 2016; Puma *et al.*, 2015).

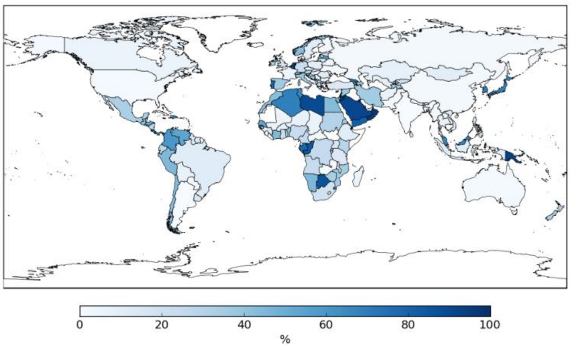


**Figure 14 - Cereal imports as a proportion of total cereal availability (imports + production – exports) per country for period 2010-2013. Data from FAOSTAT (2016), more detail on calculation given in Section 2.3.2.**

This section of the report presents findings from an initial approach to account for food imports in the HCVI. The method and data used are described in Sections 2.3.1 and 2.3.2 respectively, and results shown and discussed in Section 2.3.3. It should be noted that this is not intended to be a complete description of trade dynamics related to food security, but rather a broad tool for exploring the influence of trade based on our understanding of the key factors. The research undertaken to develop this methodology highlighted the complexity of this problem and therefore identification of further developments of the method that are out of scope of this study are described briefly in the text as suggestions of future research. We acknowledge Oscar Caccavale from the Vulnerability Assessment and Mapping unit of the WFP for helpful comments on this methodology.

### 2.3.1 Methodology for adapting the HCVI to account for food imports

The method used to adapt the HCVI to account for food imports is based on a simple conceptual model of how both local production and imported food contribute to national level food security (presented in Figure 15) and how weather and climate impact these elements. Consistent with the assumptions made in the HCVI[6], only cereal production is considered here as cereals account for around 60% of global calories consumed[7] and there is a clear relationship between cereal production and climate variability (Pope & Kent, 2017). Also in line with the HCVI assumptions, the same limitations apply such that any adaptations to the HCVI or new data incorporated must be globally consistent. Therefore, although it is recognised that local stocks and stock-to-use ratios also contribute to national level food security, these are not considered in this approach due to the differing policies on food stocks around the world.

[6] The approach used across the HCVI analysis is to understand the impact of climate change on the global food system as whole. We therefore attempt to describe the important parts of the system in order to understand the big picture.

[7] http://www.fao.org/docrep/u8480e/u8480e07.htm

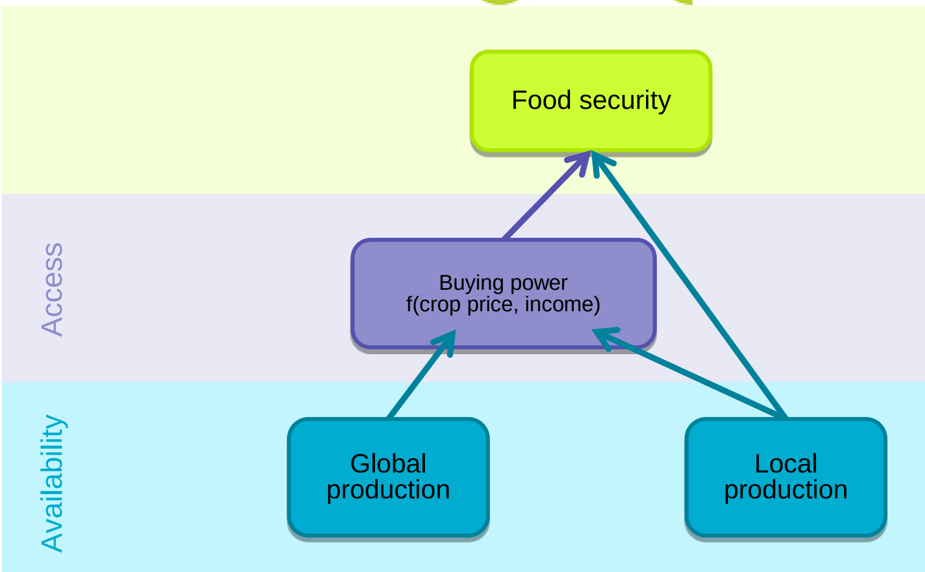


**Figure 15 – A simple model of how local and global food production contribute to national-level food security.**

The model assumes that national level food security is a function of local production of cereals (i.e. the availability component of food security analysis) and the ability to purchase cereals, namely buying power (i.e. the access component of food security analysis). Buying power is defined here to be a measure of affordability and is assumed to be a function of the crop import price and income. Due to the global-scale of the HCVI, it is further assumed that the buying power is represented at the national scale and therefore the crop price is that paid on import from the global market[8] (in order to account for the majority of global trade transactions[9]). The income component at the national level is represented by the wealth of the country (namely GDP per capita), which has a component related to local production in the form of the proportion of the GDP that comes from agriculture. In addition,

Global weather and climate directly impact the availability of food globally, for example climate variability accounts for around 60-90% of year-to-year cereal yield variations (Pope & Kent, 2017; Ray et al, 2015). This in turn impacts the global commodity price and subsequently national food security; poorer countries where people spend a large proportion of their income on food and are less able to cope with fluctuations in crop prices compared to wealthier nations (Kalkuhl *et al.*, 2016)8. However, global crop prices are driven not only by total availability, but a number of other factors, including global stocks, conflict, oil prices and exchange rates. Understanding the impacts of climate on the global commodity market is therefore not straightforward. However, this study aims to look at the impacts of climate change on vulnerability to food insecurity rather than other technological or socioeconomic factors. For this reason, changes other than climate change are excluded.

[8] It is noted that international prices transmit to domestic markets very differently depending on the country and the commodity, however given the need to consistent measures globally and the approach to capture the big picture, only the import price is accounted for at this stage6.

[9] Assessments were made of the import data and partner countries and the majority of imports were found to be imported from the countries which export around 90% of the world's supply, for each of the crops considered (wheat, maize, rice, barley, millet and sorghum; UN Comtrade, 2016). It is therefore assumed in this study that imported cereals come from the global commodity market, however it is recognized that not all regional trade relationships are captured.

Local weather and climate both directly and indirectly impact national level food security. Weather and climate impacts on local production can directly affect in-country food production and, therefore, national level food security (Bren d'Amour *et al.*, 2016; Puma *et al.*, 2014). A second indirect impact is felt via loss of income as a result of adverse weather leading to poor harvests, particularly in countries where a significant proportion of the GDP comes from agriculture and where livelihoods are agriculture dependent. **Formula for trade-weighted index**

Based on the model and assumptions described above, the trade-weighted index is designed to measure the average vulnerability resulting from in-country production and import affordability, i.e.

$$\boldsymbol{VFI = f_{prod}V_{prod} + f_{imp}V_{imp}}$$

**Eq. 1 – Formula for trade-weighted index**

where:

$f_{prod}$ is the ratio of nationally produced cereals to total cereals available nationally (imports + production – exports, see Section 2.3.2 for more detail)

$V_{prod}$ is the vulnerability to food insecurity associated with local production

$f_{imp}$ is the ratio of imported cereals to total cereals available nationally

$V_{imp}$ is the vulnerability to food insecurity associated with imports

The vulnerability to food insecurity associated with local production, $V_{prod}$, can be represented directly by the HCVI.

Following the conceptual model above, the vulnerability associated with imports is a measure of ability to afford food bought from the international market, which has both climate and non-climate elements of vulnerability. The climate element can be represented by the proportion of GDP from agriculture, which accounts for the amplified effect of climate impacts on local production also impacting livelihoods, income and ability to afford food.

The other element of affordability is the crop price. Global commodity prices are clearly influenced by the climate, along with other non-climate factors, as mentioned above. Given the complexities of understanding the impacts of climate on global commodity prices now, and the difficulties in understanding how these might change in the future, in the first instance we assume the crop price remains constant for all countries. Variability in the global commodity price and the relationship between this, climate and global production will be the subject of future work. One way of accounting for the ability import food is to rank the countries by their GDP per capita, which represents relative national wealth.

Bringing all these elements together into the above equation, the measure of vulnerability to food insecurity per country is:

$$\boldsymbol{VFI = GDP_{norm}(X + Y)}$$

where:

$$X = f_{prod}V_{prod}$$

and

$$Y = f_{imp}\left(f_{ag}V_{imp,clim} + f_{non-ag}V_{imp,non-clim}\right)$$

where:

$GDP_{norm}$ is the normalised GDP per capita to represent relative wealth – note that normalisation process is such that poorer countries have high $GDP_{norm}$ and richer countries have high $GDP_{norm}$

$f_{ag}$ is the fraction of GDP that comes from agriculture

$V_{imp,clim}$ is the climate vulnerability associated with imports, namely the exposure and sensitivity components of the HCVI
$f_{non-ag}$ is the non-agriculture fraction of GDP
$V_{imp,clim}$ is the non-climate vulnerability associated with imports, namely the adaptive capacity component of the HCVI

For each country, this equation represents the vulnerability to food insecurity as a result of both local production and ability to buy imported food, appropriately weighted by the ratio of the dependence on production to imports respectively. The ability to buy food includes the additional feedback of climate impacts on livelihoods and income by accounting for the proportion of GDP that comes from agriculture, and the whole equation is weighted by a measure of relative wealth.

The formula for the trade-weighted index, using the components of the HCVI, is:

$$\boldsymbol{VFI = GDP_{norm}\left(f_{prod}HCVI + f_{imp}\left(f_{ag}(E+S) + f_{non-ag}(AC)\right)\right)}$$

**Eq. 2 – Formula applied to calculate the trade-weighted index**

where $E$, $S$ and $AC$ are the exposure, sensitivity and adaptive capacity components of the HCVI respectively.

### 2.3.2 Data

The trade-weighted index described above is designed to make use of the existing HCVI values and the individual components that make up the HCVI, i.e. the exposure, sensitivity and adaptive capacity components. This means that these four variables in Eq. 2 are similar to those presented in Section 2.2. Note, however, that since market access is now accounted for in the trade-weighted index, OECD and EU countries are no longer excluded from the HCVI calculation. Results of this new HCVI for the set of countries for the trade-weighted index (referred to as HCVIT) are shown in Section 2.3.3.

New socio-economic datasets were used to calculate the remaining variables in Eq. 2, the datasets and years used to compute these variables are listed in Table 1. Note that a sum of the six main cereals (wheat, maize, rice, barley, millet and sorghum) was used as a proxy for all cereals in the calculation of $f_{imp}$and $f_{prod}$.

**Table 3 – Datasets and their sources used to construct the new variables in the trade-weighted index**

| Variable in trade-weighted index | Dataset | Data source | Years used |
|---|---|---|---|
| Normalised GDP per capita ($GDP_{norm}$) | GDP | World Bank (2016) | 2010-2015 |
| | Population | World Bank (2016) | 2010-2015 |
| Agricultural ($f_{ag}$) and non-agricultural ($f_{non-ag}$) fractions of GDP | Agriculture, value added (% of GDP) | World Bank (2016) | 2010-2015 |
| Ratios of imported cereals ($f_{imp}$) and local production ($f_{prod}$) to total cereals available nationally | Import quantity | FAOSTAT (2016) | 2010-2013 |
| | Export quantity | FAOSTAT (2016) | 2010-2013 |
| | Production quantity | FAOSTAT (2016) | 2010-2013 |

As the socio-economic data used in the HCVI was representative of 2010 (as in Krishnamurthy et al., 2014), averages of these new variables from 2010 to the latest year available were used. A number of exceptions were made where no data was available for the period of years considered in this calculation. For these cases an average of the five-years of data ending in the latest year reported was used. These countries and the latest available year of reported data are listed in 4.

**Table 4 – Countries with exceptions applied and reasons for exceptions for the trade-weighted index**

| Reason for exception | Countries and last available year of data in brackets |
|---|---|
| No GDP or GDP from agriculture data reported for 2010-2015 | Syria (2007) |
| No GDP from agriculture data reported for 2010-2015 | Angola (2001), Djibouti (2007), Eritrea (2009), French Polynesia (2000), Libya (2008), Myanmar (2004), Papua New Guinea (2004), Syria (2007) and Yemen (2006). |

Countries with no reported data at all in any of the datasets were excluded from the whole trade-weighted index calculation. Note that only the years 2010-2013 were used for the import, export and production data and therefore any countries that did not report data in any of these datasets during this period were also excluded. The full list of countries excluded and reasons for exclusion are shown in Table 5.

**Table 5 – Countries excluded and reasons for exclusion from the trade-weighted index.**

| Reason for exclusion | Countries excluded |
|---|---|
| No GDP data reported | North Korea |
| No GDP from agriculture data reported | Equatorial Guinea, Haiti, Iraq, Israel, North Korea, Liberia, Samoa, South Sudan, Tonga and United Arab Emirates, |
| No export data reported for 2010-2013 | Cuba, Mauritania, Sierra Leone, Turkmenistan, Lesotho, Puerto Rico, Somalia, South Sudan and Timor-Leste |
| No import data reported for 2010-2013 | Puerto Rico and South Sudan |
| No production data reported for 2010-2013 | Bahrain, Equatorial Guinea, Iceland, Saint Lucia and Singapore |

Maps of the new variables in the trade-weighted index as calculated with the data listed above are shown in Figure 16. The ratio of locally produced cereals to total available cereals nationally ($f_{prod}$) is high in most countries and low in counties across the Middle East and North Africa (MENA) region, parts of southern Africa, northern South America and Central America (Figure 16, top left panel). This is the opposite pattern to $f_{imp}$, by definition, which is not mapped here as it has the same pattern as Figure 14.

The normalised GDP per capita variable, $GDP_{norm}$, is very high in the majority of countries that were included in the original HCVI, i.e. developing and least developed countries, and relatively low across the developed OECD and EU countries. This measure of wealth is therefore not independent of the HCVI values themselves, or the measure of adaptive capacity (Figure 17, top panels). These data show there is a clear divide between wealthy and poor countries; however it is very hard to distinguish between the poor countries.

The agricultural ($f_{ag}$) and non-agricultural ($f_{non-ag}$) fractions of GDP also have opposite patterns, by definition (Figure 16, bottom panels). $f_{ag}$is highest across central Africa, and therefore again there is a non-linear relationship between $f_{non-ag}$ and $GDP_{norm}$ where the countries with the smallest (highest) proportion of GDP from agriculture are the poorest (wealthiest). The relationship between $f_{non-ag}$ and adaptive capacity, however, is not so clear (Figure 17, bottom right panels).

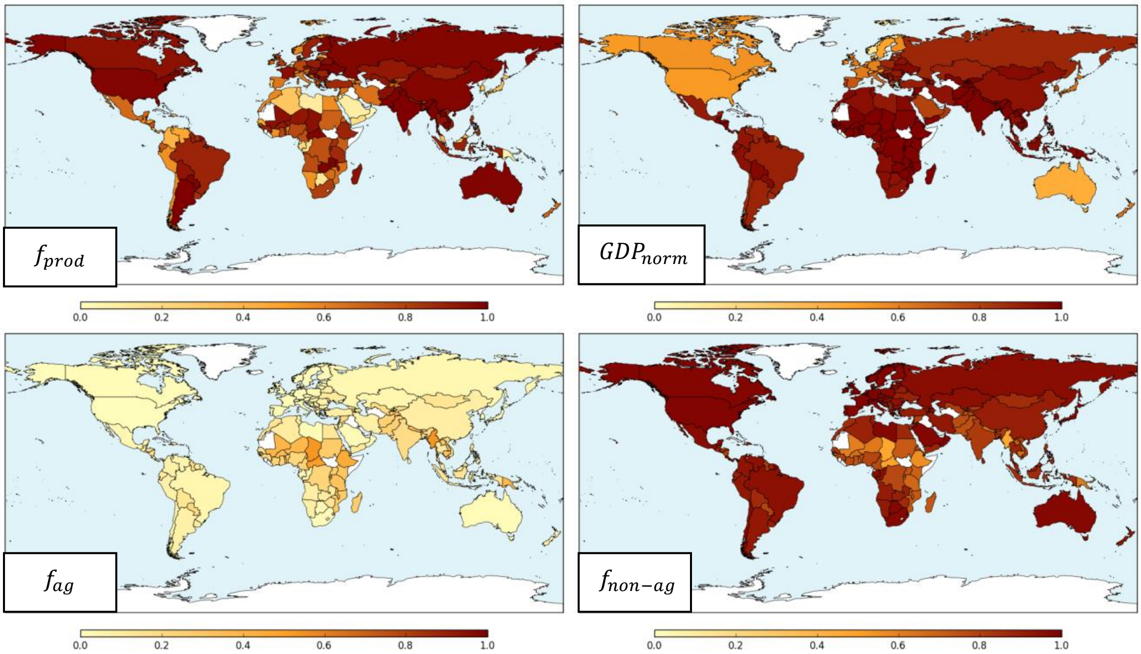


**Figure 16 – Maps of $f_{prod}$ (top left panel), $GDP_{norm}$ (top right panel), $f_{ag}$ (bottom left panel) and $f_{non-ag}$ (bottom right panel).**

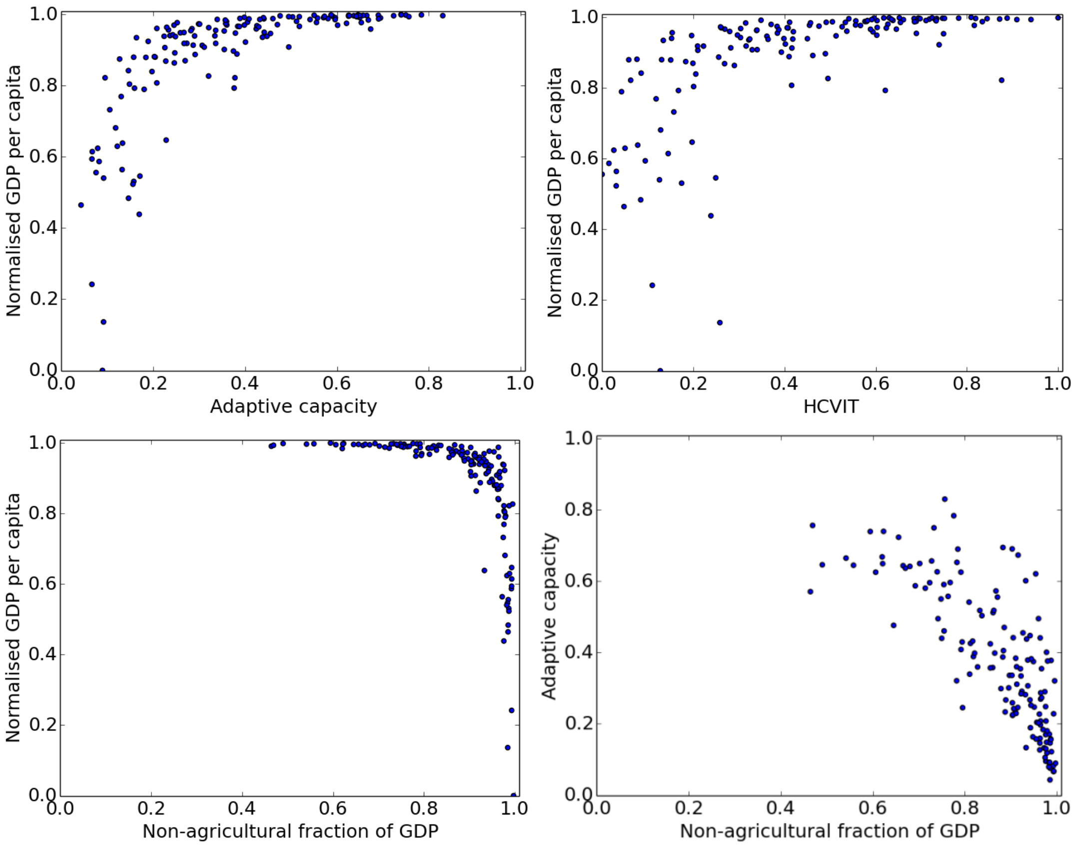


**Figure 17 - Scatter plots showing relationship between various components of trade-weighted index (for HadGEM3 driven by ACCESS1-0 as an illustration of the ensemble)**

### 2.3.3 Results and discussion

Results from the trade-weighted index are presented in this section. Firstly, a summary of results from the HCVIT is presented in Section 2.3.3.1. The HCVIT is the intermediary step to applying the trade-weighted index formula (Eq. 2) where the HCVI is calculated for a different set of countries; the country list now includes the OECD and EU countries and excludes countries with missing data from the new datasets (see Section 2.3.2).

Secondly, results from applying the trade-weighting to the HCVIT output are then presented in Section 2.3.3.2 for the baseline (see also Appendix E), Section 2.3.3.3 for the SWLs and Section 2.3.3.4 for the 2050s and 2080s to compare with results from Richardson *et al*. (2017). Adaptation scenarios were not applied to the trade-weighted index since a method for applying these scenarios to the newly included socio-economic datasets has not been developed. Similarly to Section 2.2, all results presented are for the HadGEM3 ensemble mean (five members for the future time slices and four for the SWL results5). Results from each individual ensemble member are provided in Appendix F.

#### 2.3.3.1 HCVIT

Results from the HadGEM3 ensemble mean HCVIT for the baseline and all future scenarios considered are presented in Figure 18.

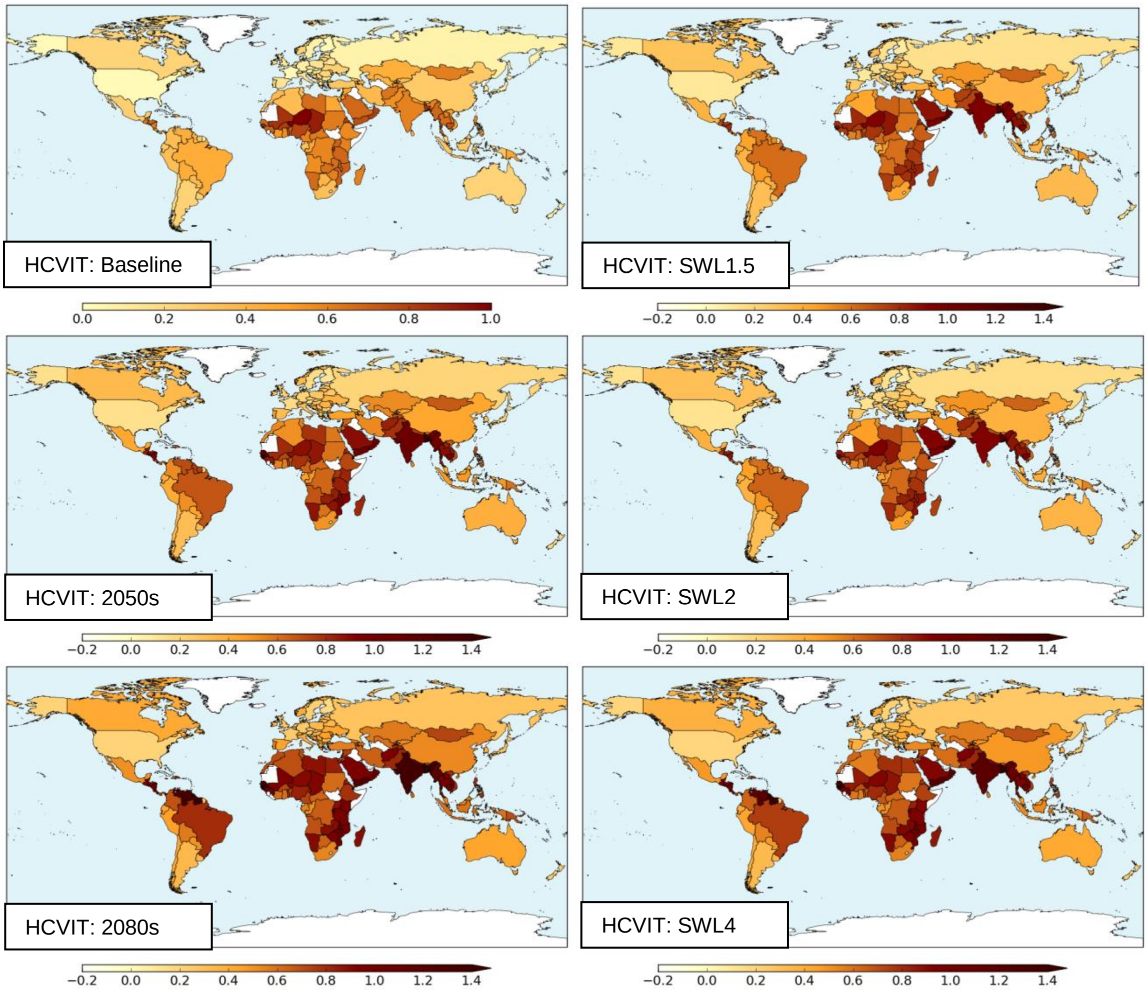


**Figure 18 – Maps of the HCVIT: the HCVI computed with the set of countries required to be included/excluded for the trade-weighted HCVIT. The HadGEM3 ensemble mean is shown for the baseline (top left panel), the 2050s and 2080s (middle and bottom left panels), and the SWLs 1.5, 2 and 4 (right panels)[5].**

The pattern of vulnerability is broadly similar to that in the HCVI (as presented in Section 2.2.2) for each of the baseline and future projection results. The inclusion of the OECD and EU countries does not impact the overall relative pattern of vulnerability as the vulnerability scores for these countries are relatively low due to the relatively higher adaptive capacity scores for these developed countries.

#### 2.3.3.2 Baseline trade-weighted HCVIT (TW-HCVIT)

The trade-weighted index (hereafter referred to as the TW-HCVIT) is calculated by weighting the HCVIT values from Section 2.3.3.1 with the new socio-economic variables described in Section 2.3.2, as presented in Eq. 2 (Figure 19). The application of the trade-weighting does not result in large differences compared to the HCVIT (Figure 19, top right panel). The overall pattern of vulnerability is similar, and the largest differences are seen in across the MENA (Middle East and North Africa) region where the trade-weighting acts to reduce the vulnerability. In 95% of the countries these differences are greater than the standard error on the ensemble mean for the baseline period and so, although small, the changes are potentially significant.

The fact that there is little change once the trade-weighting is applied is not surprising. The vulnerability associated with imports ($V_{imp}$), i.e. the right hand term in Eq. 2, turns out to have a very similar pattern to the vulnerability associated with local production ($V_{prod}$), namely the HCVIT (Figure 19, bottom panels). It is therefore the ratios of local production and imports ($f_{prod}$ and $f_{imp}$) that weight these components of the TW-HCVIT which dominate the differences between this and the HCVIT. The weighted vulnerabilities are further weighted by the normalised GDP per capita (Figure 16, top right panel), which is near 1 for most developing and least developed countries, and lower for developed countries; given further evidence for why the TW-HCVIT has a similar pattern to the HCVIT.

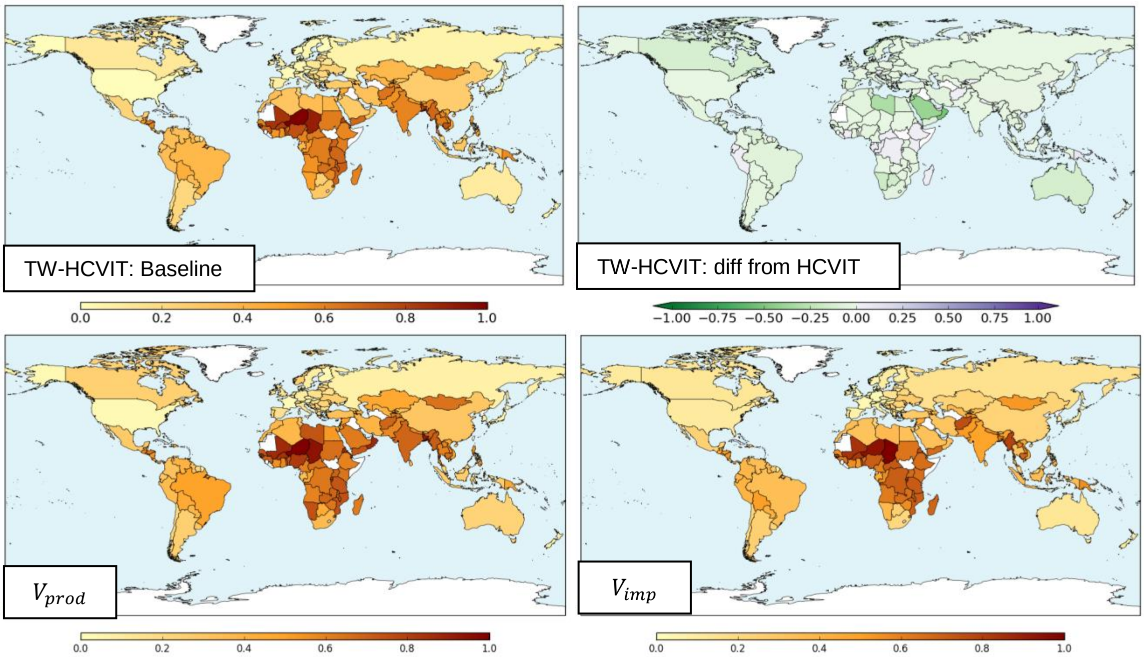


**Figure 19 – Maps of the HadGEM3 ensemble mean trade-weighted HCVIT (TW–HCVIT) for the baseline period (1981-2010; top left panel) and the difference between the left hand plot and the HCVIT ensemble mean (top right panel). Maps of the vulnerability to food insecurity associated with local production, $V_{prod}$ and imports, $V_{imp}$, (as expressed in Eq. 1) are shown in the bottom panels. The model used for these maps is HadGEM3 driven by ACCESS1-0 sea surface temperatures member as an illustration of the full ensemble.**

Given that the highest values of $f_{imp}$ are located across the MENA region (Figure 14), and $V_{imp}$ is comparatively lower in this region (compare bottom panels of Figure 19), this explains the lower vulnerability in the TW-HCVIT here (Figure 19, top left panel). This updated vulnerability measure that now accounts for food imports results in a more accurate representation of vulnerability to food insecurity in these countries where there is a high dependence on imports. However, the index only weights the in-country vulnerability measure based on the proportion of imported cereals under the assumption that cereals are imported from the global market. The index does not currently account for the climate vulnerability of the production of the cereals available on the global market, or other factors that impact imports such as oil prices and trade policies.

The decomposition of vulnerability associated with imported food into the fractions of GDP from agricultural and non-agricultural sources in the TW-HCVIT formula (Eq. 2) is designed to capture the effects of climate vulnerable livelihoods on national level vulnerability to food insecurity, and the ability to import. Namely, in countries where the fraction of GDP from agriculture ($f_{ag}$) is high, then the impacts of climate change not only affect local production, but also national GDP. In practice, however, this nonlinearity built into the trade-weighting does not impact the TW-HCVIT results since the countries with high $f_{ag}$ are also the countries which depend mostly on local production (i.e. high $f_{imp}$), resulting in the right-hand term in Eq. 2 being negligible.

#### 2.3.3.3 Vulnerability to food insecurity at 1.5, 2 and 4°C (TW-HCVIT)

The TW-HCVIT calculated with the HadGEM3 HCVIT values for the SWLs (Figure 18; right panels) show projected increases in vulnerability compared to the present-day as a result of the changing climate, with the vulnerability projected to increase progressively through the SWLs (Figure 20). The patterns of vulnerability and projected increases are consistant with the HCVI projections in Section 2.2 and Richardson *et al.* (2017), where the most vulnerable countries in the present-day are also the most vulnerable in the future, i.e. West Africa and South Asia. The largest increases are projected across South Asia and parts of northern South America and West Africa. In 99% of the countries, the difference in the HCVIT values in the SWLs as compared to the baseline are greater than the standard error in the calculation of the ensemble mean and are therefore likely to be significant.

These increases in vulnerability, however, are not as large as those projected for the HCVI without the trade-weighting (compare bottom right panel of Figure 20 with right panel of Figure 10) as a result of the reduced vulnerability in these regions due to the trade-weighting. In addition, Mauritania had one of the largest projected increases in vulnerability in the HCVI, but is not included in the TW-HCVIT due to lack of export data.

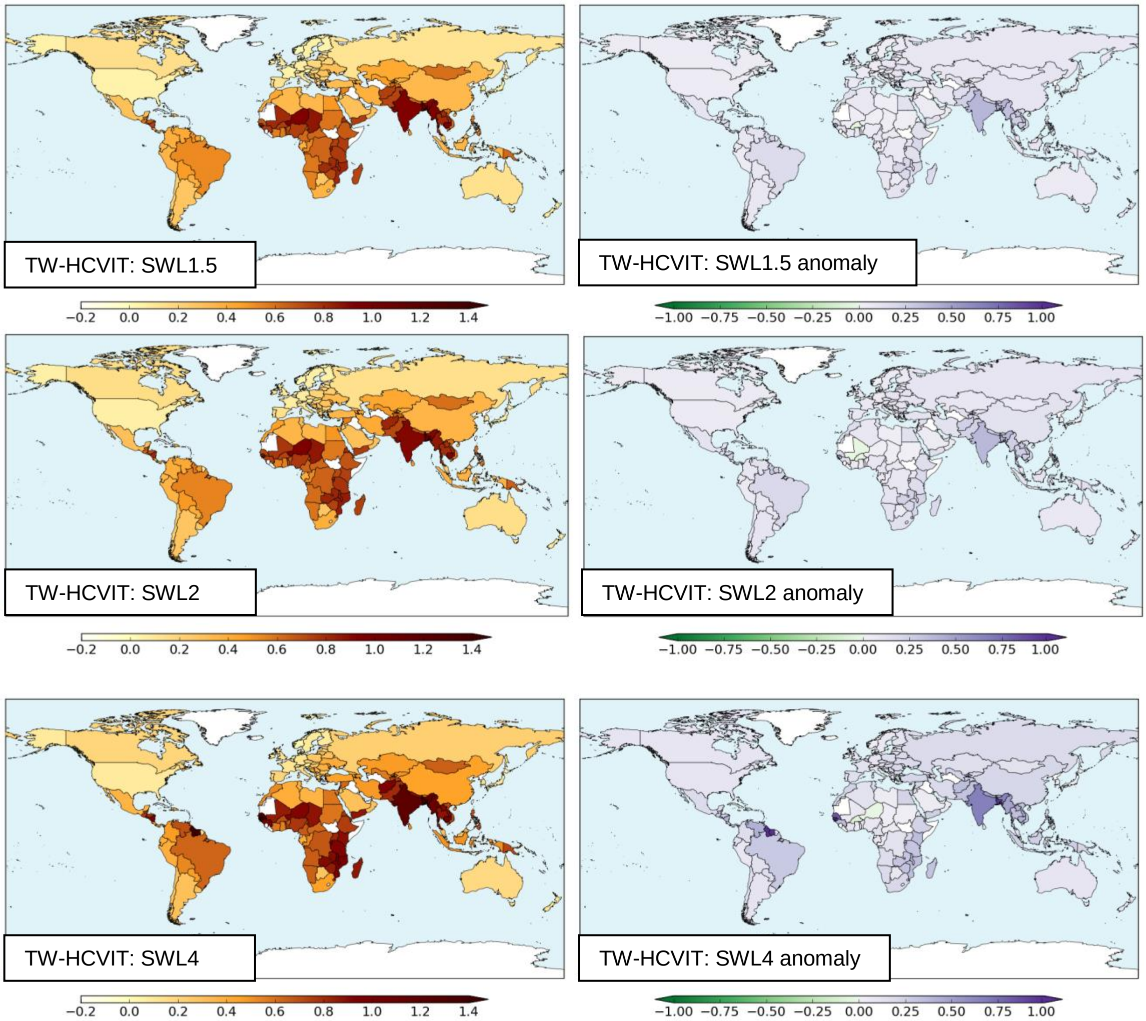


**Figure 20 – Maps of the HadGEM3 ensemble mean5 trade-weighted HCVIT (TW-HCVIT) (left panels) and the anomaly from the baseline TW-HCVIT (as shown in Figure 19; right panels) for SWL1.5 (top panels), SWL2 (middle panels) and SWL4 (bottom panels)**

#### 2.3.3.4 Vulnerability to food insecurity in the 2050s and 2080s (TW-HCVIT)

The TW-HCVIT calculated with the HadGEM3 HCVIT values for the 2050s and 2080s (Figure 18; middle and bottom left panels) show projected increases in vulnerability compared to the present-day as a result of the changing climate, with larger increases projected by the 2080s (Figure 21). The magnitudes of the increases are slightly larger in the 2050s compared to SWL2 and similarly for the 2080s compared to SWL4 (Figure 20; Figure 21). Also consistent with the TW-HCVI results at the SWLs (Section 2.3.3.3), the regions projected to see the largest increases in vulnerability without consideration of trade impacts result in slightly smaller increases once the trade-weighting is applied. Similarly, the largest increases are projected across South Asia and parts of northern South America and West Africa. In 99% of the countries, the difference in the HCVIT values in the 2050s as compared to the baseline are greater than the standard error in the calculation of the ensemble mean and are therefore likely to be significant. For the 2080s, this value drops to 97% of the countries potentially showing significant changes as compared to the baseline.

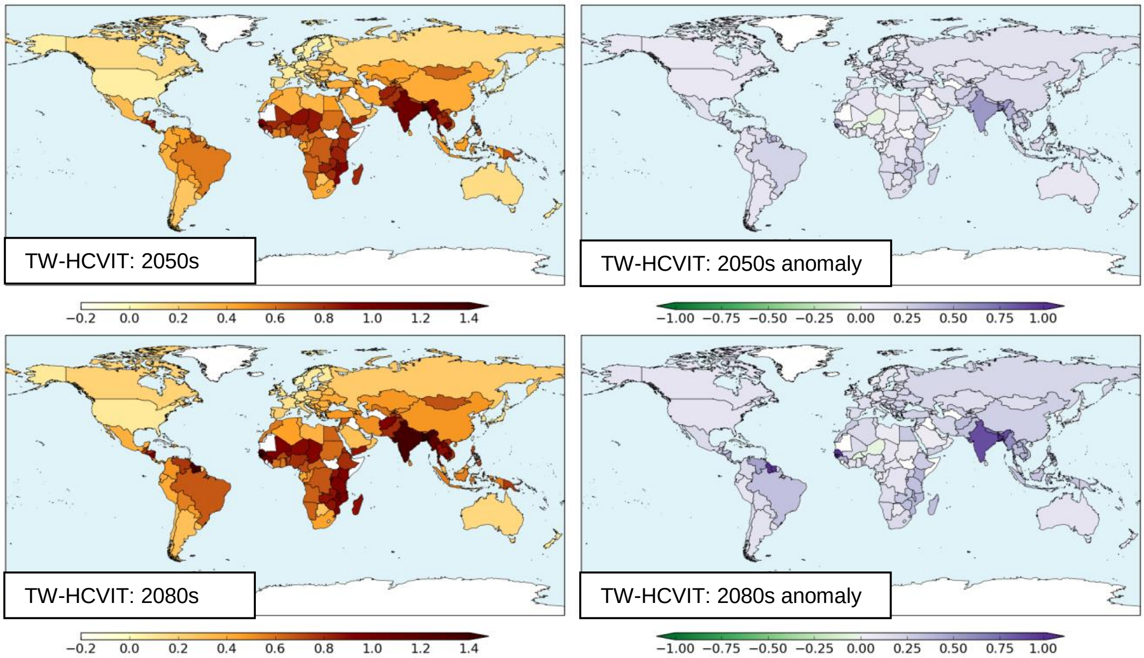


**Figure 21 – Maps of the HadGEM3 ensemble mean trade-weighted HCVIT (TW-HCVIT) (left panels) and the anomaly from the baseline TW-HCVIT (Figure 19; right panels) for the 2050s (top panels) and 2080s (bottom panels).**

## 2.4 Summary

As part of the global socio-economic impacts work package of the HELIX project, the Hunger and Climate Vulnerability Index (HCVI; Krishnamurthy et al., 2014), as adapted to incorporate future climate and adaptation scenarios (Richardson et al., 2017), has been used to assess the impacts of climate change on national-level food security. First the HCVI as presented in Richardson *et al.*, (2017) was re-assessed using the ensemble of high resolution HadGEM3 climate model simulations for RCP8.5, produced as part of HELIX WP3 (HELIX D3.1, 2017. Secondly the methodology was updated to account for food imports. In both cases, future projections of the impacts on vulnerability to food insecurity were analysed at Specific Warming Levels (SWLs; 1.5, 2 and 4°C) and at future time slices (the 2050s and 2080s).

General patterns of the impacts of climate change on vulnerability to food insecurity are similar to previous results driven by a lower resolution ensemble from the CMIP5 climate models (Richardson et al., 2017). In the baseline climate, the highest levels of vulnerability to food insecurity are found in West Africa. As the climate changes, vulnerability to food insecurity is projected to increase progressively in most countries as the different SWLs are reached (or by the 2050s, and further still by the 2080s), in the absence of adaptation. South Asia is most negatively impacted first by the changing climate (e.g. SWL2 or the 2050s) and a larger region covering western Africa, north South America and Central America is most negatively impacted at the high end of the climatic changes projected (e.g. SWL4 or the 2080s). The smallest increases in vulnerability are located across central Africa. As a result of using a different set of climate model simulations at a higher resolution, the vulnerability as assessed with the HadGEM3 ensemble is slightly less in most countries compared to that in Richardson *et al.* (2017), in both the baseline and the projections for the future.

Without future investment for climate adaptation initiatives, the HadGEM3 ensemble mean results suggest that for a 2°C warmer world, an estimated 189 million people could become more vulnerable to food insecurity than is currently experienced anywhere under the current climate . However, the individual HadGEM3 ensemble member results are inconclusive about the magnitude of the size of the population affected. In a 4°C warmer world, though, there is broad consistency amongst the ensemble members that an estimated 1.8 billion people could reach unprecedented levels of vulnerability to food insecurity.

Adaptation scenarios from Richardson *et al.* (2017) were applied for the 2050s and 2080s to assess the impact of the high resolution climate data on the overall messaging. The message continues to hold that the increases in vulnerability as a result of the changing climate are not offset by the highest level of adaptation considered in the majority of countries, and therefore both mitigation and adaptation are required to avoid the worst impacts of climate change on food security. However, the result is not as robust with these new results, as more countries appear to benefit from the adaptation scenarios compared to the results in Richardson *et al.* (2017). This is due to the lower vulnerability levels in the HadGEM3 ensemble, and the empirical nature of the adaptation scenario, and highlights the weaknesses of this approach and dependence on the climate models and resolution at which they are simulated.

An initial attempt to account for food imports in the HCVI has been developed and applied to the HCVI results from the HadGEM3 ensemble. The method used considered the average vulnerability associated with locally produced cereals and imported cereals by weighting the relevant elements of the HCVI by the fractions of local production and imports to that available at the national level, under the assumption that cereal imports come from the global market. Additional factors in the formula included accounting for the climate and non-climate vulnerability associated with imports through the use of the fraction of GDP that comes from agriculture, and the wealth of the country using GDP per capita information.

The application of the trade-weighting resulted in the inclusion of developed countries now that access to the global market is accounted for (OECD and EU countries are excluded from the HCVI in Richardson *et al.* (2017) for this reason). The inclusion of these additional countries does not significantly change the spatial pattern of the HCVI, nor does the application of the trade-weighting formula. The main result of the application of the trade weighting is that vulnerability is reduced slightly in most countries for the baseline and future projections, with the largest reductions seen in the countries which have a high fraction of imported cereals (namely the MENA region).

This first iteration of an HCVI that accounts for food imports only considers the vulnerability of a country's ability to import food. It does not currently consider the impact of climate and climate change on the production of cereals globally, the availability of cereals on the global market, nor the impact this has on global commodity prices or how these transmit to domestic prices paid; this is the subject of future developments of the HCVI.

## 2.5 References


Bren d'Amour, C., L. Wenz, M. Kalkuhl, J. C Steckel and F. Creutzig (2016): Teleconnected food supply shocks. Environ. Res. Lett., 11, no. 3, 035007, doi: 10.1088/1748-9326/11/3/035007

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P. and Bechtold, P. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(656), pp.553-597.

FAOSTAT (2016). http://www.fao.org/faostat/en/#data Accessed in 2016.

HELIX D2.1 (2014). Evaluation of timing of SWLs from existing models.

HELIX D3.1, (2017). Documentation of changes in climate variability and extremes simulated by the HELIX AGCMs at the 3 SWLs and comparison to changes in equivalent SST/SIC low-resolution CMIP5 projections.

Hempel, S., Frieler, K., Warszawki, L., Schewe, J., Piontek, F., (2013). A trend-preserving bias correction – the ISI-MIP approach, Earth System Dynamics, 4, 219-236.

Kalkuhl, M., von Braun, J., and Torero, M. (2016) Food Price Volatility and Its Implications for Food Security and Policy. Springer International Publishing. DOI: 10.1007/978-3-319-28201-5

Krishnamurthy, P. K., Lewis, K. and Choularton R. J. (2014) A methodological framework for rapidly assessing the impacts of climate risk on national-level food security through a vulnerability index. Global Environmental Change, 25, 121-132.

Monfreda, C., Ramankutty, N. and Foley, J.A., (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochemical Cycles, 22(1).

Morice, C.P., Kennedy, J.J., Rayner, N.A. and Jones, P.D. (2012): Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 dataset. Journal of Geophysical Research, 117, D08101, doi:10.1029/2011JD017187

OECD (2011) OECD Regional Typology. OECD: Paris.

Pope, E. & Kent, C., (2017). Advances in understanding climate-related wheat production variability. Met Office report for Defra.

Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso (2014) Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

Puma, M., S. Bose, S.Y. Chon, and B. Cook (2015): Assessing the evolving fragility of the global food system. Environ. Res. Lett., 10, no. 2, 024007, doi:10.1088/1748-9326/10/2/024007.

Ray, D.K., Gerber, J.S., MacDonald, G.K. and West, P.C. (2015). Climate variation explains a third of global crop yield variability. Nature communications, 6.

Richardson, K, Lewis, K., Krishnamurthy, K., Kent, C., Wiltshire, A., Hanlon, H. (2017). Food security outcomes under a changing climate: impacts of mitigation and adaptation on vulnerability to food insecurity. In review at Climatic Change.

Sheffield, J., Goteti, G. and Wood, E.F. (2006). Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. Journal of Climate, 19(13), pp.3088-3111.

Taylor, K. E., Stouffer, R. J. and Meehl, G. A. (2012) An Overview of CMIP5 and the Experiment Design. Bull. Amer. Meteor. Soc., 93, 485–498.

UN Comtrade (2016). https://comtrade.un.org/ Accessed in 2016.

UNDP (2013). Httep://hdr.undp.ord/en/data. Accessed in 2013.

UNFPA (2013). http://data.un.org Accessed in 2013.

van Vuuren, D. P., Lucas, P., and Hilderink, H. (2007) Downscaling drivers of global environmental change. Enabling use of global SRES scenarios at the national and grid levels. Global Environmental Change, 17, 114–130.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinhausen, M., Nakicenovic, N., Smith, S. J. and Rose, S. K. (2011). The respresentative concentration pathways: an overview. Climatic Change: 109, 1-2, 5-31.

Walters, D., Boutle, I., Brooks, M., Melvin, T., Stratton, R., Vosper, S., Wells, H., Williams, K., Wood, N., Allen, T., Bushell, A., Copsey, D., Earnshaw, P., Edwards, J., Gross, M., Hardiman, S., Harris, C., Heming, J., Klingaman, N., Levine, R., Manners, J., Martin, G., Milton, S., Mittermaier, M., Morcrette, C., Riddick, T., Roberts, M., Sanchez, C., Selwood, P., Stirling, A., Smith, C., Suri, D., Tennant, W., Vidale, P. L., Wilkinson, J., Willett, M., Woolnough, S., and Xavier, P. (2017): The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations, Geosci. Model Dev., 10, 1487-1520, DOI: https://doi.org/10.5194/gmd-10-1487-2017

Wanders, N., Van Lanen, H. A. J., and van Loon, A. F. (2010) Indicators for drought characterization on a global scale. WATCH Technical Report No. 24

Weedon, G. P., Gomes, S., Viterbo, P., Shuttleworth, W. J., Blyth, E., Österle, H. and Best, M. (2011) Creation of the WATCH Forcing Data and Its Use to Assess Global and Regional Reference Crop Evaporation over Land during the Twentieth Century. Journal of Hydrometeorology, 12, 5.

Williams, K. D., Harris, C. M., Bodas-Salcedo, A., Camp, J., Comer, R. E., Copsey, D., Fereday, D., Graham, T., Hill, R., Hinton, T., Hyder, P., Ineson, S., Masato, G., Milton, S. F., Roberts, M. J., Rowell, D. P., Sanchez, C., Shelly, A., Sinha, B., Walters, D. N., West, A., Woollings, T., and Xavier, P. K.

(2015): The Met Office Global Coupled model 2.0 (GC2) configuration, Geosci. Model Dev., 8, 1509-1524, DOI: https://doi.org/10.5194/gmd-8-1509-2015

World Bank (2016). http://databank.worldbank.org/data/home.aspx. Accessed in 2016.

World Resources Institute (2013). http://wri.org/resources/data_sets Accessed in 2013.

# 3. Assessment of climate impacts on migration

## 3.1 Introduction

### 3.1.1 The relationship between climate change and migration

Already in the first Assessment Report of the IPCC, migration had already been identified as one of the most severe potential impacts of climate change on populations (McTegart et al. 1990). It has long been recognized that environmental changes could induce significant migration flows, either as a direct consequence or because of the impacts of these changes upon other migration drivers, such as poverty or food security (Tacoli 2011, Foresight 2011), as detailed in the previous section.

An ever-growing body of literature has now addressed the issue, and most studies have focused on how environmental disruptions had been a contributing or dominant driver to migration and displacement. The links between environmental changes and migration are extremely complex, rather than a direct, causal relation as it is sometimes assumed. Despite the significant body of empirical studies that have been conducted, there subsists many uncertainties about the nature and strength of these linkages. It is generally acknowledged however that three key types of climate impacts can generate significant migration flows: sea-level rise, changes in precipitation patterns and water stress, and the increased intensity of natural hazards (Boano, Zetter et al. 2008).

Even if the objective of the Paris Agreement (2°C of maximum temperature change by the end of the century) is achieved, sea-level could reach one metre by the end of this century (Rahmstorf 2010), though there will be regional variations. Coastal and deltaic regions rank amongst the most densely populated regions on Earth; they are home to many major cities and will be at direct risk of flooding if adaptation measures such as dikes and coastal restoration are not implemented. For the HELIX project, we documented the case of the region near Cotonou in Benin, where entire neighbourhoods have already been engulfed by the encroachment of the sea. The case of Bangladesh is also of particular relevance here, as a significant part of the land is located under the sea-level. Small island states are naturally particularly vulnerable to even the slightest rise in sea-level. If no substantial adaptation measures are undertaken rapidly, populations living in low-lying regions could eventually be forced to relocate permanently, possibly abroad in the case of small island developing states. The timeframe of these migrations however is very important: sea-level rise is a very incremental change, which allows populations to prepare and plan their relocation, possibly over several generations.

Changes in precipitation patterns and water stress constitute the second type of climate impacts to induce migration. It is more difficult to assess the weight of environmental factors in this case, as water stress often mingles with other migration drivers such as poverty or land tenure issues. Empirical research suggests that migration patterns might be more diversified, with people migrating both temporarily and permanently, typically from rural to urban areas. In many cases, a member of the household will migrate to the city in order to gain additional income and sustain the household’s livelihoods during periods of drought, land degradation and water stress. In our research, we found very different patterns of migration related to such environmental degradation. Migration can also be part of a social routine to deal with environmental stress, as it is often the case with pastoralist populations, but can also become a permanent relocation if the crisis becomes more severe. Likewise, severe droughts can induce brutal, dramatic population displacements, in search for food and assistance. One should however be very cautious about establishing an automatic relationship here: there’s also empirical evidence that the rate of migration can decrease in cases of extreme drought, because of the households are so diminished that they cannot afford to migrate (Jonsson 2010). Migration patterns will actually be dependant upon the socio-economic context, the assistance available and the availability of migration options.

Finally, extreme weather events, whose intensity is expected to increase because of global warming, typically induce massive displacements of people. These displacements are usually confined within the borders of the country where the disasters happen, but there have been cases of cross-border migration, especially when asylum possibilities were provided abroad. For example, after hurricane Mitch struck Central America in 1998, many Hondurans and Nicaraguans were provided with temporary asylum in the United States. It has long been thought that natural disasters did not lead to permanent migration but only rather temporary displacements, as the people were supposed to return home once the disaster had ended and the reconstruction process begun. Hurricane Katrina, however, showed that this was not always the case, as roughly one third of the population of New Orleans never returned to the city. But migration can also be a key tool for reconstruction in the aftermath of a disaster: remittances, for example, can provide a significant assistance to households seeking to rebuild their livelihoods; they typically increase after a disaster.

Migration patterns related to the impacts of climate change are extremely diversified, from a temporary evacuation to a permanent migration. For the moment however, a common characteristic to these different types of migration is that most migrants move within the borders of their country, and often on very short distances (Jäger et al. 2009). This can be explained by the fact that people usually have little interest to move further, as it would further disrupt their economic and social networks and might deprive them from state-led assistance. Furthermore, migration is a very costly endeavour, and many simply don't have the resources to undertake an international migration. In a world that would be 4°C or 6°C warmer however, this might change and international migration could be a more common response to environmental stressors.

The decision to move is not only context-specific, but is also contingent upon the individual characteristics of the migrants: their age, gender, and wealth (McLeman and Smit 2006). Those who are most mobile tend to be younger, wealthier, and male, as the most vulnerable populations often find themselves unable to migrate. The poorest, in particular, often lack the resources that would allow them to afford the costs of transport, housing, and sometimes smuggling. When they move, they also do it on shorter distances than wealthier populations, meaning that they sometimes from one hazardous zone to another one, as we have been documented it in Bangladesh. This can be explained by the existence of numerous barriers to movement: those are firstly of economic nature, as migration is a very resource-consuming process. But barriers to movement are also administrative and informational: migration policies have become increasingly stringent over time, both in developed and developing countries. Even when they move within their own country, migrants need to overcome numerous administrative barriers, such as the possible loss of social benefits and protection. Furthermore, many lack the information about possible destination areas and employment possibilities, and will often need to rely on migrants' networks to secure a livelihood. Land tenure is also a critical issue: research shows that land owners are less mobile than those who rent their land, as the former are often reluctant to abandon their land. Land tenure is also a frequent problem in the destination area, as migration can lead to competition for land.

In a nutshell, migration is often one of possible responses to environmental disruption. Some will choose to migrate in order to adapt, while other will be forced to move because they have been unable to adapt. Some will adapt *in situ*, while others will not be able to adapt at all, meaning that their life, health and livelihoods will be directly exposed to the impacts of climate change. The choice between these different options will depend on the nature of the environmental changes, but also – and possibly more significantly – on the policy responses that are developed.

### 3.1.2 Migration in a warmer world: our approach in HELIX

As global warming will come closer to topping the limit of a 2°C increase in global average temperature, migration is likely to become a lesser possible option in the face of environmental changes (Gemenne 2011). At the moment, environmental changes are leading to both voluntary migration and forced displacement. These categories, however, are not discrete: most migration decisions include some elements of constraints, and very few movements are either completely voluntary or completely forced. In recent years, the line between voluntary and forced migration has become increasingly blurred, and forced and voluntary movements are better described as the two ends of a continuum than clear-cut categories (Hugo 1996). In a warmer world, where people will stand on this continuum will depend not only on climate impacts, but also, and possibly more importantly, on the way policies address climate-induced migration.

Numerous efforts have been made to try and forecast the magnitude of future migration flows associated with global warming. These efforts, however, have not allowed to provide a robust and rigorous prevision of future migration flows, even if global warming was kept below 2°C by 2100 (Gemenne 2011b). Assessing the magnitude of these flows in a +4°C or +6°C scenario is thus even a bigger challenge, as it is impossible to use a baseline scenario to formulate such forecasts. A common assumption that is often made in policy discourses is that more extreme scenarios will lead to even more massive population displacements. While one cannot exclude the possibility that migration will increase as temperatures increase, our key conclusion however is that **more extreme climate scenarios would affect the patterns and structures of migration even more than its magnitude**.

When one seeks to assess the effects of climate change on migration – be it at 2°C, 4°c or 6°C – one is confronted with a dual challenge: the first one relates to the difficulty to provide a global assessment, the second to modelling challenges.

#### 3.1.2.1 Scale of the assessment

A key problem with current assessments of population movements – especially if related to climate change – is that they seek to provide a global figure. In many countries of the world, the data and statistical apparatus are just insufficient to support that endeavour, which means that any global assessment would be, at best, an educated guess.

Current figures indicate that roughly one person out of seven – that is, 940 million people – was not born in the place where s/he currently lives. In this number, only one quarter – 230 million people – are international migrants. Only this figure is relatively robust. This means that roughly three quarters – 710 million people – are internal migrants, meaning that they still reside in the country where they were born. It is widely acknowledged, though, that this number is grossly underestimated, mostly because of the limited statistical capacities of many developing countries. To put it simply: we just don't know how many internal migrants there are. But we know that most migration related to environmental changes is internal migration. And even if we had a robust estimate for the total number of internal migrants, it would be an impossible task to disentangle migration drivers one from another: our research shows how interlinked are the drivers of migration, and how they influence each other.

Most climate models are global models, and the downscaling of such models is a considerable scientific challenge. Yet robust migration assessments cannot be global, but only national or regional. Relating climate models to migration data induces therefore an unavoidable problem of interoperability of databases. This is the reason why we have chosen an empirical, case-study-based approach in HELIX.

#### 3.1.2.2 Modelling challenges

Climate science remains largely based on modelling, especially when it comes to assessing the future impacts of climate change. Migration modelling however remains very difficult, and is still at a very experimental stage (Bie and Van den Broeck 2011). Though modelling exercises have proved promising (Henry et al. 2003, Massey et al. 2007), they remain very scarce in the literature. Different types of models have been applied to study environmental migration, and mostly gravity models or agent-based models (Kniveton et al. 2008) – no global model of migration, however, has been developed so far.

Any modelling of human behaviour remains difficult, and this is especially the case for migration, a human behaviour determined by a wide array of factors, some of them irrational – or appearing so. This means that it is impossible to feed climate data into a migration model, and that the use of climate information to forecast future migration will remain highly contingent of the context in which migration will happen.

Again, no baseline model could be used to assess the impacts of climate change and migration in extreme climate scenarios. These two difficulties were the main reasons for the methodological choices we made in HELIX.

### 3.1.3 Method

The method we have chosen for HELIX relies on a careful analysis of diverse and representative case-studies, in different contexts and for different types of climate impacts. The case-studies were chosen for their representativeness of different contexts and types of climate impacts, in West Africa (Benin, Burkina Faso, Senegal), East Africa (Ethiopia, Tanzania) and South Asia (Bangladesh). In this deliverable are presented the case-studies on Burkina Faso, Senegal and Bangladesh. The case-studies on Benin, Ethiopia and Tanzania are presented in deliverable D 8.5 on Africa. It should be noted, however, that the key findings presented in the next session are drawn from all case-studies conducted for the HELIX project, not just those presented in this deliverable.

In each case-study, the key objective was to find out how people had reacted to previous environmental changes and shocks, and try to identify the key variables that would affect how they might react to other changes or shocks in the future. Such extrapolation is of course difficult by nature, especially when the expected environmental changes are unprecedented, with a possibility of reaching some tipping points. For this reason, this extrapolation does not allow for any quantitative assessment or estimate, but highlights some key patterns of reaction to environmental changes that might help us better anticipate migration and displacement driven extreme climate scenarios. A temperature increase of +4°C or +6°C (or even +2°C for that matter) is unprecedented on a global scale, and any prevision of how societies might recat to these changes is by nature difficult. But our analysis of how people reacted to previous shocks, in different representative contexts, provides essential elements that can help draw a picture of how populations might react to similar and aggravated environmental shocks in the future.

## 3.2 Key findings

This section presents some of the key findings drawn from the case-studies conducted for the project. Together, these findings can help us better grasp the patterns of population movements associated with extreme climate change. Previous literature had already put forward the hypothesis that **patterns of migration, and not just its amplitude**, would be affected by higher temperature increases (Gemenne 2011b). Our findings allow to confirm and refine this hypothesis, delineating different patterns that will be affected.

### 3.2.1 There's no correlation between the magnitude of climate and social impacts

In public and policy discourses, it is widely assumed that there's some form of correlation between the magnitude of climate impacts and the magnitude of associated population movements (or other social impacts). To put it simply, there's an assumption that the bigger the impacts, the bigger the migration. Though such a correlation might appear logical on a first account, it is not supported by the evidence gathered in case-studies. On the contrary: **a succession of small climate impacts can result in major social transformations, while major climate impacts can have small impacts on migration**.

The migratory system of Bangladesh, for example, where migration is often routinely conducted as part of adaptation to floods, is often better able to absorb climate shocks, compared to others migratory systems without the same capacity. Yet is often a succession of small climate shocks that will drive migration movement, rather than major disasters. Migration requires indeed the mobilisation of very significant resources – most financial ones. This explains why some major climate shocks can result in small migration movements, as the populations are deprived from essential resources that would enable them to relocate in a safer place.

This absence of systematic correlation between the magnitude of climate impacts and the associated social transformations bears significant policy implications. This should not be interpreted as to mean that there are no relation between the two, but rather that this relation is not as automatic as often assumed. This invites us to pay more attention to the other social, economic and political components that will exacerbate or mitigate the impacts of climate change – even the smallest ones. This also implies that we need to operate a clear distinction between the climate hotspots and the migration hotspots: any determinism must be avoided.

**Box 1. The Bangladesh-Indian Migration Corridor in the Context of Climate Change**

The two countries share a 4,096-kilometer (2,545-mile)-long international border, the fifth-longest land border in the world, with a fence constructed by the Indian government to curb infiltration, movement of suspected terrorists, and enhance management of Indian-Bangladeshi trade.
Approximately 12-17 million Bangladeshi immigrants have come to India since the 1950s, with most residing in the northeast states of West Bengal, Assam, and Tripura. It is estimated that 'this is the largest international migration flow, with more people involved than estimated for top-ranked Mexico-United States flows" (ADB 2012).

Seasonal migration to India has long occurred, and water scarcity in some areas has propelled cross-border movements (Bangladesh Institute of International and Strategic Studies 2010, cited by McAdams & Saul 2010). Evidence suggests that sudden disasters are associated with higher migration flows to India in the hope of securing additional resources to cope with the disaster (Poncelet 2010).

**Main Findings on Social Feedbacks in Climate Migration System:**

- Awareness or experience of religio-political aggression tends to intensify feelings of insecurity and helplessness in environmentally stressed contexts, where religious-based clientelism is often suspected in recovery aid distribution and preparedness interventions.

- Intergroup cooperation during and in the aftermath of environmental shocks strengthen village solidarity and place attachment.

- Cross-border social networks produce strong positive social feedbacks for both seasonal and permanent cross-border migration.

- When remittances and income from seasonal migration are invested into structural housing improvements and livelihood adaptation, social feedbacks are directed towards building resilience at home.

- Bangladeshi migrants in India mainly seek out non-agricultural livelihoods that are not dependent on natural resources.

- Negative social experiences in India do not automatically deter return.

- Once resettled, migrants mainly identified as Indian, while largely living in predominantly Bangladeshi communities.

### 3.2.2 Aggravated climate change will not necessarily result in an increase of migration

There is a tendency to assume that climate change will result in an increase in human migration. **Yet extreme climate change will increase migration amongst certain populations, but also diminish it amongst others**. More people are expected to move as a direct or indirect result of the impacts of climate change, particularly from the Global South, with an attached assumption that these movements will be directed towards countries and regions in the Global North. This 'climate refugee' narrative gains traction when bolstered by such frequently cited numbers as 200 million people displaced by climate change by 2050 (Myers 2002). These narratives are lent further credence by the fact that scholars and researchers frequently introduce the topic with such statements as, 'climate change will (or is expected to) increase current migration flows'. Typically, these statements come without proper citation, assumed to be so obvious as not to warrant strict empirical or scientific backing.

In the case studies performed within the HELIX project, we noted the falsehood of such general, global assumptions linking the extremity of temperature rise, the increase in the scale of climate change impacts, with a corresponding augmentation in the volume of migration. Firstly, even in cases of extreme climatic events some people continue to live in areas severely affected by climate change. In slow-onset events, such as the coastal erosion experienced in the Senegalese case study, we noted that the proportion of those who leave is much smaller than the proportion that stays. Multi-causal factors contribute to this immobility, including place attachment, lack of financial resources with which to move, demographic factors such as age, life phase, etc. Importantly, human migration can also diminish in certain contexts with the increase in impacts of climate change. This thought might strike as counterintuitive, but in actuality migration takes resources of varying kinds (social, human, financial, etc.) that can be negatively impacted by climate change. For example, adverse effects on natural resource-dependent livelihoods and systemic resilience more broadly can result in fewer resources with which an individual or a household may utilize for migration. Our studies thus echo but also greatly expand on and complexify similar findings from the Foresight Report (2011) regarding the possible creation of 'trapped populations' due to climate change, communities in which people aspire to migrate but are unable to do so.

### 3.2.3 The scale of migration resulting from climate change cannot only be understood in terms of alteration of volume

Another key finding amongst several of our studies was that climate change's impacts on human mobility are not limited to increases or decreases in movement; we note that climate change also has important impacts on the **character of migration** dynamics, such as temporal and geographic scales. Even in locations where migration is a common occurrence, such as Bangladesh and Senegal, the geographic distance of migration trajectories, length of migration (temporary/permanent/circular), and geopolitical dynamics (international/internal) of historical migration patterns can be dramatically altered by climate change. In Senegal, where fishermen have long migrated seasonally to 'follow the fish', a decrease in biodiversity and depletion of local fish stocks pushed fishermen to stay much longer periods of time abroad, in Mauritania rather than historical dispersion across West Africa, and their international movements were now coupled with internal relocation because of coastal erosion. Notably, none of the case studies' primary migration destinations were in the Global North. A major finding of HELIX is thus that we must consider not only quantitative increases (or decreases) in migration because of climate change, but also how the other ways in which climate change alters the very character of migration if we are to promote appropriate policy responses, address security concerns, and facilitate migration as an adaptation strategy rather than distress or maladaptive migration.

### 3.2.4 Mobility dynamics associated with extreme climate change will often be non-linear

The human mobility dynamics that will result from extreme climate change will often be counter-intuitive, and challenge our own conception of rationality and rational choices. As mentioned above, extreme climate change can result in an increase of migrant populations, but also in an increase of immobile populations. Therefore, rather than inducing a linear migration process where more and more people would migrate as temperatures increase, climate change could divide a community into two groups, between those who have enough resources to relocate and those who do not. This is likely to create a feeling of abandonment and resentment amongst those who have no other possibility than stay.

Even in the face of immediate danger, some populations might decide to stay or ignore the danger, while others are continuing to migrate into areas severely exposed to climate impacts, attracted by economic opportunities and urban development.

Such mobility behaviours can destabilize our ‘normal’ expectations regarding how the climate change–migration nexus will play out. Though one might deem such attitudes ‘irrational’, they might appear as perfectly rational for those concerned – challenging our own (external) notion of the rationality of migration.

### 3.2.5 Much will come down to the issue of inhabitability

Extreme climate change is expected to render some place uninhabitable, because of excessive temperatures, sea-level rise, and uncultivable land. The notion of inhabitability, however, is not an objective notion, and is contingent upon one’s perspective. The case of small island states is particularly exemplary in this regard, and shows the importance of personal characteristics when discussing inhabitability. As the sea-level rises, some portions of the territory will become uninhabitable. Most likely there will be no collective decision to deem the land uninhabitable, and people will leave one after another, when they consider the land uninhabitable – meaning that this assessment will depend greatly on individual characteristics and preferences.

As our case-studies show, this notion on inhabitability is greatly dependent upon people’s perceptions of environmental changes and their causes. These perceptions are sometimes not aligned with the observed environmental changes, yet they – not the actual observations – will determine whether the threshold of uninhabitability has been reached or not. This highlights the need to provide actual climate information to those affected by climate changes, so that their decision on inhabitability can be informed by actual data and not just their own perceptions. Moreover, the perceived irreversibility of these environmental changes will also influence people’s decisions to move and the subsequent mobility patterns.

The notion of inhabitability, however, can also take a collective meaning, if a social tipping point is triggered. This will happen when a climate impacts makes a community shifts from one stable state to another, usually unstable. In this case, uninhabitability becomes a social transformation, beyond individual perceptions.

## 3.3 Case-studies

### 3.3.1 Burkina Faso

#### 3.3.1.1 In a nutshell

I. Comparison of perceptions of rainfall changes by rural dwellers in different climatic regions of Burkina Faso with actual trends recorded

II. Assessment of the importance of migration in Burkina Faso in coming decades based on migration intentions informed by climate perceptions

III. Findings:

a) Accurate perceptions of temperature changes but more pessimistic perceptions of rainfall than observed changes
b) Projected climate-induced decreases in agricultural production can lead to an increase in migration flows and a change of migration patterns over the next decades
c) Overly pessimistic climate change perceptions may spark migration before the climate actually changes

#### 3.3.1.2 Introduction

Perception of climate change is a relatively new field of research. A recent literature review showed that most research on the topic of 'perception of climate change in West Africa' were published since 2009 (Ozer & Perrin, 2014). This interest is partly a response to the fourth report of the Intergovernmental Panel on Climate Change (IPCC) which underlined serious research deficiencies in this field (Pachauri & Reisinger, 2007). By the West African Sahel, we mean arid and semi-arid areas of West Africa (with rainfall between 0 and 1200 mm) including Mauritania, Senegal, Burkina Faso, Niger, Mali and Gambia. The most important change felt by populations in this region is a decrease in total annual rainfall amount (Dieye & Roy, 2012; Mertz et al., 2009; Ouédraogo et al., 2010), a decrease in the length of the rainy season, explained by a later starting date and an earlier ending date (Mertz et al., 2012; Tambo & Abdoulaye, 2012), and an increase in dry spells during the rainy season and in periodic droughts and irregular rainfall (Tschakert, 2007; West et al., 2008). In previous studies, households' perceptions of climate change in the West African Sahel have been compared with observed climatic changes but due to limited data availability for most climate parameters this was only possible for rainfall trends, and, more specifically, only for rainfall amounts and dry spells (Mertz et al., 2012; Zampaligré et al., 2014). In this paper, we complement existing studies on the relationship between perceptions and climate change by performing an in-depth analysis of the daily rainfall and temperature data with different statistical methods. For this, we couple results of climate trends with perception data collected over 2007-2008 in the framework of the AMMA[10] project. The geographical focus in the present paper is on Burkina Faso.

With West African populations largely dependent on rain-fed agriculture (Mertz et al., 2010), variations in rainfall patterns and temperature adversely impact their livelihoods (Juana et al., 2013). Particularly, rainfall variability and drought are significant contributors to low levels of economic development, poverty, and food insecurity in drylands such as the West African Sahel (Brown, 2012; de Sherbinin, 2011). Rural populations depending on natural resources develop adaptation strategies to face climate variability and economic or political changes (Brockhaus et al., 2013). The strategies implemented by rural communities vary largely depending on the study area, the type of farming practiced and socio-cultural factors (Adger et al., 2009; Nielsen & Reenberg, 2010a). The management of soil fertility and irrigation could help counteract the

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negative impacts of climate change but most farmers do not adopt these measures due to their unavailability and high cost. Soil and water conservation practices are frequently implemented in the West African Sahel but mainly because of growing land scarcity and new market opportunities rather than climate variability (Barbier et al., 2009). In most places, the only technical adaptations in response to climate change are the use of several crop varieties or mix-cropping and/or to postpone seeding dates (Fosu-Mensah et al., 2012). In southern Burkina Faso, farmers involved in cotton production tend to specialize (Benoit, 1982). In the North, farmers do not use crop diversification but rather income diversification through off farm activities (Reardon et al., 1992). Migration is another strategy to adapt to climate change. Cyclical intraregional migration in response to seasonal variability in rainfall and periodic droughts has long been practiced in West Africa including Burkina Faso (Cordell et al., 1996; Rain, 1999). Via migration farmers are diversifying their livelihoods to avoid relying on a single rainfall-dependent activity (Lay et al., 2009) and to increase household income (D'haen et al., 2014; Kniveton et al., 2012). Much of this income is used to buy food (Nielsen & Reenberg, 2010b).

Burkina Faso has a long story of migrations and reasons to migrate have evolved through time. Before 1947 migration had its roots in colonialization and in the administrative, social and economic measures taken by the colonial authority (Coulibaly, 1978). From 1947, the main cause of departure was economic. In the 1970s by the establishment of the *Aménagement des vallées des Voltas*, the State launched the first agricultural settlement operations. Alongside these relocations, a powerful spontaneous movement of migration took place in response to climate and agricultural difficulties (Benoit, 1982). These difficulties were largely caused by droughts that can be considered as slow-onset events and major agricultural productivity failures may induce progressive and large-scale displacements of people. According to some estimations, droughts in Burkina Faso and Sudan from 1968–1973 displaced around 1 million people (Afolayan & Adelekan, 1999; Hugo, 1996). Less extreme reductions in agricultural productivity may also stimulate short-term mobility by members of a community to other rural or urban areas where alternative income sources are sought (Black et al., 2011). The response of internal migration flows to a drier climate was showed by a study which found that short distance migration to larger agglomerations increased during drought years as women and children left in search of work to contribute to household incomes (Henry et al., 2004). However, the same response to dry conditions was not expected with international migration. Indeed, the empirical evidence from the past indicated that drought was associated with decreases in international, long-distance migration as food scarcity during drought leads to increased prices, forcing people to spend more money on their basic needs rather than on long-distance migration (Kniveton et al., 2008; Van der Geest, 2011). In Burkina Faso, the migratory flows are mainly directed to the Ivory Coast and Ouagadougou, the capital. Massive displacement are also recorded from the North to the south west of the country (Benoit, 1982; Blion & Bredeloup, 1997; Henry et al., 2003).

It is a combination of factors (economic, political, demographic, social and environmental) that explains population movements (Black et al., 2011). For instance, a study by Henry et al. (2003) showed that inter-provincial migrations in Burkina Faso are influenced by high literacy and economic activity rates at the origin and destination, a high and low proportion of men respectively at the origin and the destination, as well as by unfavourable conditions concerning rainfall variability, land degradation and land availability at the origin, and favourable environmental conditions at the destination. Mertz et al. (2010) even concluded that climate factors play a limited role for past adaptation strategies in West Africa. Is this likely to remain the case? In the scientific literature, there is a lack of information and methods that enable us to forecast future migration in response to climate change (Gemenne, 2011). In this paper, to fill this gap, we propose to analyse the intention to migrate in response to climate changes as a proxy for future migration, with a distinction between temporary and permanent migration.

### 3.3.1.3 Data

***a) Data on perceptions of climate change***

Data on perception of climate change used in the present study come from the socio-economic survey of the AMMA project carried out in five West African countries between November 2007 and June 2008. In Burkina Faso, 383 households distributed in four regions and three climatic zones (Figure 22) were asked to state changes during the past 20 years (1988-2008) with respect to rainfall, temperature, winds, and dust storms (Mertz et al., 2012). The survey included questions about changes in the amount of annual rainfall, the length of the rainy season, the length of dry spells, rainfall events during the dry season, the intensity of rainfall events, flooding, the intensity of temperatures in both seasons, the length of hot and cold spells, the frequency and duration of strong winds and the intensity of dust storms. In the present study, we limit the analysis to seven parameters (see column "Perception" in Table 6). They have been chosen according to the possibility to make comparisons between perceptions and actual trends calculated based on available daily climatic data.

***b) Climate data***

Climatic data were provided by the *Direction Générale de la Météorologie du Burkina Faso*. The database includes daily rainfall, minimum and maximum temperatures from January 1988 to December 2008. We retained four synoptic stations and two additional rain gauge stations selected on the base of the proximity to the surveyed villages (Figure 22). The station of Gaoua was only used for rainfall trends because anomalies were detected in temperature data.

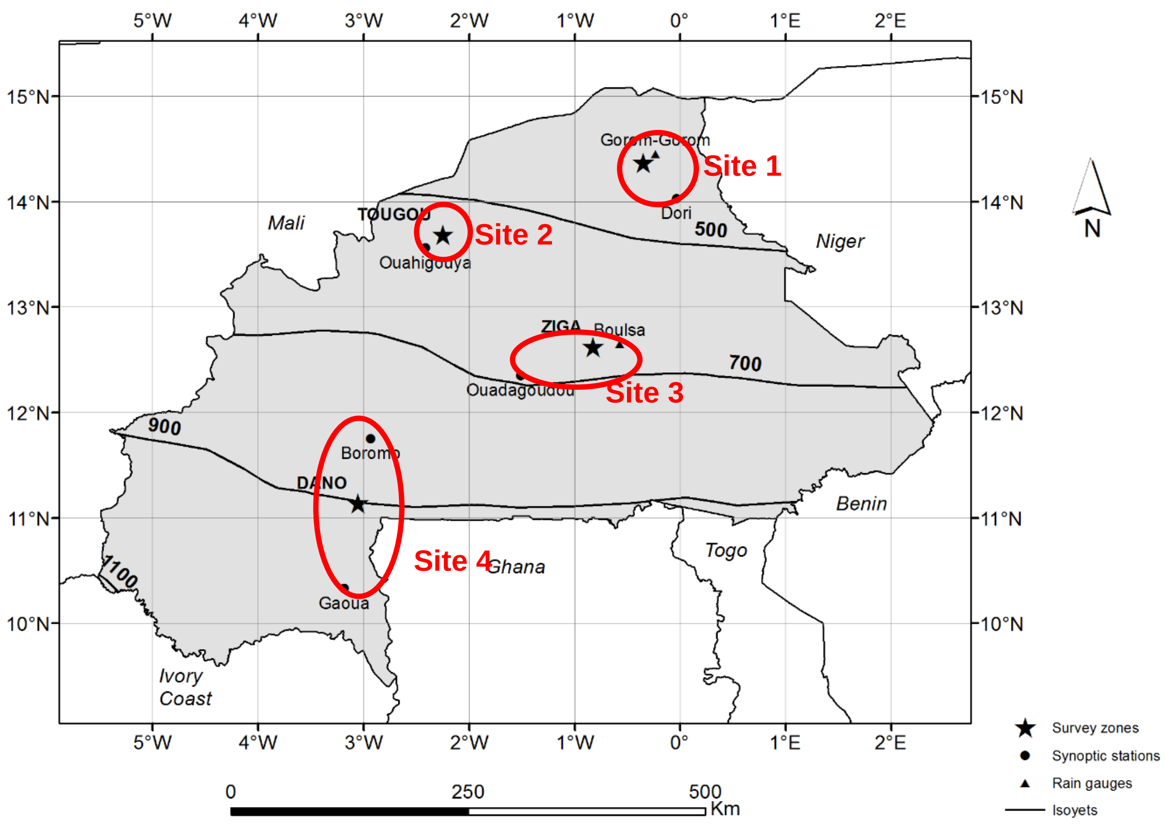


**Figure 22 - Survey distribution and the location of meteorological stations in the study area with isohyets from 1971 to 2010**

#### 3.3.1.4 Methods

***a) Climate indices***

Overall, a set of 20 rainfall indices have been defined in this study (Table 6). A part of them (TOTR, RD, SDII, R10, R10p, R20, R20p, Rmax and Rmaxp) were notably based on climate indices developed by the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI) and calculated with the RClimDex software (Zhang & Yang, 2004). They have been chosen to be consistent with questions asked to populations about climate change perceptions (Table 6). In addition, we developed several indices calculated by season (see 'ws' for wet season and 'ds' for dry season in Table 6). For this, the method of Sivakumar was used to determine the start and the end of the wet season for each year of the study period (Sivakumar, 1988). The starting day of the wet season at a given location is the date after May 1st when total rainfall over three consecutive days is at least 20 mm, with no dry spell exceeding 7 days during the following 30 days. The ending day is after 1 September following which no rain occurs for a period of 20 days. The values of indices related to a season were then calculated on the actual season (variable from one year to another). For temperature indices, we used the definition of average seasons in the country (Lodoun et al., 2013) and calculated the average daily minimal, maximal and mean temperatures as well as the average daily temperature range separately for each season, that is to say 8 indices (Table 6). There are no missing data in the database therefore trends analyses were possible.

**Table 6 - Definition and unit of rainfall and temperature indices reflecting questions of climate change perception in the AMMA survey (ws: wet season, ds: dry season)**

| | **Perception** | **Observation** | | |
|---|---|---|---|---|
| | *From AMMA survey* | *From meteorological stations* | | |
| | *Parameter* | *Translation in meteorological terms based on rainfall and temperature data* | | |
| | | Index | Definition | Unit |
| **Rainfall** | Total rainfall during the wet season | TOTRws | Total rainfall during the wet season | mm |
| | | RDws | Total days with rainfall during the wet season | days |
| | | TOTR | Total annual rainfall | mm |
| | | RD | Total annual wet days (rainfall ≥ 1 mm) | days |
| | Length of the wet season | Lws | Length of the wet season | days |
| | | Sws | Starting day of the wet season | day |
| | | Ews | Ending day of the wet season | day |
| | Rainfall events during the dry season | RDds | Number of days with rainfall during the dry season (rainfall ≥ 1 mm) | days |
| | | TOTRds | Total of rainfall during the dry season | mm |
| | | PRds | Percentage of rainfall during the dry season | % |
| | | Heug5 | Number of days with rainfall ≥ 5 mm during the dry season | days |
| | Dry spells | DDws | Number of dry days during the wet season | days |
| | | CDDws | Maximum number of consecutive dry days during the wet season | days |
| | Rainfall intensity | SDII | Average rainfall by wet day | mm/day |
| | | R10 | Annual number of days when rainfall ≥ 10 mm | days |
| | | R10p | Percentage of annual rainfall from days when rainfall ≥ 10 mm | % |
| | | R20 | Annual number of days when rainfall ≥ 20mm | days |
| | | R20p | Percentage of annual rainfall from days when rainfall ≥ 20 mm | % |
| | | Rmax | Annual maximum 1-day rainfall | mm |
| | | Rmaxp | Percentage of annual rainfall from maximum 1-day rainfall | % |
| **Temperature** | Intensity during the dry season | TNds | Average value of daily minimal temperature during the dry season | °C |
| | | TXds | Average value of daily maximal temperature during the dry season | °C |
| | | Tds | Average value of daily mean temperature during the dry season | °C |
| | | DTRds | Daily temperature range during the dry season | °C |
| | Intensity during the wet season | TNws | Average value of daily minimal temperature during the wet season | °C |
| | | TXws | Average value of daily maximal temperature during the wet season | °C |
| | | Tws | Average value of daily mean temperature during the wet season | °C |
| | | DTRws | Daily temperature range during the wet season | °C |

#### *b) Trends analyses*

Trend coefficients were calculated using Spearman's rank correlation over the 1988-2008 period to be in agreement with the survey. Two significance p level ($p < 0.05$ and $p < 0.1$) have been used to analyse the hypothesis that the slope is equal or different to 0. Each trend was categorized in six classes according to slope (positive or negative) and statistical significance (not significant ($p \geq 0.1$), moderate ($p < 0.1$) or significant ($p < 0.05$)).

#### *c) Migration data and analyses*

Even if the socio-economic survey of the AMMA project did not primarily focus on migration, we concentrate our attention on migration as a current and potential adaptation strategy to climate change on the basis of this survey. Three categories of information about migration are present in the database: (i) the number of temporary and permanent migrants in the households at the moment of the survey with the main cause of migration, (ii) the migration seen by households' heads as a positive/negative impact of observed changes, as well as a solution to solve other negative impacts, and (iii) the intention to migrate, temporarily or permanently, in the case of more frequent droughts and in the case of drier or wetter climates (Mertz et al., 2011).

Data on the intention to migrate were transformed into binary variables. Then, by the implementation of logistic regressions, we checked if there were correlations between the intention to migrate in the future and other variables that had been classed into five categories: (i) location of respondents (four regions), (ii) socio-economic profile of the households (including the existence of permanent/temporary migrant(s) in the households), (iii) perceptions of change in rainfall and temperature, (iv) positive impacts and (v) negative impacts of climate change. A total of 32 independent variables were inserted in the models to test their potential influence on the intention to migrate. The significant explanatory variables were identified based on $p < 0.05$ (significant) and $p < 0.1$ (moderate). Their importance was assessed by the value of the odds ratio. Three different models were implemented and compared: M1- Intention to temporarily migrate in response to drought, M2- Intention to temporarily migrate in response to drier climate and M3- Intention to permanently migrate in response to drier climate.

### 3.3.1.5 Results

#### *a) Perceptions of climate change*

Globally, there is a pessimistic perception of changes in rainfall over the period 1988-2008. The main agreement about rainfall change (86.3%) is the shortening of the rainy season (Figure 23). Only 7% reported an increase in the duration of the wet season and 2.5% perceived stability. A large majority of respondents (83.9%) also cited a decrease in the total amount of annual rainfall. In addition to these perceptions that reflect rainfall shortages, other perceptions are related to more erratic rains. About 85% of respondents observed an increase in the length of dry spells during the wet season and rainfall events during the dry season tended to decrease according to 68.9% of respondents. Concerning the intensity of rainfall events, opinions are more divided with 65% of respondents reporting a declining trend and 27% reporting an increase.

The region of Dano (see Figure 22) presents the greatest homogeneity in responses. More than 92% of respondents mentioned a decrease in the total amount of annual rainfall, the length of the rainy season and the intensity of rainfall events and an increase in length of dry spells during the wet season over the study period. Moreover, more than 90% reported fewer rainfall events during the dry season. In the region of Ziga, more than 90% if the respondents also agreed that total annual rainfall, the length of the wet season and the rainfall events during the dry season have decreased. Nearly 87% of the respondents observed an extension in the length of dry spells during the wet season. Perceptions are more variable concerning intensity of rainfall events. In the two other regions (Oudalan and Tougou), the driest of the surveyed zones, opinions are more divided.The decrease in the total annual rainfall, the shortening of the wet season and the extension of the length of dry spells during the wet season are also the dominant perceptions but it is less unanimous than in Dano and Ziga. Opinions are sharply divided about rainfall events during the dry season and to a lesser extent about the intensity of rainfall events. In Oudalan, 64.5% of the respondents perceived a decrease in the intensity of rainfall events, against 28.9% who reported an increase. Trends are reversed in Tougou.

Results about perceptions of changes in temperature clearly show a trend of warming experienced by the surveyed population over the study period (Figure 23). An increase in temperature during the dry season was reported by 85% of the respondents and by 72.4% during the wet season. The share of respondents who mentioned stability in these parameters is greater than for factors related to rainfall but remains low. As for the perception of change in rainfall, respondents' perceptions in Dano are more homogeneous than in other regions.

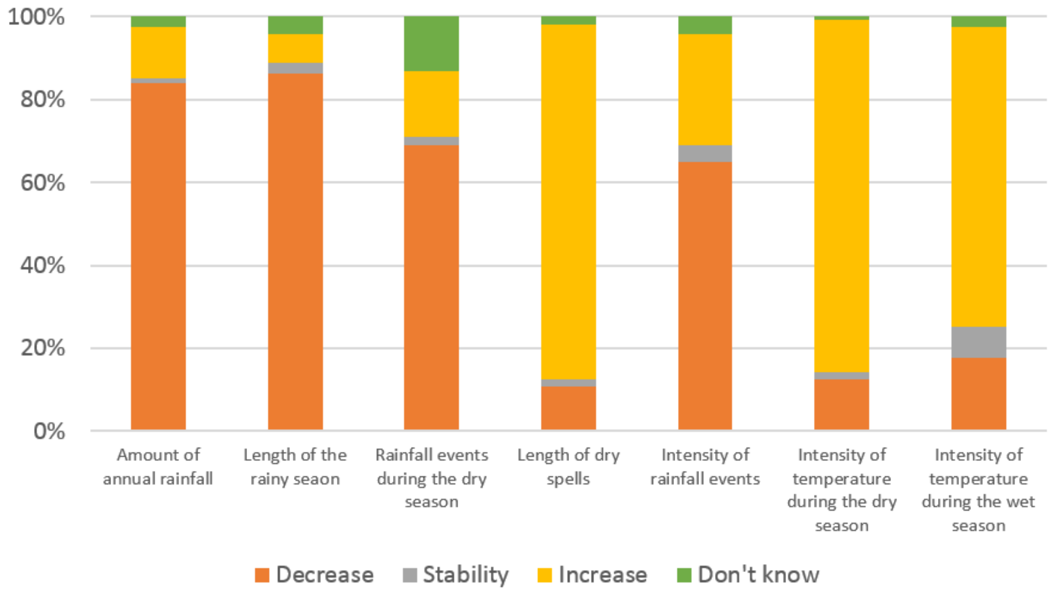


**Figure 23 - Perceptions of change in rainfall and temperature in the four surveyed sites combined (n=383)**

### *b) Changes in rainfall and temperature over the period 1988-2008*

There are few significant trends in rainfall indices over the 1988-2008 period. Only the station of Gorom-Gorom (near Oudalan) recorded significant ($p < 0.05$) positive trends for the total annual rainfall (TOTR), the average rainfall by wet day (SDII) and the annual number of days when rainfall ≥ 20 mm (R20). The stations of Gorom-Gorom and Ouahigouya (near Tougou) exhibited a moderate ($p < 0.1$) positive trend for the percentage of annual rainfall from days when rainfall ≥20 mm (R20p). Moreover, the percentage of annual rainfall from days when rainfall ≥ 10 mm (R10p) also showed a positive increase at Gorom-Gorom over the study period. These significant positive trends indicate an increase in the total annual rainfall amount and in rainfall intensity in the north of the country. At the station of Ouahigouya, the significant trend illustrates the growing importance of heavy rains in the total annual rainfall. No index has a constant sign for all the studied stations and the observation of opposite signs is common for two stations in the same region. But the fact remains that the coefficients of the slopes are not significant for most indices and stations, which indicates stability of the parameters over 1988-2008.

Contrary to the trends observed in rainfall, the trends in temperature over the period 1988-2008 are mostly significant ($p<0.05$), for the dry and wet seasons. However, there is disparity among stations because only four indices (TNds, TXds, Tds and TNws) recorded the same trend in all the regions and these positive trends were not significant for all stations. Globally the increase in minimal temperature is higher than in maximal temperature. Therefore, trends in daily temperature ranges have often been negative and more significant in the northern and southern regions than in the central zone. The increase in minimal temperature was more marked during the dry season in the driest regions (increase of nearly 2°c recorded in Dori over the study period) and during the wet season in the wettest regions (+1°c recorded in Boromo).

### *c) Comparison between perceptions and recent climate trends*

There are, globally speaking, disparities between the perceptions of populations about the changes in rainfall and recent trends calculated from 1988 to 2008, whatever the index considered (Table 3). This is most visible in the region of Oudalan for the total amount of rainfall during the wet season and the intensity of rainfall events because some recent trends of indices are very significant. In the other regions, the signs of the trends are also often in opposition to the perceptions but the coefficients of the slopes are low, which further illustrates a stability of the parameters. Consistencies between perception and recent trends are observed for the rainfall events during the dry season and dry spells during the wet season but the coefficients of the slopes are not significant. Conversely, the actual trends observed in the evolution of temperature are consistent with changes in temperature perceived by populations. The major change is an increase in mean daily minimal temperature. The mean daily maximal temperature rose too, particularly in the central region during the dry season but it is less marked than the increase in minimal temperature.

**Table 7 - Summary of the comparison between perception of change (P) and observed change (O) (+ increase; - decrease; = stability (with the sign of not significant trend in brackets); * significant at p < 0.1; ** significant at p < 0.05)**

| Perception | Meteorological index | Site 1 | | Site 2 | | Site 3 | | Site 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | P | O | P | O | P | O | P | O |
| Total rainfall during the wet season | TOTRws | - | = (+) | - | = (+) | - | = (+) | - | = (+) |
| | RDws | | = (+) | | = (+) | | = (+) | | = (+) |
| | TOTR | | +** | | = (+) | | = (-) | | = (+) |
| | RD | | = (+) | | = (-) | | = (-) | | = (-) |
| Length of the wet season | Lws | - | = (+) | - | = (+) | - | = (+) | - | = (+) |
| | Sws | | = (-) | | = (-) | | = (-) | | = (-) |
| | Ews | | = (-) | | = (+) | | = (+) | | = (-) |
| Rainfall events during the dry season | RDds | - | = (-) | - | = (-) | - | = (-) | - | = (-) |
| | TOTRds | | = (+) | | = (+) | | = (-) | | = (-) |
| | PRds | | = (+) | | = (-) | | = (-) | | = (-) |
| | Heug5 | | = (+) | | = (+) | | = (-) | | = (-) |
| Dry spells during the wet season | DDws | + | = (+) | + | = (+) | + | = (-) | + | = (+) |
| | CDDws | | = (+) | | = (+) | | = (-) | | = (-) |
| Rainfall intensity | SDII | - | +** | + | = (+) | - | = (-) | - | = (+) |
| | R10 | | = (+) | | = (+) | | = (-) | | = (+) |
| | R10p | | +* | | = (+) | | = (+) | | = (+) |
| | R20 | | +** | | = (+) | | = (-) | | = (+) |
| | R20p | | +* | | +* | | = (+) | | = (+) |
| | RMax | | = (-) | | = (-) | | = (+) | | = (-) |
| Intensity of temperature during the dry season | TNds | + | +** | + | +** | + | = (+) | + | +** |
| | TXds | | = (+) | | +** | | +** | | = (+) |
| | Tds | | +** | | +** | | +** | | +** |
| | ATds | | -** | | = (-) | | = (+) | | -** |
| Intensity of temperature during the wet season | TNws | + | +** | + | +* | + | +** | + | +** |
| | TXws | | = (-) | | = (+) | | = (+) | | = (-) |
| | Tws | | -** | | = (-) | | = (+) | | -** |
| | ATws | | -** | | = (+) | | -* | | = (-) |

### *d) The intention to migrate in response to climate change*

More than 45% of households have members who were engaged in temporary migration at the time of the survey in 2008 and nearly 14% of households had permanent migrants. In total, 28 households (7.3%) had both permanent and temporary migrants and less than half of households (48.3%) had no migrant member. Poverty was the leading cause of migration mentioned by respondents (78.1%) while rainfall deficit was stated by only 1.6% of households.

For 53 household heads (13.8%), migration was seen as a positive impact of climate variability. Increase of income is the most important aspect mentioned by populations but money transfers and the acquisition of knowledge that can be implemented in the origin area are other positive effects of migration (Cissé et al., 2010). It is also a mean to reduce pressure on households' resources (Roncoli et al., 2001). On the other hand, 40 household heads (10.4%) considered that migration is a negative impact of climate variability. Because of adverse climate conditions, farmers have to migrate despite their desire to remain in their own communities (Barbier et al., 2009). Loss of labor force in the community of origin and acculturation are the main negative points of migration (Rasmussen et al., 2012).

In response to future changes in rainfall, migration is rarely the first adaptation strategy stated by population but the intention to migrate occupies an important place. In case of drought, the populations plan first to sell livestock and to decrease food intake but households generally mentioned several strategies. Migration is cited as the first strategy by 12.7% of the surveyed population and, in total, 17.5% of the respondents have the intention to resort to temporary migration in response to a drought. In the case of a drier climate, the two first strategies planned by populations are to seek new crop varieties and to sell livestock. About 10% of the respondents mentioned temporary migration and 26% permanent migration; these would be the first strategy respectively for 7.8% and 6.9% of households. The intention to migrate is lower in response to a wetter climate since only 2.4% and 1.6% of the respondents claimed that they would migrate temporarily or permanently. It is the first strategy for less than 1% of the households. Seeking new crop varieties and increase the cropland area would be the main strategies adopted in this case.

Counting only once the people who answered positively to both questions about the intention to migrate temporarily in a situation of rainfall deficit (drought and/or drier climate), 28.5% of the respondents planned to adopt this strategy. This figure increases by 13% taking into account the intention to migrate permanently in response to drier climate. So, in all, 41.5% of the respondents planned to migrate if rainfall conditions worsen in the future.

#### *e) Modelling the intention to migrate in response to climate change*

Results of logistic regressions show that the intention to temporarily migrate in the case of drought (M1) and to permanently migrate in response to a drier climate (M3) is 4 to 5 times higher ($p < 0.05$) in the drier regions (Oudalan and Tougou) than in the region of Dano (the wetter region). There is no significant difference in the intention to temporarily migrate in response to a drier climate (M2) between regions. In terms of socio-economic features of the households, for respondents who already had members in temporary and/or permanent migrations the intention to temporarily migrate in case of drought and permanently in response to drier climate is lower ($p < 0.05$). Moreover, the more items of expenditure per household, the less the head of household planned to temporarily migrate in response to a drier climate ($p < 0.05$). Variables of perceptions played no part in the intention to migrate due to changes in rainfall. It could be explained by the fact that there is a little variability in response about perceptions. Concerning migration intentions' relationship with positive or negative impacts of climate change on activities and natural resources, results showed that household heads who have stated positive impacts on climate change of agriculture have less intention to migrate in response to drought ($p < 0.1$). Positive impacts included improving farming techniques and the construction of anti-erosion dikes that are other adaptation strategies used by rural population. Some farmers also mentioned the increase in agricultural productivity and the livestock sales at higher prices as positive impacts of climate change. These people are less likely to migrate in response to drought than the others ($p < 0.1$). Moreover, households that consider climate change to have a positive impact on solidarity are 6 times more likely to temporarily migrate in case of drought ($p < 0.05$). Finally, perceiving climate change to negatively affect water resources is linked to the intention to migrate (odds ratio: 4.1, $p < 0.1$). This variable is also significant in the third model (M3) with an odds ratio of 3.2 ($p < 0.1$). In this case, people who consider climate change to have negative impacts on solidarity have less intention to leave permanently if the climate becomes drier. For the second model (M2), no variable of impacts had a significant effect.

#### 3.3.1.6 Discussion

***a) Similarities and differences between change perceptions and the actual trends***

Our results show a good fit between perceptions of changes in temperature and actual trends calculated over the study period. It complements the results obtained in previous studies about rainfall (Mertz et al., 2012), it is consistent with results recently obtained for the Sahel during the 1960-2010 period (Mouhamed et al., 2013) and confirms the IPPC predictions about an overall temperature increase between 0.7°C and 3.5°C in Africa by 2050 (Juana et al., 2013). The perceptions of change in rainfall are not consistent with the observations over the same period but match results obtained in previous studies, even if the used methodology to study perception varies from one study to another (Nielsen & D'haen, 2014). The main point that differs from previous studies is that perceptions of change seemed, in the present case, somewhat more pronounced in the wetter region (Dano and Ziga).

Several factors can explain the differences between the perceptions of changes in rainfall and the rainfall observations highlighted in the present study. The first comes from the fact the rainfalls are highly variable in space (Hulme, 2001; Sivakumar & Hatfield, 1990). It can rain in one village while another 5 km away remain dry. Hence, the use of data from exactly the same spot when comparing perceptions with actually trends would be more relevant. Secondly, a period of twenty years is short to detect trends in temporal series. Thirdly, climate indices were relatively stable over the period 1988-2008 in comparison with trends over the long-term or with trends over other short periods, notably the 20-year dry period 1970-1989 (Lebel & Ali, 2009). If respondents had no good points of reference for considering only the recent period, it is possible that they were influenced by the fact that they intuitively found the weather better in the past (Mertz et al., 2012). Moreover, the household heads responding to the questions may think that painting a gloomy pictures of the environment could attract funding for local projects (Nielsen et al., 2012). Another explanation can lie in the fact that perceptions may be strongly influenced by media stories that tend to focus on negative developments in the environment (Mertz et al., 2012). Finally, it is likely perceptions of populations are probably not a reflection of changes in rainfall in the climatic strict-sense but are rather influenced by the trends observed in socio-economic conditions during the same period of time. This is supported by the conclusions drawn by Roncoli and colleagues suggesting that farmers think about rainfall as a process rather than a quantity (Roncoli, 2006). The data of the socio-economic survey used in the present study show that nearly 75% of the respondents reported negative impacts of these changes on agriculture and 65% on breeding over the study period even if grain yields have been increasing during this period. Other factors than climate changes, such as population growth and environmental degradation, contribute to hindering socio-economic activities and to worsening living conditions (Rasmussen et al., 2012). Nonetheless, the overwhelming agreement for some of the response categories does call for concern about the environmental conditions (Mertz et al., 2012).

***b) What could be the importance of migration as an adaptation strategy in response to future climate change in Burkina Faso?***

Human movements are very common in the study region; more than the half of the households had migrant(s) at the time of the survey, mainly in temporary migration. With only a small proportion of these migrants leaving because of the rainfall deficit (<2%), it confirms that climate *per se* is seldom the direct root of migration but it clearly can exacerbate difficult living conditions at the margin of subsistence (Barrios et al., 2006). The results of our study show that more than 40% of the respondents planned to migrate if rainfall conditions worsen. This figure is high and indicates that future migration might be more often directly explained by climate change in the next decades. Moreover, our study shows that populations will probably not wait until a severe drought or for a significant drier climate to migrate since they already perceive significant climate change not confirmed by the objective data. The vulnerability of rural dwellers in the region is constantly increasing because augmenting pressures of several types (demographic, environmental) (Müller et al., 2014). For example, rapid population growth is reducing land per capita ratios, and low yields for staple crops hinder food security (Naylor et al., 2011). Consequently, it is increasingly difficult for people to find strategies that allow them to maintain their standard of living in their village and their resilience to future climate variability decreases gradually. Their ability to absorb an actual climate shock such as a severe drought or, as is increasingly seen in this region, a flood also decreases.

In a recent study, Warner and Afifi (2014) distinguish four patterns of response to rainfall variability by migration: (1) households that use migration to improve their resilience, (2) households that use migration to survive, (3) households that use migration as a last resort and (4) households that cannot use migration and are struggling to survive in their areas of origin. It is wise, therefore, to keep in mind that there is a difference between having the intention to migrate and actually migrate. Some people who intended to migrate at the time of the survey may change their mind or may be prevented due to financial or political constraints. On the other hand, some people who did not intend to migrate at the time of the survey might be forced to do so in the future. According to a study from the northern part of Burkina Faso, facilitating migration appears last in the farmers' ranking of policies perceived to improving their current situation, the top three being agricultural credit, irrigation and food aid (Zorom et al., 2013). However, policy is different from personal intention. Particularly migration policies are unpopular because it looks like a recognition of defeat. The present study hence calls for longitudinal research to see if and when migration intentions become actions.

Our study confirms results of empirical work on environmental migration done in the region. Cyclical intraregional migration as an adaptation strategy to seasonal rainfall variability has long been practiced (Cordell et al., 1996; Rain, 1999) and can be expected to continue (McLeman, 2013; Rasmussen et al., 2012). But the obtained results shed new light on migration patterns. The socio-economic survey showed that in case of a drier climate, permanent migration could become more important than temporary migration (26% vs 13.1%). The results showed this trend most clearly for drier regions but it was observed across all regions. It is important to distinguish between temporary and permanent migrations. Permanent migration means leaving house, land and many relatives. In some cases, they generate significant remittances to the relatives stayed in the origin area and positive impacts in zone of destination as in Ivory Coast, with the cocoa boom. But it might also generate a variety of difficulties in the area of destination including conflicts. Moreover, this type of migration risks to substantially increase the size of populations in the cities (as these are often migration destinations) already struggling to absorb population growth. In-formal housing in inappropriate areas (coastal zones affected by erosion, flooded areas) are often a result (de Sherbinin et al., 2012; Ould Sidi Cheikh et al., 2007).

#### 3.3.1.7 Conclusion

This study sheds new light on the links between climate change and migration because it is based on subjective data: the perceptions of climate change and intentions to migrate in response to future change. Results showed pessimistic perceptions of climate change by the surveyed population over the period 1988-2008. This is consistent with previous studies from the sub-region, but these perceptions are generally not confirmed by the analyses of rainfall data. Several reasons have been put forward to explain these differences, primarily including the overall long-term evolution of the climate and lower socio-economic conditions due to other co-occurring climate change factors (demographic pressure, environmental degradation). While researchers often consider the effects of climate change on the migration, this study highlights the importance of taking into account populations' perceptions of climate change as it affects their adaptation responses. In total, 41.5% of the surveyed people claimed to have the intention to resort to temporary or permanent migration if the rainfall conditions worsen. This shows that migration in direct response to climate change could increase in the future. More than 25% of the respondents had the intention to permanently migrate in response to a drier climate. This might lead, as indicated by our results, to a change in migration patterns, from predominately temporary to more permanent. Moreover, knowing that most of the respondents already considered degradation of rainfall conditions over the period 1988-2008, while it is not clearly observed in the climate data, a significant increase in migration could occur faster than expected, if climate predictions hold. We conclude that, in the coming decades, because of climate change and its array of impacts, the magnitude of human displacements could change but also the patterns of migration.

### 3.3.2 Senegal

#### 3.3.2.1 In a nutshell

**"The fish migrate and so must we": The relationship between international and internal environmental mobility in a Senegalese fishing community**

I. Inquiry into international South-South labour movements related to environmental change in West Africa
II. Inquiry into the impacts of international migration on internal movements in the Saint-Louis region of Senegal
III. Findings:
   1. International labour migration provides livelihood diversification and income maximization in response to local fish stock depletion, while internal relocation is a response to coastal erosion
   2. The poorest and most vulnerable benefit less from remittances from international migration and are therefore less protected from sea-level rise
   3. International mobility mainly serves as a long-term adaptation strategy for the wealthiest, while future sea-level rise will exacerbate the vulnerability of those that are unable to organise their relocation

#### 3.3.2.2 Introduction

One of the most frequently discussed human aspects of climate change is its potential for massive human displacement and what has been termed 'climate refugees' (McTegart et al. 1990; Myers 2002; Stern 2007). Estimates of the people at risk of displacement in the future, although widely debated and challenged in academic circles, proliferate in public and political discourse (Gemenne 2011). Often population movements in developing countries instigated to some degree by climate change and other forms of environmental transformations are framed in terms of victimization and/or as posing security threats to developed countries. Firstly, this belies the fact that much human mobility related to environmental degradation involves labour migration due to decreasing livelihood sustainability. Migration can therefore act as a means of adaptation to climate change through diversifying household livelihood strategies, decreasing pressure on local resources, or facilitating social remittances (Barnett and Webber 2010; Black et al. 2011), much like other forms of voluntary migration, even if numerous obstacles may impede it from reaching its full potential (McLeman and Smit 2006).

Secondly, much environmental degradation results in South-South mobility, rather than movements from the Global South to the Global North (Schellnhuber 2010). The waves of 'climate refugees' threatening European and other Western countries' security portrayed in the media do not account for the fact that migration requires some degree of capital (human, social, and financial), especially for traversing long distances across national borders. Moreover, in regions such as West Africa, intra-regional mobility (environmental or otherwise) is much more statistically significant than intercontinental migration. Examining environmental mobility between South-South countries is therefore necessary to understand current migratory dynamics associated with areas affected by environmental changes as well as for projecting future scenarios of climate change-related mobility.

Thirdly, the importance of internal mobility within affected countries has not been adequately depicted in public discourse, even as disaster displacement is often confined within the borders of the affected nation-state. While migration and refugee studies often focus on international impacts, such as the Nansen Initiative's focus on disaster-induced cross-border displacement, internal mobility responses to environmental degradation must equally be considered if one is to adequately understand the impact of environmental changes, slow-onset or sudden disasters, on population dynamics within a nation-state and to create appropriate policies including integrating environmental mobility within National Adaptation Plans for Action (NAPAs).

Lastly, focusing on either internal or international migratory responses to climate change and other forms of environmental degradation can obscure the relationships between the two – including how one may facilitate the other. Adaptation to climate change is often considered in terms of the benefits for migrants themselves and, to a lesser extent, for the families 'left behind' in the community of origin. This separation between the study of internal and international mobility is reflective of a gap in migration studies more generally, whose empirical and theoretical frameworks tend to only analyze one form of migration without simultaneous acknowledgment of the other (King and Skeldon 2010).

In recognition of these tendencies and gaps, the goals of the following paper are to examine international South-South labour movements related to environmental change in the highly mobile region of West Africa, and also to demonstrate how international migration impacts internal movements in the Saint-Louis region of Senegal. Rather than taking a victimization approach or strictly examining human displacement, this case study integrates international labor migration from Saint-Louis to Mauritania with the associated internal relocation of households within Saint-Louis. In doing so, it therefore calls for future theoretical and empirical frameworks that incorporate both international and internal mobility, assess the transnational impacts of environmental migration on the country of origin including their potential to facilitate local adaptation, and that do not attempt to isolate environmental changes from other drivers of migration (economic, social, demographic and political) (Black et al. 2011).

#### 3.3.2.3 Environmental changes as migration drivers

West Africa has the highest number of mobile peoples of any region in the world. According to the bilateral migration matrix developed by the World Bank (2010a), over 58% of migration flows take place within the region. The importance of intra-regional migration in West Africa can be partly attributed to the establishment in the late 1970s of an area of free movement of people within the Economic Community of African States West (ECOWAS). Immigration in West African countries is mostly from neighbouring countries (World Bank 2010b). In fact, it is the only region of Africa where intra-regional migration is greater than outward migration (34.5%, mainly to Europe) (Ndiaye and Robin 2010). With some 8.4 million people, West Africa also has the largest stock of migrants of any sub-region in the world (UN DESA 2009). In addition to its high intra-regional mobility rates, West Africa is one of the most pertinent regions in which to examine the mobility impacts of climate change. From the Sahel to its coasts, it faces sea level rise, soil salinization, floods, drought, desertification, intensifying winds and heat waves (IPCC 2014; DARA 2013).

The country of Senegal is no exception: the Senegalese population has a long history of internal and international migration of varying sorts, especially marked by movement for labor and economic reasons (Diatta and Mbow 1999). Senegalese people have come to constitute significant migrant populations in a number of European countries, including Spain and Italy, as regular and irregular labour migrants, students, professionals, etc. However, many Senegalese mobility patterns are also intimately intertwined with transformations to the natural environment in various regions of the country, from drought and desertification to flooding and coastal erosion. While it is difficult if not impossible to neatly isolate the influence of slow-onset environmental changes from political, economic, social and demographic factors (Black et al. 2011), the expected changes to the physical environment due to climate change will certainly play an increasing role in shaping migratory dynamics in the decades to come. Senegal's vast experience with man-made and climate change-related environmental degradation and projected impacts in tandem with its history of inter-continental, intra-regional and internal migration makes it an ideal site for the study of environmental mobility patterns and their impacts on adaptation.

Environmental migration can be witnessed across Senegal, from displacement due to flooding and in migration patterns associated with slow-onset changes. The Senegalese coastline is threatened by climate change impacts of coastal erosion, sea level rise, flooding, soil salinization, and increasing storm surges (Salem 2013). These environmental changes threaten the livelihoods of the approximately 600,000 people directly or indirectly working in the Senegalese fishing industry (FAO 2008), augmenting and diversifying existing mobility patterns, yet fishing communities have received scant attention. Although many regions provide useful contexts of study, this case study specifically targets the city of Saint-Louis. The Saint-Louis region of Senegal is one of the most environmentally fragile in the country. In 2008, UN-Habitat designated the Saint-Louis the "the city most threatened by rising sea levels in the whole of Africa" (BBC 2008). The Langue de Barbarie on the northwest coast of the country faces concomitant sea level rise, coastal erosion, soil salinization, maritime storms and depletion of fish stocks and biodiversity (IPCC 2014). Additionally, the opening of a breach in 2003 had disastrous effects for rural villages in the southern part of the Langue de Barbarie, with many villages being destroyed. While entire rural communities were displaced because of this government initiative (Tacoli 2011), which was amplified due to climate change, the northern urban portion of the island experiences the most directly visible impacts of climate change. Saint-Louis consists of three primary geographical sites, the western-most being home to its fishing industry and also the most threatened by concomitant economic, demographic and environmental pressures. In terms of the environment, the people of Guet Ndar, a busy, densely populated fishing quarter, are coping with environmental challenges on two fronts: on one hand, coastal erosion and storms have destroyed sea-front homes, displacing locals, and, on the other, overfishing and climate change's maritime impacts are making local artisanal fishing, the main source of income for the population, more difficult as a livelihood strategy. Compounding local vulnerability, the quarter is one of the most densely populated districts in all of West Africa, with more than 25,000 inhabitants occupying an area of 1 km long and 300 m wide according to regional statistics (CLUVA 2013; Ateliers 2010). These various stressors have resulted in both international and internal mobility out of Guet Ndar. As we shall see, some of these mobility patterns reflect and have intensified longstanding migration routes while others have been created in response to the local population's increasing vulnerability on a number of fronts.

**Figure 24 - Map of Saint-Louis (source: Google Earth)**

#### 3.3.2.4 Methods

In order to investigate the relationship between international and internal mobility related to environmental drivers and particularly climate change (without dismissing the importance of other factors), a qualitative case study was performed over a five-week fieldwork during the summer of 2014 in and around Saint-Louis, Senegal. Data was collected in the Langue de Barbarie in both rural and urban locations, however the majority of fieldwork was concentrated in the urban fishing quarter of Guet Ndar and its neighbouring quarters of Santhiaba and Goxum Bacc. These quarters were selected over rural environments in the southern part of the island after initial investigation based on their more visible struggles with climate change, rather than the aforementioned breach opening in 2003. The study targeted these areas not only for their location on the frontlines of coastal erosion, but also because of their economic reliance on natural resources, specifically the maritime environment. Along with an extensive literature review and document analysis of existing evidence on West African mobility, the primary tools of investigation were 40 qualitative, in-depth interviews[11] as well as focus groups with fishermen (migrant and non-migrant) and women working in the local fishing industry. Additional interviews and consultations were conducted with researchers, NGO representatives and community and association leaders in Saint-Louis and with experts based in Dakar.[12]

Semi-structured interviews covered themes of local challenges (environmental or otherwise) facing the people of Guet Ndar and its surrounding neighborhoods, their causes and the coping

[11] Interviews with experts were conducted in French while interviews with local populations were conducted with the help of a local Wolof translator.

[12] The USAID project COMFISH operating in Guet Ndar and the GERM laboratory of the University of Gaston-Berger led by Prof. Aly Tandian were vital in providing access and information in the conduct of fieldwork.

strategies currently implemented by households; migration histories, intentions and motivations; and the relationships between mobile and immobile members of households. This qualitative data was then complemented with local geographers' assessments of environmental transformations and future threats.

#### 3.3.2.5 International and internal mobility responses to environmental degradation

***Differentiated vulnerability and migratory responses***

Although Guet Ndar accounts for a relatively small geographical portion of the city of Saint-Louis, and it has a homogenous economy in that nearly all residents rely directly and/or indirectly on the fishing sector, Guet Ndarians have differentiated vulnerability to the impacts of climate change and migration capacities. Several variables affected individual and household vulnerability levels, including proximity to the coast, age, gender, and socio-economic status. In turn, these factors contributed to different mobility responses.

In terms of geography, households located nearest to the ocean were clearly more vulnerable to storm surges and coastal erosion. Many of these homes have been either partially or entirely destroyed in the past few years. These respondents also perceived coastal erosion to be a more imminent threat in contrast to their neighbours in the central and eastern parts of the island, who were more concerned by the economic impacts of diminished local fish stocks than coastal erosion. These perceptions of vulnerability were crucial for migratory responses and intentions in that coastal homes, if not already in the process of relocating or building a second home elsewhere, felt an urgent need to move. One respondent's home – in which dozens of family members of multiple generations resided – had already been partially destroyed and thus reported losing sleep because of the waves crashing against the remaining portions of the family home (See Figure 25 below).

**Figure 25 - Partially destroyed home in Guet Ndar, Saint-Louis[13]**

Aside from the geographical location of households, age also affected vulnerability and migratory responses. As has been established elsewhere (Patwardhan et al. 2007), the elderly are often amongst the most vulnerable populations to environmental changes because of their limited

[13] All photos were taken by the author, C. Zickgraf.

physical capacity to move for example, but also to directly support their households as wage-earners when confronted with the economic impacts of environmental degradation. Retired fishermen often depended exclusively on their sons' and wives' incomes (women's retirement occurred often much later in life than their men's), even if it was they who in fact own their pirogues (fishing boats). Even those older but active fishermen were limited in their ability to garner livelihoods from fishing. The physical capacity necessary to navigate rough seas and perform sea-based fishing over long periods meant that oceanic fishing was considered the task of the young. As fishermen aged, they transitioned to river fishing and eventually retiring by their early 50s. On the other hand, young boys started fishing locally around nine to ten years old, with some fishing internationally already by age 13 or 14.

Gender-wise, men were much more mobile than their female counterparts, leaving women more vulnerable to local impacts of climate change than their spouses and other male relatives. While it is indeed true that many women were immobile thanks to their positions as the managers of the family home and guardians to young children, many Guet Ndarian women are active in the local fishing sector. The two primary occupations of women are first as 'transformatrices'[14] (the women who process fish by salting, curing or smoking) and as 'mareyeuses' (fish vendors in the local market). With coastal erosion exacerbating an already overcrowded district, women's local workplaces continue to shrink. Because of their land-based occupations in tandem with their household responsibilities, the women of Guet Ndar are highly vulnerable to the effects of climate change economically as well as residentially. Unlike their male fishermen counterparts, most do not see migration as a viable option to improve their livelihoods.[15] Many women as well as the elderly thus rely on the remittances sent by their active male household members to constitute or supplement household income.

***International migration***

As the elderly and women were typically less able to leave Guet Ndar even for short periods to engage in labour migration, international migrants were almost exclusively active, young fishermen. The fishermen of Guet Ndar have long-been a highly mobile people, moving seasonally along the coasts of West Africa in pursuit of the best catches to maximize household income. Retired fishermen frequently reported having worked in Mauritania, Guinea-Bissau, Guinea, The Gambia, Sierra Leone and Liberia in addition to other parts of Senegal throughout their careers. Most fishermen however migrated seasonally and returned to Guet Ndar to fish locally for at least part of the year, taking the summer months off (during the reproductive season for fish). Labour migration from Guet Ndar has therefore always been intimately intertwined with the patterns and changes in West Africa's maritime environment. However, accelerated environmental degradation has transformed and exacerbated fishermen's migration patterns and extended their duration significantly, with very few active people living in Guet Ndar year-round. A decline in local fish stocks and a decrease in maritime bio-diversity around Saint-Louis has pushed artisanal fishermen farther out into the ocean (increasing the dangers with rougher seas), but especially northward up the Mauritanian coast. On one hand, the diminishment of local livelihood sustainability has been caused by overfishing in Senegalese waters, with local fishermen affected by the harmful practices of licensed and irregular foreign vessels that arrive from places such as the EU[16], Russia and Korea, whose trawling often indiscriminately picks up fish that are traditionally left in the waters, for example by catching fish before full maturity and therefore harming reproduction (Sall and Morand 2008). On the other hand, changes in maritime currents

[14] This profession is almost exclusively female.

[15] There were a few reported instances of women migrating with their husbands to Mauritania to either manage large houses of Guet Ndarian migrants or to process fish.

[16] S. Lafranière, "Europe takes Africa's fish, and boatloads of migrants follow", *New York Times,* 14 January 2008. http://www.nytimes.com/2008/01/14/world/africa/14fishing.html?pagewanted=all&_r=0

and temperatures have also affected available fish stocks and diversity, with attainable fish being of lower valuable such as sardines rather than the more lucrative White Grouper (*Thiof*) previously more widely available in Senegalese waters. Together, these environmental transformations make it less and less feasible for fishermen to stay and work in Guet Ndar even seasonally.

Relying on their sector's historical mobility, Guet Ndarian fishermen engage in international migration southward to Guinea-Bissau but the vastly dominant migration trajectory is northward to Mauritania, especially in the last ten years (Sall and Morand 2008). Mauritania, without a strong traditional fishing history of its own, has seen a swell in the sector, including the establishment of factories in Nouakchott and Nouadhibou. Without skilled national fishermen, it relies on its more experienced neighbours to the south to provide its labour force.[17] The location of these factories in Nouakchott and Nouadhibou makes these cities the primary destinations for Guet Ndarians and other Senegalese (see Figure 26).

**Figure 26 - Senegal-Mauritania Map with Key Migration Destination (author's elaboration from source: Google Earth)**

The primary migration path amongst Guet Ndarians is to work with such Mauritanian factories through contract-based labor. Representatives from the factories are sent to recruit in fishing communities, especially Guet Ndar, relatively nearby and well known for its skilled fishermen. Local fishermen easily obtain contracts with the factories, which also provide upfront costs for equipment such as nets and motors – a great incentive for Guet Ndarians who struggle to obtain financial credit in Senegal for such equipment because of their unreliable income and high interest rates. However, as they are paid based on their catches, which cannot be guaranteed, many artisanal fishermen quickly become heavily indebted to the factories and then must work off their debt before seeing much, if any, profit and extending the duration of their migration often far beyond initial expectations.

[17] At least one Mauritanian is required on each fishing boat, but respondents reported that they were rarely involved in fishing and only present on the boat to satisfy authorities.

The preferred migration pattern is in fact to obtain one of 300 licenses granted to Senegalese fishermen each year (recently increased to 400 in December 2014), who after a period of 15 days fishing for Mauritania are allowed to bring back their catches to sell in Senegal.[18] These licenses, however, are hard to come by, especially considering the high demand and boom in the number of Senegalese and other West African *pirogues* in recent decades (Sall and Morand 2008). Some fishermen who were unable to obtain one of the licenses cross into Mauritanian waters illegally and bring fish back to Guet Ndar. This migration, however, is a dangerous one, especially considering the history of conflict between the two countries (Parker 1991). Even fishermen granted licenses reported abuse and corruption among the fervent Mauritanian coast guard, but those caught without licenses reported being beaten, jailed, heavily fined and having their materials confiscated. These abuses caused some fishermen to stay in Guet Ndar, preferring to cut their household expenditures including food for their families rather than to risk their safety in Mauritania. However, most respondents and relatives of respondents, unable to support their large families locally, unable to get licenses for circular migration, and unwilling to risk life, limb and income to fish irregularly, saw long-term migration to Mauritania through contract labour as their best option. This type of migration, a rarity in the past, has become the new normal among Guet Ndarian men. While some men moved to Mauritania for three weeks to three months at a time (especially to the closer destination of Nouakchott), most respondents would travel to Nouakchott and Nouadhibou with their male relatives working the same pirogues or in pairs of pirogues, live in fishermen's camps or rented homes with dozens of other Guet Ndarians, work for factories for anywhere from ten to eleven months, and then return to their families only for Muslim holidays of Korité and Tabaski, when able. Despite the longer term nature of migration to Mauritania, Senegalese respondents and their kin in Guet Ndar did not report investing in homes in Mauritania. Although vacation was the only time many returned to their home city, migrants themselves conceived of their migration as temporary rather than permanent.

***Internal migration***

Environment-related human mobility amongst Guet Ndarians is not, however, limited to male-dominated international labour migration. At the same time that local livelihoods are threatened by fish stock degradation, the very land that comprises Guet Ndar is subjected to coastal erosion and storm surges. To the east, Guet Ndar is limited by the Senegal River, while to the west it borders the Atlantic Ocean. The oceanic coastline has progressively retreated over the past years, and now rubble where front-line homes once stood lines the shores. Some households in this area of Saint-Louis are partially protected by an old colonial French seawall, but further north, newer neighbourhoods such as Goxum Bacc have no such protection, increasing their vulnerability to the impacts of climate change and man-made erosion. Without government assistance, families build makeshift barriers in front of their homes consisting of sand bags, netting, and remnants of destroyed structures. Although sand is no longer allowed to be taken for building projects elsewhere in the island because of the recognized exacerbation of erosion, without alternatives families living on the 'front lines' continue to quarry sand to stabilize their homes with sand bags despite the environmental harm (see Figure 27 below).

[18] Under the December 2014 agreements, Senegalese crews are allowed to capture up to 50,000 tons each year. 12 tons must stay in Mauritania.

**Figure 27 - Sand bag barriers stabilized with old fish netting. Goxum Bacc, Saint-Louis, Senegal.**

However they perceived the imminence of the threat to their own households, nearly all respondents recognized that sooner or later the sea 'would arrive'. As one woman reported, "One thing is certain, in forty or fifty years, the sea will meet the river and Guet Ndar will disappear". Historically, however, leaving Guet Ndar permanently was out-of-the-question culturally. Most of Guet Ndar consists of traditional family homes that house multiple generations with up to 30 people living in one place. These ancestral homes are passed down and it is considered essential that they are maintained. Therefore, it was taboo for people to move out of Guet Ndar, even with the extreme and growing demographic pressures. Moreover, the seaside location of the neighborhood is practically and culturally significant. A community defined by its links to the sea, moving away from the ocean, storing boats out of sight, and living on the mainland seemed unfathomable to many in the past. As their cultural attachment to their land is strong, so too is their attachment to fishing. Few moved out of the fishing industry, especially after the 2008 crisis when fishermen reported that at least in fishing their children would be able to eat. However, while attachments to land remain strong, the recognition of potential displacement has shifted local mentalities towards relocation. Without giving up their traditional homes, many respondents had either completed or begun the process of building another 'back up' home outside of Guet Ndar in response to both overcrowding (exacerbated by coastal erosion) and the encroaching sea. This relocation was often to Hydrobase, south of Guet Ndar on the Langue de Barbarie, or to neighbourhoods on the mainland, a 10-minute drive to the ocean.[19]

International labour migration provided livelihood diversification and income maximization in response to local fish stock depletion whereas internal relocation was motivated by coastal erosion, but the former was deeply connected to the latter. Some Guet Ndarians were able to fund their home-building projects outside of their neighbourhood thanks to their higher levels of financial capital: those who, for example, had made significant profits as owners of local businesses, the proprietors of boat fleets who did not themselves need to migrate but rather benefited from the fishing of others or from their facilitation of Mauritanian recruitment contracts. Mauritanian recruiters, in fact, required local go-betweens to locate fishermen and negotiate their contracts because of their social connections. These middlemen were often

[19] Commuting experiences in Mauritania lessened the cultural aversion to commuting to the sea amongst migrant fishermen.

trusted, older community members. Earning money from local businesses or from this practice gave them enough income to build their second homes outside of Guet Ndar. Income earned locally directly from fishing was rarely significant enough to fund building projects. International labour migration was therefore crucial because of its remittance potential to facilitate internal household relocation.

The ability to utilize remittances for adaptation to environmental transformations in the form of relocation, however, was far from homogenous. "All fishermen are not equal," reported one person. In fact, it was those fishermen who already had significant capital that benefited the most from remittances. These men were the owners of the largest fishing pirogues (25m), typically two or more that fished in tandem. Some owned multiple 'fishing teams' consisting of their male relatives but also who hired non-kin to work their boats. The size of the pirogues and their fishing techniques allowed them to bring in much larger catches than their smaller counterparts. This, in turn, boosted their earnings, and therefore their remittances. These men were the first to leave Guet Ndar and their housing projects were completed in the shortest timeframe.

As the size of the boats decreased, so too did the remittance potential of migrants. For migrants with lower levels of capital, money sourced from Mauritanian migration was sent back to households in Guet Ndar, and depending on the sum, would be saved until a plot could be purchased, after which homes were slowly built over a period of years through the accumulation of migrant remittances. Even still, this was only attainable for the middle- to upper- earning fishermen. Those with smaller boats and/or without ownership were often those with the lowest socio-economic status to begin with. Migration for these fishermen could still result in remittances to their families in Guet Ndar, but remittances were rarely enough to put towards home construction. The first priority for these men was to provide for the immediate security of their households – including their wives, children, as well as their parents and other extended kin – in the form of food, water, and other basic expenditures. Remittances were used to cope with the economic struggles of their families because of diminished returns in Guet Ndar, but were not able to cover the purchasing of plots, construction materials or labor costs despite a desire to move elsewhere. In addition to their limited profits (if any depending on their catches), incomes earned in Mauritania had to be exchanged into local currency in Senegal (CFA). Respondents complained that their low wages in Mauritania (some referring to it as a form of slave labor or indentured servitude by Mauritania factories, in which they could never escape their accumulated debts) were further diminished by the unfavorable exchange rate. Those fishermen able to obtain licenses to fish in Mauritania and then return with catches to Senegal, moreover, battled with corruption and abuse by the Mauritanian coast guard. Even as the 'lucky few' who were licensed, the fines and confiscation of fishing equipment could wipe out any profit made during circular migration.

In effect, while remittances gained through labor migration could increase the adaptation capacity of households in the country of origin by enabling internal mobility, this was only the case for the wealthiest of non-migrant and migrant households. Although some benefitted from the migration industry either as migrants or as non-migrant middlemen, for the most vulnerable Guet Ndarians migration could increase the resilience of local households to environmental degradation only as an immediate coping strategy but not as one that could create long-term protection from coastal erosion. Without government assistance to mitigate local effects of climate change or to protect migrants from abuses and exploitation, international migration in response to environmental and economic pressures will not facilitate internal mobility for the poorest and most vulnerable households but will rather benefit the wealthiest and least vulnerable.

#### 3.3.2.6 Conclusions

Driven by concomitant residential destruction due to coastal erosion and economic strife caused by maritime resource degradation, urban fishermen and their families are highly vulnerable to the current impacts of climate change, which will only augment migratory pressures in the future. In order to protect these coastal populations, firstly local and national governments must intervene to mitigate the effects of climate change insofar as possible and to help communities adapt, whether in situ or through internal and international mobility. As is, outside of makeshift barriers, departure is often seen as the only solution for those who have the capacities to do so. Environmental degradation is already significantly influencing both internal and international mobility patterns in Saint-Louis, especially among fishermen along the coast. However, Guet Ndarian households' vulnerability varies and so does their capacity for migration and resilience. Even within local populations affected by the same climatic threats, their vulnerability and likelihood to migrate is affected by their socio-economic status (with those having some form of financial and social capital more able adapt locally and/or through migration), their dependence on natural resources, and their demographic characteristics (age, gender, etc.). Active fishermen are able (if not always willing because of precarious conditions) to move up the coast in order to sustain their livelihoods, while those who are retired, elderly, whose occupations are land-based and women are less able to enact migration as an adaptation strategy and therefore rely on household members' labour migration to provide or supplement household income.

But while most fishermen are able to embark on international labour migration in one form or another (whether with contracts, with licenses or irregularly), only the most successful fishermen are currently able to relocate their families within Senegal. These migrants, however, are already classed among the richest households in Guet Ndar in terms of human, social and economic capital. The case of Guet Ndarians therefore demonstrates the importance of integrating livelihood strategies and socio-economic status variations into vulnerability and resilience assessments and local, national and intra-regional adaptation plans, but also in examining the potential of migration to increase the adaptive capacities of households in the countries of origin. Policies and government initiatives must also make relocation available to the most vulnerable households, those in imminent danger of displacement, and those without the capital to move out of harm's way.

Lastly, the enmeshment of internal and international mobility patterns exposes the importance of addressing environment-related population movements holistically and integrating local and regional solutions. Climate change's effects on West African mobility cannot be isolated to a singular outcome. Environmental degradation, whether resulting from slow-onset changes or sudden shocks, affects populations' vulnerability and resilience capacities in complex manners. As demonstrated by empirical investigation, these mobility responses are highly interrelated, and therefore call for cooperation among different levels of government and other key stakeholders. Despite its challenges and differentiated outcomes, migration's *potential* to increase adaptive capacity (here exemplified by financial remittances but also in terms of social remittances) should be considered as it benefits migrants themselves, their families in the communities of origin, but also as labour mobility may facilitate other types of environmental mobility.

### 3.3.3 Bangladesh

#### 3.3.3.1 In a nutshell

**Tipping points for cross-border climate-related migration: Southwestern Bangladesh and West Bengal, India**

I. Assessment of the role of multiple social feedbacks on Bangladeshi cross-border migration to India as a tipping element in the context of extreme climate events

II. Findings:

1. Climate change rarely leads automatically to migration but is caused by the interaction of socio-economic and political feedbacks in an environmentally vulnerable area
2. Some move from a risk area into another risk area
3. Some refuse to migrate as they have habituated to the environmental vulnerability
4. Circular migration serves as a preferable alternative to permanent migration in providing an additional coping strategy by opening up other livelihood possibilities

#### 3.3.3.2 Introduction

In attempting to understand how extreme climate events beyond 2°C warming will impact livelihoods and affect coping capacity and resilience to sudden changes in the Earth's climate system, it becomes important to understand how societies will respond in their anticipation and perception of environmental change. Increasingly, studies are attempting to apply Early Warning Signals, normally used to predict natural tipping points (Lenton 2011), to social systems (Scheffer 2009; Haldane & May 2011; Neuman et al 2011, all cited in Bentley et al 2010). In acknowledging the difficulty in applying such physical systems models to predict social systems, Bentley et al (2014) recommends focusing on probabilistic insights from research on heterogeneity, connectivity through social networks and individual thresholds to change. Kopp et al. (2016) emphasizes the importance of clarifying the terminology used to distinguish climatic and social tipping elements from economic shocks and state changes in order to better understand their linkages.

In the case of Bangladesh, one of the most exposed countries in the event of future extreme climate events, analyzing critical thresholds of social tipping elements is critical to understanding the risks and associated costs of climate-related tipping points. While state intervention on disaster reduction and the development of early warning systems has contributed to substantial decline in cyclone-related deaths in the country (Haque et al 2012), migration, typically short-term in nature and over short distances, continues to be a primary social response to rapid-onset disasters as people seek shelter and survival in the short term.

Evidence suggests that sudden disasters are usually associated with higher migration flows to India in the hope of securing additional resources to cope (Poncelet 2010). Observations in south-western Bangladesh in the aftermath of cyclone Aila in 2009 demonstrated a process of step migration from rural to urban areas, then further on to locations in India (Mehedi and Roy 2010). Cross-border migration is expected to increase especially in areas where historical, familial and cultural ties exist across borders (Bhattacharyya and Werz 2012).

Situated in the cyclone forming Bay of Bengal, with 68% of its land surface vulnerable to flood, Bangladesh's natural exposure to hydro-meteorological disasters is compounded by the structural effects of poverty on its inhabitants. It is the poorest country in South Asia, with 31.5% of its population living below the national poverty line (ADB 2016), a fact that makes it disproportionately vulnerable to loss of livelihood and displacement in the face of climate change (Canon et al 2003). Increased vulnerability greatly increases the costs of environmental risks, making even the smallest fluctuation in temperature or rainfall potentially disastrous (Bartlett et al 2010) and capable of tipping populations into nonlinear behavioral change.

Public perception of climate change and subsequent feedback may produce varied behavior, making 'tipping behavior' hard to predict. De Longueville et al's (above) study of climate change perception and migration intention concludes that if public perception of environmental change proves more pessimistic than actual observations, migration could increase substantially before an event occurs as people move in anticipation of a worsening climate. The study's authors explained that perceptions are probably not a reflection of actual changes in the strict climatic sense, but are rather influenced by socio-economic trends over time, given that farmers, for example, think about rainfall as a process rather than a quantity (Roncoli 2006, cited by De Longueville et al, undated). Social thresholds are therefore to a large extent defined by individual beliefs.

In the case of Bangladesh, where pre-cyclone evacuation remains a challenge, coastal residents still believe in a wait-and-see approach (Haque et al 2012). Mistrust of warning messages, which are often unreliable and lack sufficient information about tropical storm landfall, often make evacuation decisions difficult for residents (Roy et al. 2015). The decisive criterion for evacuations is often individual thresholds that villagers have for the costs involved in following false warnings, fear of property loss, poor conditions of and distance to public shelters (Haque et al 2012). More long-term cross-border migration tipping elements may involve individual thresholds for crop failure, lack of livelihood opportunities, extent of and frequency of damage, and access to recovery and adaptation assistance.

As migration tends to occur most often when environmental degradation affects the livelihood and coping mechanisms of people with ecologically dependent livelihoods, much of the literature on the environment-migration nexus tends to focus on assessing socio-environmental thresholds (Afifi & Jäger 2010).
Hence, to define a tipping point, environmental events and vulnerability of those exposed to them should be looked at simultaneously. A rapid sequence of environmental stresses seems to matter more than facing one single event, no matter how large it is (idem, p.264).

While others have supported the idea that the migration threshold is a point at which the resilience of the social-ecological system collapses under the pressure of climate change impacts (Bardsley and Hugo 2010), Kopp et al. (2016) emphasizes the role of social feedbacks in migration systems, that, in the Gladwellian sense, shape contagion through a network, thus highlighting the dynamic nature of social change. Such feedbacks can substantially broaden the limits of individual thresholds by changing perceptions. Knowledge that others are cooperating (eg. through mass migration from villages, or through early evacuations) can introduce a positive feedback that impacts individual psychological thresholds (Hauser et al 2014, cited in Bentley et al 2014; Kopp et al 2016). Such reflections follow the lead of tipping points literature that considers the extent to which complex systems are vulnerable to feedbacks and the way in which straightforward social interventions (eg. early warning signals) may cascade into unanticipated events (May 1972, Gibson & Gurmu 2012, both cited in Bentley et al 2014).

The potential for unanticipated tipping behavior multiplies when a plethora of other variables act simultaneously. Non-linear behavior and abrupt changes in social systems responding to future extreme climate scenarios may be better understood by looking more closely at how dynamic social responses to environmental stress interact to 'tip' behavior. Ultimately, cross-border climate migration in Bangladesh occurs at the threshold of multiple social feedbacks that determine the nature of that migration.

In addition to socioeconomic factors, feedbacks may extend from a range of historical and political drivers implicated in Bangladesh's long history of civil religious conflicts. Cross-border Bangladeshi Hindu migration into West Bengal, has occurred since 1947 partition, and subsequent anti-Hindu uprisings led by the pro-Pakistani and pro-Islam Jamaat-e-Islami Bangladesh party militants. Meanwhile, there have been long-established flows of Bangladeshi Muslims to the Indian state of Assam. Pre-state traditional patterns of local movement in the border areas, often involving trade, are now increasingly securitized in the name of economic protectionism or ethno-religious nationalism promulgated by Indian politicians (McAdams and Saul 2010). Still with many parts remaining porous, the Indian-Bangladeshi border is estimated to surpass Mexico and the United states as the world's largest junction of international migration flows (ADB 2012)

This study considers the role of multiple social feedbacks on cross-border migration as a tipping element in the context of extreme climate events, drawing on fieldwork that took place in border communities in Southwest Bangladesh and West Bengal, India. It challenges causal assumptions that climate change automatically leads to migration by presenting a more complicated tableau of migration provoked by the interaction of socio-economic and political feedbacks in an environmentally vulnerable area.

#### 3.3.3.3 Methods

In order to understand the relationship between tipping points, environmental events, vulnerability and cross-border migration, a 3-week qualitative study was carried out in villages on both sides of the Indian-Bangladeshi border. While national or international policies may affect adaptation, most adaptive responses will be made at the local level by resource managers, municipal planners, and individuals (Posey 2009). Questionnaires were therefore designed to capture vulnerability indicators that were specific to the local context, but also to reflect the IPCC definition of vulnerability (2001) as a function of exposure, sensitivity, and adaptive capacity.

Environmental migrants are defined as people whose natural resource-dependent livelihoods (agriculture, fishing, etc.) have been comprised by environmental degradation or climate change-induced disasters, and who migrate either temporarily to diversify their livelihoods as a coping strategy through seasonal movement, or permanently to find new land or new livelihood opportunities (EACH-FOR (2009). Research was thus conducted in both destination areas – to get an understanding of how migration has altered conditions of vulnerability, and to understand the factors that may have tipped decisions towards migration – and origin areas – to understand the migration potential of households that have not migrated, factors that may prevent migration, and at what point migration intent becomes an active decision.

Field study destinations were purposefully chosen along the geographical trajectory of a step pattern for climate migrants: Bangladeshi border towns (Bangladeshi internal migrants/displaced people and potential cross-border migrants) à Indian border towns (Bangladeshi cross-border migrants). Case studies began at the origin communities to final destinations as a strategic way to find destinations indicated by potential migrants and family members of those who had already migrated. In order to isolate climate concerns, control for religious factors, and capture nuances in migrant experiences, both Muslims and Hindus study participants were sought out.

The study took place in one origin area in Bangladesh, and two destination areas in India. In Bangladesh, in-depth interviews were conducted among 28 potential migrants (households intending to migrate, and those whose members who have previously or currently migrated), and a negative instance sampling involving a few households with no intention to migrate). Case studies were found in seven communities of Munshiganj union of Shyamnagar, one of the four worst Aila-affected Upazilas in the country (Mehedi 2010). The area was severely affected by Cyclones Sidr in November 2007 and Aila in 2009, which killed 193 people, relatively fewer people than previous cyclones, while displacing more than 297,000 (Shamsuddoha et al 2012).

The lack of access to basic services such as fresh water and their preferred livelihoods left many in a situation of protracted displacement, many to urban areas, with evidence of cross-border migration to India (Mehedi et al 2010). FDG Reports organized by Humanitywatch stated that 29% of the people who migrated from the affected district came from Shyamnagar, from which step migration patterns were observed first to Satkhira District, then onto Khulna city, then Dhaka, or alternatively first to Satkhira District, then onto West Bengal, India (Mehedi et al 2010).

In Shyamnagar, livelihoods depend mainly on the surrounding natural resources made available by the Sundarbans mangrove forest, which involve collecting wood, and harvesting crabs, fish and shrimp. A few respondents owned small plots of shrimp ponds or crab fattening ponds, while some worked as day laborers on shrimp or agricultural farms, often supplementing their incomes as van pullers or seasonal brick field workers.

The case studies in India were chosen based on information provided by study participants about the whereabouts of their family members and destination intentions. Interviews with 40 Bangladeshi migrants were conducted with communities in two districts: in Scheme 2 of Jharkhali, a Gram Panchayat bordering the Sundarbans forest in the Basanti Block, in the relatively land-abundant South 24 Parganas District, and in Uttar Kolsur, located in the considerably more industrialized Basarat Sadar subdivision located near the Indian border, in the North 24 Parganas district where the city of Kolkata is situated.

Located in similar coastal and riverine geographic and climatic conditions as Southwestern Bangladesh , the South 24 Parganas district is prone to storm surges, tidal currents, and tropical cyclones originating in the Bay of Bengal. The population of Jharkali, is predominantly rural as there is very little industry. Agriculture of rice, vegetables, and pulses is the main occupation, followed by fishing.

In the North 24 Parganas district, migrants were interviewed in the Uttar Kolsur community of Dagenga Block. Lying east of the Hooghly River, the district is further inland than its southern counterpart, but is equally as flat, barely above flood levels, and infiltrated by swamps. The area is densely populated, mainly due to large scale refugee flows of Hindus from erstwhile East Pakistan, particularly during the period 1947 to 1955, in the aftermath of the 1947 Partition. People take up work largely as cultivators, agricultural laborers, household industry workers, with 39.64% of the male population working in non-agricultural, and non-household activities (Gov West Bengal 2010).

#### 3.3.3.4 Results and discussion

***a) Climate change does not inevitably lead to migration but is caused by the interaction of socio-economic and political feedbacks in an environmentally vulnerable area***

While most Bangladeshi migrant respondents reported having left Bangladesh in the years during and directly following major cyclones Sidr and Aila in 2007 and 2009 respectively, climate hazards were not always given as the primary reason for migrating, though they contributed significantly to secondary effects. Soil erosion, floods, heavy rainfall, repetitive storms and cyclones were largely responsible for massive material and livelihood losses, destitution, and starvation in the affected communities. Most respondents cited lack of livelihood as their main reasons to migrate, supporting findings that housing damage, cultivable land loss, and lack of work opportunity were the main migration drivers in the aftermath of cyclone Aila (Mehedi and Roy 2010). Often the effects were cumulative and gradual, with one family's land eroding over a period of four years of repetitive flooding, at the end of which they sought the aid of relatives in India in order to migrate.

Inter-religious conflicts significantly compounded environmental degradation and economic impacts. Hindu respondents overwhelmingly revealed strong feelings of insecurity as religious minorities in predominantly Muslim Bangladesh, despite residing in the Hindu-dominated Southwest region of the country. Moreover, there were various claims of inequitable access to government benefits and NGO project outreach on the basis of religion, signaling the extent to which socio- political factors may contribute to citizens' level of vulnerability and ability to adapt. Among Muslim respondents, politically aggravated trauma rarely factored into their migration decisions. The few Muslim migrants interviewed in the study had migrated to India between 1971 and 1988, and did so for reasons related to major floods and cyclone events. Many had suffered from famine due to crop destruction, loss of livelihoods, and financial ruin due to unpaid debts. Cross-border religious networks have likely played a part in facilitating cultural and religious affiliations.

The study reveals a strong tendency for Hindu Bangladeshi to have more family members in India than in other parts of Bangladesh – relatives who had migrated for both political and environmental reasons decades beforehand. Regularly sending remittances and relaying anecdotes of a better living standard in India, migrant family members encouraged and assisted both with finding seasonal labor jobs. This evidence supports the wide-held notion that cross-border networks facilitate migration by providing financial capital and support (Massey, Aysa 2005; Doraï 2016; Hillman, et al). Likewise, persons with few or no cross-border contacts were often less willing and/or able to migrate even after suffering socio-environmental hardships.

Kopp et al (2016) identifies social networks as providing positive social feedbacks that encourage migration. Likewise, other studies have found that available information on decisions made by others may influence decision-making (Salganik et al 2006; De Longueville et al, undated), while prior social trends can become locked-in (Schulte (2015). Accounts of prior migrants and their earnings, which are often exaggerated to save face, can induce a sense of deprivation in the home community (Garip 2017), disparaging their perceptions of environmental change, particularly when those perceptions are based on socio-economic sensibilities (De Longueville et al, undated).

*b)* ***Some move from one risk area to another***

While clearly aiming to reduce the effects of environmental hazards on their lives, study participants often migrated without a clear understanding of the ecological conditions on the other side of the border. Migrants situated near the Indian Sundarbans had moved into areas that were of similar proximity to the river and seabed, and thus were often just as exposed to storm surges and flooding as their previous dwelling places. One repatriated Bangladeshi said,

> "I migrated to India 17-18 years ago originally.  It was a spur of the moment choice I made when going to visit relatives in India. But we [later] returned to Bangladesh because of the weather. [The village in India] was in a low lying area where we often fell victim to fever and skin diseases [due to all the storms and floods]."

For others, living in India, where they gained substantially more access to coping mechanisms such as durable building materials and job diversification, enabled them to improve their resilience and preparedness for future calamities. For this reason, the same natural disasters were perceived to be less impactful in India than they were in Bangladesh.

The loss of livelihoods in the coastal area was largely the result of the widespread uptake of shrimp farming (IOM 2010), which exacerbated the effects of flooding and salinization of the soil. Moving to India presented an opportunity to access better government allocations and a job market that was less dependent on an increasingly volatile natural environment.  Rarely reinvesting in farmland, migrants were often able to gain considerable income at seasonal construction sites in nearby cities, which allowed them to invest in more robust housing structures. For some, investing in their children's education and attainment of a civic career was a key household strategy aimed at 'lifting' the family out of poverty, thereby improving their resilience to environmental stresses in the long term. One household head, whose family had migrated from Southwest Bangladesh in 2011 said,

> "Our principle reason to leave was because of climate hazards, which makes everything uncertain.  India has permanent livelihoods and far more opportunities. Bangladesh is more vulnerable to climate change. The livelihoods in Bangladesh are more connected to the weather, but in India, there is more choice."

While in some aspects, moving into a risk-prone area may be described as maladaptive (Niemeyer et al 2005), for inhabitants of the south-western coastal region of Bangladesh, both permanent and circular migration to India was perceived as a pre-emptive strategy to increase resilience in the long run, attain upward social mobility and to minimize the economic uncertainty of living in an ecologically vulnerable area with few livelihood alternatives.

*c)* ***Some refuse to migrate as they have habituated to the environmental vulnerability***

The way individuals residing in a coastal community may assess the threat of rising sea levels and their coping capacity may be influenced by prior personal or vicarious experience with inundation or dramatic environmental change or displacement (Reser & Swim 2011).  Different kinds of environmental stresses trigger different degrees of action. Continuous  or chronic stresses such as slow-onset events like drought, soil erosion, salinisation and sea level rise may go unnoticed because they are subtle or people habituate to them (Adeola 2000; Edelstein 2002, cited Reser & Swim 2011). In the case of Bangladesh, storm and flood survivors are largely accustom to the environmental reality of their surroundings, remaining unmoved by repetitive storms and cyclones.  Some had come to conceptualize natural disasters as a way of life, with reconstruction as part of the routine recovery process.

Observers have linked such resignation to fatalism, implying an unwillingness and inability to adapt to climate change and disasters (Landry and Rogers 1982; van Aalst, Cannon, and Burton 2008; Howlader, Akanda, and Zaman 2015). While the literature often portrays fatalism as a passive measure, other studies have portrayed it as a source of psychological strength. Paul and Routray's study on a poorly developed Bangladeshi island demonstrates that "climbing trees and praying to God provide the people with the determination to overcome disaster impacts, which is reflected in the lower number of deaths in Island …"(2013, p. 28-29).   Furthermore, such attitudes may allow inhabitants of disaster prone areas to conceive of and incorporate subtler ways of adaptation into their lifestyles. Most houses in the study village made of non-durable materials such as mud and bamboo splits with thatched roofs that are affordable and easy to reconstruct. This is not meant to imply that there were no attempts made to improve the integrity of such structures, as many interviewed residents intended to add cement-filled metal pipe pillars, while incorporating more durable materials such as brick and wood in the construction of their house foundation and walls. But, in the absence of the necessary economic resources to invest (and reinvest), the main goal is to minimize losses and focus on protecting essential items such as important documents and animals.

According to Reser (2004), "fear and anxiety, though 'adaptive' responses to threat, can also 'get in the way' of clear thinking and very necessary adaptive responses in the context of imminent natural disaster warning situations" (cited in Reser & Swim 2011). In Bangladesh, such fear may have resulted in immobility in threatened areas, or a lack of active participation in NGO adaptation programming. Such feelings are often accompanied by a lack of trust in the ability or willingness of authorities to respond. Indeed, respondents in the current study expressed a general lack of trust in support structures, complaining that they were disconnected from NGO projects aimed at disaster preparedness and often never selected to receive government assistance. Others felt that they had been overlooked because they could not afford the time to attend association meetings nor to pay the monthly membership fees. Clientelism in cyclone preparedness and relief efforts has been shown to disproportionately affect the poor (Mahmud and Prowse 2012) and socio-politically vulnerable who tend to be more displaced as a result of natural disasters (Mallick 2012).

While social networks abroad are often prioritized in migratory systems (Massey and Zenteno 1999), a strong social support base at home may serve to moderate aspirations to migrate. Studies on return migration reveal the importance of maintaining or forging social capital in the home country in order to facilitate reintegration, employment and the establishment of businesses resettling upon return (De Vreyer, Gubert, and Robilliard 2010). Likewise, in situations of environmental strain, social capital at home can become a source of resilience as neighbours rely on each other for shelter, meal provisions, or rebuilding assistance in the aftermath of major weather events. This sense of solidarity is particularly important in interreligious group relations, where trust between neighbours may decrease feelings of isolation and mistrust. It may also affect individuals' psychological thresholds for withstanding disasters *in situ* by increasing confidence in existing informal support structures when government structures are out-of-reach.

Migration or socially circulated information on migration may also lead to negative feedbacks when such experiences are unpleasant. Ordeals of detention or discrimination in India may provoke feelings of rejection and isolation, especially when moving from the socio-centric culture of one's home village to the egocentric culture of rapidly developing India (Bhugra 2004). When accounts of such experiences reach the home village, they may sober ideals of cultural and religious affinity that potential migrants may expect of life in India. Nonetheless, such seemingly troubling experiences abroad did not always deter migrants in the case study from returning to seek labor opportunities in the agricultural off-season.

### *d) Circular migration serves as a preferable alternative to permanent migration in providing an additional coping strategy by opening up other livelihood possibilities*

Circular migration, in providing an additional coping strategy by opening up other livelihood possibilities, has served as a preferable alternative to permanent migration, even though such migration has turned into permanent migration for some. One village informant suggested that, against the historical backdrop of anti-Hindu tensions that are often roused by politicians to attract more supporters, Hindus were more inclined than Muslims to migrate permanently in response to environmental change:

> "Migration to India depends on vulnerability and exposure to climate in the areas [people] live. Muslims don't want to go to India permanently, [but they want to go] just for circular migration. Hindus are more willing to go permanently for political reasons and justice. Those who leave permanently have to uproot their lives, sell all their land and resources, and start over, and when they leave. They realize that they didn't get much in return for what they lost. But those who only migrate temporarily are doing quite well."

This demonstrates the way in which migration system feedbacks differ across diverse social groups and different sets of drivers. While permanent migration as a tipping point has already been diffused through the Bangladeshi Hindu network via previously established migrants who facilitate the settlement and integration of those who follow suit, such feedbacks are not present among Muslim migrants whose social networks at home may be stronger than those abroad.

Climate-induced weather changes may eventually lead to migration of a more permanent nature, though the links between temporary and permanent migration in Bangladesh are still inconclusive (Gray and Mueller 2012). Observations that rainfall deficit-induced crop failure has driven long term mobility in Bangladesh (idem) support data suggesting that slow-onset events with lasting impacts on natural resources may lead to non-linear permanent migration(Henry et al 2004; Tacoli 2011; Bohra-Mishra et al 2013). As exposure to such shocks increases people's vulnerability, often limiting their ability to rely on well-tested coping strategies like temporary migration to diversify their livelihoods, such environmental events can also become 'precipitating events,' that lead to distress migration (Tacoli 2011, Jonsson 2010).

There are several indicators from the study that those who eventually migrate permanently do so after years of working seasonally in India during which they have saved, purchased land and gradually increased their social networks in the destination area, after which, they are able to facilitate the move of the entire household. This suggests that circular migration, for some, may be a prerequisite or precursor to permanent migration, allowing people to accumulate resources and social networks, which may inevitably facilitate their migration later on. Circular migration may also spark the initial desire to migrate permanently by exposing migrants to greater economic possibilities abroad.

## 3.4 4. References


Adger, W. N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D. R., Naess, L. O., Wolf, J., and Wreford, A. (2009). Are there social limits to adaptation to climate change? *Climatic Change*, 93, 335-354.

Afifi, T., and Jäger, J. (2010). *Environment, forced migration and social vulnerability*. Springer Science & Business Media.

Afolayan, A., and Adelekan, I. (1999). The role of climatic variations on migration and human health in Africa. *Environmentalist*, 18, 213-218.

Alam, M., Bhatia, R., and Mawby, B. (2013). *Women and climate change: impact and agency in human rights, security, and economic development*. Georgetown Institute for Women, Peace and Security.

Ali, A. (1999). Climate change impacts and adaptation assessment in Bangladesh. *Climate Research*, 12, 109-116.

Asian Development Bank (2012). *Addressing climate change and migration in Asia and the Pacific.* Asian Development Bank. https://www.adb.org/publications/addressing-climate-change-and-migration-asia-and-pacific.

Asian Development Bank (2016). *Overseas employment of Bangladeshi workers: trends, prospects, and challenges*. https://www.adb.org/publications/overseas-employment-bangladeshi-workers.

Ateliers (Les Ateliers Internationaux de Maîtrise d'oeuvre urbaine) (2010), *Saint-Louis 2030: New African Metropolis*. Accessed 14.02.2015. http://www.ateliers.org/IMG/pdf/2__dossier_analyse_eng.pdf.

Barbier, B., Yacouba, H., Karambiri, H., Zoromé, M., and Somé, B. (2009). Human vulnerability to climate variability in the Sahel: farmers' adaptation strategies in northern Burkina Faso. *Environmental management*, 43, 790-803

Bardsley, D. K., and Hugo, G. J. (2010). Migration and climate change: examining thresholds of change to guide effective adaptation decision-making. *Population and Environment*, 32, 238-262.

Barnett, J., and Webber, M. (2010). *Accomodating migration to promote adaptation to climate change*. Washington (DC): The World Bank. 5270.

Barrios, S., Bertinelli, L., and Strobl, E. (2006). Climatic change and rural–urban migration: the case of sub-Saharan Africa. *Journal of Urban Economics*, 60, 357-371.

Bartlett, R., Bharati, L., Pant, D., Hosterman, H., and McCornick, P. (2010). *Climate change impacts and adaptation in Nepal*. IWMI Working Paper 139, p.35, International Water Management Institute, Colombo, Sri Lanka.

Benoit, M. (1982). *Oiseaux de mil: les Mossi du Bwamu (Haute-Volta)*. IRD Editions, No. 95.

Bentley, R. A, Maddison, E., Ranner, P. H., Bissell, J., Caiado, C. C, Bhatanacharoen, P., Clark, T., Botha, M., Akinbami, F., Hollow, M., Michie, R., Huntley, B., Curtis, S. E., and Garnett, P. (2014). Social tipping points and Earth systems dynamics. *Frontiers in Environmental Science*, 2, 25. doi:10.3389/fenvs.2014.00035.

Bhattacharyya, A., and Werz, M. (2012). *Climate change, migration, and conflict in South Asia*. Center for American Progress. https://www.americanprogress.org/issues/security/reports/2012/12/03/46382/climate-change-migration-and-conflict-in-south-asia/.

Bhowmik, A. K., and Cabral, P. (2013). Cyclone Sidr impacts on the Sundarbans floristic diversity. *Earth Science Research*, 2, 62-79.

Bhugra, D. (2004). Migration, distress and cultural identity, *British Medical Bulletin*, 69, 129–141.

Bie, H., & Van Den Broeck, K. (2011). Economic drivers of migration and climate change in LDCs. *Global Environmental Change*. doi:10.1016/j.gloenvcha.2011.09.002

Black, R., Adger, W. N., Arnell, N. W., Dercon, S., Geddes, A., and Thomas, D. (2011). The effect of environmental change on human migration. *Global Environmental Change*, 21, S3-S11.

Blion, R., and Bredeloup, S., 1997. La Côte d'Ivoire dans les stratégies migratoires des Burkinabè et des Sénégalais. In *B. Contamin, H. Memel-Foté (eds.). Le modèle ivoirien en question. Crises, ajustements, recompositions* (pp. 707-737). Paris: Karthala.

Boano, C., Zetter, R., & Morris, T. (2008). *Environmentally displaced people: Understanding the linkages between environmental change, livelihoods and forced migration*. *Forced Migration Policy Briefing*. Oxford: Refugee Studies Centre.

Bohra-Mishra, P., Oppenheimer, M., and Hsiang, S. M. (2014). Nonlinear permanent migration response to climatic variations but minimal response to disasters. *Proceedings of the National Academy of Sciences*, 111, 9780–9785.

Brockhaus, M., Djoudi, H., and Locatelli, B. (2013). Envisioning the future and learning from the past: adapting to a changing environment in northern Mali. *Environmental Sciences & Policy*, 25, 94-106.

Brouwer, R., Akter, S., Brander, L., and Haque, E. (2007). Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. *Risk Analysis*, 27, 313-326.

Brown, C. (2012). Water ecosystems and poverty: roadmap for the coming challenge. In *Integrating Ecology and Poverty Reduction* (pp. 151-161). Springer New York.

Cannon, T., Twigg, J., and Rowell, J. (2003). *Social vulnerability, sustainable livelihoods and disasters*. DFID Report, Conflict and Humanitarian Assistance Department and Sustainable Livelihoods Support Office.

Chindarkar, N. (2012). Gender and climate change-induced migration: proposing a framework for analysis. *Environmental Research Letters*, 7, 025601

Cissé, P., Zorom, M., Barbier, B., and Maiga, A. (2010). Les migrations, une stratégie d'adaptation à la variabilité climatique en zones sahéliennes. *Revue de Géographie du Laboratoire Leïdi*, 8, 184-196.

Cluva, (Climate change and vulnerability of African cities) (2013). *Saint-Louis, Senegal*. Accessed 13.02.2015, http://www.cluva.eu/CLUVA_publications/CLUVA_Climate-change-and-vulnerability-of-African-cities-Saint-Louis.pdf.

Cordell, D. D., Gregory, J. W., and Piché, V. (1996). *Hoe and wage: a social history of a circular migration system in West Africa*. Boulder, Colorado: Westview press.

Cormier-Salem, M. C. (2013). L'aménagement du littoral: un enjeu crucial pour les pêcheries artisanales. In *Artisans de la mer: une histoire de la pêche maritime sénégalaise* (pp. 136-145). <ird-00827404>

Coulibaly, S. (1978). Les migrations voltaïques systèmes de mobilité espaces de vie : à la recherche de modèles. *L'Espace Géographique*, 3, 265-275.

Dara (2013). *Indice de réduction des risques (RRI) en Afrique de l'Ouest. Analyse des conditions et des capacités de réduction des risques de catastrophes. Le Cap-Vert, la Gambie, le Ghana, la Guinée, le Niger et le Sénégal*, http://daraint.org/risk-reduction-index/.

De Longueville, F., Hountondji, Y. C., Kindo, I., Gemenne, F., and Ozer, P. (2016). Long-term analysis of rainfall and temperature data in Burkina Faso (1950–2013). *International Journal of Climatology*, 36, 4393-4405.

de Sherbinin, A. (2011). The biophysical and geographical correlates of child malnutrition in Africa. *Population, Space and Place*, 17, 27-46.

De Sherbinin, A., Levy, M., Adamo, S., MacManus, K., Yetman, G., Mara, V., Razafindrazay, L., Goodrich, B., Srebotnjak, T., Aichele, C., and Pistolesi, L. (2012). Migration and risk: net migration in marginal ecosystems and hazardous areas. *Environmental Research Letters*, 7, 045602.

De Vreyer, P., Gubert, F., and Robilliard, A. S. (2010). Are there returns to migration experience? An empirical analysis using data on return migrants and non-migrants in West Africa. *Annals of Economics and Statistics*, 97-98, 307-328.

d'Haen, S. A. L., Nielsen, J. Ø., and Lambin, E. F., 2011. Beyond local climate: rainfall variability as a determinant of household nonfarm activities in contemporary rural Burkina Faso. *Climate and Development*, 6, 144-165.

Diatta, M. A., and Mbow, N. (1999). Releasing the development potential of return migration: the case of Senegal. *International Migration*, 37, 243-266.

Dieye, A. M., and Roy, D. P. (2012). A study of rural Senegalese attitudes and perceptions of their behavior to changes in the climate. *Environmental Management*, 50, 929-941.

District Human Development Report: North 24 Parganas (PDF). Intro Pp 3, 6, 8, 22, 38, 202; Block specific Pp 20, 22, 27, 28, 31, 86, 89, 123, 145, 151, 189, Development & Planning Department, Government of West Bengal, 2010., https://index08.hoisthospitality.com/hscp.php/index/login?NASID=HES948049&LgnURL=https%3A%2F%2Fclblgn.sceur.ch%3A8090%2Fgoform%2FHtmlLoginRequest&NASIP=clblgn.sceur.ch&CallerID=2C%3AF0%3AEE%3A15%3A98%3A1A&CustIP=192.168.54.161&VLAN=4&Location=Hotspot&Port=8090.

Doraï, K. (2016). The role of transnational networks and cross-border circulation in Palestinian migration in a conflict situation. In *Aksaz, E., and Pérouse, J. F. (eds) Guests and Aliens. Re-configuring new mobilities in the Eastern Mediterranean after 2011 – with a special focus on Syrian refugees* (pp. 1-4). Istanbul, Turkey: Institut français d'études anatoliennes.

Emanuel, K., Sundararajan, R., and Williams, J. (2008). Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. *Bulletin of the American Meteorological Society*, 89, 347-367.

Etzold, B., and Mallick, B. (2016). Moving Beyond the Focus on Environmental Migration Towards Recognizing the Normality of Translocal Lives: Insights from Bangladesh. In *Migration, Risk Management and Climate Change: Evidence and Policy Responses* (pp. 105-128). Springer International Publishing.

Food and Agriculture Organization of the United Nations (2008). *Vue générale du secteur des pêches national: La République du Sénégal*. ftp://ftp.fao.org/Fi/DOCUMENT/fcp/fr/FI_CP_SN.pdf.

Fosu-Mensah, B. Y., Vlek, P. L., and MacCarthy, D. S. (2011). Farmers' perception and adaptation to climate change: a case study of Sekyedumase district in Ghana. *Environment, Development and Sustainability*, 14, 495-505.

Garip, F. (2016). *On the move: Changing mechanisms of Mexico-US migration*. Princeton University Press.

Gemenne, F. (2011). Climate-induced population displacements in a 4 C+ world. *Philosophical Transactions of the Royal Society A*, 369, 182-195.

Gemenne, F. (2011b). Why the numbers don't add up: A review of estimates and predictions of people displaced by environmental changes. *Global Environmental Change*, 21, S41-S49.

Gray, C. L., and Mueller, V. (2012). Natural disasters and population mobility in Bangladesh. *Proceedings of the National Academy of Sciences*, 109, 6000-6005.

Habib, A., Shahidullah, M., and Ahmed, D. (2012). The Bangladesh cyclone preparedness program. A vital component of the nation's multi-hazard early warning system. In *Institutional Partnerships in Multi-Hazard Early Warning Systems* (pp. 29-62). Springer Berlin Heidelberg.

Hampshire, K. (2002). Fulani on the move: seasonal economic migration in the Sahel as a social process. *Journal of Development Studies*, 38, 15-36.

Haque, U., Hashizume, M., Kolivras, K. N., Overgaard, H. J., Das, B., and Yamamoto, T. (2012). Reduced death rates from cyclones in Bangladesh: what more needs to be done? *Bulletin of the World Health Organization*, 90, 150-156.

Henry, S., Boyle, P., and Lambin, E. F. (2003). Modelling inter-provincial migration in Burkina Faso, West Africa: the role of socio-demographic and environmental factors. *Applied Geography*, 23, 115-136.

Henry, S., Piché, V., Ouédraogo, D., and Lambin, E. F. (2004). Descriptive analysis of the individual migratory pathways according to environmental typologies. *Population and Environment*, 25, 397-422.

Henry, S., Schoumaker, B., and Beauchemin, C. (2004). The impact of rainfall on the first out-migration: A multi-level event-history analysis in Burkina Faso. *Population & Environment*, 25, 423-460.

Hillmann, F., Pahl, M., Rafflenbeul, B., and Sterly, H. (2015). *Environmental Change, Adaptation and Migration: Bringing in the Region*. Springer.

Howlader, M. S., Akanda, M. G. R., and Zaman, A. K. M. M. (2015). Adaptation towards climate change effects on coastal agriculture by the farmers of Patuakhali District of Bangladesh. *International Journal of Agricultural Innovations and Research*, 3, 1560-1566.

Hugo, G. (1996). Environmental concerns and international migration. *International Migration Review*, 3, 105-131.

Hulme, M. (2001). Climatic perspectives on Sahelian desiccation: 1973–1998. *Global Environmental Change*, 11, 19-29.

International agencies (ActionAid, Concern WorldWide, DanChurchAid, MuslimAid, Islamic Relief, Oxfam-GB and Save the Children-UK) involved in Aila response programme funded by ECHO (2009). In-depth Recovery Needs Assessment of Cyclone Aila Affected Areas, https://fr.scribd.com/document/206691387/In-Depth-Recovery-Needs-Assessment-of-Cyclone-Aila-Affected-Areas-ECHO-Funded.

IPCC (2014). *Climate change 2014: Impacts, Adaptation and Vulnerability*. http://ipcc-wg2.gov/AR5/.

Islam, T., and Peterson, R. E. (2004). *A Climatological Study of the Landfalling Tropical Cyclones of Bangladesh*. Conference Paper, 26th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, Miami, USA.

Jäger, J., Frühmann, J., Grünberger, S., & Vag, A. (2009). *EACH-FOR Synthesis Report*. Budapest: EACH-FOR.

Jónsson, G. (2010). *The Environmental Factor in Migration Dynamics: A Review of African Case Studies*. IMI Working Paper Series 21, https://www.imi.ox.ac.uk/publications/wp-21-10.

Juana, J. S., Kahaka, Z., and Okurut, F. N. (2013). Farmers' perceptions and adaptations to climate change in Sub-Sahara Africa: a synthesis of empirical studies and implications for public policy in African agriculture. *Journal of Agricultural Science*, 5, 121.

King, R., and Skeldon, R. (2010). 'Mind the Gap!'Integrating approaches to internal and international migration. *Journal of Ethnic and Migration Studies*, 36, 1619-1646.

Kniveton, D. R., Smith, C. D., and Black, R. (2012). Emerging migration flows in a changing climate in dryland Africa. *Nature Climate Change*, 2, 444-447.

Kniveton, D., Rowhani, P., and Martin, M. (2013). *Climate scenarios in Bangladesh*, Working Paper 2, Refugee and Migratory Movements Research Unit, Sussex Centre for Migration Research, http://migratingoutofpoverty.dfid.gov.uk/files/file.php?name=wp2-ccrmb-scenario.pdf&site=354.

Kniveton, D., Schmidt-Verkerk, K., Smith, C., and Black, R. (2008). *Climate change and migration: improving methodologies to estimate flows*, IOM Migration Research series, 33, http://www.iom.cz/files/Climate_Change_and_Migration_MRS_331.pdf.

Kopp, R. E., Shwom, R. L., Wagner, G., and Yuan, J. (2016). Tipping elements and climate–economic shocks: Pathways toward integrated assessment. *Earth's Future*, 4, 346-372.

Lafranière S. (2008). Europe takes Africa's fish, and boatloads of migrants follow. *New York Times*, 14 January 2008, http://www.nytimes.com/2008/01/14/world/africa/14fishing.html.

Lardry, T., and Rogers, G. (1982). *Warning confirmation and dissemination*. Pittsburgh: Center for Social and Urban Research, University of Pittsburgh.

Lay, J., Narloch, U., and Mahmoud, T. O. (2009). Shocks, structural change, and the patterns of income diversification in Burkina Faso. *African Development Review*, 21, 36-58.

Lebel, T., and Ali, A. (2009). Recent trends in the Central and Western Sahel rainfall regime (1990–2007). *Journal of Hydrology*, 375, 52-64.

Lenton, T. M. (2011). Early warning of climate tipping points. *Nature Climate Change*, 1, 201-209.

Lodoun, T., Giannini, A., Traoré, P. S., Somé, L., Sanon, M., Vaksmann, M., and Rasolodimby, J. M. (2013). Changes in seasonal descriptors of precipitation in Burkina Faso associated with late 20th century drought and recovery in West Africa. *Environmental Development*, 5, 96-108.

Mahmud, T., and Prowse, M. (2012). Corruption in cyclone preparedness and relief efforts in coastal Bangladesh: Lessons for climate adaptation? *Global Environmental Change*, 22, 933-943.

Mallick, B. (2012). *Social Disparities in Disaster-Induced Migration Process*. Retrieved from https://ssrn.com/abstract=2173166 on January 4th, 2017.

Martin, M., Kang, Y. H., Billah, M., Siddiqui, T., Black, R., and Kniveton, D. (2013). *Policy analysis: Climate change and migration Bangladesh*. Working paper 4, Output of research on climate change related migration in Bangladesh, conducted by RMMRU, University of Dhaka, and SCMR, University of Sussex.

Massey, D. S., and Aysa, M. (2005). *Social Capital and International Migration from Latin America*. Expert Group Meeting on International Migration and Development in Latin America and the Caribbean. Population Division Department of Economic and Social Affairs, United Nations Secretariat, Mexico City UN/POP/EGM-MIG/2005/04.

Massey, D. S., and Zenteno, R. M. (1999). The dynamics of mass migration. *Proceedings of the National Academy of Sciences*, 96, 5328-5335.

Massey, D. S., Axinn, W., & Ghimire, D. (2007). *Environmental Change and Out-Migration: Evidence from Nepal*. *Research Reports*. Ann Arbor: University of Michigan, Population Studies Center.

McAdam, J., and Saul, B. (2010). Displacement with Dignity: International Law and Policy Responses to Climate Change Mitigation and Security in Bangladesh. *German YB Int'l L.*, 53, 233.

McLeman, R, and Smit, B, 2006. Migration as an adaptation to climate change. *Climatic Change*, 76, 31-53.

McLeman, R. (2013). Developments in modelling of climate change-related migration. *Climatic Change*, 117, 599-611.

McTegart, W.J., Sheldon, G.W., and Griffiths, D.C. (1990). *Impacts Assessment of Climate Change*. Report of Working Group II.

Mehedi, H., and Roy, K. (2010). *Climate induced displacement: case study of cyclone Aila in the southwest coastal region of Bangladesh*. Technical Report, Coastal Livelihood and Environmental Action Network (CLEAN), doi: 10.13140/RG.2.1.3490.9921.

Mertz, O., D'haen, S., Maiga, A., Moussa, I. B., Barbier, B., Diouf, A., Diallo, D., Da, E. D., and Dabi, D. (2012). Climate variability and environmental stress in the Sudan-Sahel zone of West Africa. *Ambio*, 41, 380-392.

Mertz, O., Mbow, C., Nielsen, J. Ø., Maiga, A., Diallo, D., Reenberg, A., Diouf, A., Barbier, B., Moussa, I. B., Zorom, M., Ouattara, I., and Dabi, D. (2010). Climate factors play a limited role for past adaptation strategies in West Africa. *Ecology and Society*, 15, 25.

Mertz, O., Mbow, C., Reenberg, A., and Diouf, A. (2009). Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. *Environmental Management*, 43, 804-816.

Mertz, O., Mbow, C., Reenberg, A., Genesio, L., Lambin, E. F., D'haen, S., Zorom, M., Rasmussen, K., Diallo, D., Barbier, B., Moussa, I. B., Diouf, A., Nielsen, J. Ø., and Sandholt, I. (2011). Adaptation strategies and climate vulnerability in the Sudano-Sahelian region of West Africa. *Atmospheric Science Letters*, 12, 104-108.

Mouhamed, L., Traore, S. B., Alhassane, A., and Sarr, B. (2013). Evolution of some observed climate extremes in the West African Sahel. *Weather and Climate Extremes*, 1, 19-25.

Müller, C., Waha, K., Bondeau, A., and Heinke, J. (2014). Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development. *Global Change Biology*, 20, 2505-2517.

Myers, N. (2002). Environmental refugees: a growing phenomenon of the 21st century. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 357, 609-613.

Naylor, R., Burney, J., and Postel, S. (2011). Smallholder irrigation and crop diversification under climate change in sub-Saharan Africa: evidence and potential for simultaneous food security adaptation and mitigation. *AGU Fall Meeting Abstracts 12/2011*.

Ndiaye, M., and Robin, N. (2010). Les migrations internationales en Afrique de l'Ouest, *Hommes & Migrations*, 1286-1287, 48-61.

Nielsen, J. Ø., and D'haen, S. A. L. (2014). Asking about climate change: reflections on methodology in qualitative climate change research published in Global Environmental Change since 2000. *Global Environmental Change*, 24, 402-409.

Nielsen, J. Ø., and Reenberg, A. (2010a). Cultural barriers to climate change adaptation: A case study from Northern Burkina Faso. *Global Environmental Change*, 20, 142-152.

Nielsen, J. Ø., and Reenberg, A. (2010b). Temporality and the problem with singling out climate as a current driver of change in a small West African village. *Journal of Arid Environment*, 74, 464-474.

Nielsen, J. Ø., D'haen, S., and Reenberg, A. (2012). Adaptation to climate change as a development project: A case study from Northern Burkina Faso. *Climate and Development*, 4, 16-25.

Niemeyer, S., Petts, J., and Hobson, K. (2005). Rapid climate change and society: assessing responses and thresholds. *Risk Analysis*, 25, 1443-1456.

Ouédraogo, M., Dembélé, Y., and Somé, L. (2010). Perceptions et stratégies d'adaptation aux changements des précipitations: cas des paysans du Burkina Faso. *Sécheresse*, 21, 87-96.

Ould Sidi Cheikh, M. A., Ozer, P., and Ozer, A. (2007). Risques d'inondation dans la ville de Nouakchott (Mauritanie). *Geo-Eco-Trop*, 31, 19-42.

Ozer, P., and Perrin, D. (2014). Eau et changement climatique. Tendances et perceptions en Afrique de l'Ouest. In *Ballouche, A., and Taïbi, N.A. (eds.) Eau, milieux et aménagement Une recherche au service des territoires* (pp 227-245). Angers, France: Presses universitaires d'Angers.

Pachauri, R. K., and Reisinger, A. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC

Parker, R. (1991). The Senegal–Mauritania conflict of 1989: a fragile equilibrium. *The Journal of Modern African Studies*, 29, 155-171.

Patwardhan, A, Semenov, S., Schnieder, S., Burton, I., Magadza, C., Oppenheimer, M., Pittock, B., Rahman, A., Smith, J., and Suarez, A. (2007). Assessing key vulnerabilities and the risk from climate change, Climate change 2007: Impacts, adaptation and vulnerability: Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change:779-810.

Paul, B. K. (2009). Why relatively fewer people died? The case of Bangladesh's Cyclone Sidr. *Natural Hazards*, 50, 289-304.

Paul, S. K., and Routray, J. K. (2013). An analysis of the causes of non-responses to cyclone warnings and the use of indigenous knowledge for cyclone forecasting in Bangladesh. In *Climate change and disaster risk management* (pp. 15-39). Springer Berlin Heidelberg.

Pethick, J., and Orford, J. D. (2013). Rapid rise in effective sea-level in southwest Bangladesh: its causes and contemporary rates. *Global and Planetary Change*, 111, 237-245.

Poncelet, A. (2010). Bangladesh, un pays fait de catastrophes. *Hommes & Migrations*, 2, 16-27.

Pramanik, B. (2005). Illegal migration from Bangladesh to West Bengal - A case study of West Bengal. *Dialogue*, 6, 43.

Rahmstorf, S. (2010). A new view on sea level rise. *Nature Reports*, *4*, 44–45.

Rain, D. (1999). *Eaters of the dry season: Circular labor migration in the West African Sahel*. Boulder, Colorado: Perseus.

Rasmussen, L. V., Rasmussen, K., Reenberg, A., and Proud, S. (2012). A system dynamics approach to land use changes in agro-pastoral systems on the desert margins of Sahel. *Agricultural Systems*, 107, 56-64.

Reardon, T., Delgado, C., and Matlon, P. (1992). Determinants and effects of income diversification amongst farm households in Burkina Faso. *The Journal of Development Studies*, 28, 264-296.

Reser, J. P., and Swim, J. K. (2011). Adapting to and coping with the threat and impacts of climate change. *American Psychologist*, 66(4), 277-289.

Roncoli, C. (2006). Ethnographic and participatory approaches to research on farmers' responses to climate predictions. *Climate Research*, 33, 81-99.

Roncoli, C., Ingram, K., and Kirshen, P. (2001). The costs and risks of coping with drought: livelihood impacts and farmers' responses in Burkina Faso. *Climate Research*, 19, 119-132.

Roy, C., Sarkar, S. K., Åberg, J., and Kovordanyi, R. (2015). The current cyclone early warning system in Bangladesh: providers' and receivers' views. *International Journal of Disaster Risk Reduction*, 12, 285-299.

Salganik, M. J., Dodds, P. S., & Watts, D. J. (2006). Experimental study of inequality and unpredictability in an artificial cultural market. *Science*, 311, 854-856.

Sall, A., and Morand, P. (2008). Pêche artisanale et émigration des jeunes africains par voie piroguière. *Politique africaine*, 109, 32-41.

Schellnhuber, H. J. (2010). *Climate Change as a Security Risk*. London: Routledge.

Schulte, B. K. (2015). *Exploring the Individual Lock-in Process in Service Relationships, Staying the Consumption Course*. Springer.

Shamsuddoha, M., Islam, M., Haque, M. A., Rahman, M. F., Roberts, E., Hasemann, A., and Roddick, S. (2013). *Local perspective on loss and damage in the context of extreme events: Insights from cyclone-affected communities in coastal Bangladesh*. Center for Participatory Research and Development (CRPD): Dhaka, Bangladesh.

Sivakumar, M. (1998). Predicting rainy season potential from the onset of rains in Southern Sahelian and Sudanian climatic zones of West Africa. *Agricultural and Forest Meteorology*, 42, 295-305.

Sivakumar, M., and Hatfield, J. (1990). Spatial variability of rainfall at an experimental station in Niger West Africa. *Journal Theoretical and Applied Climatology*, 42, 33-39.

Stern, N. H. (2007). *The economics of climate change: the Stern review*. Cambridge University press.

Tacoli, C. (2011). *Not only climate change: mobility, vulnerability and socio-economic transformations in environmentally fragile areas in Bolivia, Senegal and Tanzania*. IIED Human Settlements Working Paper Series, Rural-Urban Interactions and Livelihood Strategies - No 28.

Tambo, J. A., and Abdoulaye, T. (2012). Climate change and agricultural technology adoption: the case of drought tolerant maize in rural Nigeria. *Mitigation and Adaptation Strategies for Global Change*, 17, 277-292.

Tschakert, P. (2007). Views from the vulnerable: understanding climatic and other stressors in the Sahel. *Global Environmental Change*, 17, 381-396.

Van Aalst, M. K., Cannon, T., and Burton, I. (2008). Community level adaptation to climate change: the potential role of participatory community risk assessment. *Global Environmental Change*, 18, 165-179.

Van der Geest, K. (2011). North-South migration in Ghana: what role for the environment? *International Migration*, 49, e69-e94.

Warner, K., and Afifi, T. (2014). Enhancing adaptation options and managing human mobility: the United Nations framework convention on climate change. *Social Research: An International Quarterly*, 81, 299-326.

Webster, P. J., Holland, G. J., Curry, J. A., and Chang, H. R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, 309, 1844-1846.

West, C. T., Roncoli, C., and Ouattara, F. (2008). Local perceptions and regional climate trends on the central plateau of Burkina Faso. *Land Degradation and Development*, 19, 289-304.

Wong-Parodi, G., Fischhoff, B., and Strauss, B. (2015). Resilience vs. adaptation: framing and action. *Climate Risk Management*, 10, 1-7.

World Bank (2010a). *Migration and Remittances Fact Book 2011*. Development Prospects Group. Washington DC. http://data.worldbank.org/data-catalog/migration-and-remittances, Accessed 10/05/2017.

World Bank (2010b). *World Development Report 2010*. Development and Climate Change Washington DC. http://siteresources.worldbank.org/INTWDR2010/Resources/5287678-1226014527953/WDR10-Full-Text.pdf, Accessed 15/05/2017.

Zampaligré, N., Dossa, L. H., and Schlecht, E. (2014). Climate change and variability: perception and adaptation strategies of pastoralists and agro-pastoralists across different zones of Burkina Faso. *Regional Environmental Change*, 14, 769-783.

Zhang, X., and Yang, F. (2004). RClimDex (1.0) user manual. Ontario: Downsview.

Zorom, M., Barbier, B., Mertz, O., and Servat, E. (2013). Diversification and adaptation strategies to climate variability: A farm typology for the Sahel. *Agricultural Systems*, 116, 7-15.

# Appendices

## *Appendix A – Previous results of the HCVI*

Results from the future projections of the HCVI from Richardson *et al.* (2017) are shown in Figure A 1. The future projections of the HCVI were calculated using the exposure component as assessed by the precipitation data from the CMIP5 ensemble of global climate models for the 2050s (2041-2070) and 2080s (2071-2100) time periods. A range of greenhouse gas emissions scenarios were also analysed, ranging from RCP2.6 (the so-called 'aggressive mitigation' scenario) to RCP8.5 (the so-called 'business-as-usual' scenario) though only the results from RCP8.5 can be compared to those presented in this report since this was the only RCP run at high resolution within HELIX. The adaptation scenarios applied are those developed in Richardson *et al.* (2017) and consist of scaled changes applied to the sensitivity and adaptive capacity components of the HCVI that reduce sensitivity and improve adaptive capacity by an amount that is dependent on each country's present-day values.

The CMIP5 results show that vulnerability to food insecurity is projected to increase as a result of climate change by the 2050s (Figure A 1, panels c and g), and that larger increases are projected in the 2080s, particularly under the RCP8.5 scenario (Figure A 1, panel h) compared to the RCP2.6 scenario (Figure A 1, panel d). The high adaptation scenario acts to reduce the increases in vulnerability that are projected as a result of the changing climate. However, the reductions do not fully offset these increases in most cases (Figure A 1, panels a, e and f). The only scenario where improvements in vulnerability are projected compared to the present day is with the highest mitigation (RCP2.6), and highest adaptation (Figure A 1, panel b). The results highlight the dual requirement for both mitigation and adaptation to avoid the worst impacts of climate change and to make gains in tackling food security.

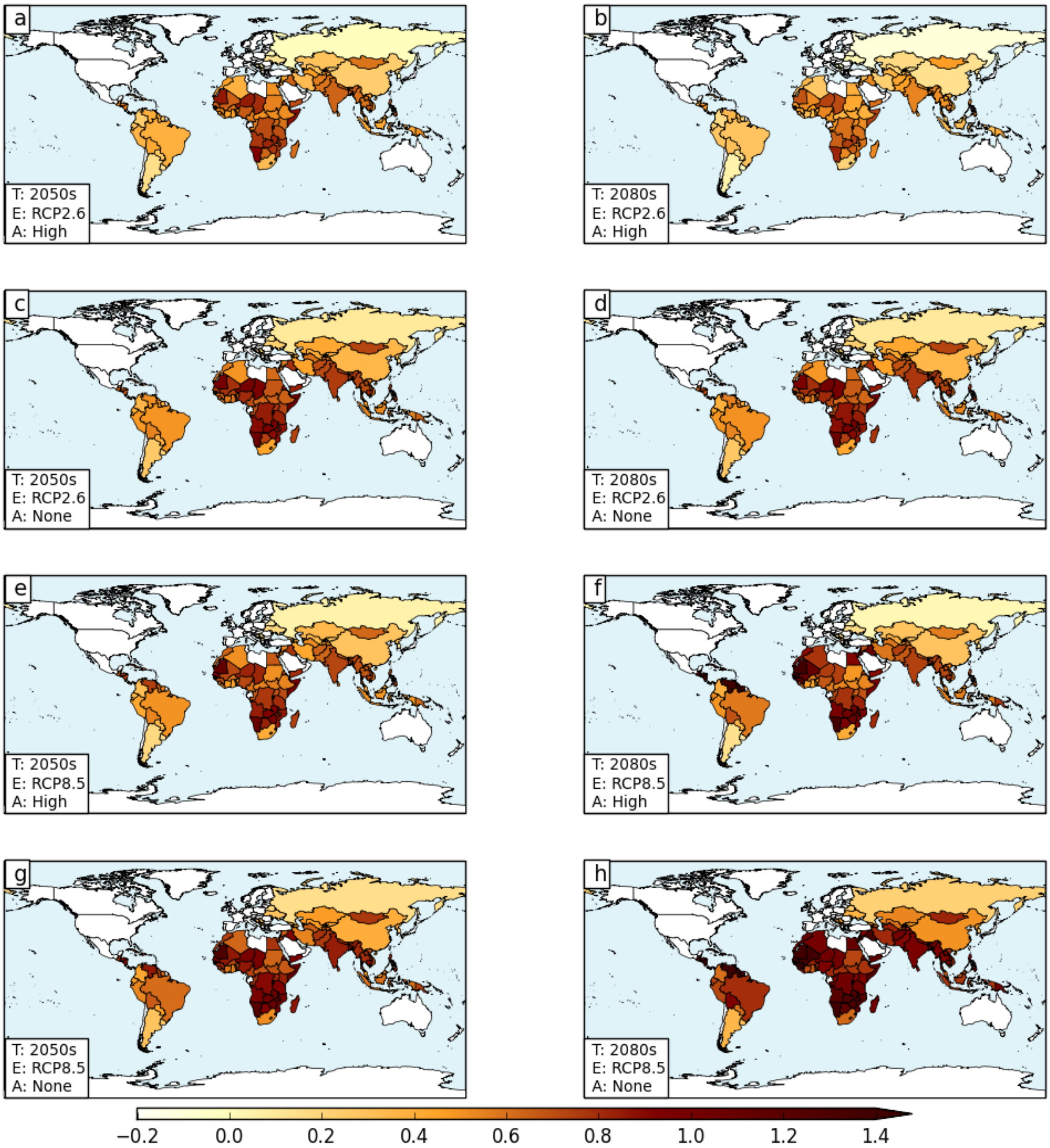


**Figure A 1 - Future projections of the HCVI from the CMIP5 ensemble mean (figure taken from Richardson *et al.* 2017. Results are shown for a range of future time periods (T; left panels (a, c, e and g) show the 2050s and the right panels (b, d, f and h) show the 2080s), emissions scenarios (E; top two rows (panels a-d) show RCP2.6 and the bottom two rows (panels e-h) show RCP8.5), and scenarios of adaptation investment (A; panels a, b, e and f show high adaptation and panels c, d, g and h show no adaptation).**

## *Appendix B – Impact of ensemble size on results*

The HadGEM3 ensemble used for the results in this report consists of five ensemble members3: each atmosphere-only simulations of HadGEM3 driven by lower resolution sea surface temperatures from a set of CMIP5 models (Section 2.2.1). As one of the ensemble members (HadGEM3 driven by the GFDL-ESM2M sea surface temperatures) did not reach SWL4 (an increase in global average temperature 4°C above pre-industrial levels) this model was excluded from the ensemble mean for all the SWL results to ensure a fair comparison of the ensemble means across the SWLs. This resulted in an ensemble mean across four models and not five, as shown for the 2050s and 2080s results.

The impact of the ensemble size on the HCVI results is minimal; an example of the HCVI results for SWL2 for the five-member and four-member ensembles for comparison is shown in Figure B 1. The effect of excluding this model from the ensemble is to increase the standard error on the ensemble mean by an average of less than 0.01%[20] and the mean standard error is small, typically <0.003 for each country.

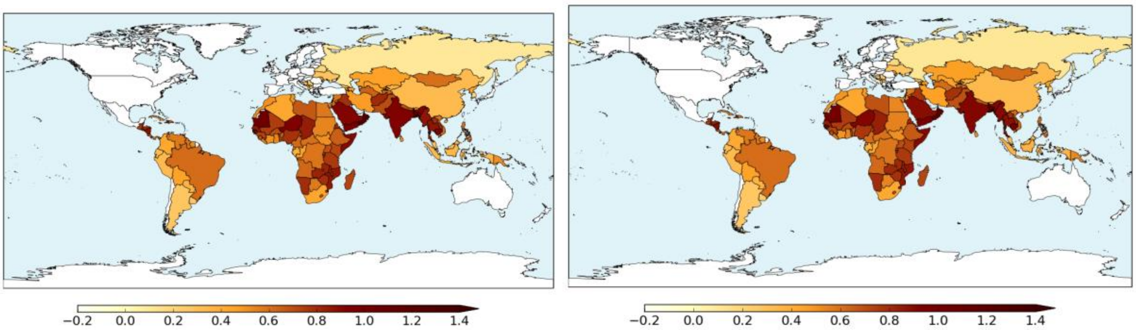


**Figure B 1 - HadGEM3 ensemble mean HCVI values for SWL2. Left panel: ensemble mean calculated using all five ensemble members, right panel: ensemble mean calculated using four ensemble members (excluding the GFDL-ESM2M ensemble member).**

[20] The standard error on the mean is given by $\sigma/\sqrt{n}$ where $n$ is the sample size, and $\sigma$ is the standard deviation of the ensemble member values

# *Appendix C – Flood and drought indicator plots*

Maps of the average length of flood and drought events indicators for each of the individual ensemble members for the baseline, SWL1.5, SWL2, SWL4, the 2050s and the 2080s are shown in Figures C 1 – C 12. Refer to Table 2 for the SWL central years.

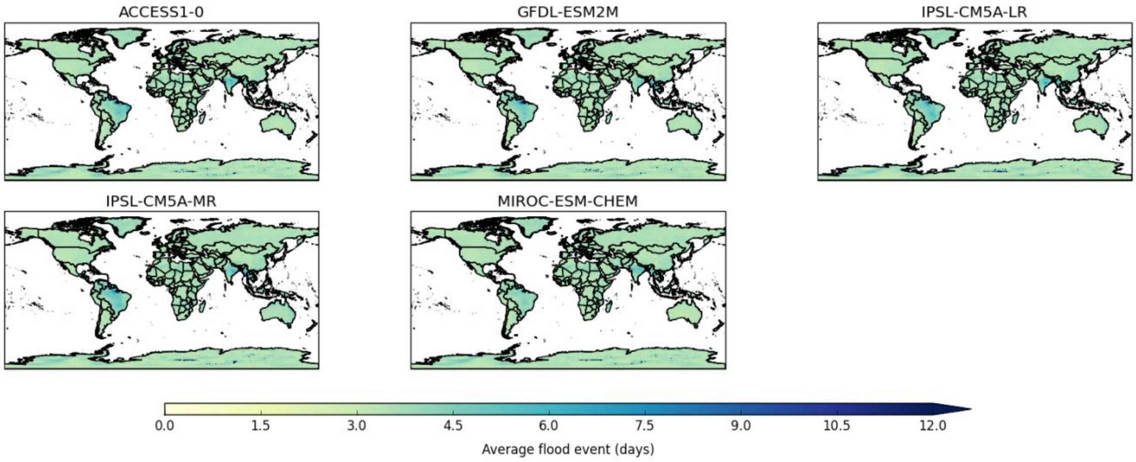


**Figure C 1 - Maps of average length of flood events indicator over the baseline period for each individual model**

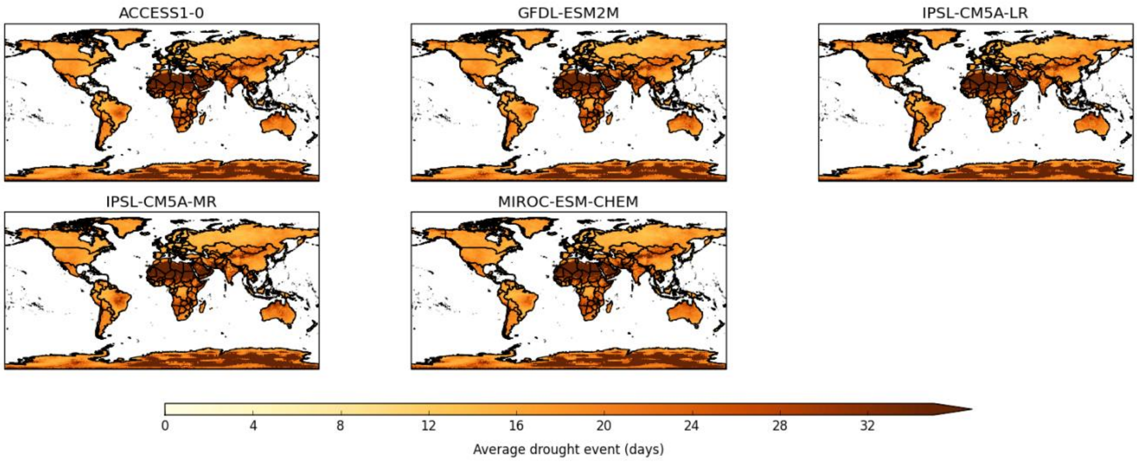


**Figure C 2 - Maps of average length of drought events indicator over the baseline period for each individual model**

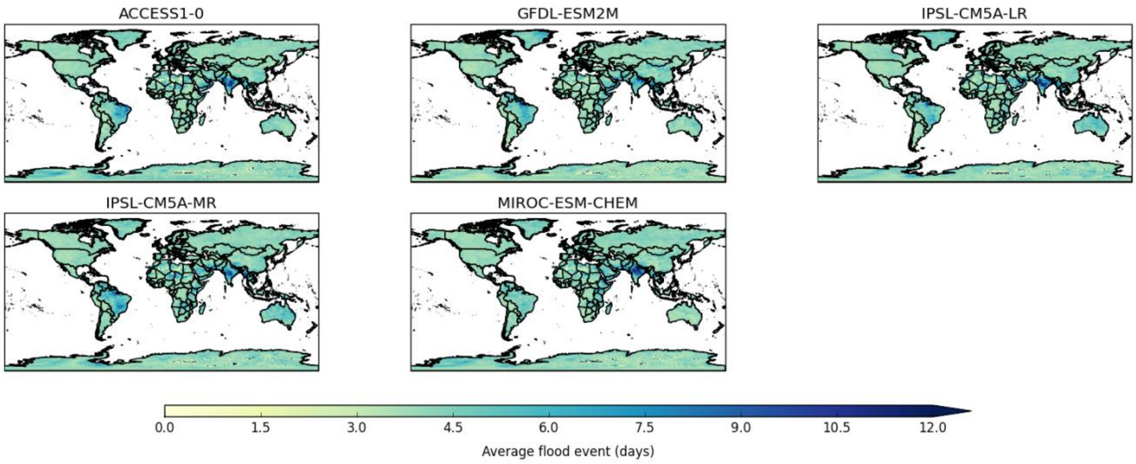


**Figure C 3 - Maps of average length of flood events indicator for SWL1.5 for each individual model**

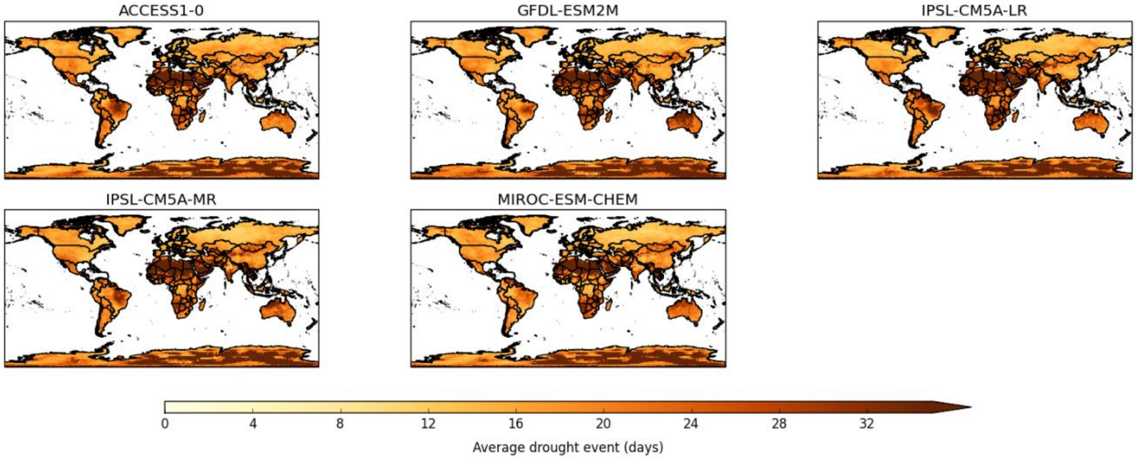


**Figure C 4 - Maps of average length of drought events indicator for SWL1.5 for each individual model**

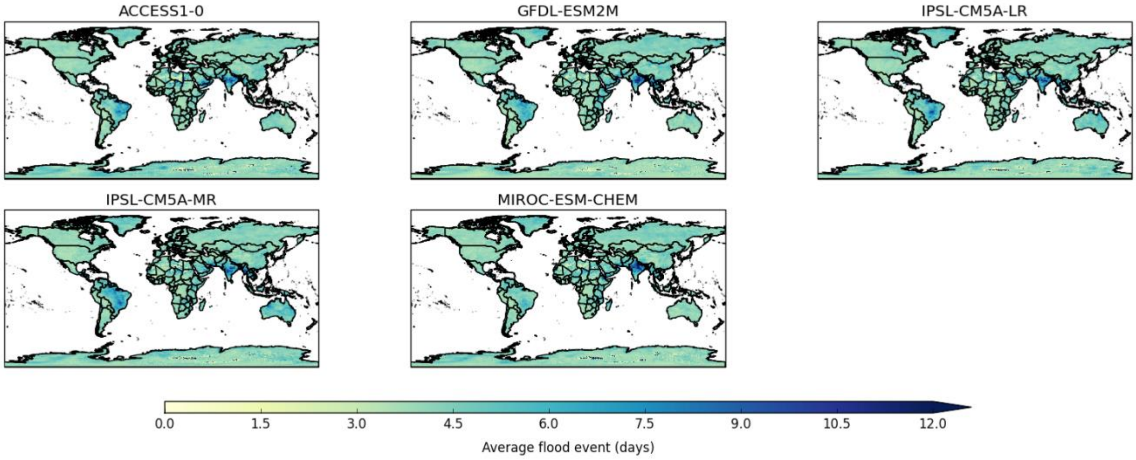


**Figure C 5 - Maps of average length of flood events indicator for SWL2 for each individual model**

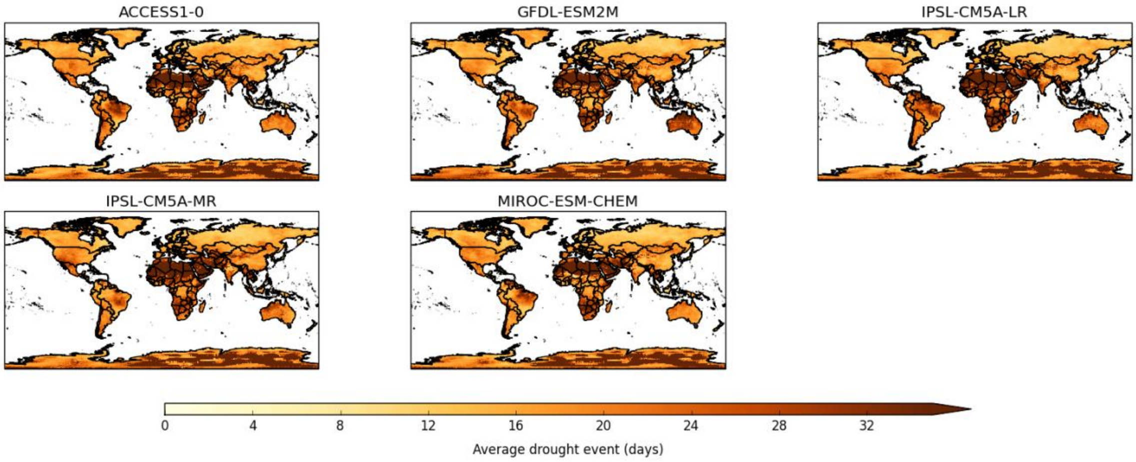


**Figure C 6 - Maps of average length of drought events indicator for SWL2 for each individual model**

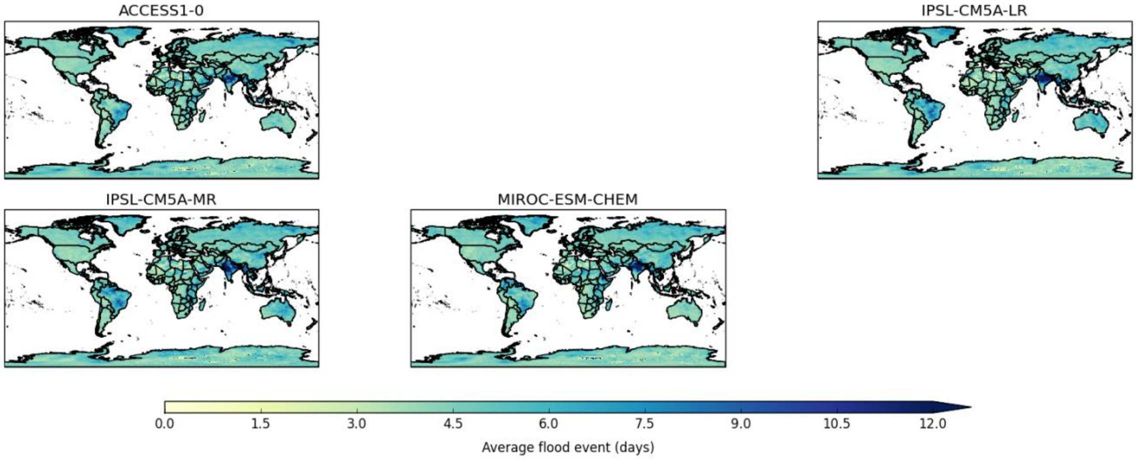


**Figure C 7 - Maps of average length of flood events indicator for SWL4 for each individual model**

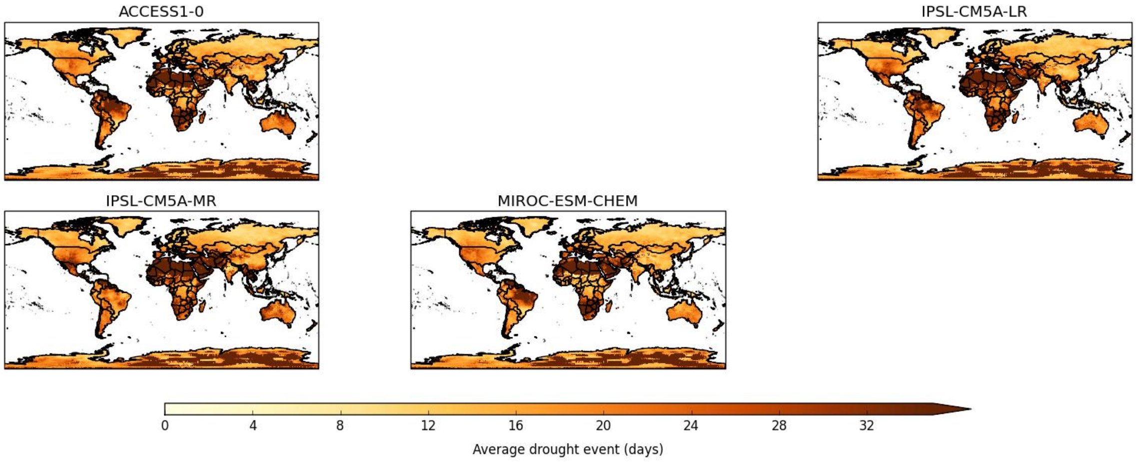


**Figure C 8 - Maps of average length of drought events indicator for SWL4 for each individual model**

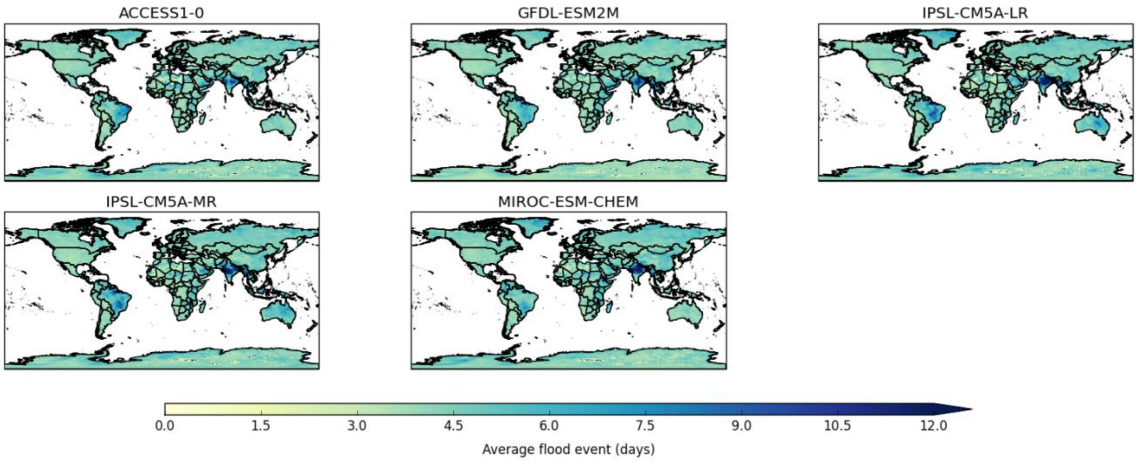


**Figure C 9 - Maps of average length of flood events indicator for the 2050s for each individual model**

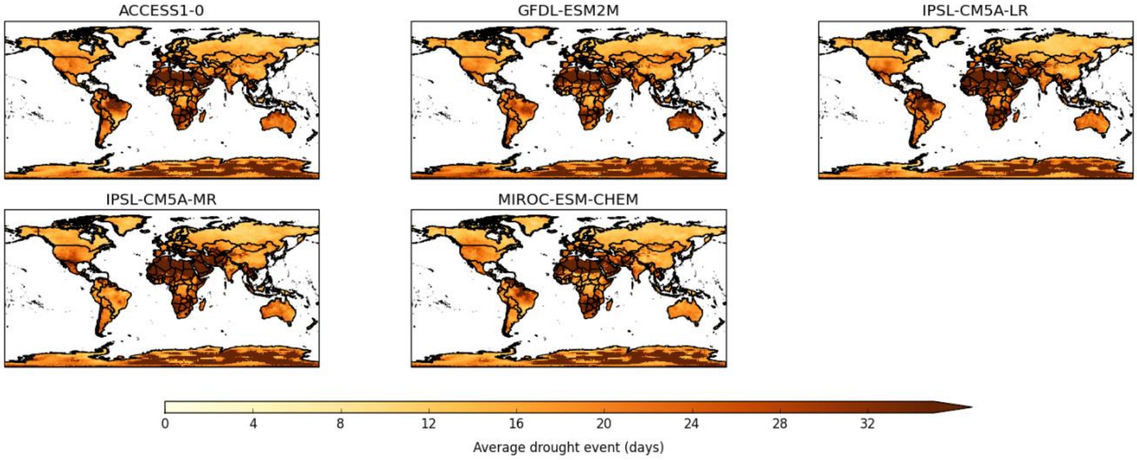


**Figure C 10 - Maps of average length of drought events indicator for the 2050s period for each individual model**

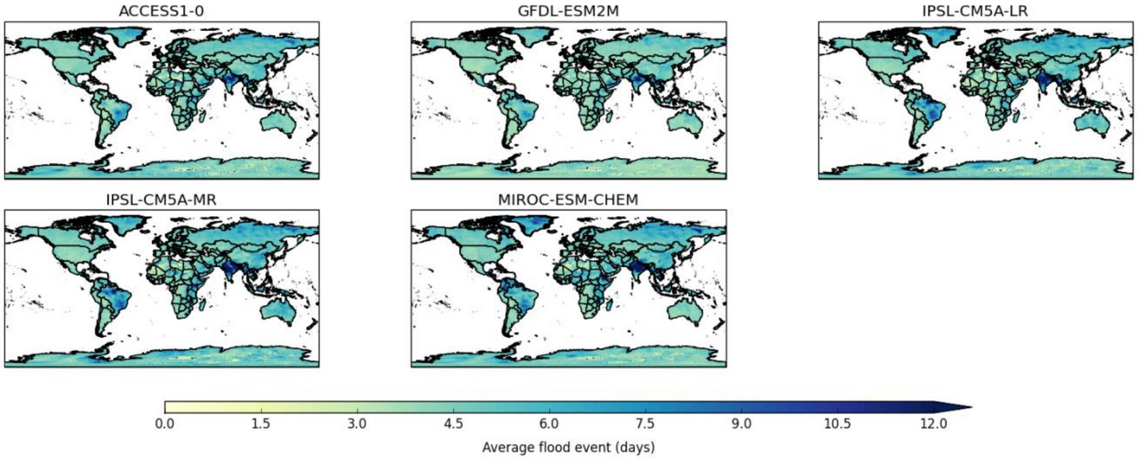


**Figure C 11 - Maps of average length of flood events indicator for the 2080s for each individual model**

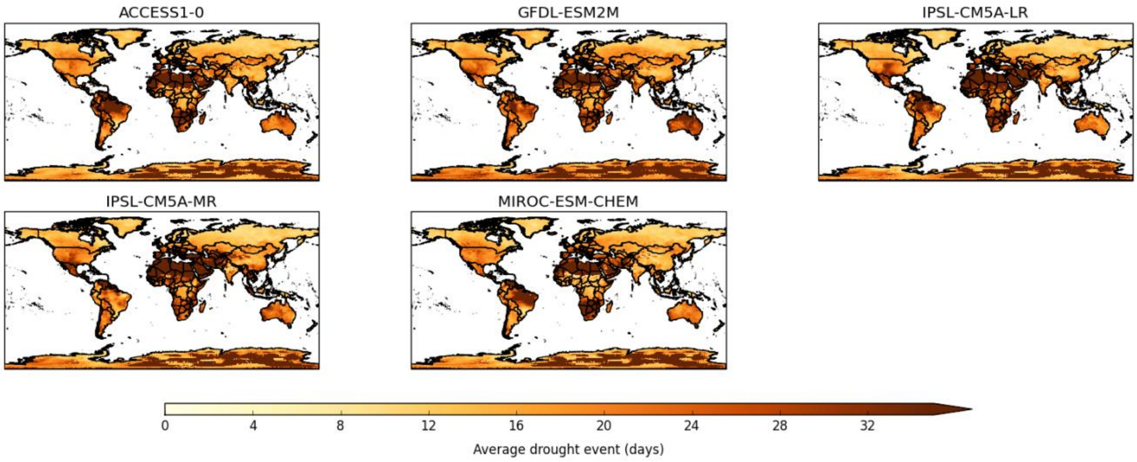


**Figure C 12 - Maps of average length of drought events indicator for the 2080s for each individual model**

## *Appendix D – HCVI HadGEM3 ensemble spread plots*

Maps of the ensemble spread of HCVI results are shown for the baseline and future projections in Figures D 1 – D 15, along with the ensemble mean. For each of the future projections the anomaly from the baseline is also shown. Note that for the SWLs only 4 models have been used as SWL4 was not available for the GFDL-ESM2M driven simulation.

### *Baseline*

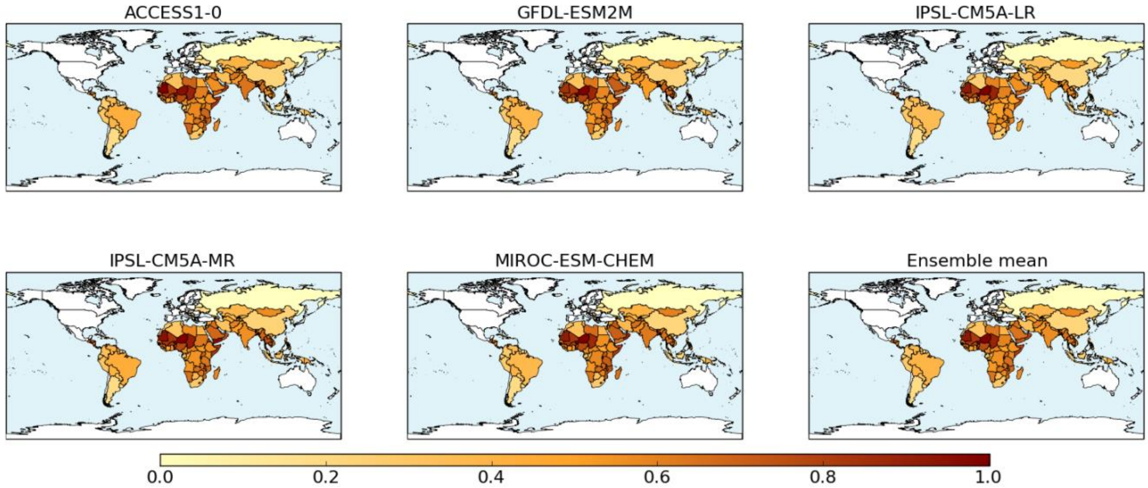


**Figure D 1 - Maps of the baseline HCVI for the individual ensemble members and the ensemble mean (bottom right panel).**

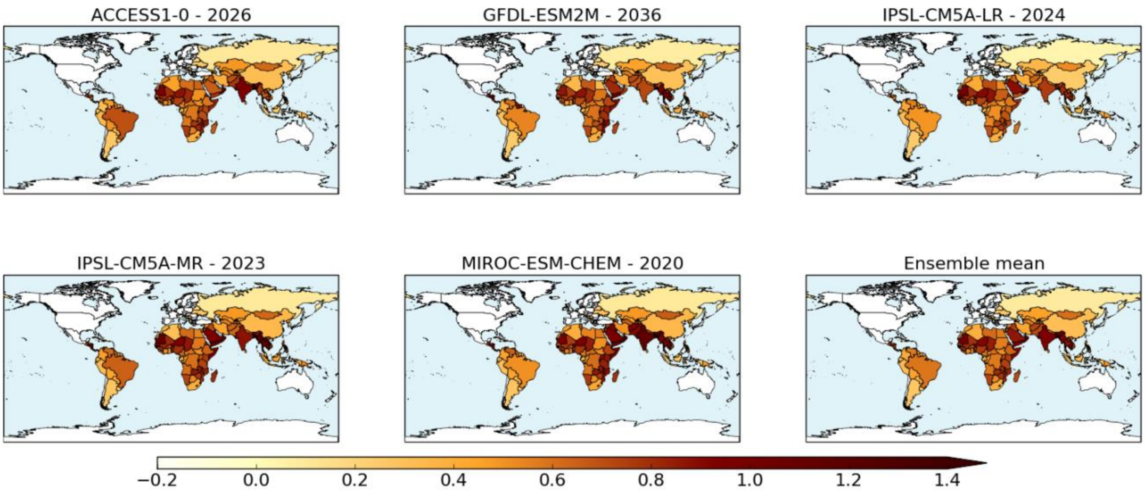


**Figure D 2 – Maps of the HCVI for SWL1.5 for the individual ensemble members and the ensemble mean (bottom right panel). The central year for SWL1.5 for each model is given in the panel title. Note the ensemble mean excludes data for the GFDL-ESM2M driven ensemble member to ensure fair comparison across ensemble means for the SWL results given that this model did not reach SWL4.**

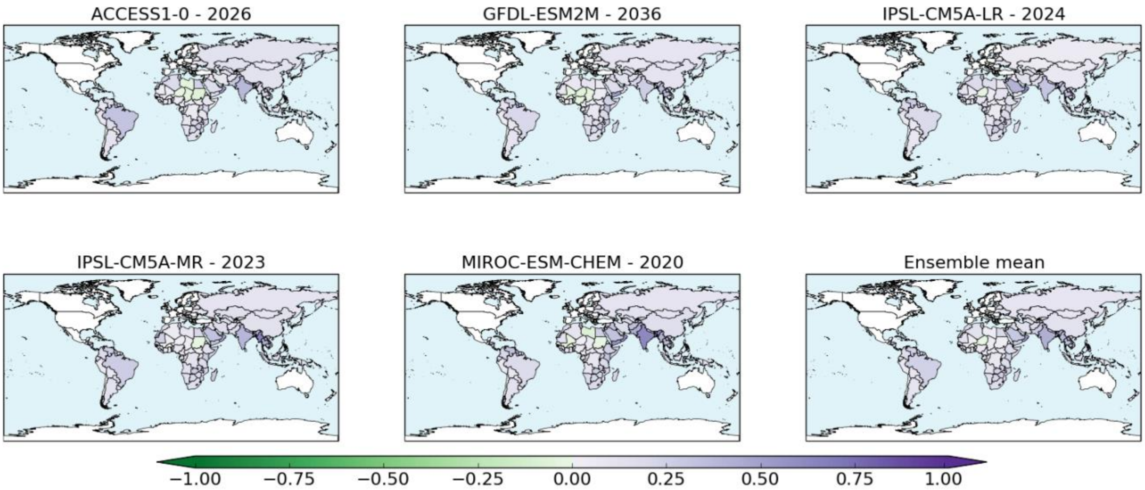


**Figure D 3 – Maps of the HCVI anomaly from the baseline for SWL1.5 for the individual ensemble members and the ensemble mean (difference between Figure D 2 and Figure D 1; bottom right panel). The central year for SWL1.5 for each model is given in the panel title. Note the ensemble mean excludes data for the GFDL-ESM2M driven ensemble member to ensure fair comparison across ensemble means for the SWL results given that this model did not reach SWL4.**

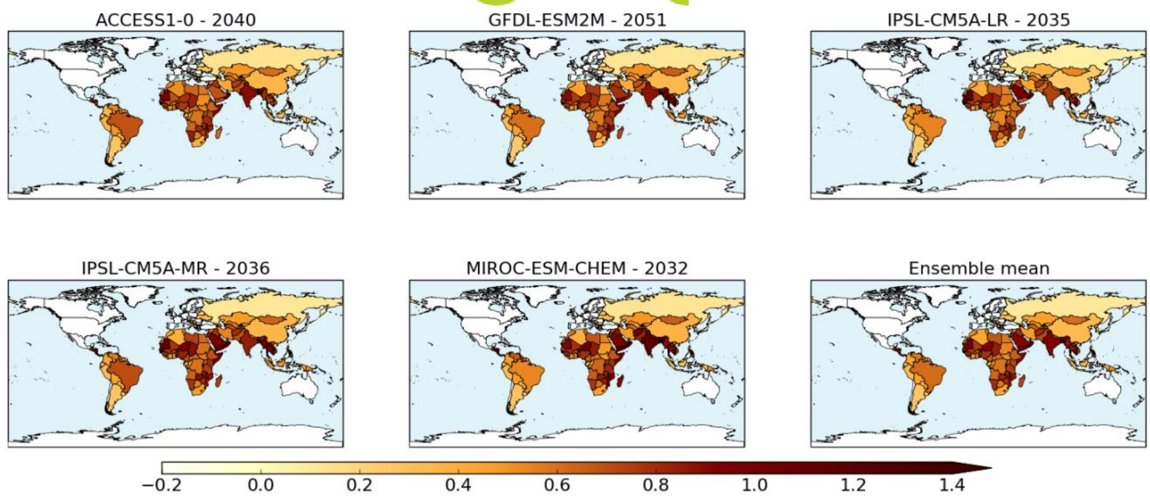


**Figure D 4 – Maps of the HCVI for SWL2 for the individual ensemble members and the ensemble mean (bottom right panel). The central year for SWL2 for each model is given in the panel title. Note the ensemble mean excludes data for the GFDL-ESM2M driven ensemble member to ensure fair comparison across ensemble means for the SWL results given that this model did not reach SWL4.**

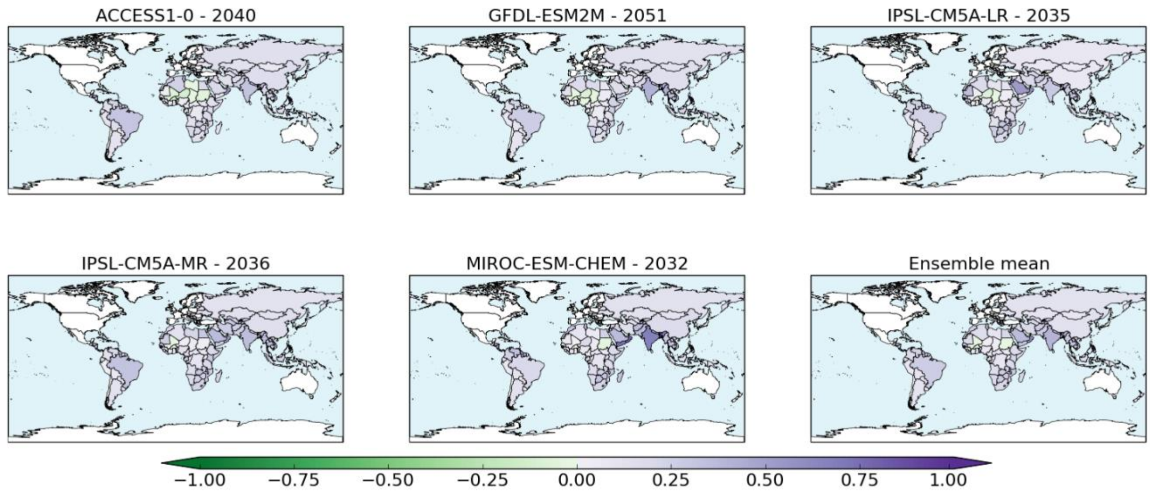


**Figure D 5 – Maps of the HCVI anomaly from the baseline for SWL2 for the individual ensemble members and the ensemble mean (difference between Figure D 4 and Figure D 1; bottom right panel). The central year for SWL2 for each model is given in the panel title. Note the ensemble mean excludes data for the GFDL-ESM2M driven ensemble member to ensure fair comparison across ensemble means for the SWL results given that this model did not reach SWL4.**

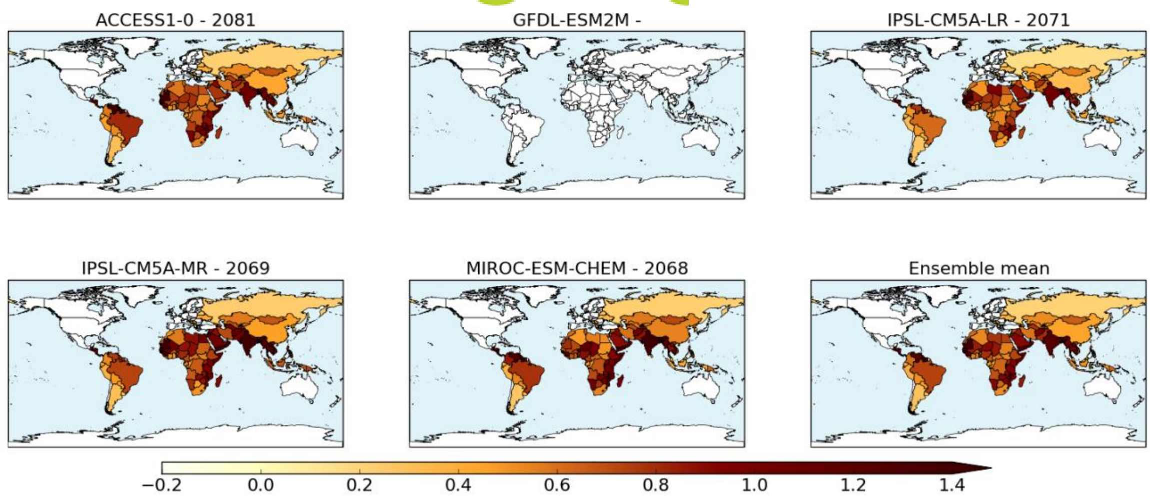


**Figure D 6 – Maps of the HCVI for SWL4 for the individual ensemble members and the ensemble mean (bottom right panel). The central year for SWL4 for each model is given in the panel title. Note the GFDL-ESM2M driven ensemble member is excluded as SWL4 was not available for this ensemble member.**

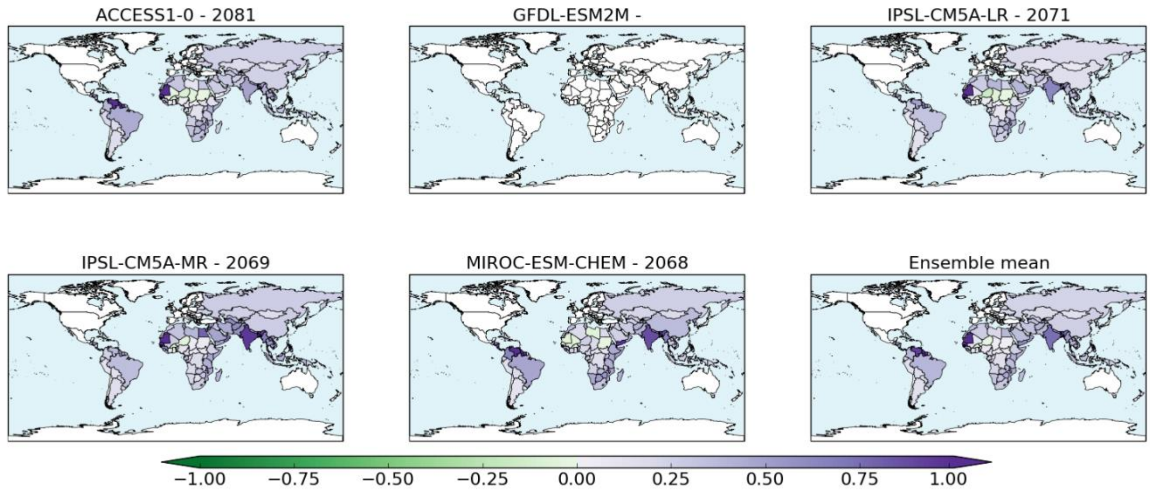


**Figure D 7 – Maps of the HCVI anomaly from the baseline for SWL4 for the individual ensemble members and the ensemble mean (difference between Figure D 6 and Figure D 1; bottom right panel). The central year for SWL4 for each model is given in the panel title. Note the GFDL-ESM2M driven ensemble member is excluded as SWL4 was not available for this ensemble member.**

## *Projected changes in vulnerability to food insecurity at future time slices*

### *a) Response to climate change alone*

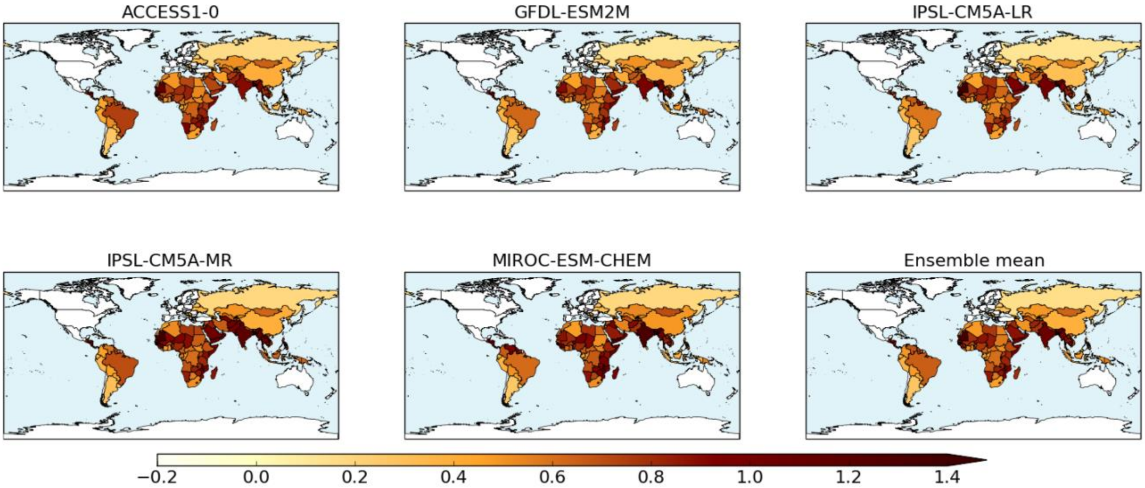


**Figure D 8 - Maps of the HCVI for the 2050s for the individual ensemble members and the ensemble mean (bottom right panel).**

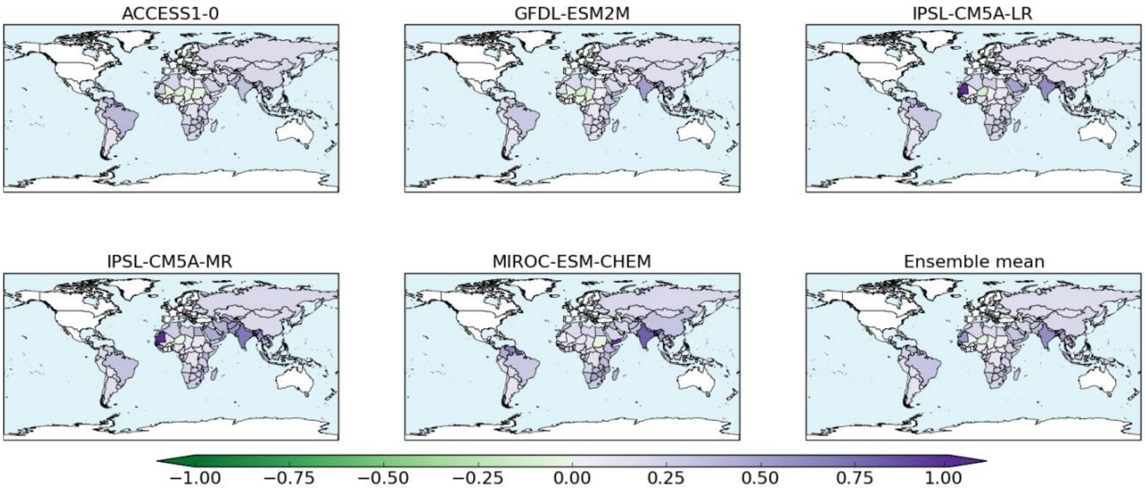


**Figure D 9 – Maps of the HCVI anomaly from the baseline for the 2050s for the individual ensemble members and the ensemble mean (difference between Figure D 8 and Figure D 1; bottom right panel).**

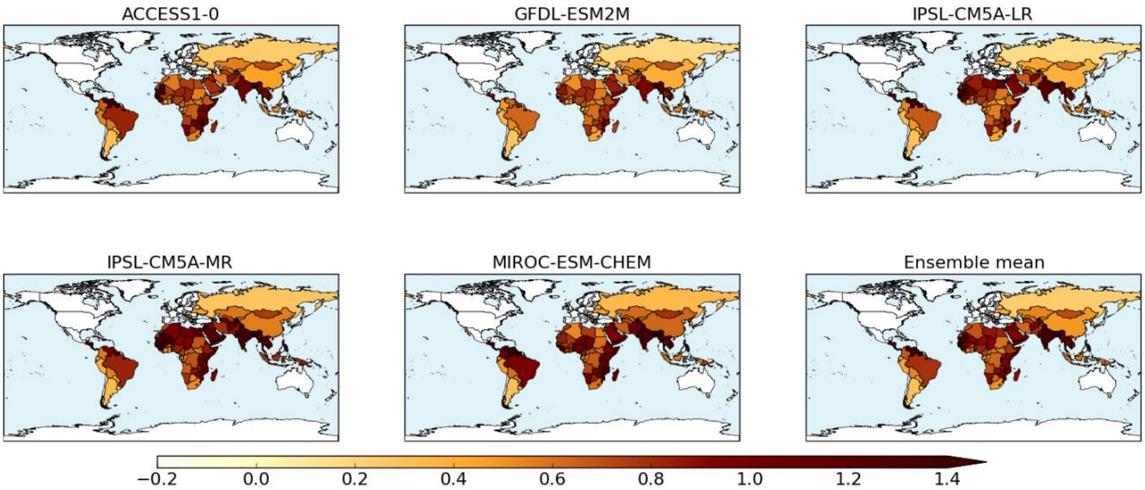


**Figure D 10 – Maps of the HCVI for the 2080s for the individual ensemble members and the ensemble mean (bottom right panel).**

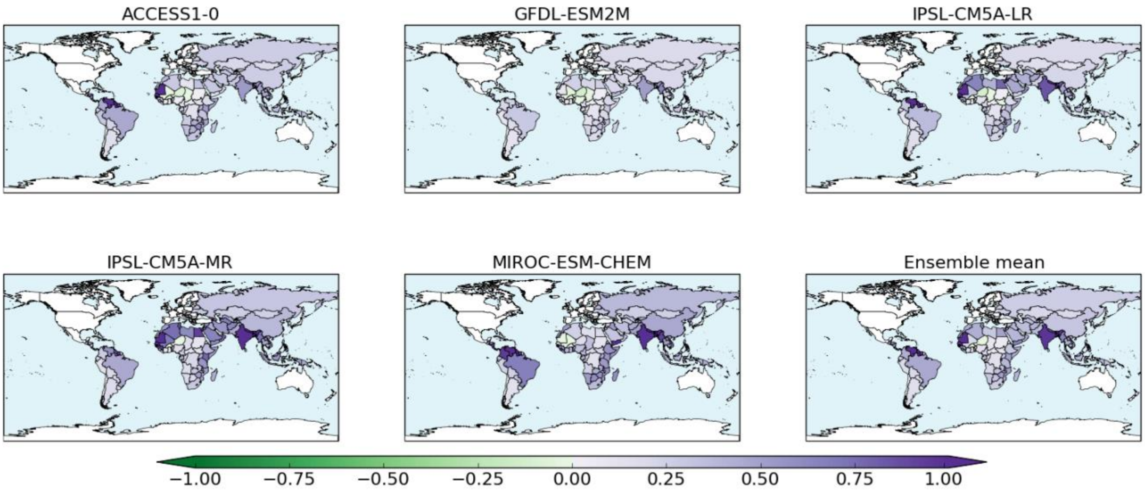


**Figure D 11 – Maps of the HCVI anomaly from the baseline for the 2050s for the individual ensemble members and the ensemble mean (difference between Figure D 10 and Figure D 1; bottom right panel).**

*b) Response to climate change with adaptation*

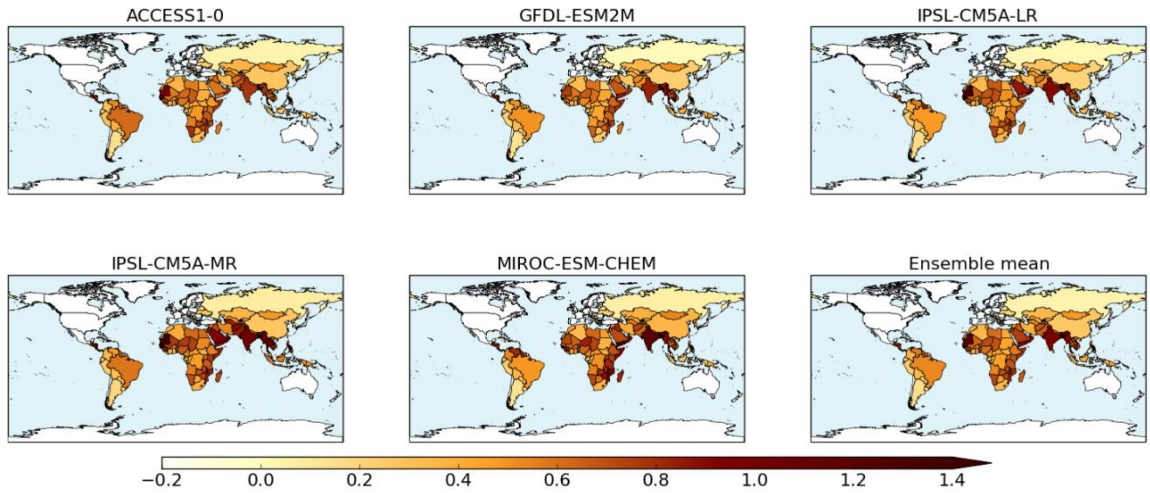


**Figure D 12 – Maps of the HCVI for the 2050s under the high adaptation scenario for the individual ensemble members and the ensemble mean (bottom right panel).**

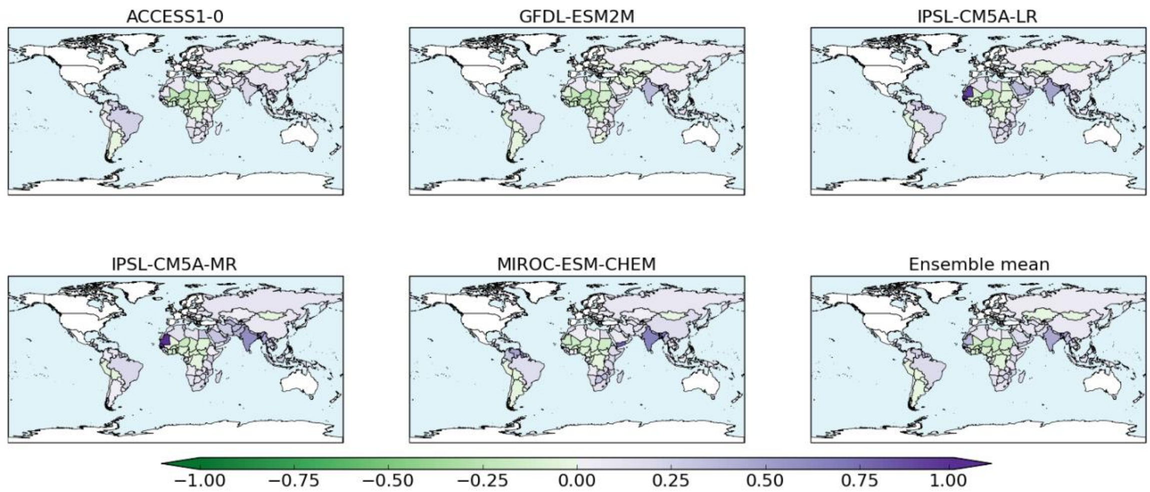


**Figure D 13 - Maps of the HCVI anomaly from the baseline for the 2050s under the high adaptation scenario for the individual ensemble members the ensemble mean (difference between Figure D 12 and Figure D 1; bottom right panel).**

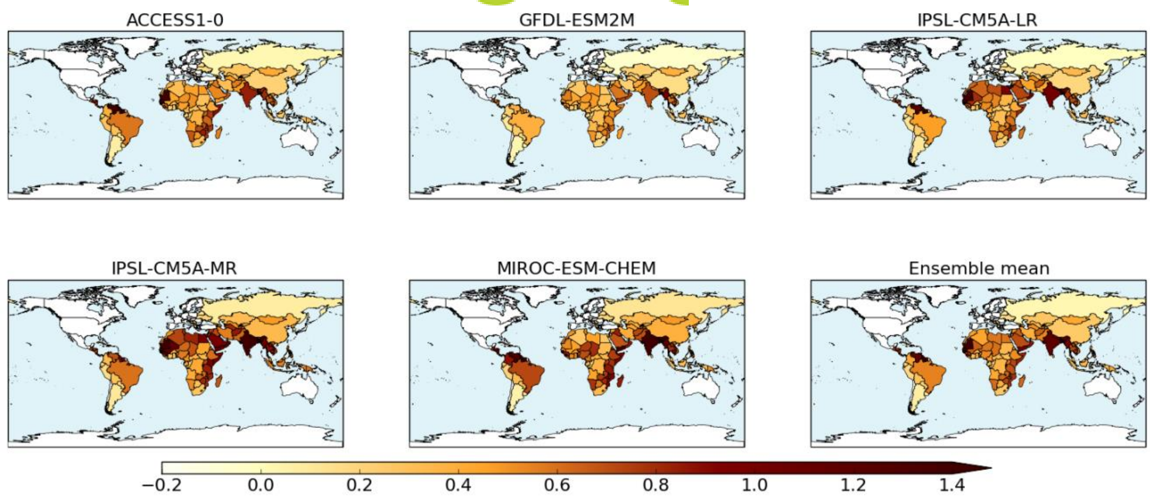


**Figure D 14 – Maps of the HCVI for the 2080s under the high adaptation scenario for the individual ensemble members and the ensemble mean (bottom right panel).**

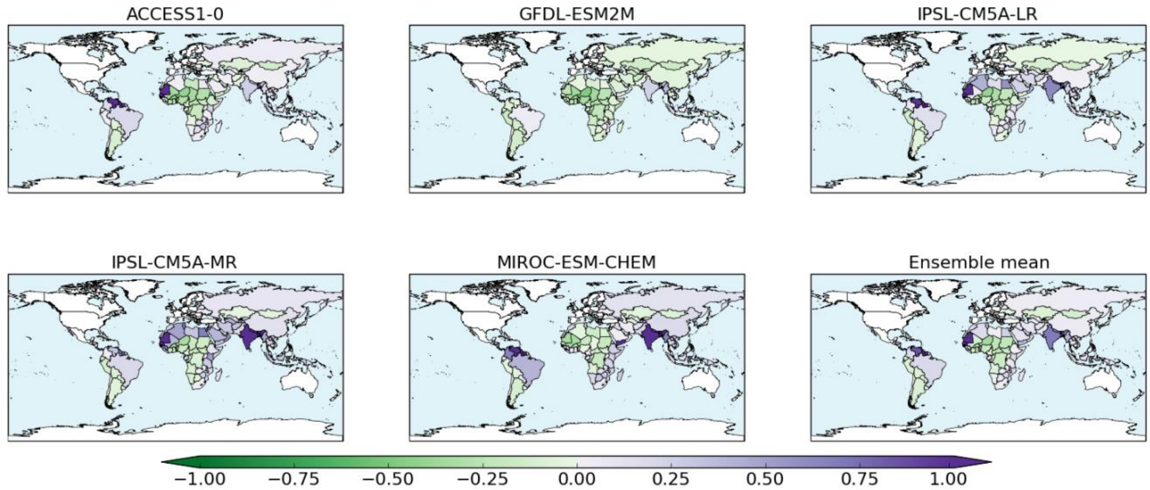


**Figure D 15 – Maps of the HCVI anomaly from the baseline for the 2050s under the high adaptation scenario for the individual ensemble members and the ensemble mean (difference between Figure D 14 and Figure D 1; bottom right panel).**

## *Appendix E – Trade-weighted HCVIT (TW-HCVIT) values*

**Table E 1 – Values of the indicators in the trade weighted HCVI from the baseline ensemble mean**

| Country name (from Natural Earth database[21]) | Trade-weighted HCVIT | HCVIT | Normalised GDP value (2010-2015 mean) – inverted | Proportion of GDP from agriculture (2010-2015 mean) | Faction of GDP not from agriculture | Imports as a proportion of food available (2010-2013 mean) | Fraction of local production | Reason for exclusion |
|---|---|---|---|---|---|---|---|---|
| Afghanistan | 0.64 | 0.64 | 1.00 | 0.24 | 0.76 | 0.05 | 0.95 | |
| Aland Islands | | | | | | | | < 500km$^2$ |
| Albania | 0.32 | 0.32 | 0.96 | 0.22 | 0.78 | 0.35 | 0.65 | |
| Algeria | 0.31 | 0.35 | 0.96 | 0.10 | 0.90 | 0.69 | 0.31 | |
| American Samoa | | | | | | | | < 500km$^2$ |
| Andorra | | | | | | | | < 500km$^2$ |
| Angola | 0.55 | 0.56 | 0.96 | 0.08 | 0.92 | 0.24 | 0.76 | |
| Anguilla | | | | | | | | < 500km$^2$ |
| Antarctica | | | | | | | | No socio-economic data |
| Antigua and Barbuda | | | | | | | | < 500km$^2$ |
| Argentina | 0.21 | 0.24 | 0.89 | 0.08 | 0.92 | 0.00 | 1.00 | |
| Armenia | 0.33 | 0.38 | 0.97 | 0.20 | 0.80 | 0.53 | 0.47 | |
| Aruba | | | | | | | | |
| Ashmore and Cartier Islands | | | | | | | | < 500km$^2$ |
| Australia | 0.10 | 0.23 | 0.44 | 0.02 | 0.98 | 0.01 | 0.99 | |
| Austria | 0.01 | 0.00 | 0.56 | 0.01 | 0.99 | 0.31 | 0.69 | |
| Azerbaijan | 0.37 | 0.39 | 0.94 | 0.06 | 0.94 | 0.38 | 0.62 | |
| Bahamas | | | 0.80 | 0.02 | 0.98 | 0.92 | 0.08 | |
| Bahrain | | | | | | | | No production data for 2010-2013 |
| Bangladesh | 0.81 | 0.83 | 0.99 | 0.17 | 0.83 | 0.07 | 0.93 | |
| Barbados | | | | | | | | < 500km$^2$ |
| Belarus | 0.13 | 0.14 | 0.94 | 0.09 | 0.91 | 0.04 | 0.96 | |
| Belgium | 0.02 | 0.01 | 0.59 | 0.01 | 0.99 | 0.84 | 0.16 | |
| Belize | 0.49 | 0.52 | 0.96 | 0.14 | 0.86 | 0.15 | 0.85 | |
| Benin | 0.68 | 0.70 | 0.99 | 0.25 | 0.75 | 0.40 | 0.60 | |

[21] naturalearthdata.com

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Bermuda | | | | | | | | < 500km² |
| Bhutan | 0.35 | 0.36 | 0.98 | 0.17 | 0.83 | 0.24 | 0.76 | |
| Bolivia | 0.43 | 0.44 | 0.98 | 0.13 | 0.87 | 0.06 | 0.94 | |
| Bosnia and Herzegovina | 0.25 | 0.27 | 0.96 | 0.08 | 0.92 | 0.35 | 0.65 | |
| Botswana | 0.25 | 0.40 | 0.94 | 0.03 | 0.97 | 0.86 | 0.14 | |
| Brazil | 0.38 | 0.44 | 0.90 | 0.05 | 0.95 | 0.11 | 0.89 | |
| British Indian Ocean Territory | | | | | | | | < 500km² |
| British Virgin Islands | | | | | | | | <500km² |
| Brunei Darussalam | 0.11 | 0.22 | 0.65 | 0.01 | 0.99 | 1.00 | 0.00 | |
| Bulgaria | 0.12 | 0.13 | 0.93 | 0.05 | 0.95 | 0.04 | 0.96 | |
| Burkina Faso | 0.81 | 0.81 | 1.00 | 0.34 | 0.66 | 0.08 | 0.92 | |
| Burundi | 0.79 | 0.78 | 1.00 | 0.41 | 0.59 | 0.19 | 0.81 | |
| Côte d'Ivoire | 0.53 | 0.53 | 0.99 | 0.24 | 0.76 | 0.45 | 0.55 | |
| Cambodia | 0.74 | 0.74 | 0.99 | 0.33 | 0.67 | 0.01 | 0.99 | |
| Cameroon | 0.59 | 0.59 | 0.99 | 0.23 | 0.77 | 0.25 | 0.75 | |
| Canada | 0.12 | 0.23 | 0.55 | 0.02 | 0.98 | 0.05 | 0.95 | |
| Cape Verde | | | 0.97 | 0.08 | 0.92 | 0.93 | 0.07 | |
| Cayman Islands | | | | | | | | < 500km² |
| Central African Republic | 0.62 | 0.62 | 1.00 | 0.51 | 0.49 | 0.02 | 0.98 | |
| Chad | 0.91 | 0.91 | 0.99 | 0.53 | 0.47 | 0.05 | 0.95 | |
| Chile | 0.17 | 0.18 | 0.87 | 0.04 | 0.96 | 0.43 | 0.57 | |
| China | 0.27 | 0.29 | 0.94 | 0.09 | 0.91 | 0.02 | 0.98 | |
| Colombia | 0.34 | 0.35 | 0.94 | 0.07 | 0.93 | 0.60 | 0.40 | |
| Comoros | | | 1.00 | 0.38 | 0.62 | 0.59 | 0.41 | |
| Cook Islands | | | | | | | | < 500km² |
| Costa Rica | 0.30 | 0.48 | 0.91 | 0.06 | 0.94 | 0.78 | 0.22 | |
| Croatia | 0.06 | 0.07 | 0.88 | 0.05 | 0.95 | 0.03 | 0.97 | |
| Cuba | | | | | | | | No export data for 2010-2013 |
| Curaçao | | | | | | | | < 500km² |
| Cyprus | 0.16 | 0.37 | 0.81 | 0.02 | 0.98 | 0.87 | 0.13 | |
| Czech Republic | 0.05 | 0.06 | 0.82 | 0.02 | 0.98 | 0.05 | 0.95 | |
| Dem. Rep. Korea | | | | | | | | No GDP or GDP from agriculture data |
| Democratic Republic Of The Congo | 0.61 | 0.59 | 1.00 | 0.22 | 0.78 | 0.25 | 0.75 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Denmark | 0.02 | 0.04 | 0.46 | 0.02 | 0.98 | 0.09 | 0.91 | |
| Djibouti | 0.42 | 0.76 | 0.99 | 0.04 | 0.96 | 1.00 | 0.00 | |
| Dominica | | | 0.94 | 0.15 | 0.85 | 0.82 | 0.18 | |
| Dominican Republic | 0.37 | 0.47 | 0.95 | 0.06 | 0.94 | 0.67 | 0.33 | |
| Ecuador | 0.30 | 0.29 | 0.95 | 0.09 | 0.91 | 0.27 | 0.73 | |
| Egypt | 0.38 | 0.46 | 0.97 | 0.12 | 0.88 | 0.44 | 0.56 | |
| El Salvador | 0.48 | 0.58 | 0.97 | 0.12 | 0.88 | 0.44 | 0.56 | |
| Equatorial Guinea | | | | | | | | No GDP data and no production or export data for 2010-2013 |
| Eritrea | 0.78 | 0.80 | 1.00 | 0.22 | 0.78 | 0.32 | 0.68 | |
| Estonia | 0.16 | 0.20 | 0.84 | 0.04 | 0.96 | 0.14 | 0.86 | |
| Ethiopia | 0.58 | 0.57 | 1.00 | 0.44 | 0.56 | 0.11 | 0.89 | |
| Faeroe Islands | | | | | | | | < $500km^2$ |
| Falkland Islands | | | | | | | | < $500km^2$ |
| Federated States Of Micronesia | | | 0.97 | 0.28 | 0.72 | | | |
| Fiji | | | 0.96 | 0.11 | 0.89 | 0.96 | 0.04 | |
| Finland | 0.01 | 0.01 | 0.56 | 0.03 | 0.97 | 0.02 | 0.98 | |
| France | 0.02 | 0.03 | 0.62 | 0.02 | 0.98 | 0.04 | 0.96 | |
| French Polynesia | | | | 0.04 | 0.96 | | | |
| French Southern And Antarctic Lands | | | | | | | | < $500km^2$ |
| Gabon | 0.37 | 0.32 | 0.91 | 0.04 | 0.96 | 0.78 | 0.22 | |
| Georgia | 0.30 | 0.25 | 0.97 | 0.09 | 0.91 | 0.76 | 0.24 | |
| Germany | 0.04 | 0.08 | 0.59 | 0.01 | 0.99 | 0.22 | 0.78 | |
| Ghana | 0.55 | 0.57 | 0.99 | 0.25 | 0.75 | 0.22 | 0.78 | |
| Greece | 0.12 | 0.17 | 0.79 | 0.04 | 0.96 | 0.26 | 0.74 | |
| Greenland | | | | | | | | No socio-economic data |
| Grenada | | | | | | | | < $500km^2$ |
| Guam | | | | | | | | < $500km^2$ |
| Guatemala | 0.55 | 0.63 | 0.97 | 0.11 | 0.89 | 0.41 | 0.59 | |
| Guernsey | | | | | | | | < $500km^2$ |
| Guinea | 0.68 | 0.69 | 1.00 | 0.21 | 0.79 | 0.10 | 0.90 | |
| Guinea-Bissau | 0.81 | 0.80 | 1.00 | 0.46 | 0.54 | 0.22 | 0.78 | |
| Guyana | 0.38 | 0.39 | 0.97 | 0.19 | 0.81 | 0.11 | 0.89 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Haiti | | | | | | | | No GDP from agriculture data |
| Heard I. and Mcdonald Islands | | | | | | | | < 500$km^2$ |
| Honduras | 0.60 | 0.69 | 0.98 | 0.14 | 0.86 | 0.51 | 0.49 | |
| Hong Kong | | | | | | | | No socio-economic data |
| Hungary | 0.12 | 0.14 | 0.88 | 0.04 | 0.96 | 0.05 | 0.95 | |
| Iceland | | | | | | | | No production data for 2010-2013 |
| India | 0.59 | 0.60 | 0.99 | 0.18 | 0.82 | 0.00 | 1.00 | |
| Indian Ocean Territories | | | | | | | | < 500$km^2$ |
| Indonesia | 0.30 | 0.30 | 0.97 | 0.14 | 0.86 | 0.10 | 0.90 | |
| Iran | 0.33 | 0.38 | 0.94 | 0.08 | 0.92 | 0.35 | 0.65 | |
| Iraq | | | | | | | | No GDP data |
| Ireland | 0.07 | 0.16 | 0.53 | 0.01 | 0.99 | 0.33 | 0.67 | |
| Isle of Man | | | | | | | | < 500$km^2$ |
| Israel | | | | | | | | No GDP data |
| Italy | 0.07 | 0.13 | 0.68 | 0.02 | 0.98 | 0.38 | 0.62 | |
| Jamaica | 0.28 | 0.61 | 0.95 | 0.07 | 0.93 | 0.99 | 0.01 | |
| Japan | 0.04 | 0.06 | 0.63 | 0.01 | 0.99 | 0.68 | 0.32 | |
| Jersey | | | | | | | | < 500$km^2$ |
| Jordan | 0.18 | 0.48 | 0.96 | 0.04 | 0.96 | 0.97 | 0.03 | |
| Kazakhstan | 0.37 | 0.43 | 0.89 | 0.05 | 0.95 | 0.08 | 0.92 | |
| Kenya | 0.61 | 0.60 | 0.99 | 0.30 | 0.70 | 0.29 | 0.71 | |
| Kiribati | | | 0.99 | 0.26 | 0.74 | | | |
| Kosovo | | | | | | | | No socio-economic data |
| Kuwait | | | 0.61 | 0.00 | 1.00 | 0.97 | 0.03 | |
| Kyrgyzstan | 0.33 | 0.33 | 0.99 | 0.18 | 0.82 | 0.21 | 0.79 | |
| Lao Pdr | 0.58 | 0.59 | 0.99 | 0.29 | 0.71 | 0.01 | 0.99 | |
| Latvia | 0.11 | 0.17 | 0.87 | 0.04 | 0.96 | 0.58 | 0.42 | |
| Lebanon | 0.18 | 0.37 | 0.92 | 0.06 | 0.94 | 0.88 | 0.12 | |
| Lesotho | | | | | | | | No export data for 2010-2013 |
| Liberia | | | | | | | | No GDP data |
| Libya | 0.36 | 0.66 | 0.92 | 0.02 | 0.98 | 0.90 | 0.10 | |
| Liechtenstein | | | | | | | | < 500$km^2$ |
| Lithuania | 0.21 | 0.25 | 0.87 | 0.04 | 0.96 | 0.13 | 0.87 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Luxembourg | 0.00 | 0.12 | 0.00 | 0.00 | 1.00 | 0.56 | 0.44 | |
| Macao | | | | | | | | < 500km$^2$ |
| Macedonia | 0.15 | 0.15 | 0.96 | 0.11 | 0.89 | 0.21 | 0.79 | |
| Madagascar | 0.60 | 0.60 | 1.00 | 0.27 | 0.73 | 0.05 | 0.95 | |
| Malawi | 0.68 | 0.68 | 1.00 | 0.31 | 0.69 | 0.05 | 0.95 | |
| Malaysia | 0.20 | 0.25 | 0.91 | 0.10 | 0.90 | 0.66 | 0.34 | |
| Maldives | | | | | | | | <500km$^2$ |
| Mali | 0.84 | 0.84 | 1.00 | 0.39 | 0.61 | 0.05 | 0.95 | |
| Malta | | | | | | | | No import data for 2010-2013 |
| Marshall Islands | | | | | | | | < 500km$^2$ |
| Mauritania | | | | | | | | No export data for 2010-2013 |
| Mauritius | 0.21 | 0.33 | 0.92 | 0.03 | 0.97 | 1.00 | 0.00 | |
| Mexico | 0.23 | 0.26 | 0.91 | 0.04 | 0.96 | 0.33 | 0.67 | |
| Moldova | 0.32 | 0.32 | 0.98 | 0.14 | 0.86 | 0.01 | 0.99 | |
| Monaco | | | | | | | | < 500km$^2$ |
| Mongolia | 0.58 | 0.61 | 0.97 | 0.14 | 0.86 | 0.10 | 0.90 | |
| Montenegro | 0.22 | 0.30 | 0.94 | 0.10 | 0.90 | 0.76 | 0.24 | |
| Montserrat | | | | | | | | < 500km$^2$ |
| Morocco | 0.35 | 0.36 | 0.97 | 0.14 | 0.86 | 0.42 | 0.58 | |
| Mozambique | 0.70 | 0.71 | 1.00 | 0.27 | 0.73 | 0.35 | 0.65 | |
| Myanmar | 0.68 | 0.68 | 0.99 | 0.54 | 0.46 | 0.01 | 0.99 | |
| Namibia | 0.51 | 0.67 | 0.95 | 0.08 | 0.92 | 0.45 | 0.55 | |
| Nauru | | | | | | | | < 500km$^2$ |
| Nepal | 0.50 | 0.50 | 1.00 | 0.35 | 0.65 | 0.05 | 0.95 | |
| Netherlands | 0.03 | 0.12 | 0.54 | 0.02 | 0.98 | 0.95 | 0.05 | |
| New Caledonia | | | | | | | | No socio-economic data |
| New Zealand | 0.05 | 0.07 | 0.64 | 0.07 | 0.93 | 0.32 | 0.68 | |
| Nicaragua | 0.60 | 0.62 | 0.99 | 0.19 | 0.81 | 0.26 | 0.74 | |
| Niger | 1.00 | 1.00 | 1.00 | 0.38 | 0.62 | 0.07 | 0.93 | |
| Nigeria | 0.75 | 0.79 | 0.98 | 0.22 | 0.78 | 0.23 | 0.77 | |
| Niue | | | | | | | | < 500km$^2$ |
| Norfolk Island | | | | | | | | < 500km$^2$ |
| Northern Cyprus | | | | | | | | < 500km$^2$ |
| Northern Mariana Islands | | | | | | | | < 500km$^2$ |
| Norway | 0.02 | 0.23 | 0.14 | 0.02 | 0.98 | 0.42 | 0.58 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Oman | 0.28 | 0.80 | 0.82 | 0.01 | 0.99 | 0.97 | 0.03 | |
| Pakistan | 0.55 | 0.55 | 0.99 | 0.25 | 0.75 | 0.01 | 0.99 | |
| Palau | | | | | | | | < 500km$^2$ |
| Palestine | 0.25 | 0.49 | 0.98 | 0.06 | 0.94 | 0.92 | 0.08 | |
| Panama | 0.33 | 0.44 | 0.90 | 0.03 | 0.97 | 0.59 | 0.41 | |
| Papua New Guinea | 0.57 | 0.48 | 0.98 | 0.38 | 0.62 | 0.94 | 0.06 | |
| Paraguay | 0.35 | 0.36 | 0.96 | 0.21 | 0.79 | 0.02 | 0.98 | |
| Peru | 0.35 | 0.34 | 0.95 | 0.07 | 0.93 | 0.45 | 0.55 | |
| Philippines | 0.53 | 0.56 | 0.98 | 0.12 | 0.88 | 0.14 | 0.86 | |
| Pitcairn Islands | | | | | | | | < 500km$^2$ |
| Poland | 0.13 | 0.15 | 0.88 | 0.03 | 0.97 | 0.09 | 0.91 | |
| Portugal | 0.10 | 0.18 | 0.80 | 0.02 | 0.98 | 0.78 | 0.22 | |
| Puerto Rico | | | | | | | | No import or export data for 2010-2013 |
| Qatar | | | 0.20 | 0.00 | 1.00 | 0.99 | 0.01 | |
| Republic Of Congo | 0.52 | 0.45 | 0.98 | 0.05 | 0.95 | 0.85 | 0.15 | |
| Republic Of Korea | 0.07 | 0.11 | 0.77 | 0.02 | 0.98 | 0.70 | 0.30 | |
| Romania | 0.20 | 0.22 | 0.92 | 0.06 | 0.94 | 0.11 | 0.89 | |
| Russian Federation | 0.06 | 0.07 | 0.88 | 0.04 | 0.96 | 0.02 | 0.98 | |
| Rwanda | 0.71 | 0.71 | 1.00 | 0.33 | 0.67 | 0.20 | 0.80 | |
| São Tomé And Principe | | | 0.99 | 0.23 | 0.77 | 0.87 | 0.13 | |
| Saint Helena | | | | | | | | < 500km$^2$ |
| Saint Kitts and Nevis | | | | | | | | < 500km$^2$ |
| Saint Lucia | | | | | | | | No production data for 2010-2013 |
| Saint Pierre and Miquelon | | | | | | | | < 500km$^2$ |
| Saint Vincent and the Grenadines | | | | | | | | < 500km$^2$ |
| Saint-Barthélemy | | | | | | | | < 500km$^2$ |
| Saint-Martin | | | | | | | | < 500km$^2$ |
| Samoa | | | | | | | | No GDP data |
| San Marino | | | | | | | | < 500km$^2$ |
| Saudi Arabia | 0.29 | 0.68 | 0.79 | 0.02 | 0.98 | 0.91 | 0.09 | |
| Senegal | 0.59 | 0.67 | 0.99 | 0.16 | 0.84 | 0.54 | 0.46 | |
| Serbia | 0.17 | 0.18 | 0.95 | 0.10 | 0.90 | 0.01 | 0.99 | |
| Seychelles | | | | | | | | < 500km$^2$ |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sierra Leone | | | | | | | | No export data for 2010-2013 |
| Singapore | | | | | | | | No production data for 2010-2013 |
| Sint Maarten | | | | | | | | < 500km$^2$ |
| Slovakia | 0.08 | 0.09 | 0.84 | 0.04 | 0.96 | 0.12 | 0.88 | |
| Slovenia | 0.08 | 0.06 | 0.79 | 0.02 | 0.98 | 0.59 | 0.41 | |
| Solomon Islands | | | | | | | | No GDP from agriculture data |
| Somalia | | | | | | | | No export data for 2010-2013 |
| South Africa | 0.29 | 0.34 | 0.94 | 0.02 | 0.98 | 0.19 | 0.81 | |
| South Georgia and South Sandwich Islands | | | | | | | | < 500km$^2$ |
| South Sudan | | | | | | | | No GDP from agriculture data and no import/export data for 2010-2013 |
| Spain | 0.08 | 0.14 | 0.73 | 0.03 | 0.97 | 0.37 | 0.63 | |
| Sri Lanka | 0.39 | 0.42 | 0.97 | 0.09 | 0.91 | 0.21 | 0.79 | |
| Sudan | 0.61 | 0.62 | 0.99 | 0.28 | 0.72 | 0.30 | 0.70 | |
| Suriname | 0.28 | 0.31 | 0.92 | 0.10 | 0.90 | 0.14 | 0.86 | |
| Swaziland | 0.55 | 0.60 | 0.97 | 0.07 | 0.93 | 0.65 | 0.35 | |
| Sweden | 0.04 | 0.07 | 0.48 | 0.01 | 0.99 | 0.11 | 0.89 | |
| Switzerland | 0.02 | 0.10 | 0.24 | 0.01 | 0.99 | 0.46 | 0.54 | |
| Syria | 0.46 | 0.48 | 0.99 | 0.21 | 0.79 | 0.36 | 0.64 | |
| Taiwan | | | | | | | | No socio-economic data |
| Tajikistan | 0.55 | 0.56 | 0.99 | 0.26 | 0.74 | 0.33 | 0.67 | |
| Tanzania | 0.68 | 0.68 | 0.99 | 0.32 | 0.68 | 0.13 | 0.87 | |
| Thailand | 0.61 | 0.67 | 0.95 | 0.11 | 0.89 | 0.06 | 0.94 | |
| The Gambia | 0.75 | 0.78 | 1.00 | 0.25 | 0.75 | 0.28 | 0.72 | |
| Timor-Leste | | | | | | | | No export data for 2010-2013 |
| Togo | 0.74 | 0.74 | 1.00 | 0.38 | 0.62 | 0.14 | 0.86 | |
| Tonga | | | | | | | | No production or export data for 2010-2013 |
| Trinidad And Tobago | 0.22 | 0.42 | 0.83 | 0.00 | 1.00 | 0.98 | 0.02 | |
| Tunisia | 0.25 | 0.32 | 0.96 | 0.09 | 0.91 | 0.65 | 0.35 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Turkey | 0.27 | 0.30 | 0.91 | 0.09 | 0.91 | 0.13 | 0.87 | |
| Turkmenistan | | | | | | | | No export data for 2010-2013 |
| Turks and Caicos Islands | | | | | | | | < 500km$^2$ |
| Uganda | 0.69 | 0.70 | 1.00 | 0.26 | 0.74 | 0.15 | 0.85 | |
| Ukraine | 0.24 | 0.25 | 0.97 | 0.10 | 0.90 | 0.00 | 1.00 | |
| United Arab Emirates | | | | | | | | No GDP from agriculture data |
| United Kingdom | 0.06 | 0.12 | 0.61 | 0.01 | 0.99 | 0.18 | 0.82 | |
| United States | 0.01 | 0.03 | 0.52 | 0.01 | 0.99 | 0.02 | 0.98 | |
| United States Virgin Islands | | | | | | | | < 500km$^2$ |
| Uruguay | 0.21 | 0.25 | 0.86 | 0.09 | 0.91 | 0.15 | 0.85 | |
| Uzbekistan | 0.39 | 0.40 | 0.99 | 0.19 | 0.81 | 0.07 | 0.93 | |
| Vanuatu | | | 0.97 | 0.27 | 0.73 | 0.90 | 0.10 | |
| Vatican | | | | | | | | |
| Venezuela | 0.34 | 0.43 | 0.89 | 0.06 | 0.94 | 0.54 | 0.46 | |
| Vietnam | 0.48 | 0.49 | 0.99 | 0.18 | 0.82 | 0.09 | 0.91 | |
| Wallis and Futuna Islands | | | | | | | | < 500km$^2$ |
| Western Sahara | | | | | | | | No socio-economic data |
| Yemen | 0.68 | 0.76 | 0.99 | 0.12 | 0.88 | 0.82 | 0.18 | |
| Zambia | 0.65 | 0.66 | 0.99 | 0.10 | 0.90 | 0.01 | 0.99 | |
| Zimbabwe | 0.58 | 0.60 | 0.99 | 0.13 | 0.87 | 0.34 | 0.66 | |

## *Appendix F – Trade-weighted HCVIT (TW-HCVIT) HadGEM3 ensemble spread plots*

Maps of the ensemble spread of the TW-HCVIT results are shown for the baseline and future projections in Figures F 1 – F 11. For each of the future projections the anomaly from the baseline is also shown. Note that for the SWLs only 5 models have been used as SWL4 was not available for the GFDL-ESM2M driven simulation and was therefore excluded from the other SWL results to ensure a fair comparison.

### *Baseline*

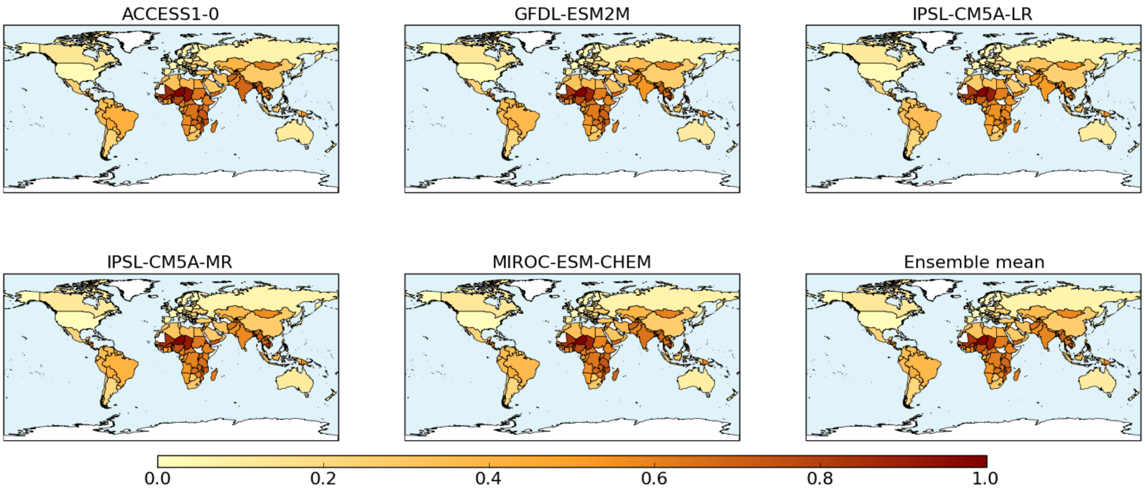


**Figure F 1 – Maps of the baseline trade-weighted HCVIT (TW-HCVIT) for the individual ensemble members and the ensemble mean (bottom right panel).**

## *Projected changes in vulnerability to food insecurity at 1.5, 2 and 4°C*

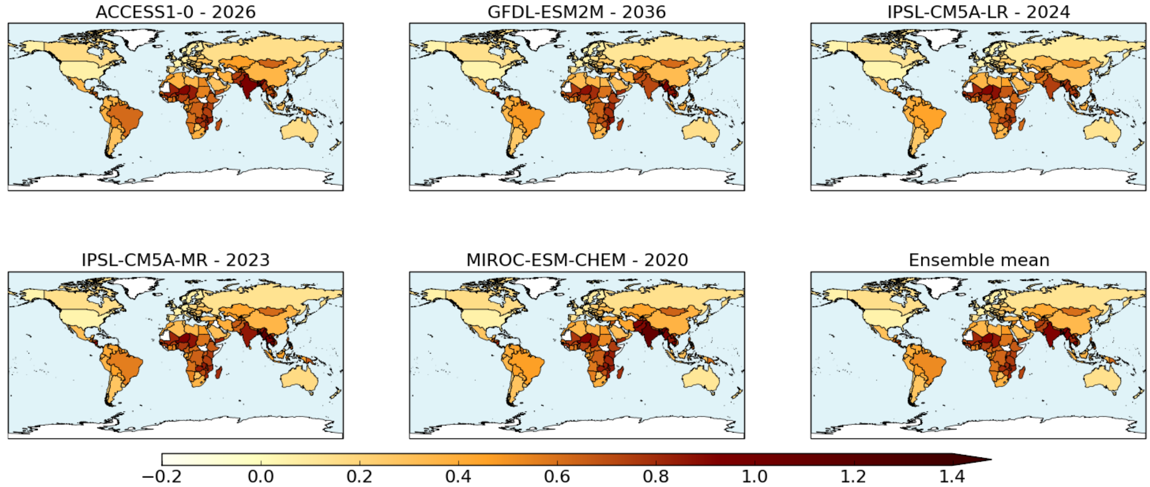


**Figure F 2 – Maps of the trade-weighted HCVIT (TW-HCVIT) for SWL1.5 for the individual ensemble members and the ensemble mean (bottom right panel). The central year for SWL1.5 for each model is given in the panel title. Note the ensemble mean excludes data for the GFDL-ESM2M driven ensemble member to ensure fair comparison across ensemble means for the SWL results given that this model did not reach SWL4.**

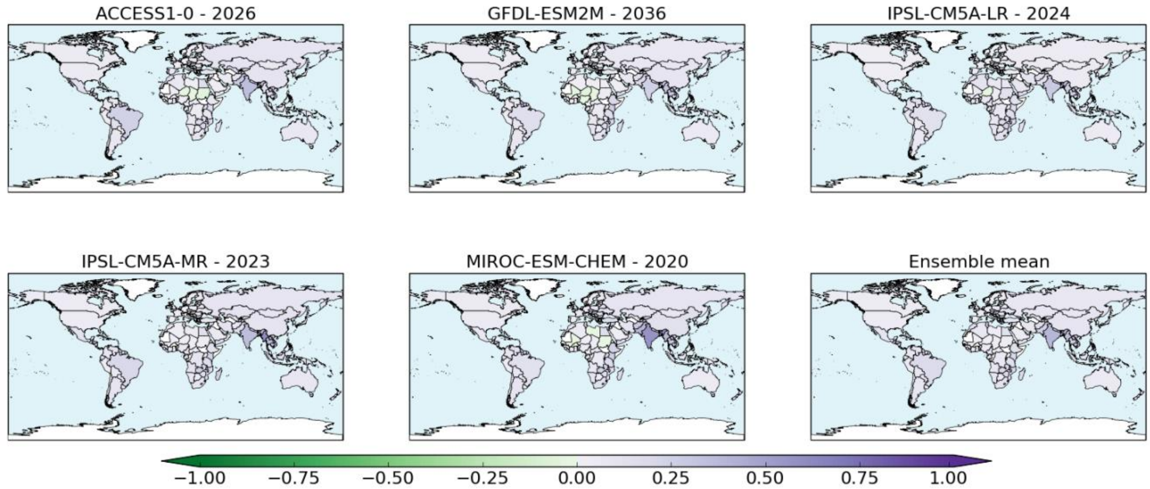


**Figure F 3 – Maps of the trade-weighted HCVIT (TW-HCVIT) anomaly from baseline for SWL1.5 for the individual ensemble members and the ensemble mean (difference between Figure F 2 and Figure F 1; bottom right panel). The central year for SWL1.5 for each model is given in the panel title. Note the ensemble mean excludes data for the GFDL-ESM2M driven ensemble member to ensure fair comparison across ensemble means for the SWL results given that this model did not reach SWL4.**

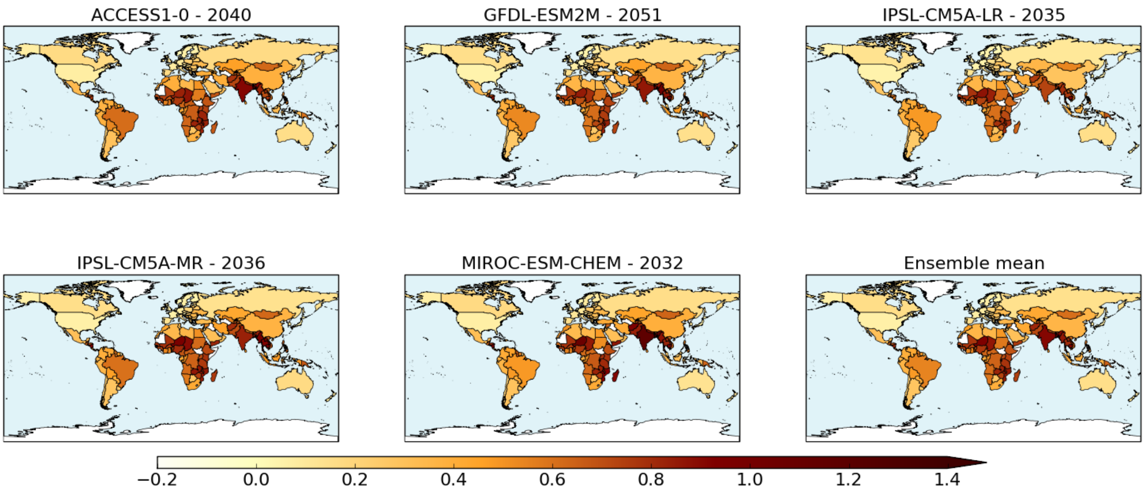


**Figure F 4 - Maps of the trade-weighted HCVIT (TW-HCVIT) for SWL2 for the individual ensemble members and the ensemble mean (bottom right panel). The central year for SWL2 for each model is given in the panel title. Note the ensemble mean excludes data for the GFDL-ESM2M driven ensemble member to ensure fair comparison across ensemble means for the SWL results given that this model did not reach SWL4.**

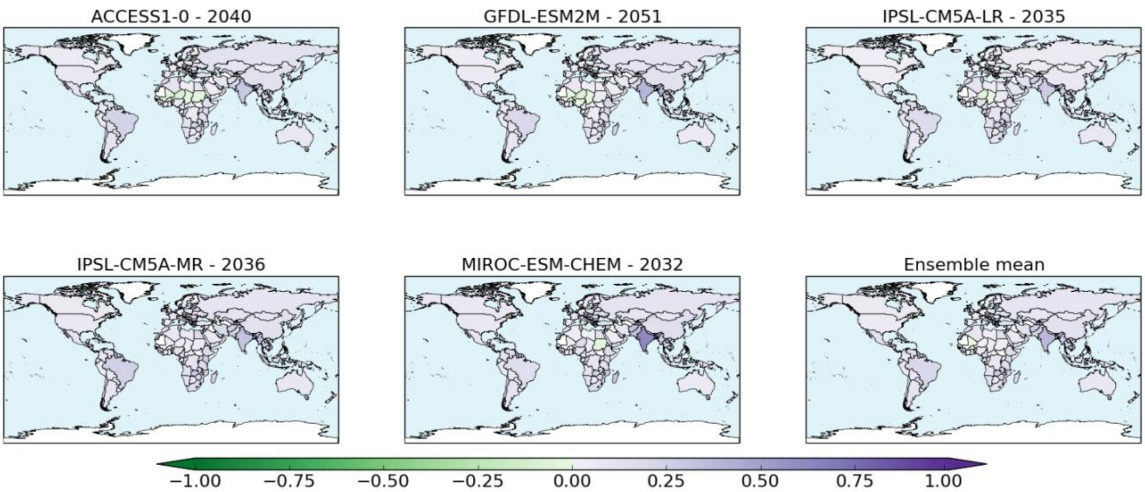


**Figure F 5– Maps of the trade-weighted HCVIT (TW-HCVIT) anomaly from baseline for SWL2 for the individual ensemble members and the ensemble mean (difference between Figure F 4 and Figure F 1; bottom right panel). The central year for SWL2 for each model is given in the panel title. Note the ensemble mean excludes data for the GFDL-ESM2M driven ensemble member to ensure fair comparison across ensemble means for the SWL results given that this model did not reach SWL4.**

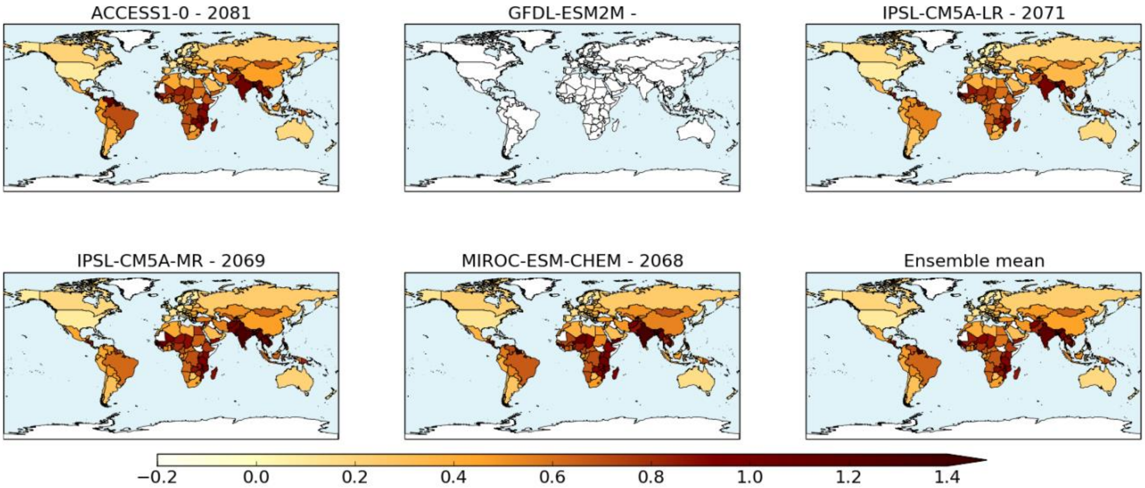


**Figure F 6 – Maps of the trade-weighted HCVIT (TW-HCVIT) for SWL4 for the individual ensemble members and the ensemble mean (bottom right panel). The central year for SWL4 for each model is given in the panel title. Note the GFDL-ESM2M driven ensemble member is excluded as SWL4 was not available for this ensemble member.**

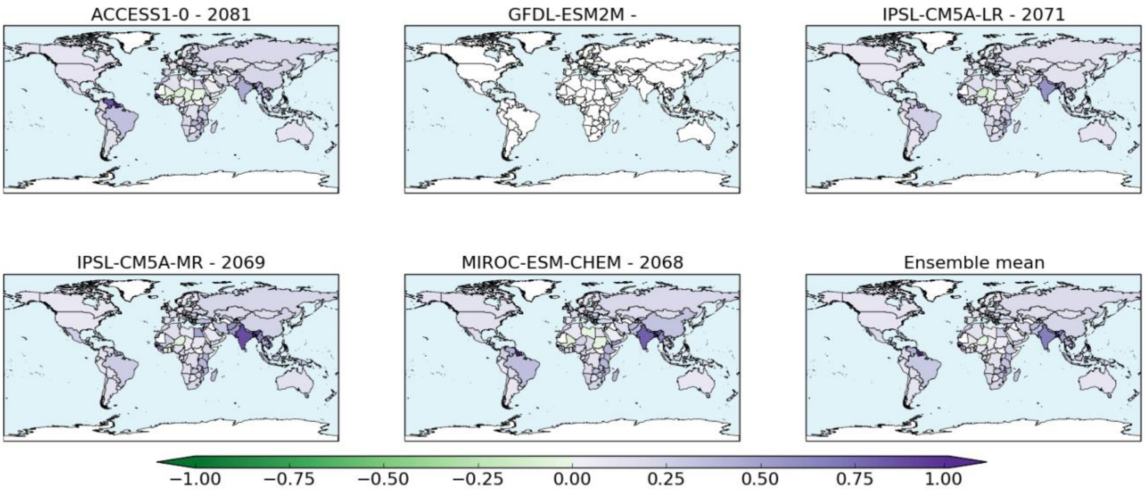


**Figure F 7 – Maps of the trade-weighted HCVIT (TW-HCVIT) anomaly from baseline for SWL4 for the individual ensemble members and the ensemble mean (difference between Figure F 6 and Figure F 1; bottom right panel). The central year for SWL4 for each model is given in the panel title. Note the GFDL-ESM2M driven ensemble member is excluded as SWL4 was not available for this ensemble member.**

*Projected changes in vulnerability to food insecurity at future time slices*

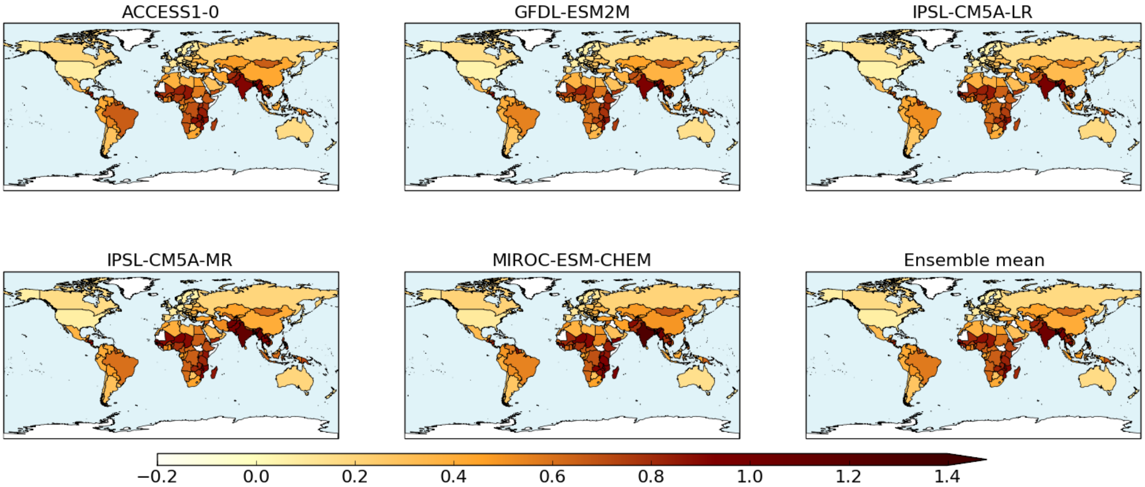


**Figure F 8 – Maps of the trade-weighted HCVIT (TW-HCVIT) for the 2050s for the individual ensemble members and the ensemble mean (bottom right panel).**

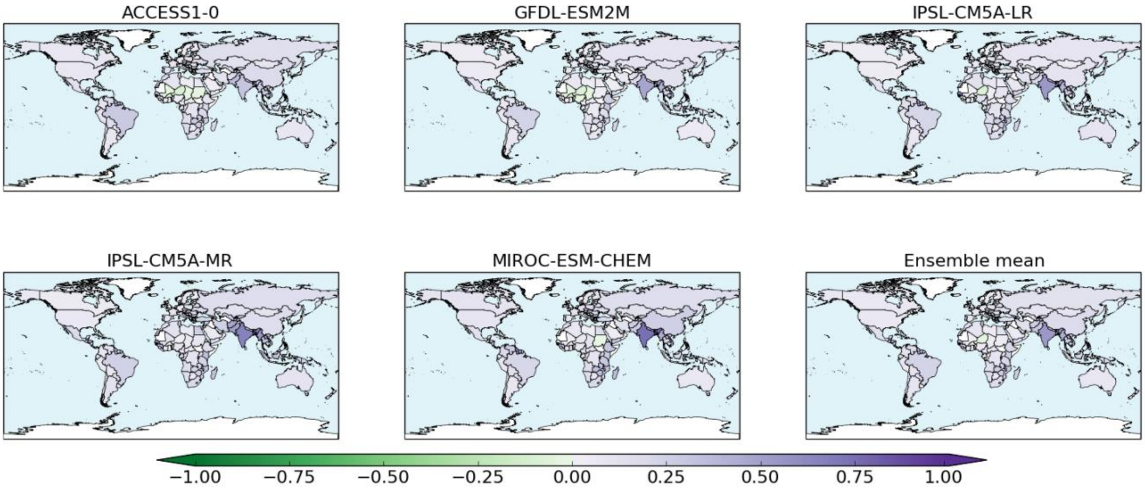


**Figure F 9 – Maps of the trade-weighted HCVIT (TW-HCVIT) anomaly from baseline for the 2050s for the individual ensemble members and the ensemble mean (difference between Figure F 8 and Figure F 1; bottom right panel).**

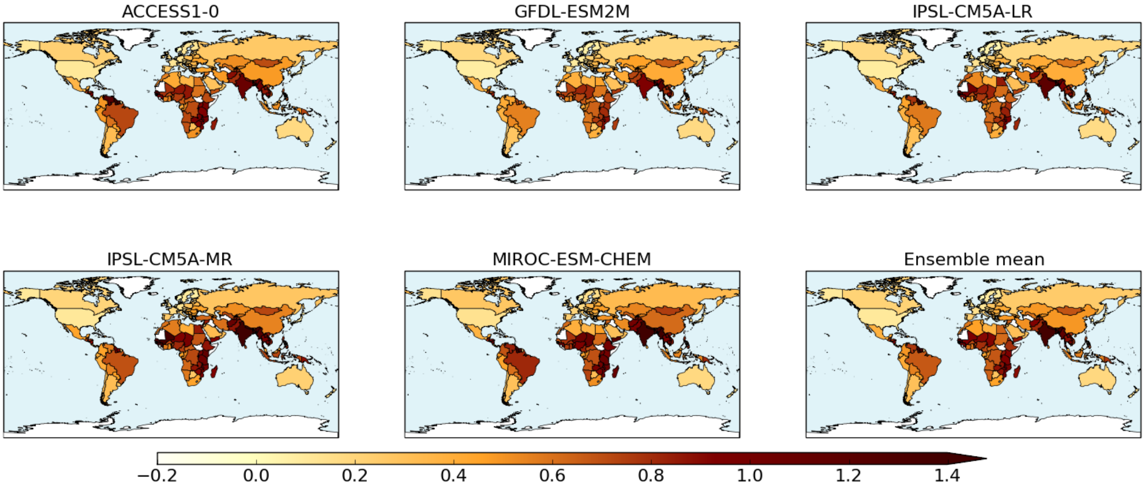


**Figure F 10 – Maps of the trade-weighted HCVIT (TW-HCVIT) for the 2080s for the individual ensemble members and the ensemble mean (bottom right panel).**

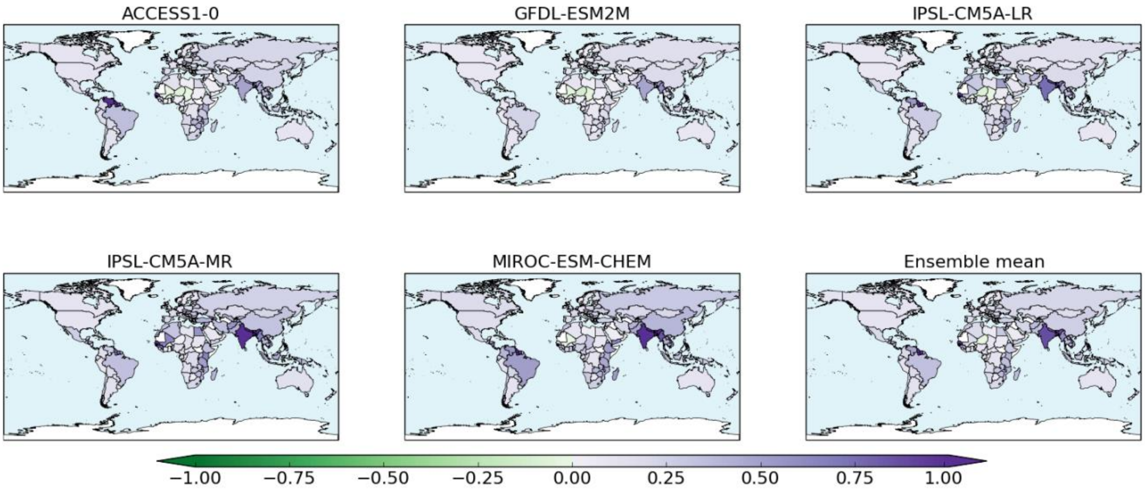


**Figure F 11 – Maps of the trade-weighted HCVIT (TW-HCVIT) anomaly from baseline for the 2080s for the individual ensemble members and the ensemble mean (difference between Figure F 10 and Figure F 1; bottom right panel).**