TREPA
Transforming Eastern Province through Adaptation

RFA
Rwanda Forestry Authority

GREEN CLIMATE FUND

CIFOR

World Agroforestry

Output 3.3: Enhancing tree seed and seedling supply to provide diverse and climate adapted species and varieties within the framework of TREPA 2022-2027

A CLIMATE CHANGE ANALYSIS FOR RWANDA

Projected changes for the middle of the 21st century inferred from WorldClim and AFRICLIM geospatial data.

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Google Scholar profile

This report represents a summarized representation of projected trends in climate change for Rwanda. The report would be expanded further during developing of the project proposal. All data and software used are open access.

March 2019

1. Project area

The project area consists of seven districts in the eastern province of Rwanda (figures 1.1 and 1.2) . Most of the project area experiences dry subhumid conditions with a moisture index between 0.5 and 0.65 (Figure 1.3).

Figure 1.1. Focal districts for the project have been labelled in this map. Administrative boundaries from the GADM database (www.gadm.org; version 3.6; downloaded 2-DEC-18). Boundary of Akagera National Park (green) obtained from World Database on Protected Areas (https://www.protectedplanet.net/862; version 1.4; downloaded 2-DEC-18) Map prepared in QGIS with OpenLayers plugin.

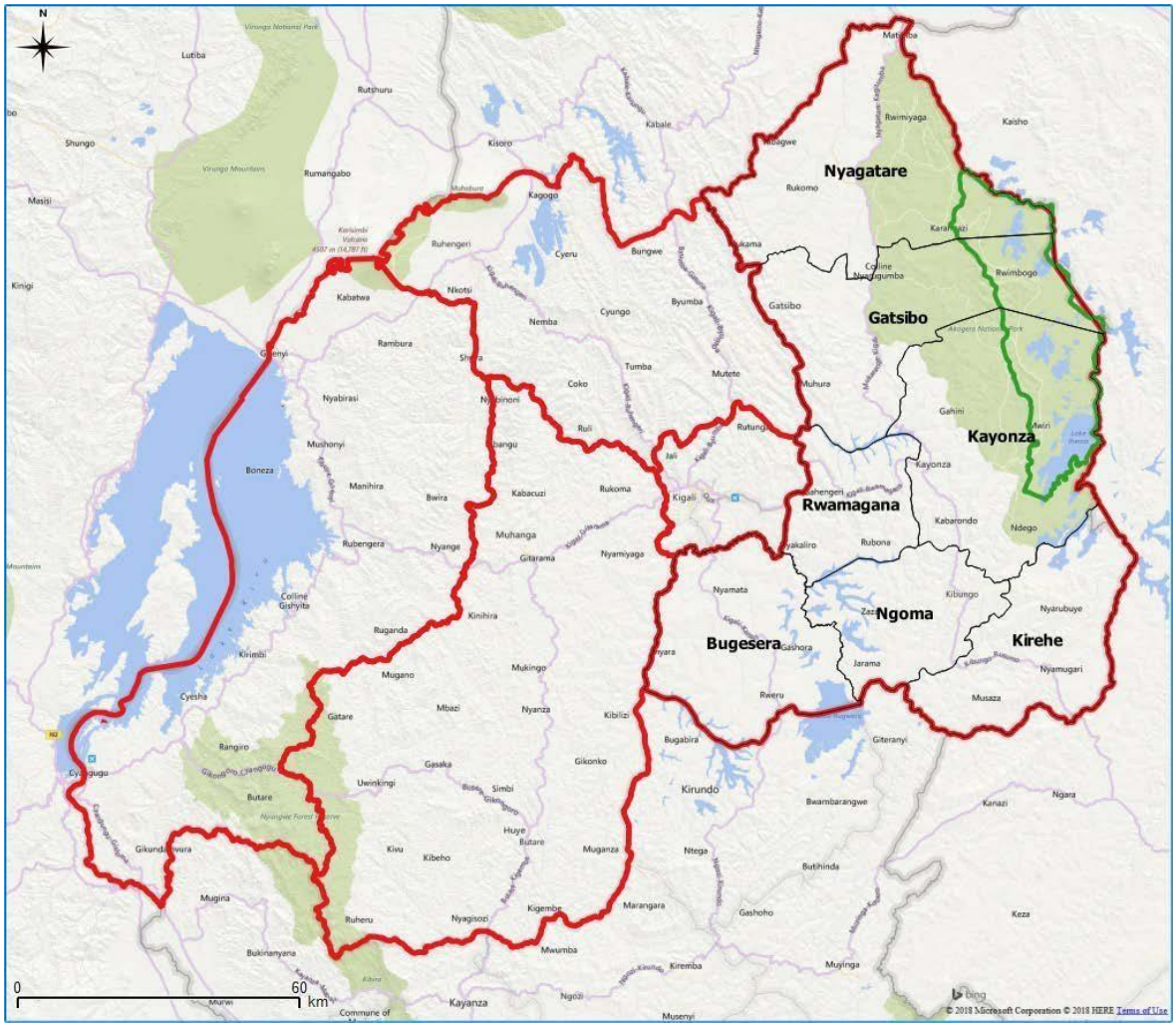


Figure 1.2.

Focal districts for the project have been labelled in this map. Administrative boundaries from the GADM database (www.gadm.org; version 3.6; downloaded 2-DEC-18). Map prepared in QGIS with OpenLayers plugin, using the OSM map background instead of Bing as in Figure 1.1.

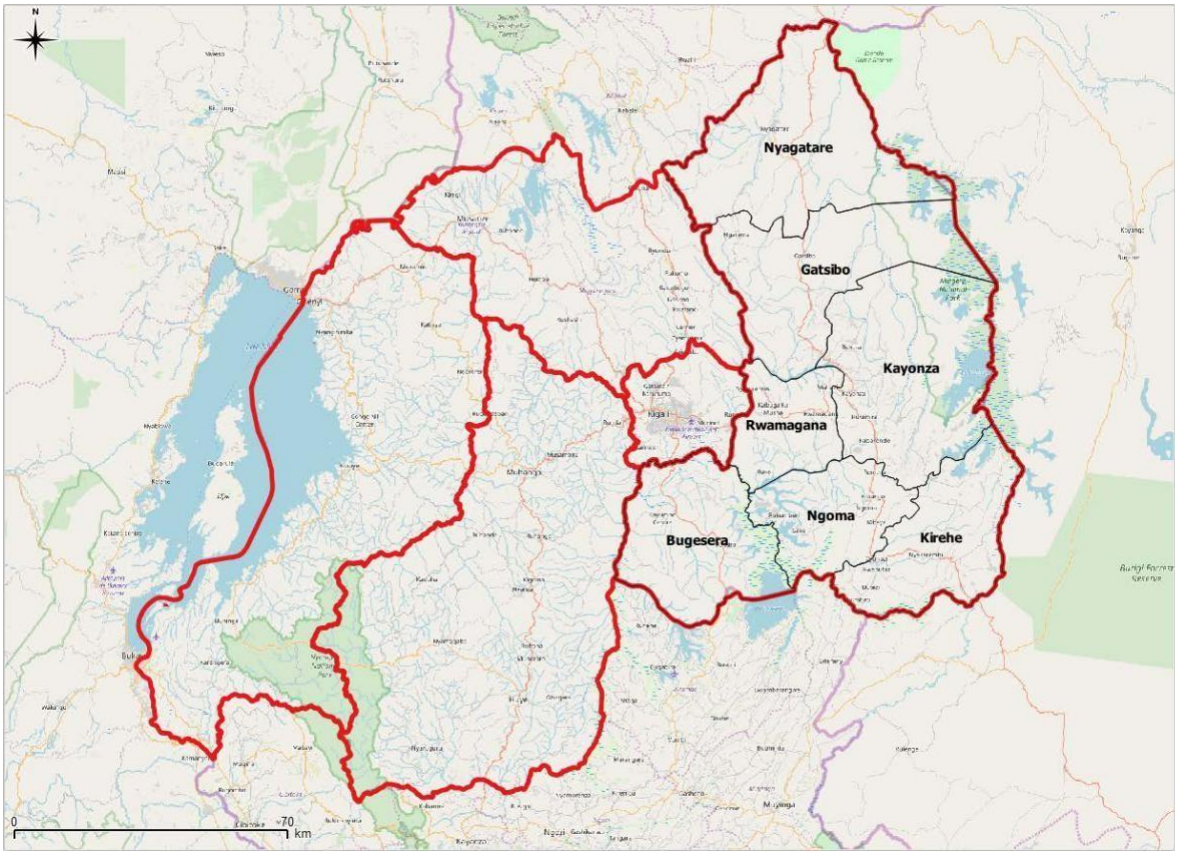
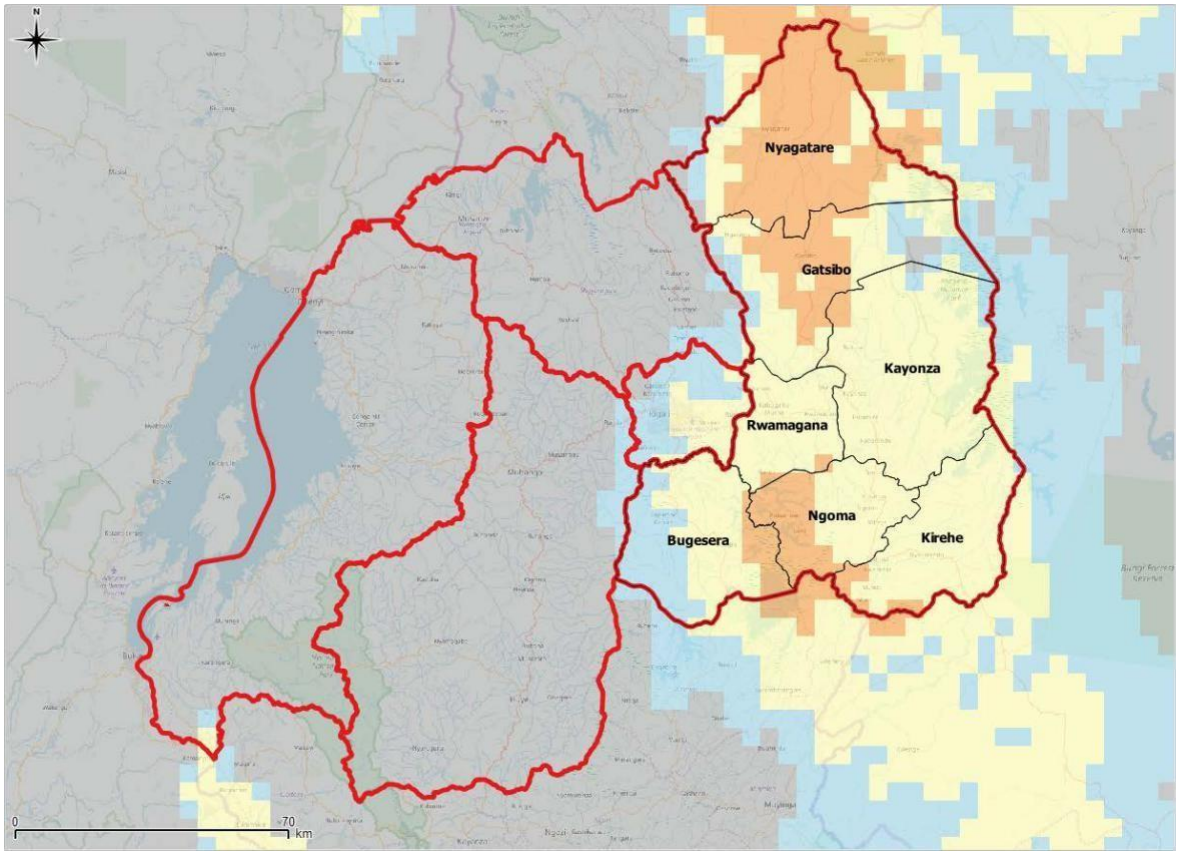


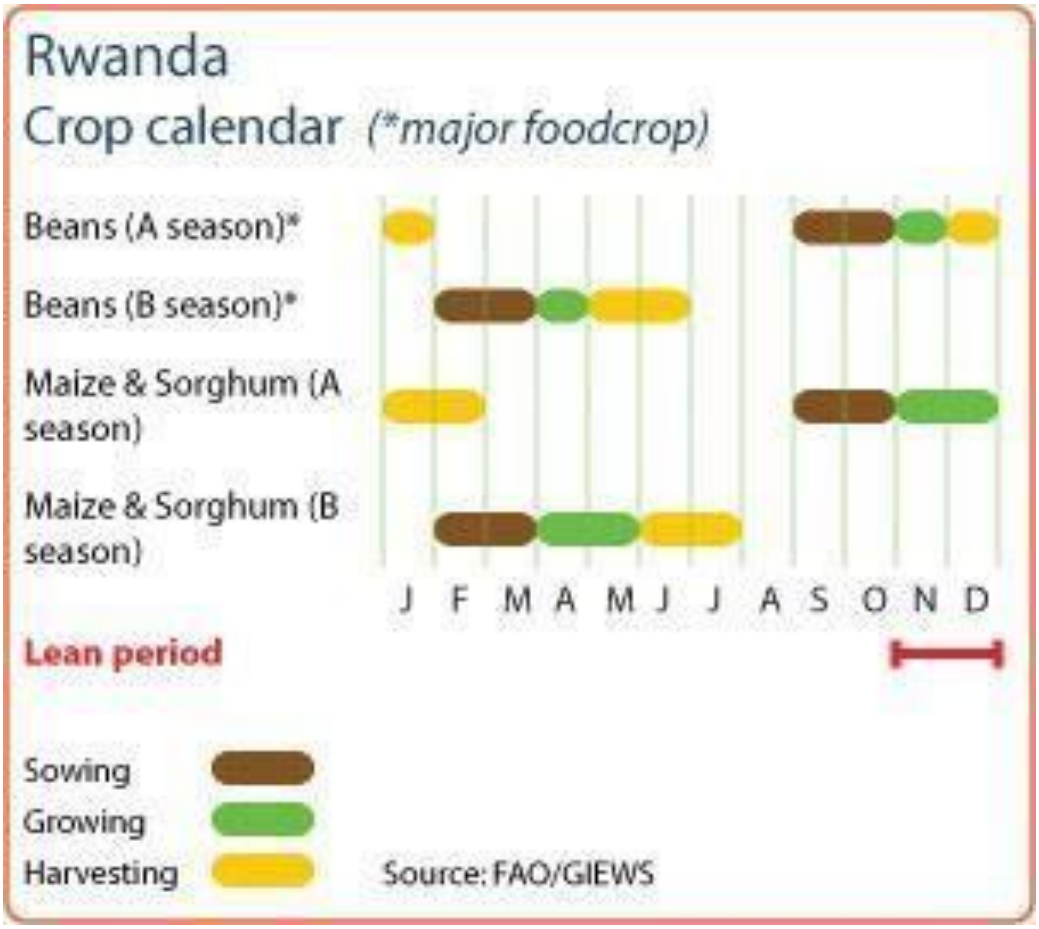
Figure 1.3.

Differences in moisture index. Orange: 0.5-0.55; yellow: 0.55-0.6; blue: 0.6-0.65; grey: > 0.65. Moisture index overlay on map depicted in Figure 1.2. Note that orange, yellow and blue zones are classified as dry subhumid by UNCCD drylands criteria (moisture index 0.50 -0.65)



Crop calendar for Rwanda.

Figure 1.4.



Source: http://www.fao.org/giews/countrybrief/country.jsp?lang=en&code=RWA

Rwanda has two main cropping seasons (Figure 1.4). These seasons correspond to the long rains (MAM) and short rain (SOND) precipitation patterns of Rwanda and East Africa that are associated with the latitudinal migration of the Inter-Tropical Convergence Zone (Ngarukiyimana *et al.* 2018).

2. Changes in bioclimatic conditions

To deal with uncertainties in projecting future climatic changes, analyses focused on consensus among General Circulation Models (it is generally recommended to treat the different GCM projections as equally likely and to adopt ensemble [consensus] approaches). All mid-21st century projections available from AFRICLIM (Platts *et al.* 2015) for Representative Concentration RCP 4.5 (a medium emissions scenario) and RCP 8.5 (a high emissions scenario) were included (see methodology). In checking for consensus among models, the likelihood scale recommended for the fifth assessment report of the IPCC (Mastrandea *et al.* 2011) was adopted. As such, results were reported as **likely** in case that at least 66% of models showed the same trend and as **unlikely** in case that at most 33% of models showed the same trend.

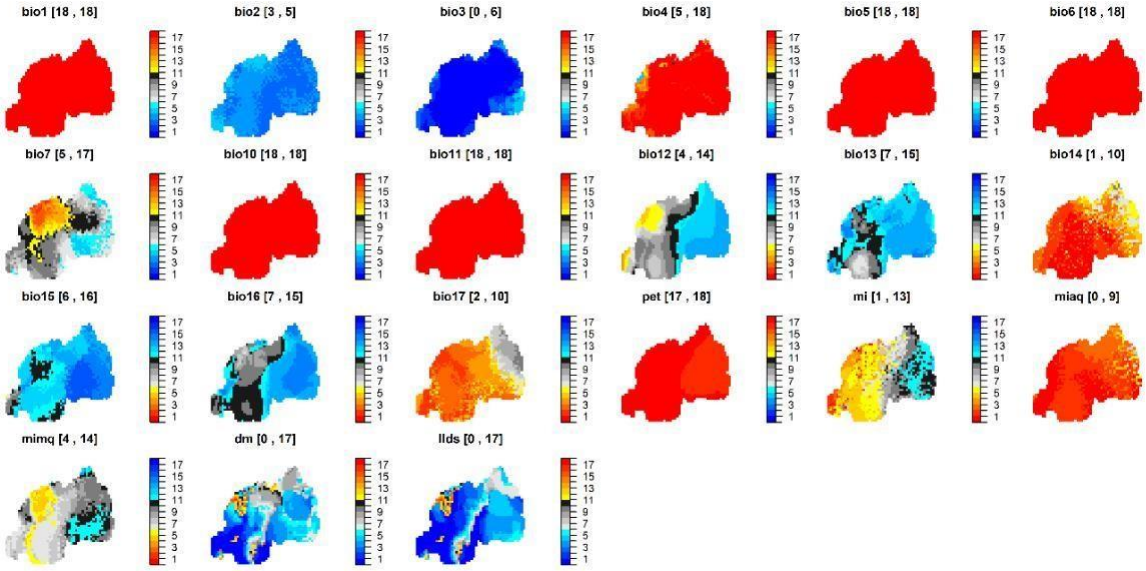
There was consensus among downscaled global circulation models that by the middle of the 21st century, Rwanda would experience increases in most of the temperature-related bioclimatic variables such as the mean annual temperature (Bio1), the maximum temperature of the warmest month (Bio5), the mean temperature of the warmest quarter (Bio10) and the mean temperature of the coolest quarter (Bio11). These trends depicted in Figure 2.1 agree with significant changes observed between 1930 and 2013 within the five states of the Lake Victoria Basin (including Rwanda), ranging between 0.7°C and 1.2°C for average monthly maximum temperature and between 1.0°C and 1.1°C for the average monthly minimum (Lake Victoria Basin Climate Change Adaptation Strategy and Action Plan 2018-2023). Differences in magnitude between difference GCM projections can be inferred from Figure 2.2, whereas the common legend indicates that minimum changes will be 1.3°C for RCP4.5 and 1.9°C for RCP8.5.

For eastern Rwanda, models reached consensus that annual precipitation (Bio12) would increase in the project area (figures 2.1 and 2.3). Predicted to increase for most of the country is the rainfall seasonality (Bio15, Figure 2.1). There was less consensus among models about an increase in the moisture index in the eastern part of Rwanda, whereas it was likely that the moisture index would decrease in the western part of the country (*mi*, figures 2.1 and 2.4).

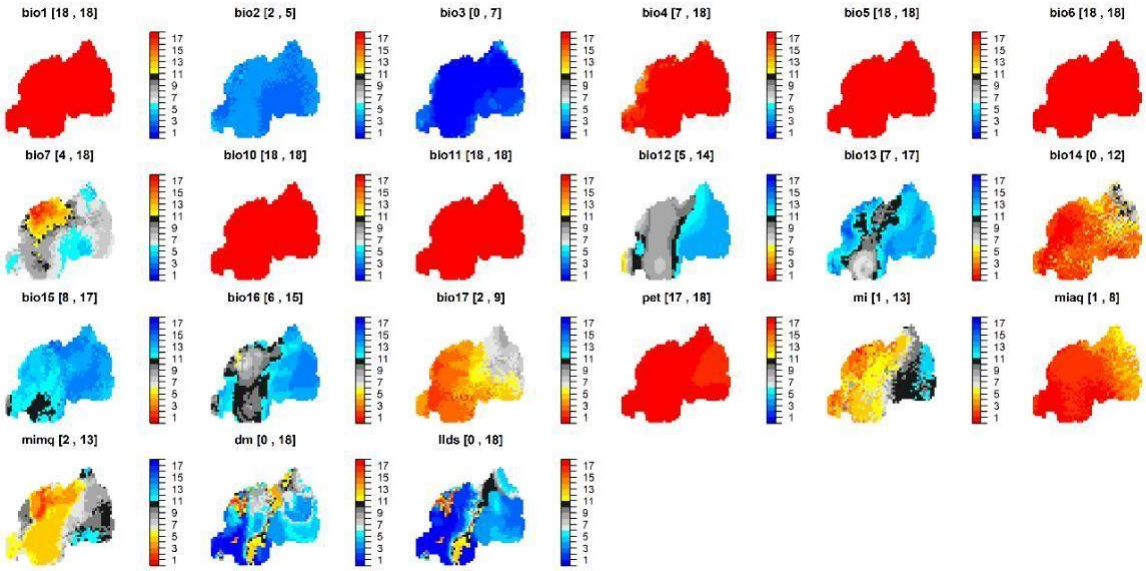
Figure 2.1.

Counts of General Circulation Models that project monthly increases in bioclimatic variables by the 2050s for RCP4.5 and RCP8.5 compared to the baseline centred on 1975. The major changes in the colour schemes correspond to the likelihood scale recommended for the fifth Assessment Report of the IPCC (see methods). Note that the colour ranges are different for temperature- or precipitation-derived variables.

RCP4.5 (medium emissions)



RCP8.5 (high emissions)



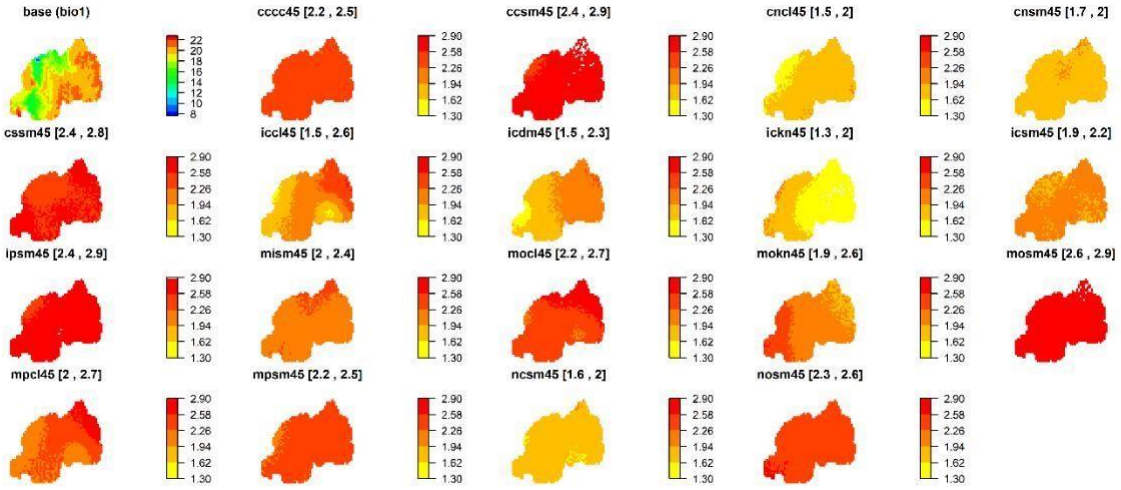
Bio1 : mean annual temperature; **Bio2**: mean diurnal range; **Bio3**: isothermality; **Bio4**: temperature seasonality (standard deviation of monthly values); **Bio5**: maximum temperature of the warmest month; **Bio6**: minimum temperature of the coldest month; **Bio7**: annual temperature range; **Bio10**: mean temperature of the warmest quarter; **Bio11**: mean temperature of the coolest quarter; **Bio12**: mean annual rainfall; **Bio13**: rainfall of the wettest month; **Bio14**: rainfall of the driest month; **Bio15**: rainfall seasonality (standard deviation of monthly values); **Bio16**:

Figure 2.2.

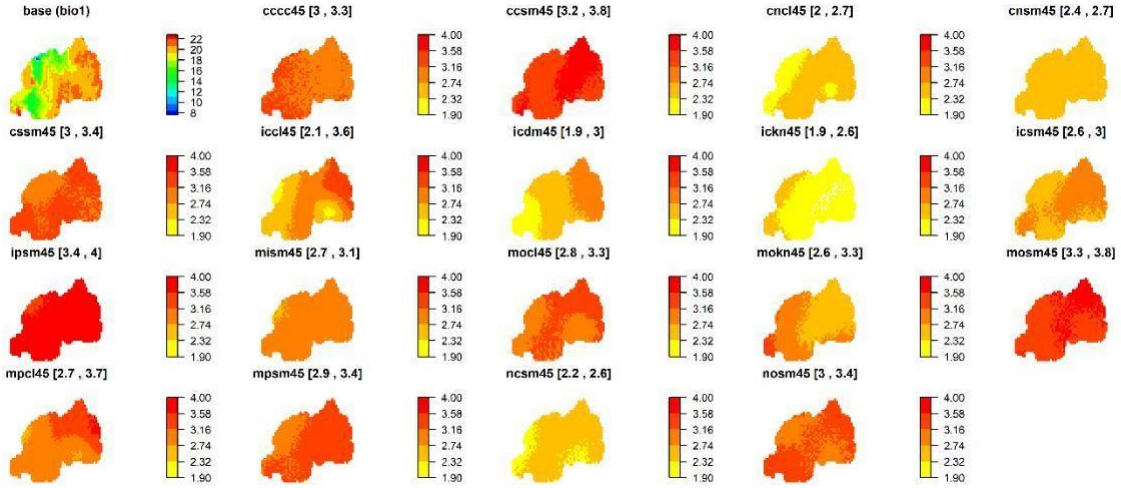
rainfall of the wettest quarter; **Bio17**: rainfall of the driest quarter; **pet**: potential evapotranspiration; **mi**: moisture index; **miaq**: moisture index of the most arid quarter; **mimq**: moisture index of the most moist quarter; **dm**: number of dry months; **llds**: length (months) of the longest dry season

Projected changes in mean annual temperature from baseline. Model abbreviations provided in the *Methods* section. Figures between square brackets indicate the range for the particular model.

RCP4.5 (medium emissions)



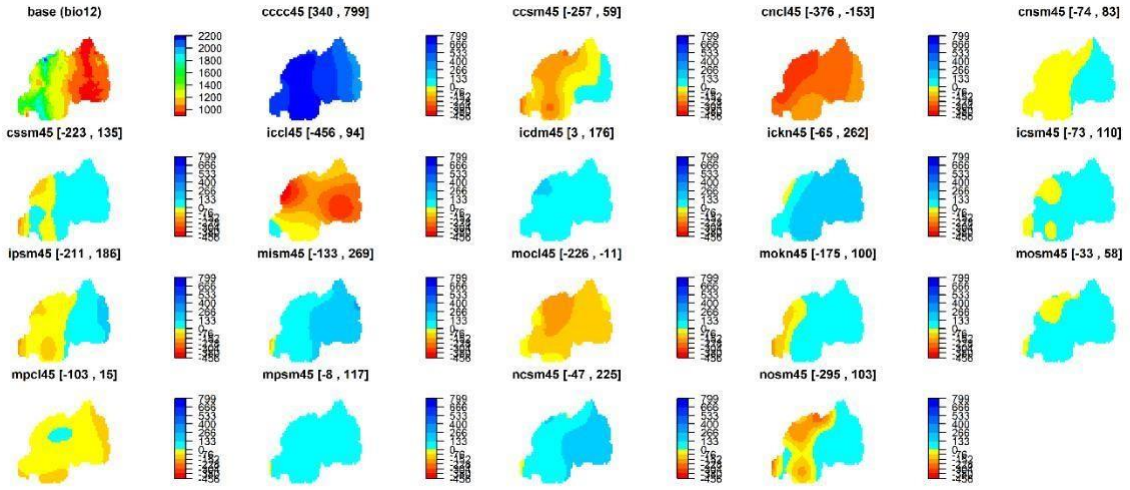
RCP8.5 (high emissions)



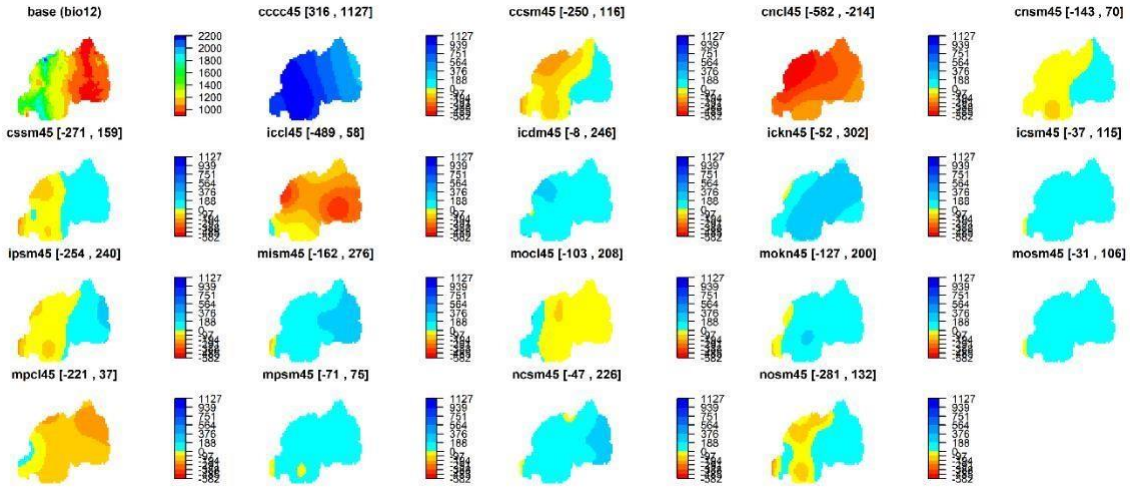
Projected changes in mean annual precipitation from baseline. Model abbreviations provided in the *Methods* section. Figures between square brackets indicate the range for the particular model.

Figure 2.3.

RCP4.5 (medium emissions)

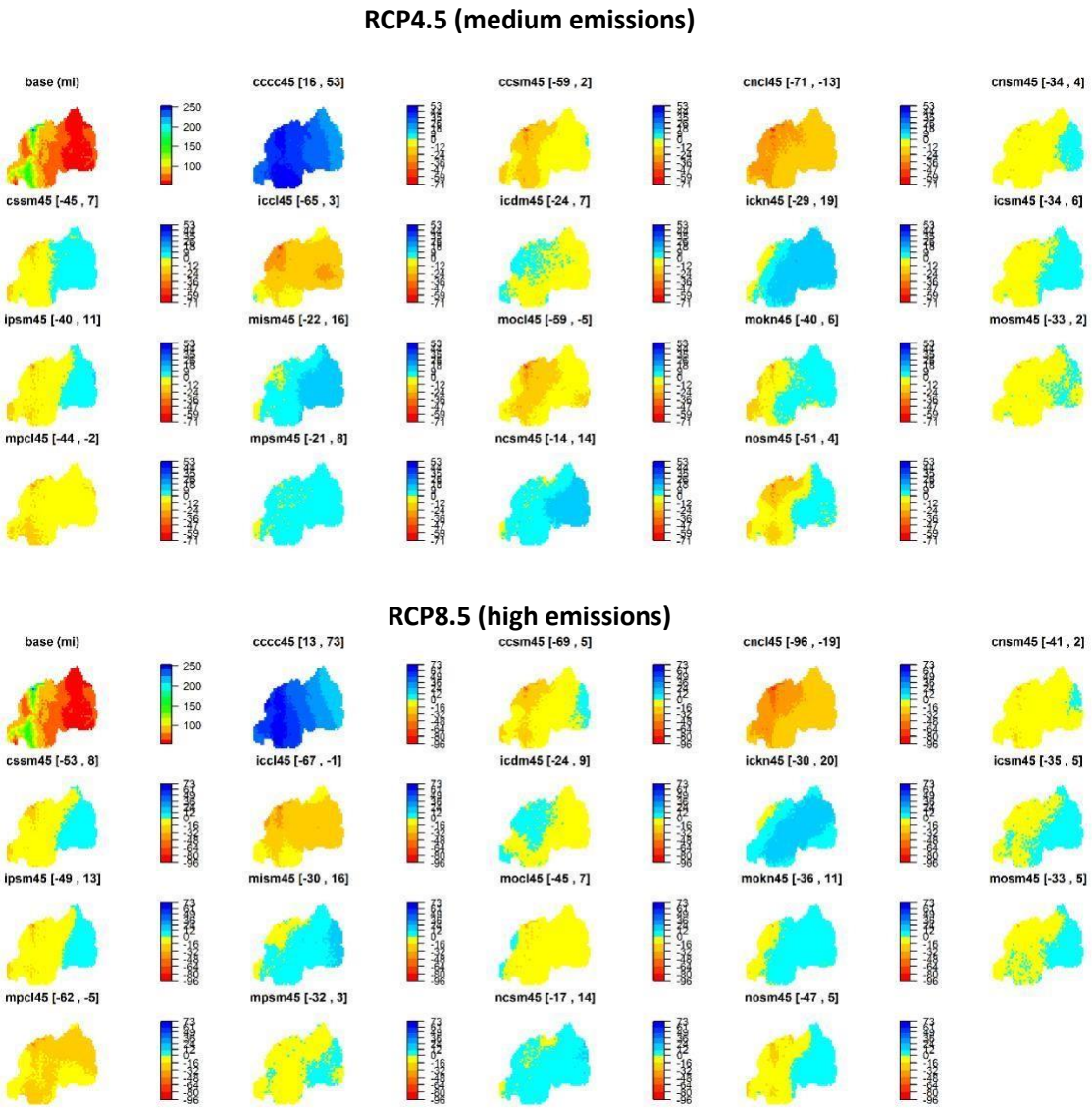


RCP8.5 (high emissions)



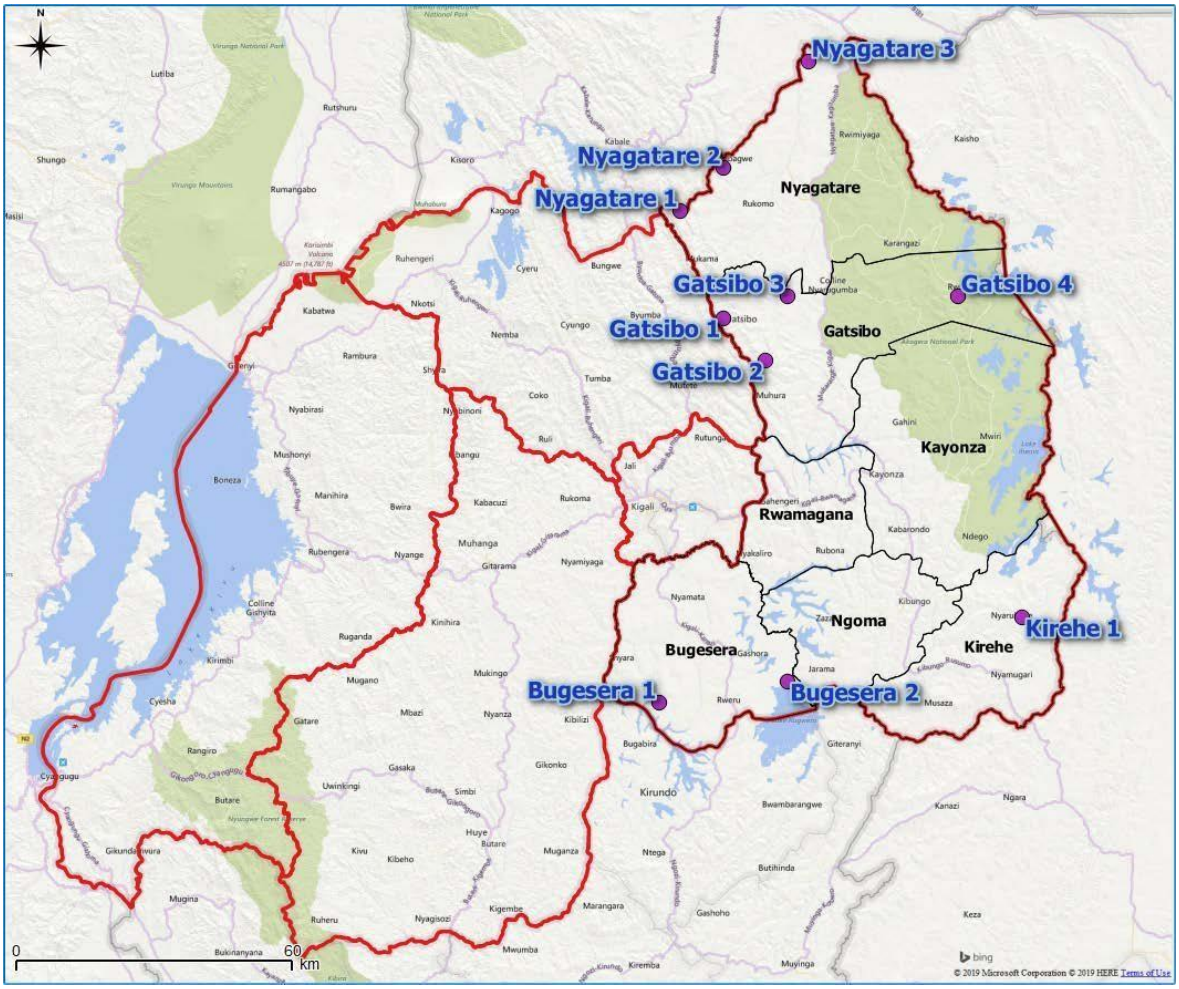
Projected changes in moisture index from baseline. Model abbreviations provided in the *Methods* section. Figures between square brackets indicate the range for the particular model.

Figure 2.4.



Locations (centres of grid cells) selected in Eastern Province for Dumbbell plot summary graphs. Administrative boundaries from the GADM database (www.gadm.org; version 3.6 ; downloaded 2-DEC-18). Map prepared in QGIS with OpenLayers plugin.

Figure 2.5.

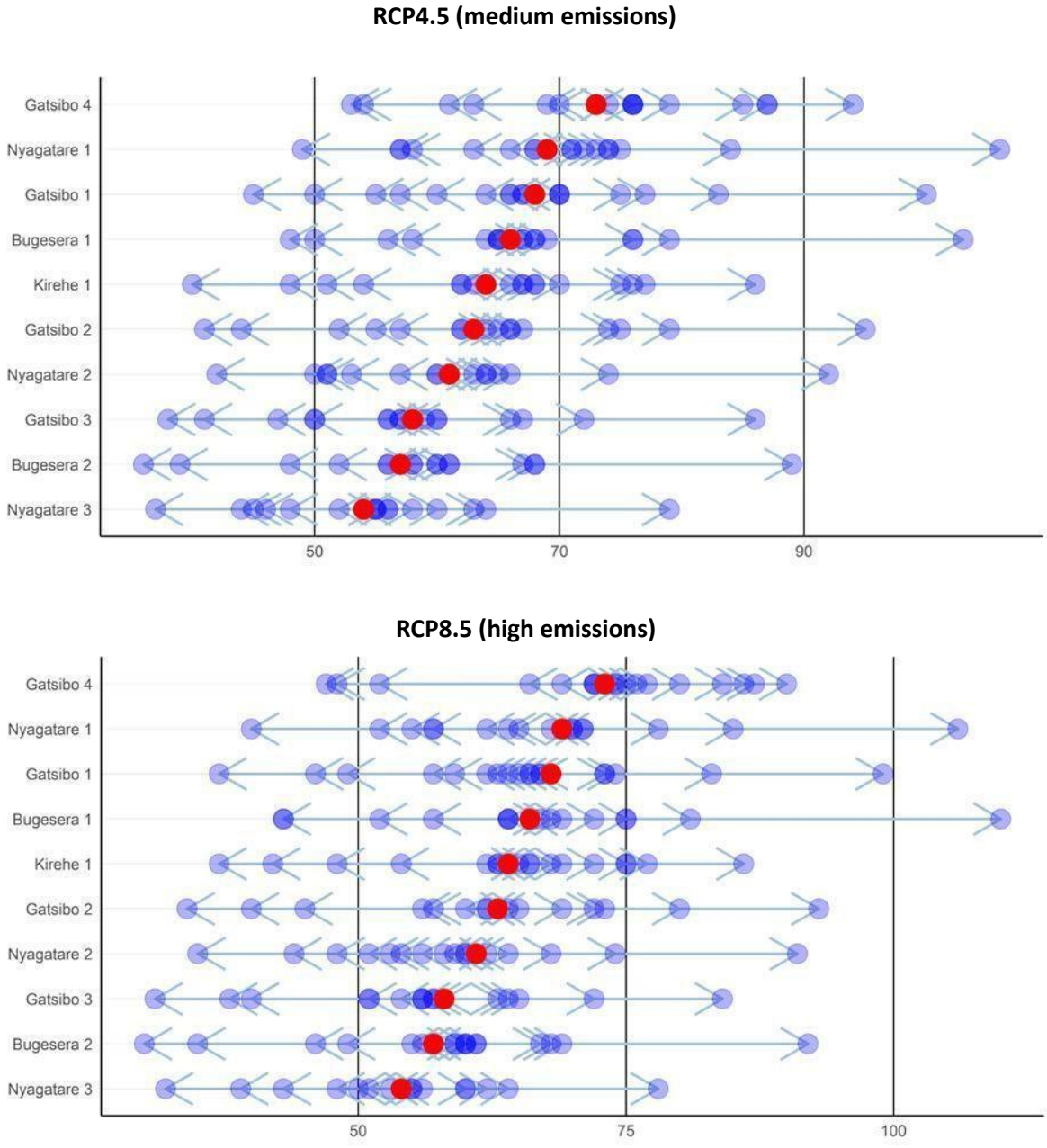


An environmental thinning algorithm was used to select 10 locations in Eastern Province that had the largest distances in the environmental space defined by the bioclimatic variables available from AFRICLIM. Plotting these locations on a map (Figure 2.5) shows that these locations represent three West-East transects (Bugesera 1 – Bugesera 2 – Kirehe 1; Gatsibo 123 – Gatsibo 4; Nyagatare 1 – Nyagatare 2 – Nyagatare 3).

The following set of graphs and tables in this section show the projected bioclimatic changes for these locations for a subset of bioclimatic variables. Whereas there was no evidence for changes in the moisture index (Figure 2.6, Table 2.1), the maximum temperature of the warmest month (Figure 2.8, Table 2.3), the minimum temperature of the coldest month (Figure 2.9, Table 2.4) and the mean annual temperature (Figure 2.11, Table 2.6) are likely to increase and the mean diurnal range (Table 2.2, Figure 2.7) is likely to decrease. The mean annual rainfall is likely to increase for most of the selected locations (Figure 2.12, Table 2.7), but there is no evidence for changes in the driest month (Figure 2.10, Table 2.5).

Figure 2.6.

Projected changes for the moisture index. Project locations are sorted by baseline moisture index. Red circle indicates the baseline and blue circles bioclimatic conditions projected for the 2050s.



RCP4.5	**Nyagatare 3**	54.0	54.5	37.0	52.7	55.0	56.0	79.0
	Bugesera 2	57.0	58.5	36.0	56.3	58.0	60.7	89.0
	Gatsibo 3	58.0	57.7	38.0	56.0	57.0	59.7	86.0
	Nyagatare 2	61.0	60.8	42.0	58.0	61.0	63.7	92.0
	Gatsibo 2	63.0	63.9	41.0	62.0	64.0	66.0	95.0
	Kirehe 1	64.0	64.7	40.0	62.3	67.0	68.0	86.0
	Bugesera 1	66.0	67.3	48.0	65.0	67.0	68.0	103.0
	Gatsibo 1	68.0	67.2	45.0	64.7	67.0	70.0	100.0
	Nyagatare 1	69.0	69.8	49.0	66.7	71.0	72.7	106.0
	Gatsibo 4	73.0	73.7	53.0	71.0	76.0	76.0	94.0
RCP8.5	**Nyagatare 3**	54.0	53.8	32.0	52.3	54.0	55.3	78.0
	Bugesera 2	57.0	58.0	30.0	56.7	59.5	60.3	92.0
	Gatsibo 3	58.0	56.2	31.0	55.3	56.5	58.0	84.0
	Nyagatare 2	61.0	58.8	35.0	55.3	59.5	61.0	91.0
	Gatsibo 2	63.0	62.3	34.0	61.3	63.0	64.3	93.0
	Kirehe 1	64.0	64.0	37.0	63.0	65.5	68.3	86.0
	Bugesera 1	66.0	66.8	43.0	64.0	66.0	68.3	110.0

Table 2.1. Summary statistics of projected changes for the moisture index. Colour scheme corresponds to likely increases or decreases using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

				37.0	62.7	65.5	67.0	

RCP	Location	Baseline	Future					
			Mean	Min	33%	50%	66%	Max
	Nyagatare 1	69.0	67.2	40.0	63.3	68.5	70.0	106.0
	Gatsibo 4	73.0	72.3	47.0	72.0	74.0	76.3	90.0
	Gatsibo 1	68.0	65.0					99.0

Figure 2.7. Projected changes for the mean diurnal range (Bio2). Project locations are sorted by baseline moisture index. Red circle indicates the baseline and blue circles bioclimatic conditions projected for the 2050s.

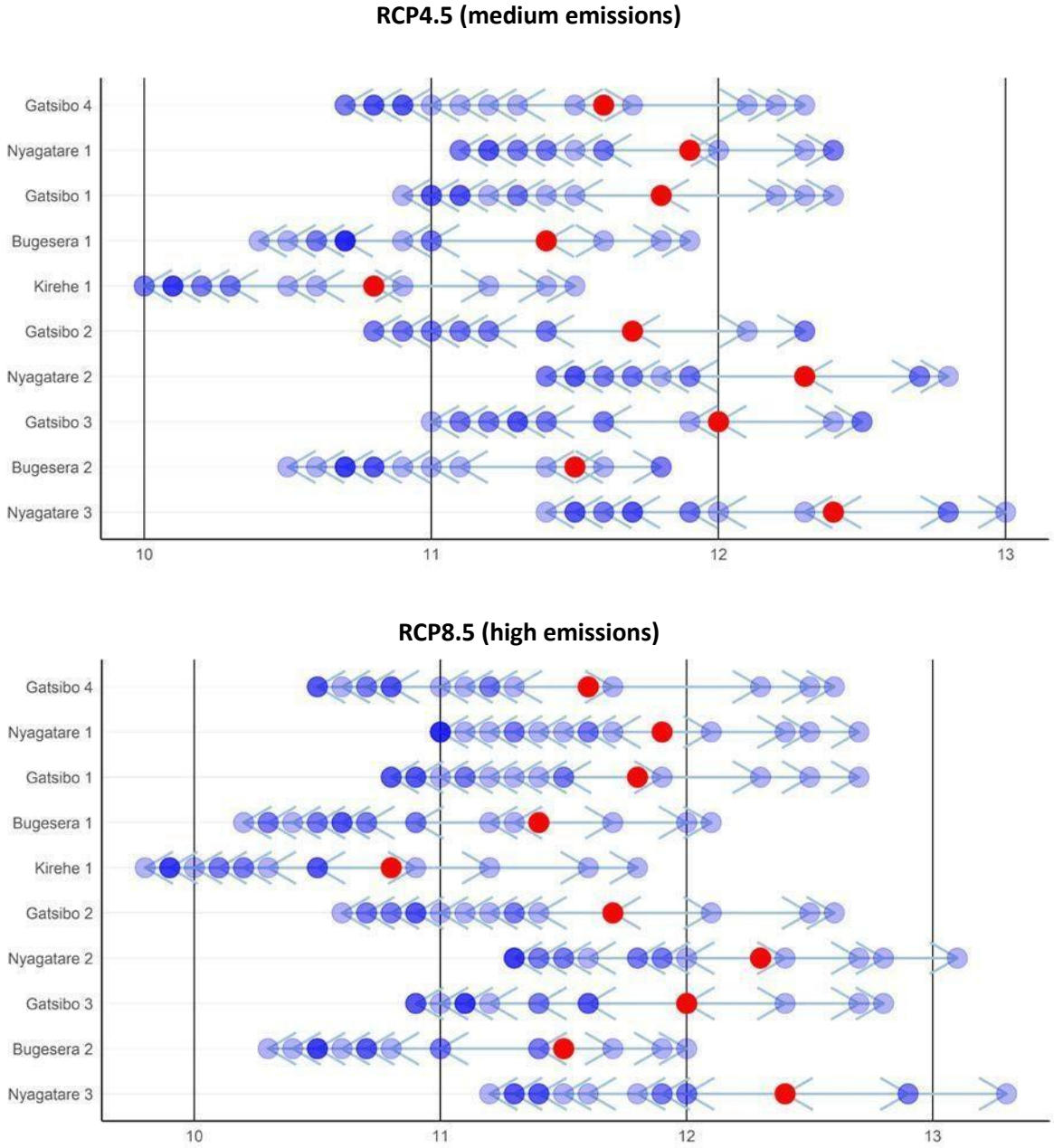


Table 2.2. Summary statistics of projected changes for the mean diurnal range (Bio2). Colour scheme corresponds to likely increases or decreases using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline	Future					
RCP4.5	Nyagatare 3	12.4	12.0	11.4	11.6	11.7	12.0	13.0
	Bugesera 2	11.5	11.0	10.5	10.7	10.8	11.1	11.8
	Gatsibo 3	12.0	11.6	11.0	11.3	11.4	11.6	12.5
	Nyagatare 2	12.3	11.9	11.4	11.6	11.7	11.9	12.8
	Gatsibo 2	11.7	11.4	10.8	11.0	11.2	11.4	12.3
	Kirehe 1	10.8	10.5	10.0	10.1	10.3	10.6	11.5
	Bugesera 1	11.4	11.0	10.4	10.7	10.7	11.0	11.9
	Gatsibo 1	11.8	11.4	10.9	11.1	11.3	11.5	12.4
	Nyagatare 1	11.9	11.6	11.1	11.3	11.4	11.6	12.4
	Gatsibo 4	11.6	11.2	10.7	10.9	11.0	11.3	12.3
RCP8.5	Nyagatare 3	12.4	11.9	11.2	11.4	11.7	11.9	13.3
	Bugesera 2	11.5	10.9	10.3	10.6	10.7	11.0	12.0
	Gatsibo 3	12.0	11.5	10.9	11.1	11.3	11.6	12.8
	Nyagatare 2	12.3	11.8	11.3	11.5	11.7	11.9	13.1
	Gatsibo 2	11.7	11.3	10.6	10.9	11.1	11.3	12.6
	Kirehe 1	10.8	10.4	9.8	10.1	10.2	10.5	11.8
	Bugesera 1	11.4	10.9	10.2	10.6	10.7	10.9	12.1
	Gatsibo 1	11.8	11.4	10.8	11.0	11.2	11.4	12.7
	Nyagatare 1	11.9	11.5	11.0	11.2	11.4	11.6	12.7
	Gatsibo 4	11.6	11.2	10.5	10.8	10.9	11.2	12.6
			Mean	Min	33%	50%	66%	Max

Figure 2.8. Projected changes for the maximum temperature of the warmest month (Bio5). Project locations are sorted by baseline moisture index. Red circle indicates the baseline and blue circles bioclimatic conditions projected for the 2050s.

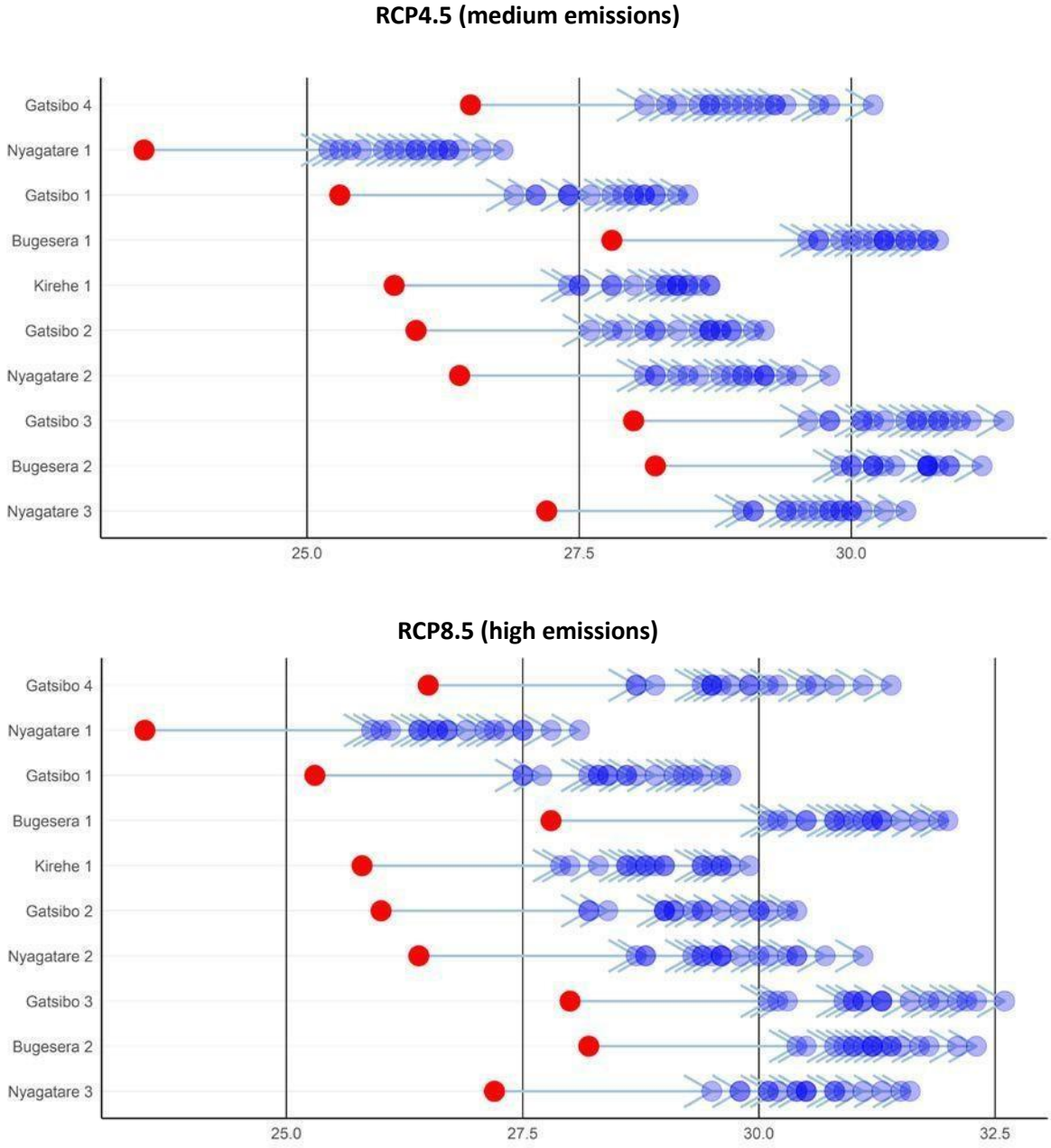


Table 2.3. Summary statistics of projected changes for the maximum temperature of the warmest month (Bio5) . Colour scheme corresponds to likely increases or decreases using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline	Future					
RCP4.5	Nyagatare 3	27.2	29.7	29.0	29.5	29.8	29.9	30.5
	Bugesera 2	28.2	30.5	29.9	30.2	30.7	30.7	31.2
	Gatsibo 3	28.0	30.5	29.6	30.2	30.6	30.8	31.4
	Nyagatare 2	26.4	28.9	28.1	28.7	29.0	29.2	29.8
	Gatsibo 2	26.0	28.5	27.6	28.3	28.7	28.8	29.2
	Kirehe 1	25.8	28.2	27.4	28.1	28.3	28.4	28.7
	Bugesera 1	27.8	30.3	29.6	30.1	30.3	30.5	30.8
	Gatsibo 1	25.3	27.8	26.9	27.5	27.9	28.1	28.5
	Nyagatare 1	23.5	26.0	25.2	25.8	26.0	26.2	26.8
	Gatsibo 4	26.5	29.0	28.1	28.7	29.0	29.3	30.2
RCP8.5	Nyagatare 3	27.2	30.5	29.5	30.3	30.5	30.8	31.6
	Bugesera 2	28.2	31.3	30.4	31.1	31.2	31.4	32.3
	Gatsibo 3	28.0	31.3	30.1	31.1	31.3	31.7	32.6
	Nyagatare 2	26.4	29.8	28.7	29.5	29.6	30.0	31.1
	Gatsibo 2	26.0	29.4	28.2	29.1	29.4	29.7	30.4
	Kirehe 1	25.8	29.0	27.9	28.8	29.0	29.4	29.9
	Bugesera 1	27.8	31.0	30.1	30.8	31.1	31.2	32.0
	Gatsibo 1	25.3	28.6	27.5	28.4	28.6	29.0	29.7
	Nyagatare 1	23.5	26.9	25.9	26.6	26.7	27.1	28.1
	Gatsibo 4	26.5	29.9	28.7	29.5	29.8	30.1	31.4
			Mean	Min	33%	50%	66%	Max

Figure 2.9. Projected changes for the minimum temperature of the coldest month (Bio6). Project locations are sorted by baseline moisture index. Red circle indicates the baseline and blue circles bioclimatic conditions projected for the 2050s.

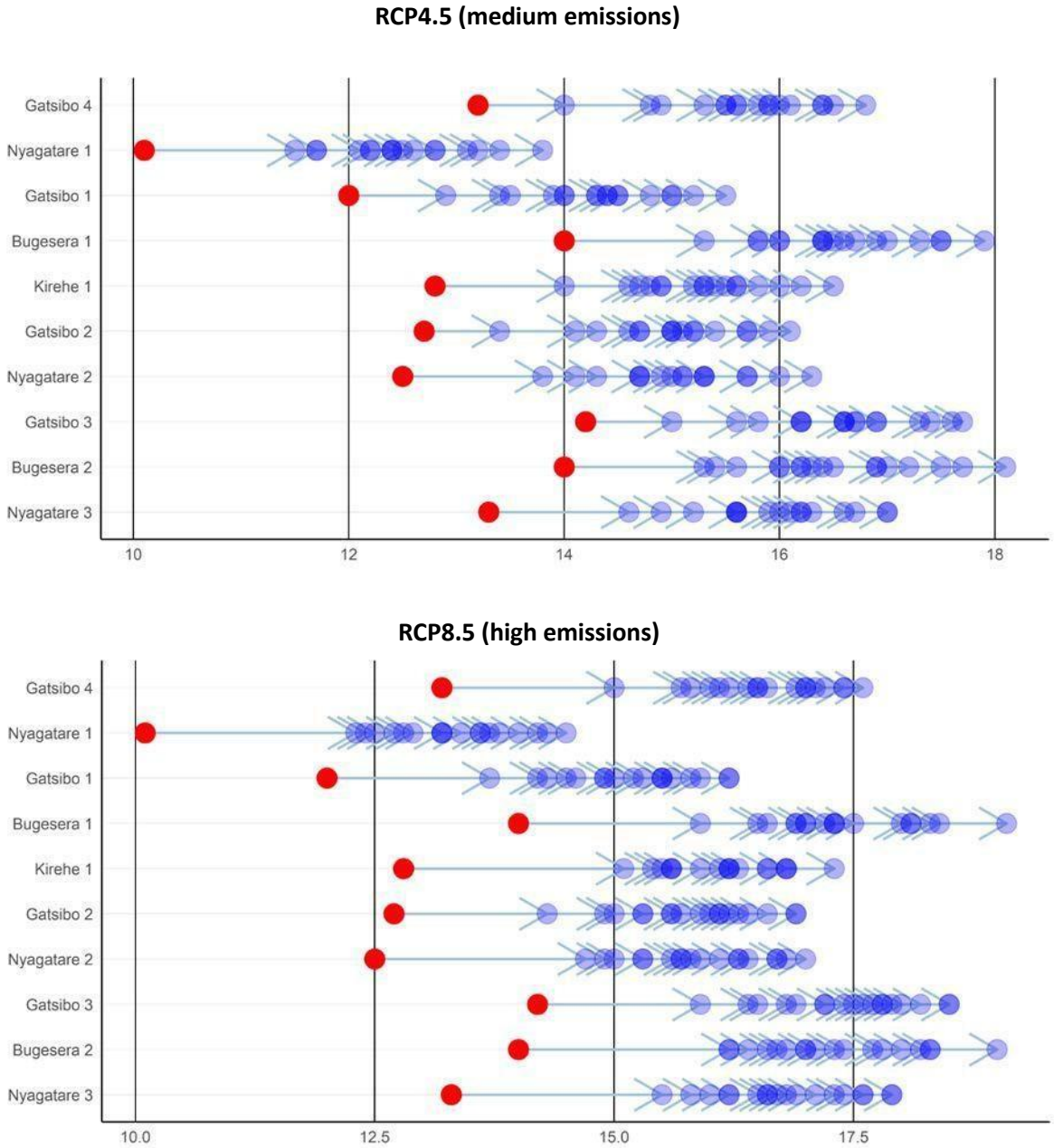


Table 2.4. Summary statistics of projected changes for the minimum temperature of the coldest month (Bio6) . Colour scheme corresponds to likely increases or decreases using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline	Future					
			Mean	Min	33%	50%	66%	Max
RCP4.5	**Nyagatare 3**	13.3	16.0	14.6	15.6	16.0	16.2	17.0
	Bugesera 2	14.0	16.5	15.3	16.2	16.4	16.9	18.1
	Gatsibo 3	14.2	16.6	15.0	16.3	16.6	16.8	17.7
	Nyagatare 2	12.5	15.1	13.8	14.8	15.1	15.3	16.3
	Gatsibo 2	12.7	15.0	13.4	14.8	15.0	15.2	16.1
	Kirehe 1	12.8	15.3	14.0	15.0	15.3	15.6	16.5
	Bugesera 1	14.0	16.6	15.3	16.4	16.5	16.8	17.9
	Gatsibo 1	12.0	14.3	12.9	14.1	14.4	14.5	15.5
	Nyagatare 1	10.1	12.5	11.5	12.3	12.4	12.7	13.8
	Gatsibo 4	13.2	15.7	14.0	15.5	15.8	16.0	16.8
RCP8.5								
	Nyagatare 3	13.3	16.8	15.5	16.6	16.8	17.2	17.9
	Bugesera 2	14.0	17.3					16.2
16.9	17.2	17.7	19.0	15.9	17.2	17.6	17.8	
	Gatsibo 3	14.2	17.4	14.7	15.7	15.9	16.3	18.5
	Nyagatare 2	12.5	15.9	14.3	15.6	16.0	16.1	17.0
	Gatsibo 2	12.7	15.8	15.1	15.8	16.2	16.4	16.9
	Kirehe 1	12.8	16.1	15.9	17.0	17.3	17.7	17.3
	Bugesera 1	14.0	17.4	13.7	14.9	15.3	15.5	19.1
	Gatsibo 1	12.0	15.2					16.2
	Nyagatare 1	10.1	13.4	12.3	13.1	13.3	13.6	14.5
	Gatsibo 4	13.2	16.6	15.0	16.3	16.6	17.0	17.6

Figure 2.10. Projected changes for the rainfall of the driest month (Bio14). Project locations are sorted by baseline moisture index. Red circle indicates the baseline and blue circles bioclimatic conditions projected for the 2050s.

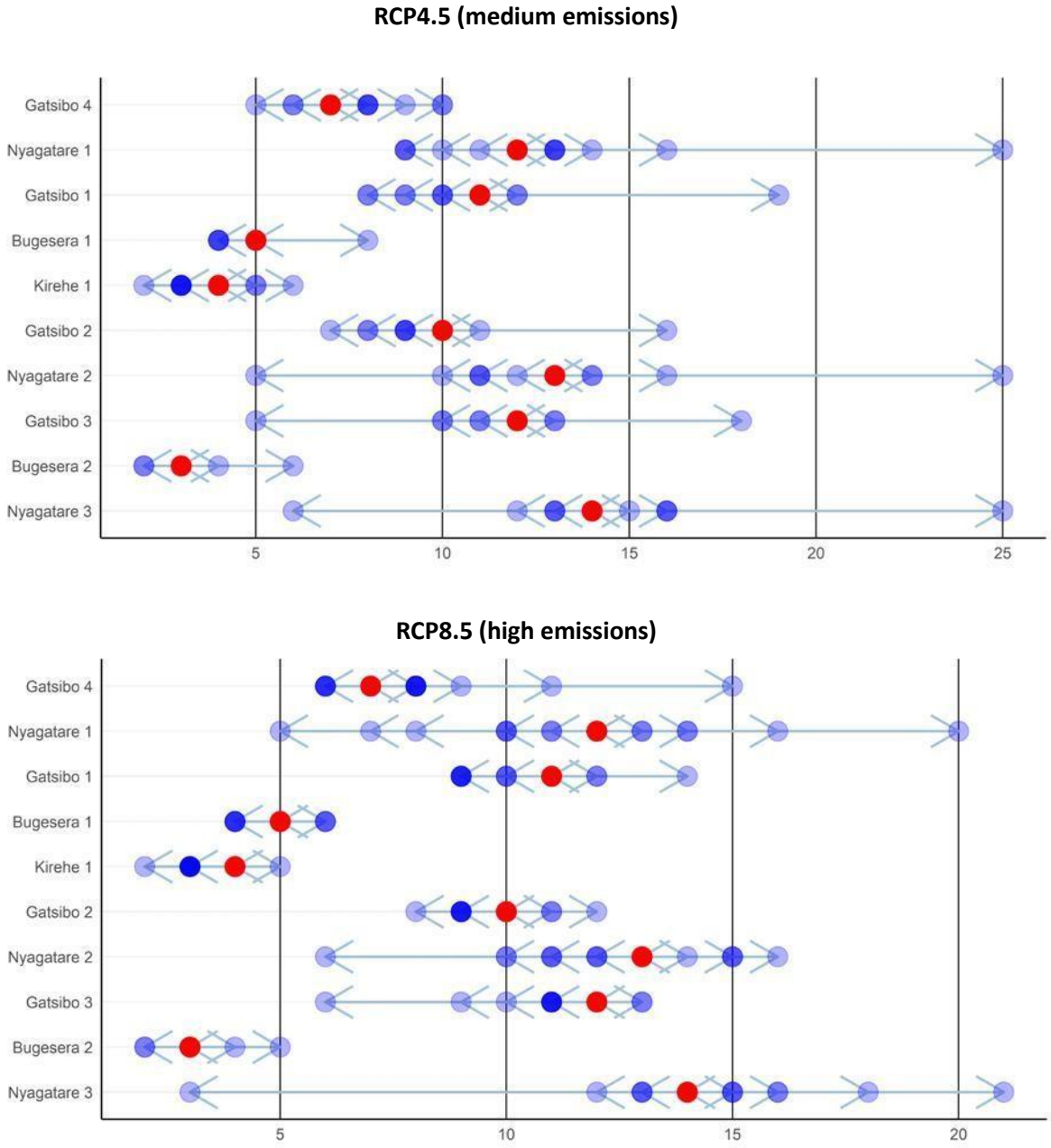


Table 2.5. Summary statistics of projected changes for the rainfall of the driest month (Bio14). Colour scheme corresponds to likely increases or decreases using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP4.5	**Nyagatare 3**	14.0	14.3	6.0	14.0	14.0	14.0	25.0
	Bugesera 2	3.0	3.1	2.0	3.0	3.0	3.0	6.0
	Gatsibo 3	12.0	11.7	5.0	12.0	12.0	12.0	18.0
	Nyagatare 2	13.0	12.9	5.0	12.3	13.0	13.0	25.0
	Gatsibo 2	10.0	9.8	7.0	9.0	10.0	10.0	16.0
	Kirehe 1	4.0	3.7	2.0	3.0	4.0	4.0	6.0
	Bugesera 1	5.0	4.9	4.0	5.0	5.0	5.0	8.0
	Gatsibo 1	11.0	10.8	8.0	10.0	11.0	11.0	19.0
	Nyagatare 1	12.0	12.7	9.0	12.0	12.0	13.0	25.0
	Gatsibo 4	7.0	7.5	5.0	7.0	7.0	8.0	10.0
RCP8.5	**Nyagatare 3**	14.0	14.1	3.0	14.0	14.0	15.0	21.0
	Bugesera 2	3.0	3.1	2.0	3.0	3.0	3.0	5.0
	Gatsibo 3	12.0	11.1	6.0	11.0	11.0	12.0	13.0
	Nyagatare 2	13.0	12.3	6.0	11.7	12.5	13.0	16.0
	Gatsibo 2	10.0	9.7	8.0	9.0	10.0	10.0	12.0
	Kirehe 1	4.0	3.4	2.0	3.0	3.0	4.0	5.0
	Bugesera 1	5.0	4.9	4.0	5.0	5.0	5.0	6.0
	Gatsibo 1	11.0	10.4	9.0	9.7	10.5	11.0	14.0
	Nyagatare 1	12.0	11.7	5.0	10.7	12.0	12.3	20.0
	Gatsibo 4	7.0	7.9	6.0	7.0	8.0	8.0	15.0

RCP	**Location**	**Baseline**		**Future**				
			Mean					
				Min	**33%**	**50%**	**66%**	**Max**

Figure 2.11. Projected changes for the mean annual temperature (Bio1). Project locations are sorted by baseline moisture index. Red circle indicates the baseline and blue circles bioclimatic conditions projected for the 2050s.

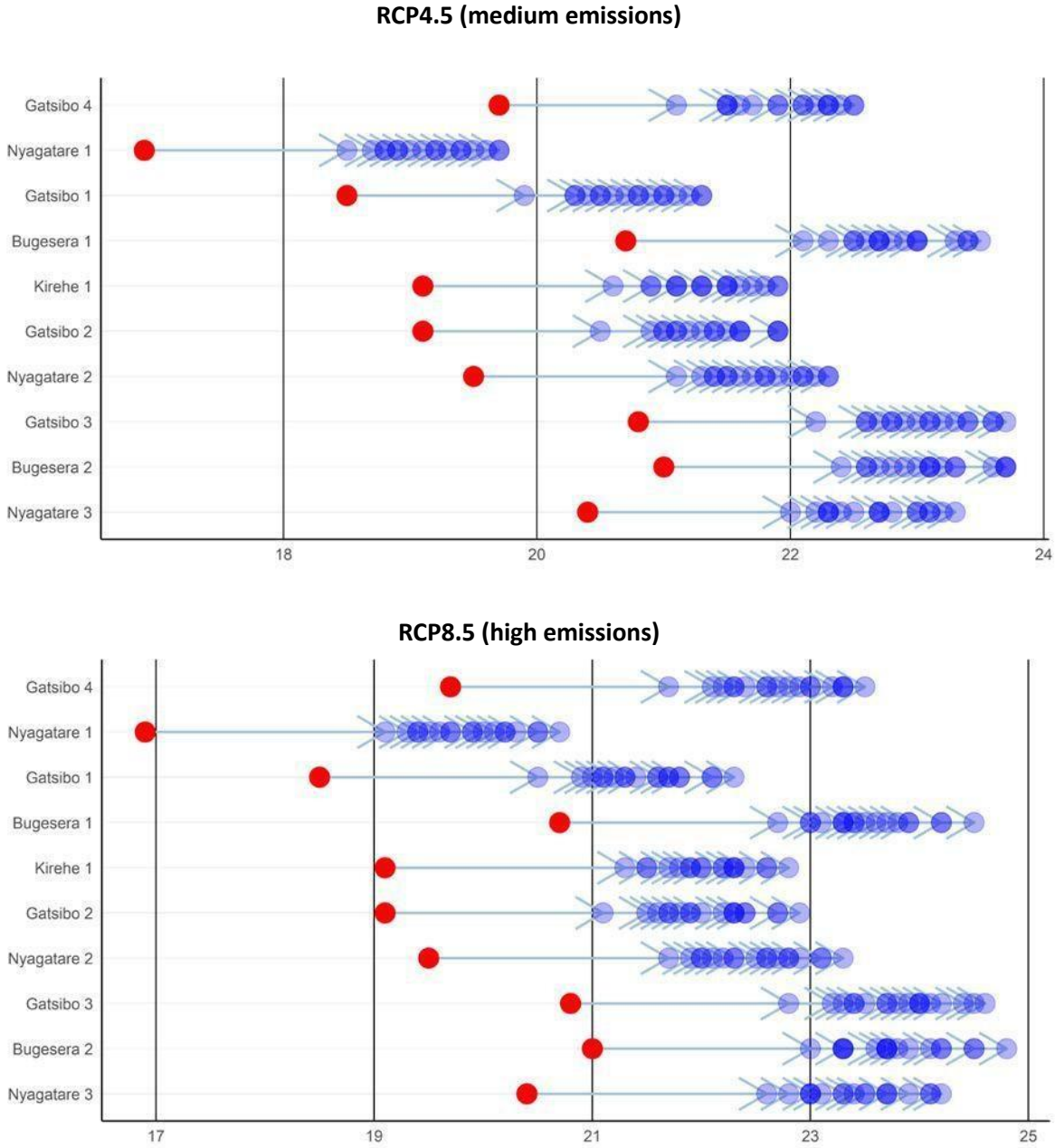


Table 2.6. Summary statistics of projected changes for the mean annual temperature (Bio1). Colour scheme corresponds to likely increases or decreases using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline	Future					
RCP4.5	Nyagatare 3	20.4	22.7	22.0	22.4	22.7	22.9	23.3
	Bugesera 2	21.0	23.1	22.4	22.9	23.1	23.3	23.7
	Gatsibo 3	20.8	23.1	22.2	22.8	23.1	23.3	23.7
	Nyagatare 2	19.5	21.8	21.1	21.5	21.8	22.0	22.3
	Gatsibo 2	19.1	21.4	20.5	21.1	21.4	21.6	21.9
	Kirehe 1	19.1	21.4	20.6	21.2	21.3	21.5	21.9
	Bugesera 1	20.7	22.9	22.1	22.7	22.8	23.0	23.5
	Gatsibo 1	18.5	20.7	19.9	20.5	20.8	21.0	21.3
	Nyagatare 1	16.9	19.2	18.5	18.9	19.2	19.4	19.7
	Gatsibo 4	19.7	22.0	21.1	21.8	22.1	22.3	22.5
RCP8.5	Nyagatare 3	20.4	23.4	22.6	23.2	23.5	23.7	24.2
	Bugesera 2	21.0	23.8	23.0	23.7	23.7	24.0	24.8
	Gatsibo 3	20.8	23.8	22.8	23.6	23.9	24.0	24.6
	Nyagatare 2	19.5	22.5	21.7	22.3	22.6	22.7	23.3
	Gatsibo 2	19.1	22.1	21.1	21.9	22.1	22.3	22.9
	Kirehe 1	19.1	22.1	21.3	21.9	22.1	22.3	22.8
	Bugesera 1	20.7	23.5	22.7	23.3	23.5	23.7	24.5
	Gatsibo 1	18.5	21.5	20.5	21.3	21.5	21.7	22.3
	Nyagatare 1	16.9	19.9	19.1	19.7	19.9	20.1	20.7
	Gatsibo 4	19.7	22.7	21.7	22.5	22.8	23.0	23.5
			Mean	Min	33%	50%	66%	Max

Figure 2.12. Projected changes for the mean annual rainfall (Bio12). Project locations are sorted by baseline moisture index. Red circle indicates the baseline and blue circles bioclimatic conditions projected for the 2050s.

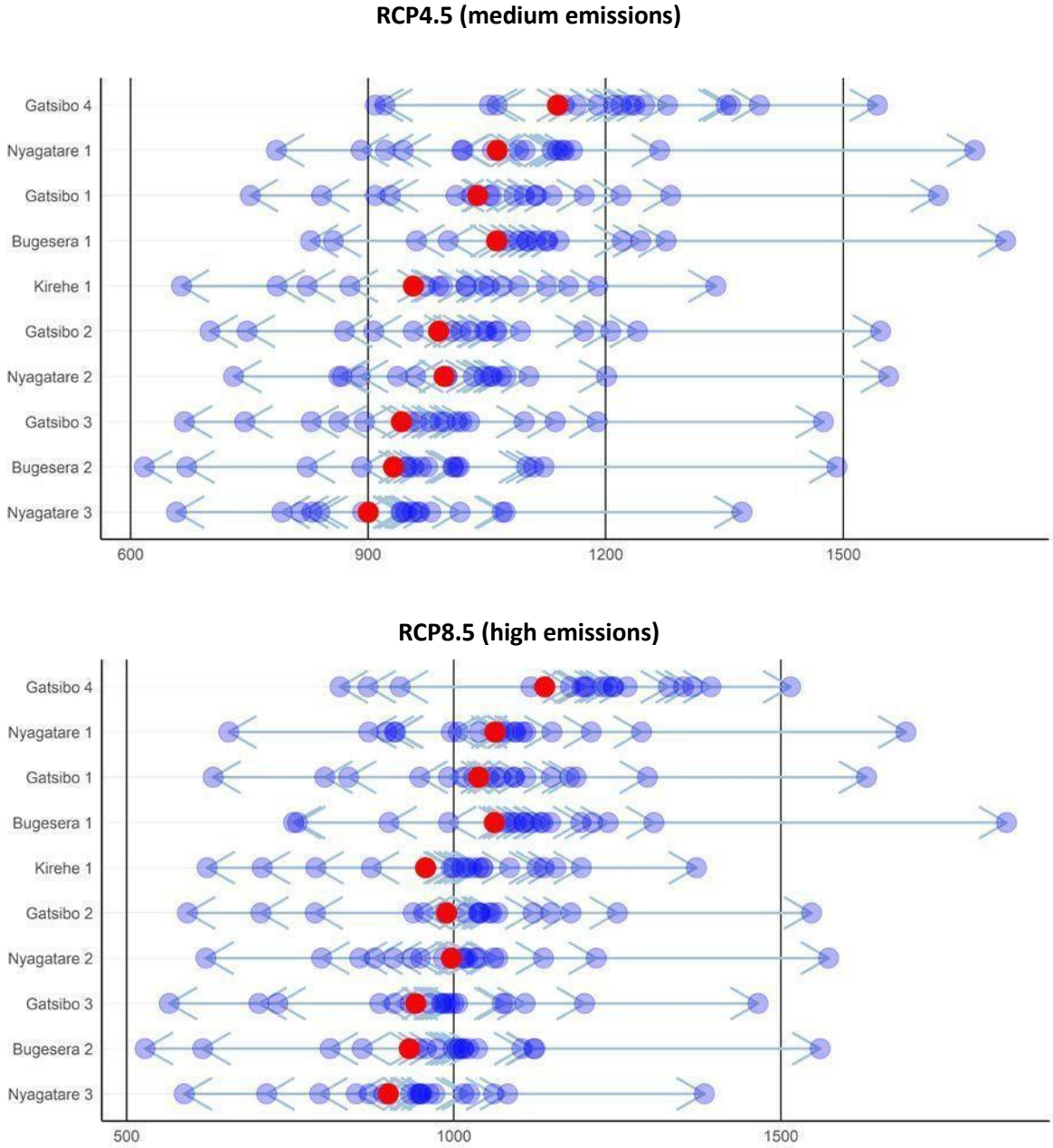


Table 2.7. Summary statistics of projected changes for the mean annual rainfall (Bio12). Colour scheme corresponds to likely increases or decreases using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

	Gatsibo 1	1038.0	1065.6	632.0	1024.7	1067.5	1098.7	1631.0
	Nyagatare 1	1063.0	1065.1	656.0	1003.3	1073.0	1098.3	1691.0
RCP	**Location**	**Baseline**			**Future**			
			Mean	**Min**	**33%**	**50%**	**66%**	**Max**
RCP4.5	**Nyagatare 3**	900.0	944.1	658.0	909.0	948.0	964.3	1372.0
	Bugesera 2	932.0	980.2	617.0	951.7	975.0	1010.7	1492.0
	Gatsibo 3	942.0	990.1	668.0	955.3	990.0	1016.0	1475.0
	Nyagatare 2	996.0	1025.8	730.0	973.0	1033.0	1056.0	1557.0
	Gatsibo 2	989.0	1041.8	700.0	1009.7	1047.0	1062.3	1547.0
	Kirehe 1	957.0	1012.7	664.0	990.7	1024.0	1063.7	1339.0
	Bugesera 1	1062.0	1119.2	827.0	1080.0	1101.0	1126.3	1705.0
	Gatsibo 1	1038.0	1082.9	751.0	1038.3	1084.0	1111.7	1620.0
	Nyagatare 1	1063.0	1090.8	784.0	1032.3	1090.0	1136.7	1666.0
	Gatsibo 4	1139.0	1207.0	909.0	1172.0	1219.0	1245.0	1543.0
RCP8.5	**Nyagatare 3**	900.0	941.0	588.0	920.3	949.0	965.0	1383.0
	Bugesera 2	932.0	983.5	528.0	969.3	1006.5	1017.7	1560.0
	Gatsibo 3	942.0	976.1	565.0	953.0	986.0	1002.0	1465.0
	Nyagatare 2	996.0	1005.9	621.0	944.7	1015.5	1033.3	1573.0
	Gatsibo 2	989.0	1029.1	593.0	1008.0	1039.5	1061.0	1547.0
	Kirehe 1	957.0	1013.7	623.0	1008.0	1033.0	1058.3	1371.0
	Bugesera 1	1062.0	1123.0	755.0	1092.3	1113.0	1140.0	1845.0

Gatsibo 4	1139.0	1204.2	1198.7	1231.0	1251.0	1515.0	826.0

3. Projected changes in monthly precipitation

Changes in monthly precipitation were inferred from mid-21st century climatic raster layers obtained from WorldClim 1.4 (downloaded June 2018; Hijmans *et al.* 2005).

RCP4.5 models reached consensus that monthly precipitation would **decrease from April to July**, a period that includes the April 'B' growing seasons for beans and April-May 'B' season for maize and sorghum (figure 3.1, 3.7 – 3.9; tables 3.1 – 3.3). There was less evidence for RCP8.5 for decreases in April for RCP8.5 (possibly a result from having fewer models available for this pathway), but there was also consensus on decreases in rainfall in May and June (figure 3.8 – 3.9, tables 3.2 – 3.3) . Variation among models for April and May precipitation can be inferred from the figures and Tables referred to in this section.

There was consensus among the RCP4.5 and RCP8.5 models (and clearly for the eastern part of Rwanda; figures 3.10 – 3.12; tables 3.4 – 3.6) that monthly precipitation would **increase in the period from November to January**. This period includes the growing 'A' seasons for beans (November), maize and sorghum (November and December). Variation among models for these months can be seen in figures 3. 4- 3.6 and 3.10 – 3.12.

Annual precipitation trends for 1981 - 2010 for the Lake Victoria Basin (LVB) showed that drier periods are getting longer during the long rains (MAMJ; Lake Victoria Basin Climate Change Adaptation Strategy and Action Plan 2018-2023), which agree with the results obtained here for the middle of the 21st century. In the same LVB study, a significant increase in monthly rainfall for October and November was reported. Again, these trends are reflected in the GCM projections.

Despite overall increases in precipitation, the LVB report also reported following trends in drought and flooding:

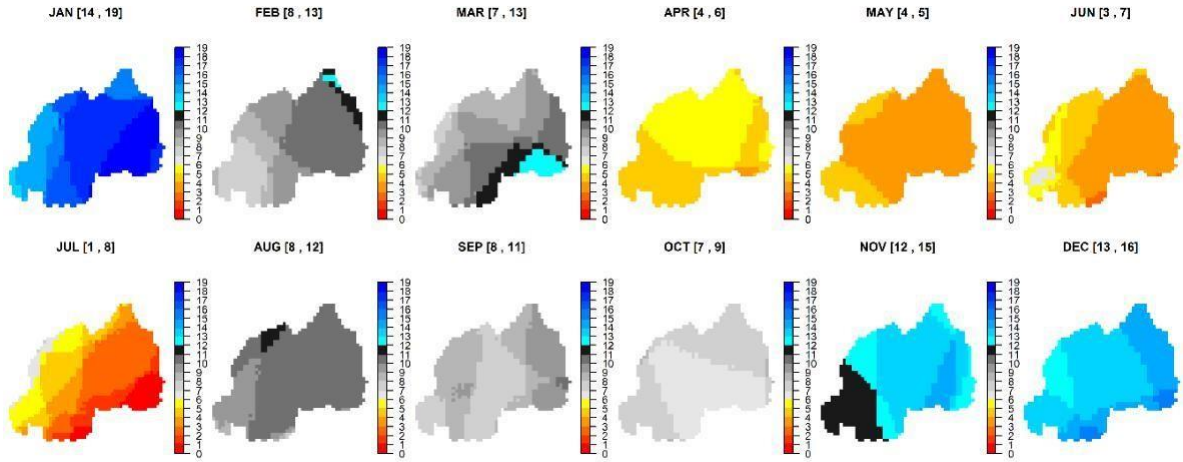
> *Drought is a recurrent phenomenon in the region. By comparing Standardized Precipitation Index (SPI) values for 1981–2014, a pattern of recurring drought is illustrated in Figure 1 for the five East Africa countries. Increased frequency of severe droughts (SPI>-1.5), interspersed with short-lived recovery periods or sometimes back-to-back with extreme flooding, such as the 2006, 2009, and 2015 El Niño events, allows insufficient periods for recovery, especially for pastoralists, who require 3–5 years of good rainfall to restock.*

What the net-effect of decreased precipitation during the long rains and increased precipitation during the short rains would need to be estimated by correlative and mechanistic models (? Jawoo & Cox 2014; Luedeling *et al.* 2014). An analysis based on Ecocrop limits predicted negative changes in suitable area or productivity in Eastern Africa for beans and maize (Ramirez-Villegas & Thornton 2015; Girvetz et al. 2019).

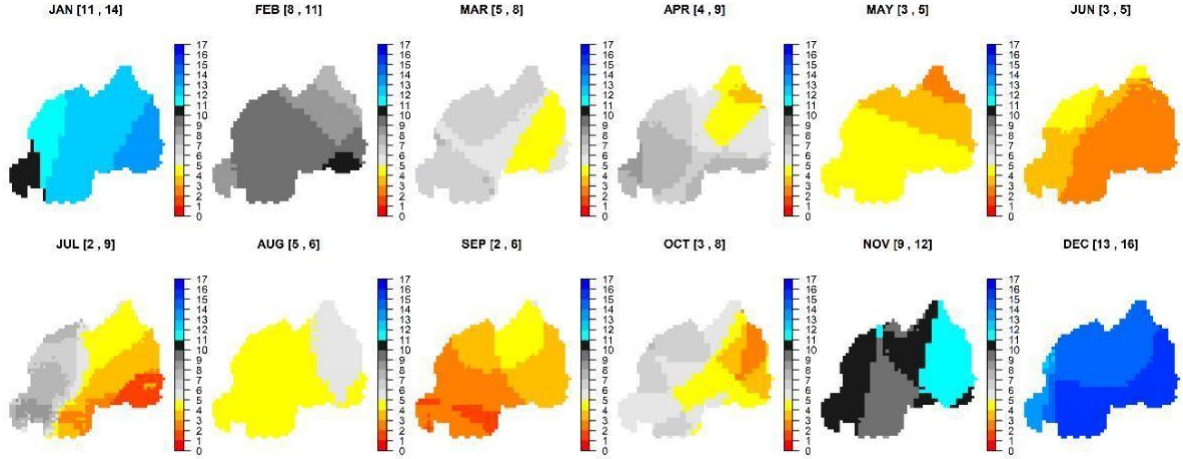
Figure 3.1.

Counts of General Circulation Models that project monthly increases in bioclimatic variables by the 2050s for RCP4.5 and RCP8.5 compared to the baseline centred on 1975. The major changes in the colour schemes correspond to the likelihood scale recommended for the fifth Assessment Report of the IPCC.

RCP4.5 (medium emissions)

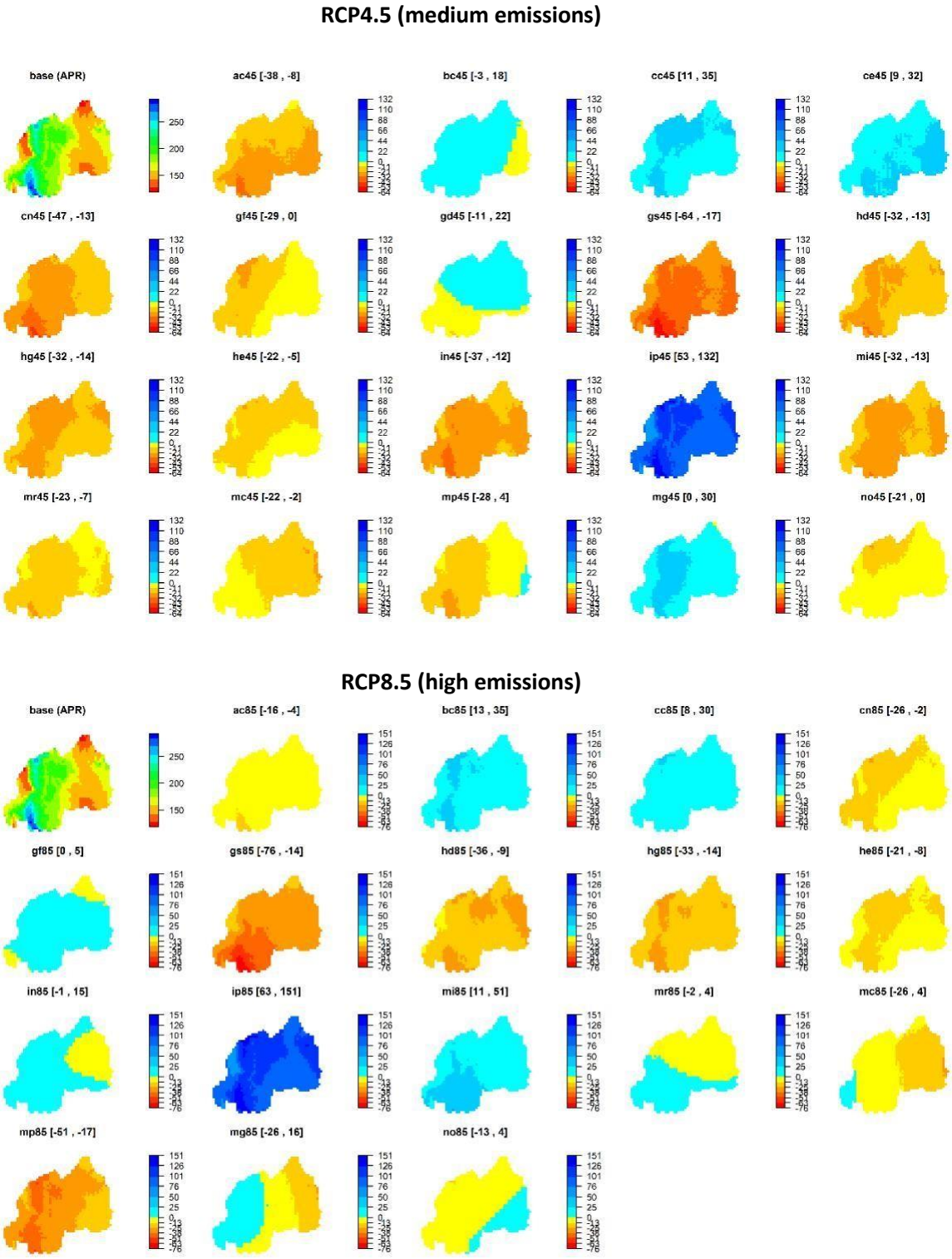


RCP8.5 (high emissions)



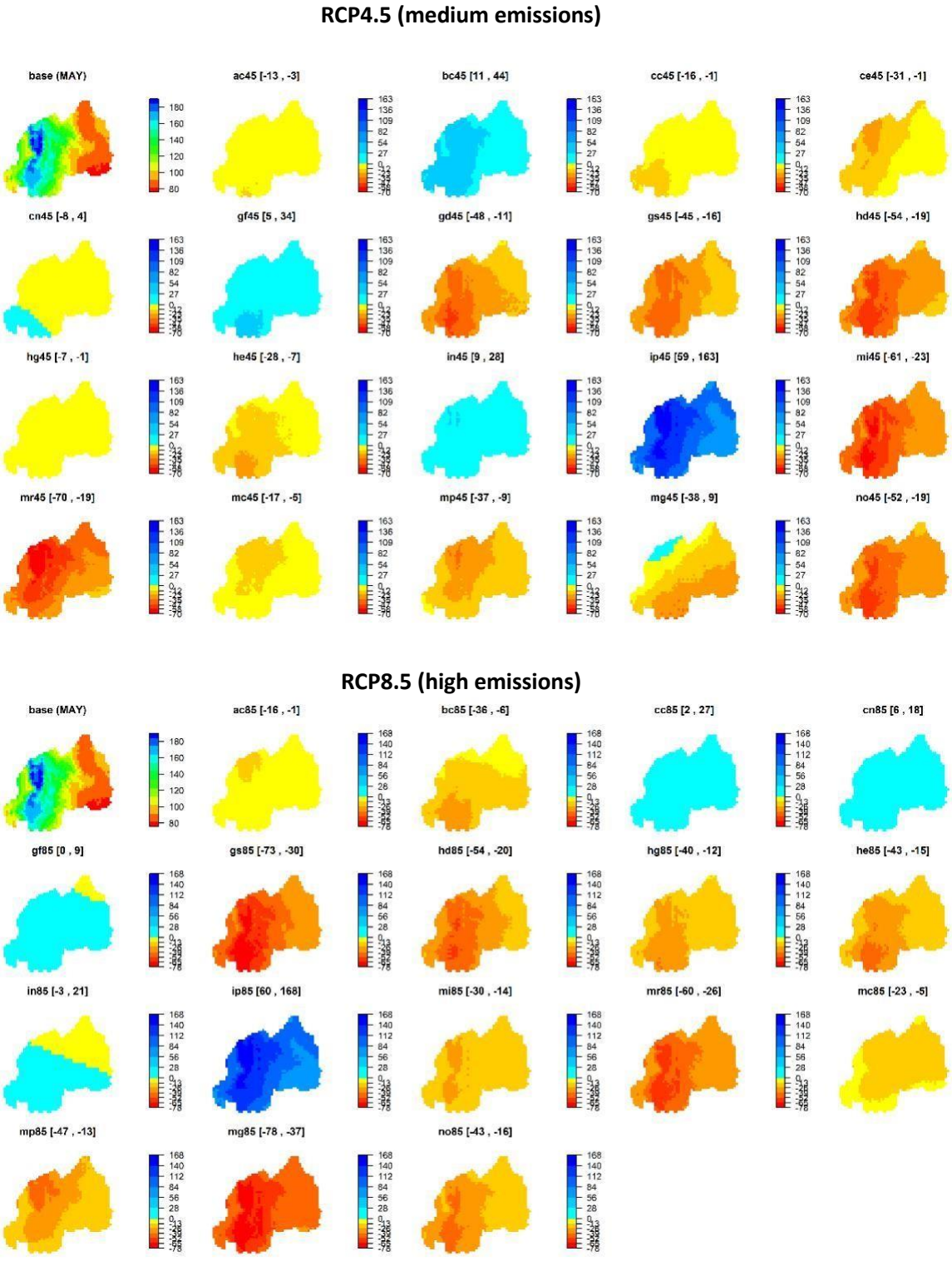
Projected changes in April precipitation from baseline. Model abbreviations provided in the *Methods* section. Figures between square brackets indicate the range for the particular model.

Figure 3.2.



Projected changes in May precipitation from baseline. Model abbreviations provided in the *Methods* section. Figures between square brackets indicate the range for the particular model.

Figure 3.3.



Projected changes in November precipitation from baseline. Model

Figure 3.4.
abbreviations provided in the *Methods* section. Figures between square brackets indicate the range for the particular model.

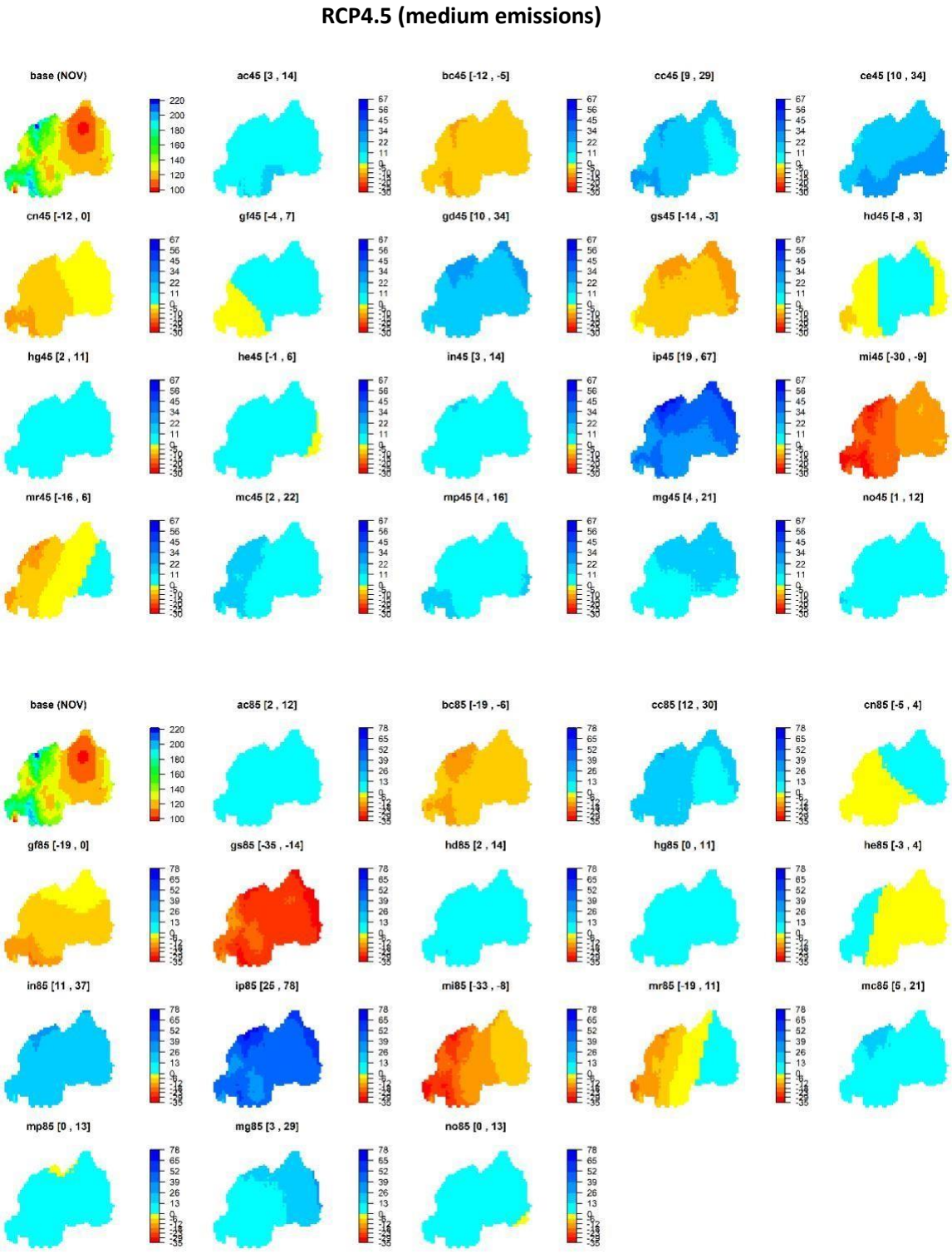


Figure 3.5.

RCP8.5 (high emissions)

Projected changes in December precipitation from baseline. Model abbreviations provided in the *Methods* section. Figures between square brackets indicate the range for the particular model.

RCP4.5 (medium emissions)

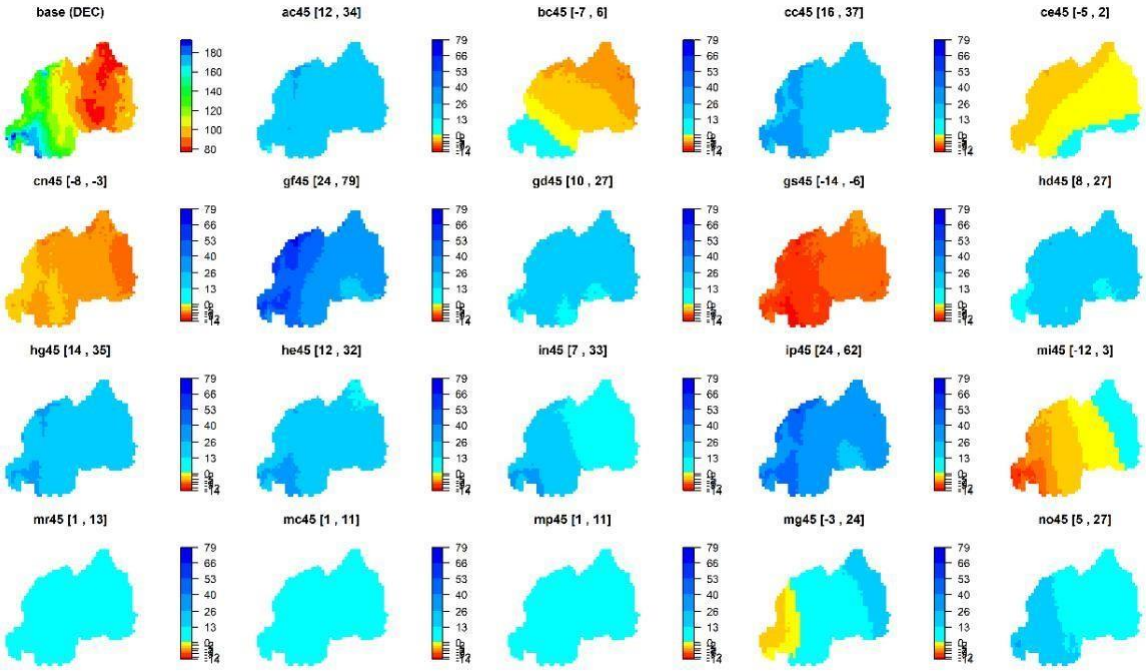


Figure 3.6.

RCP8.5 (high emissions)

Projected changes in January precipitation from baseline. Model abbreviations provided in the *Methods* section. Figures between square brackets indicate the range for the particular model.

RCP4.5 (medium emissions)

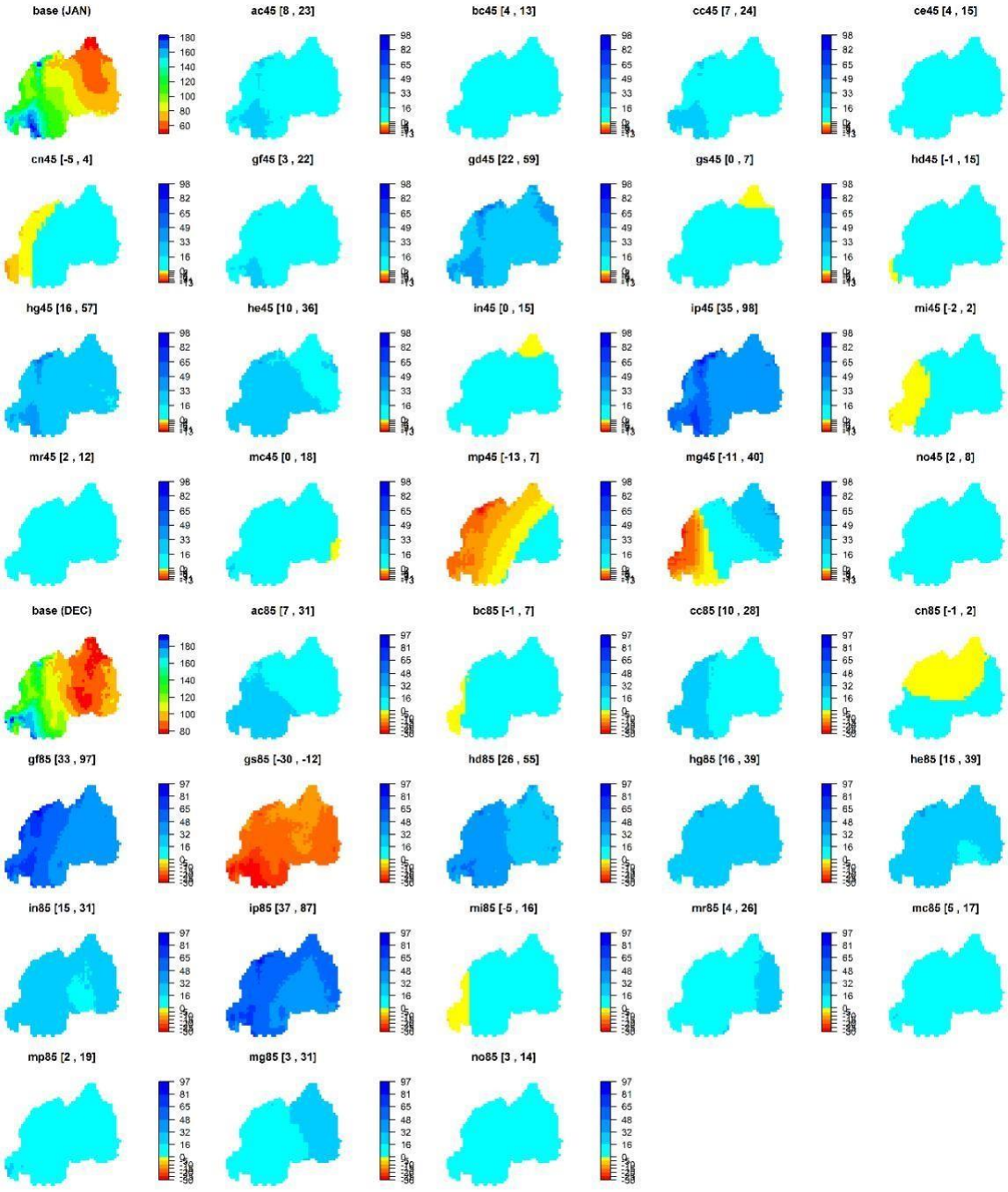
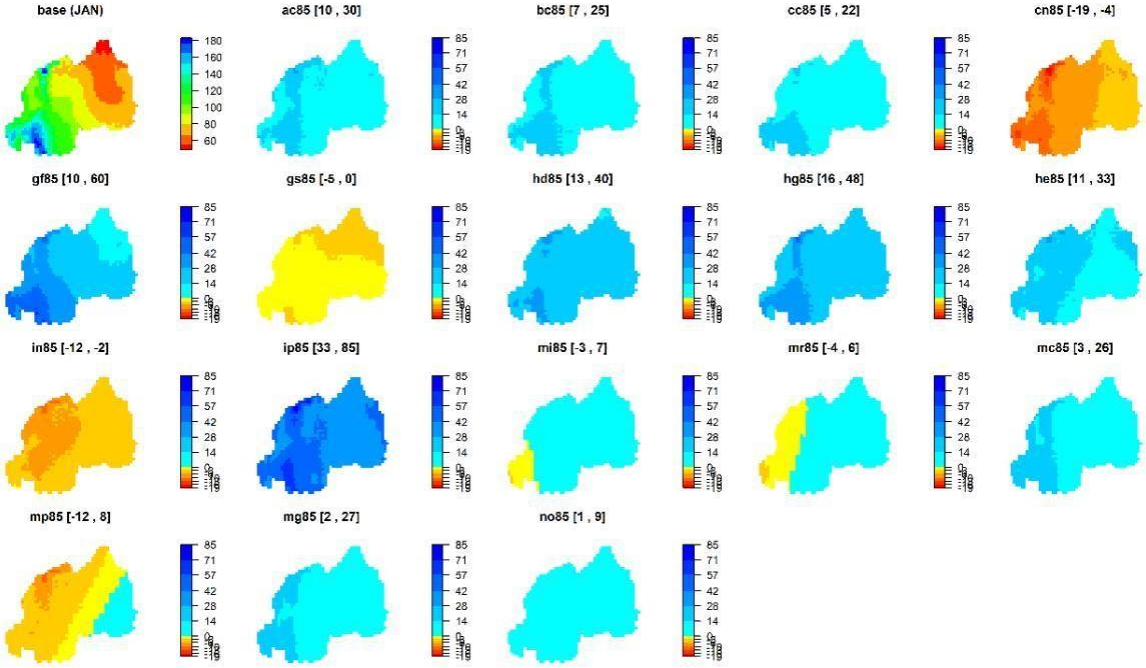


Figure 3.7.

RCP8.5 (high emissions)



Projected changes for the precipitation in April. Project locations are sorted by baseline moisture index. Red circle indicates the baseline precipitation and blue circles precipitation projected for the 2050s.

RCP4.5 (medium emissions)

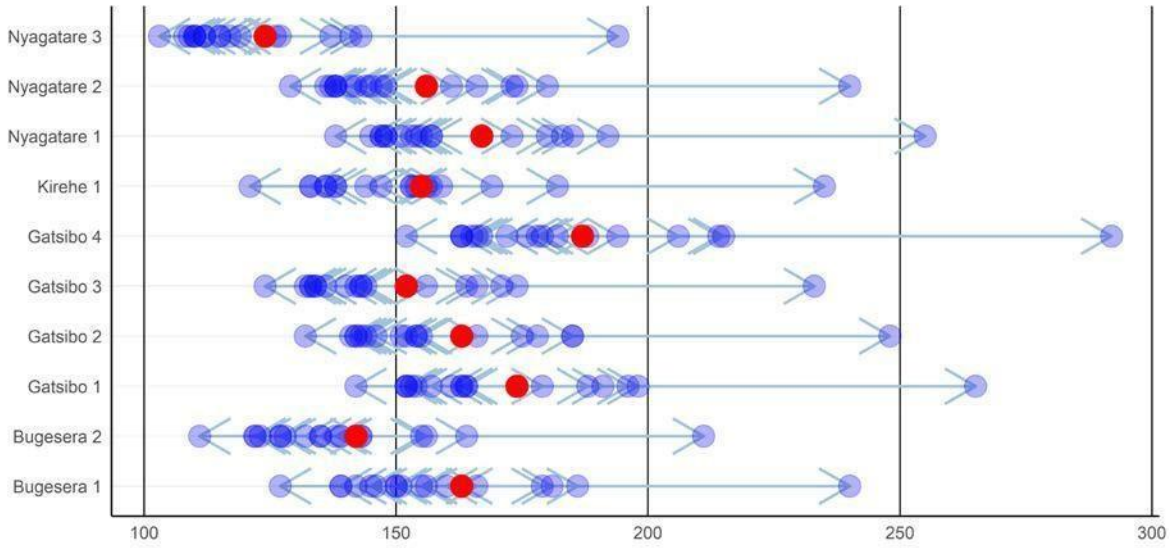


Figure 3.8.

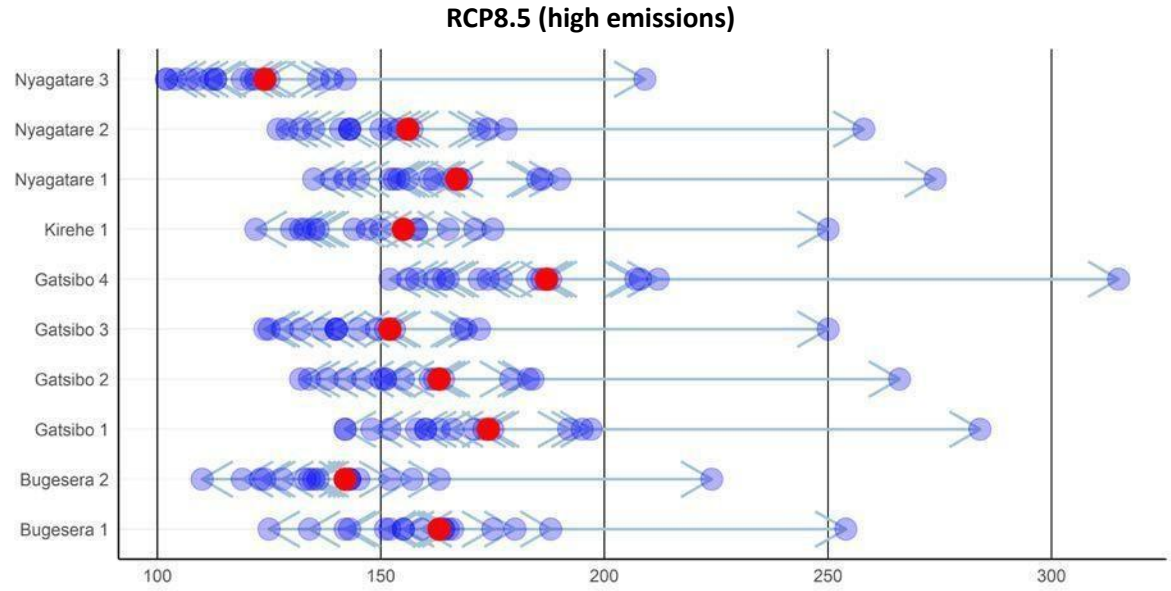

RCP8.5 (high emissions)
Nyagatare 3
Nyagatare 2
Nyagatare 1
Kirehe 1
Gatsibo 4
Gatsibo 3
Gatsibo 2
Gatsibo 1
Bugesera 2
Bugesera 1
100
150
200
250
300

Table 3.1. Summary statistics of projected changes in April precipitation. Colour scheme corresponds to likely increases or decreases in precipitation using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline	Future					
			Mean	Min	33%	50%	66%	Max
RCP4.5	**Nyagatare 3**	124.0	122.7	103.0	111.3	115.0	121.3	194.0
	Bugesera 2	142.0	139.5	111.0	127.7	135.0	140.3	211.0
	Gatsibo 3	152.0	150.1	124.0	135.3	142.5	148.0	233.0
	Nyagatare 2	156.0	154.3	129.0	140.0	144.5	152.3	240.0
	Gatsibo 2	163.0	160.7	132.0	145.3	153.0	158.7	248.0
	Kirehe 1	155.0	152.4	121.0	138.0	150.0	154.7	235.0
	Bugesera 1	163.0	159.7	127.0	148.7	153.0	161.0	240.0
	Gatsibo 1	174.0	171.9	142.0	156.0	163.0	169.0	265.0
	Nyagatare 1	167.0	164.9	138.0	150.0	154.5	162.3	255.0
	Gatsibo 4	187.0	185.3	152.0	166.7	177.0	184.0	292.0
RCP8.5								
	Nyagatare 3	124.0	123.5	102.0	112.3	119.0	123.3	209.0
	Bugesera 2	142.0	141.9					110.0
133.3	136.0	143.0	224.0	124.0	140.0	145.0	151.7	
	Gatsibo 3	152.0	151.5	127.0	143.0	150.0	155.3	250.0
	Nyagatare 2	156.0	155.5	132.0	150.3	155.0	162.7	258.0
	Gatsibo 2	163.0	162.4	122.0	138.7	150.0	157.0	266.0
	Kirehe 1	155.0	153.9	125.0	153.0	159.0	164.7	250.0
	Bugesera 1	163.0	163.1	142.0	160.0	166.0	173.7	254.0
	Gatsibo 1	174.0	173.7					284.0
	Nyagatare 1	167.0	166.8	135.0	153.3	161.0	167.3	274.0
	Gatsibo 4	187.0	186.4	152.0	167.3	177.0	186.7	315.0

Figure 3.8. Projected changes for the precipitation in May. Project locations are sorted by baseline moisture index. Red circle indicates the baseline precipitation and blue circles precipitation projected for the 2050s.

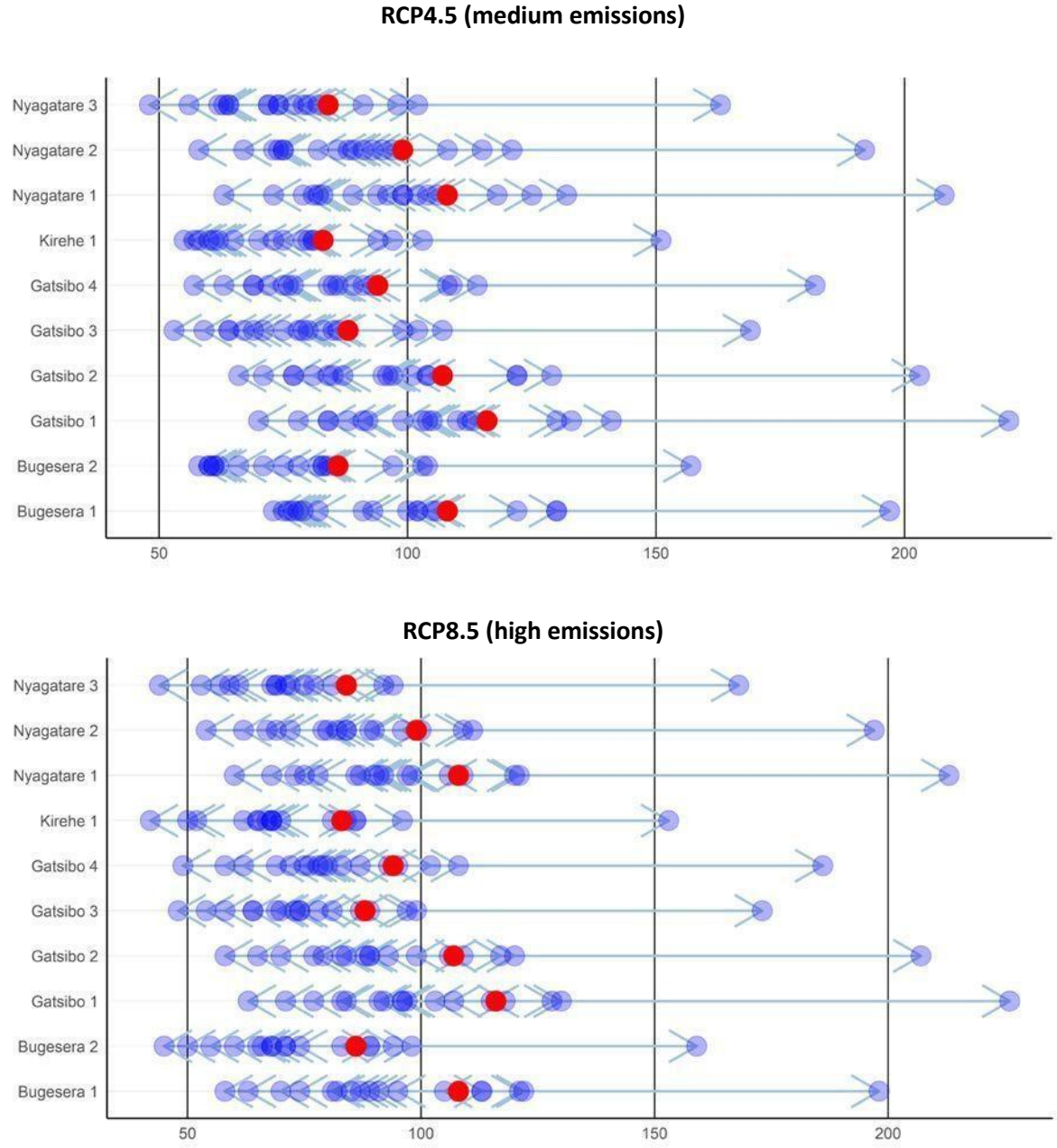


Table 3.2. Summary statistics of projected changes in May precipitation. Colour scheme corresponds to likely increases or decreases in precipitation using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline		Future				
RCP4.5	**Nyagatare 3**	84.0	78.9	48.0	69.3	74.0	79.3	163.0
	Bugesera 2	86.0	80.3	58.0	64.7	76.5	83.0	157.0

	Gatsibo 3	88.0	82.8	53.0	70.3	78.5	83.7	169.0
	Nyagatare 2	99.0	93.3	58.0	79.7	88.5	93.7	192.0
	Gatsibo 2	107.0	100.1	66.0	84.7	95.5	102.0	203.0
	Kirehe 1	83.0	77.9	55.0	64.0	74.0	80.3	151.0
	Bugesera 1	108.0	101.0	73.0	81.0	96.5	103.0	197.0
	Gatsibo 1	116.0	108.8	70.0	91.7	103.5	110.7	221.0
	Nyagatare 1	108.0	101.8	63.0	87.0	97.5	102.7	208.0
	Gatsibo 4	94.0	88.8	57.0	75.7	84.5	89.7	182.0
RCP8.5	**Nyagatare 3**	84.0	76.1	44.0	68.3	71.0	76.3	168.0
	Bugesera 2	86.0	76.8	45.0	66.7	71.0	80.0	159.0
	Gatsibo 3	88.0	79.5	48.0	69.3	74.0	80.0	173.0
	Nyagatare 2	99.0	89.7	54.0	79.3	84.0	89.7	197.0
	Gatsibo 2	107.0	96.1	58.0	83.3	89.0	97.0	207.0
	Kirehe 1	83.0	74.3	42.0	65.7	68.0	77.3	153.0
	Bugesera 1	108.0	96.9	58.0	83.0	89.0	101.7	198.0
	Gatsibo 1	116.0	104.5	63.0	91.3	96.0	105.7	226.0
	Nyagatare 1	108.0	97.9	60.0	86.3	91.0	97.7	213.0
	Gatsibo 4	94.0	85.4	49.0	75.3	79.0	85.7	186.0
			Mean	**Min**	**33%**	**50%**	**66%**	**Max**

Figure 3.9. Projected changes for the precipitation in June. Project locations are sorted by baseline moisture index. Red circle indicates the baseline precipitation and blue circles precipitation projected for the 2050s.

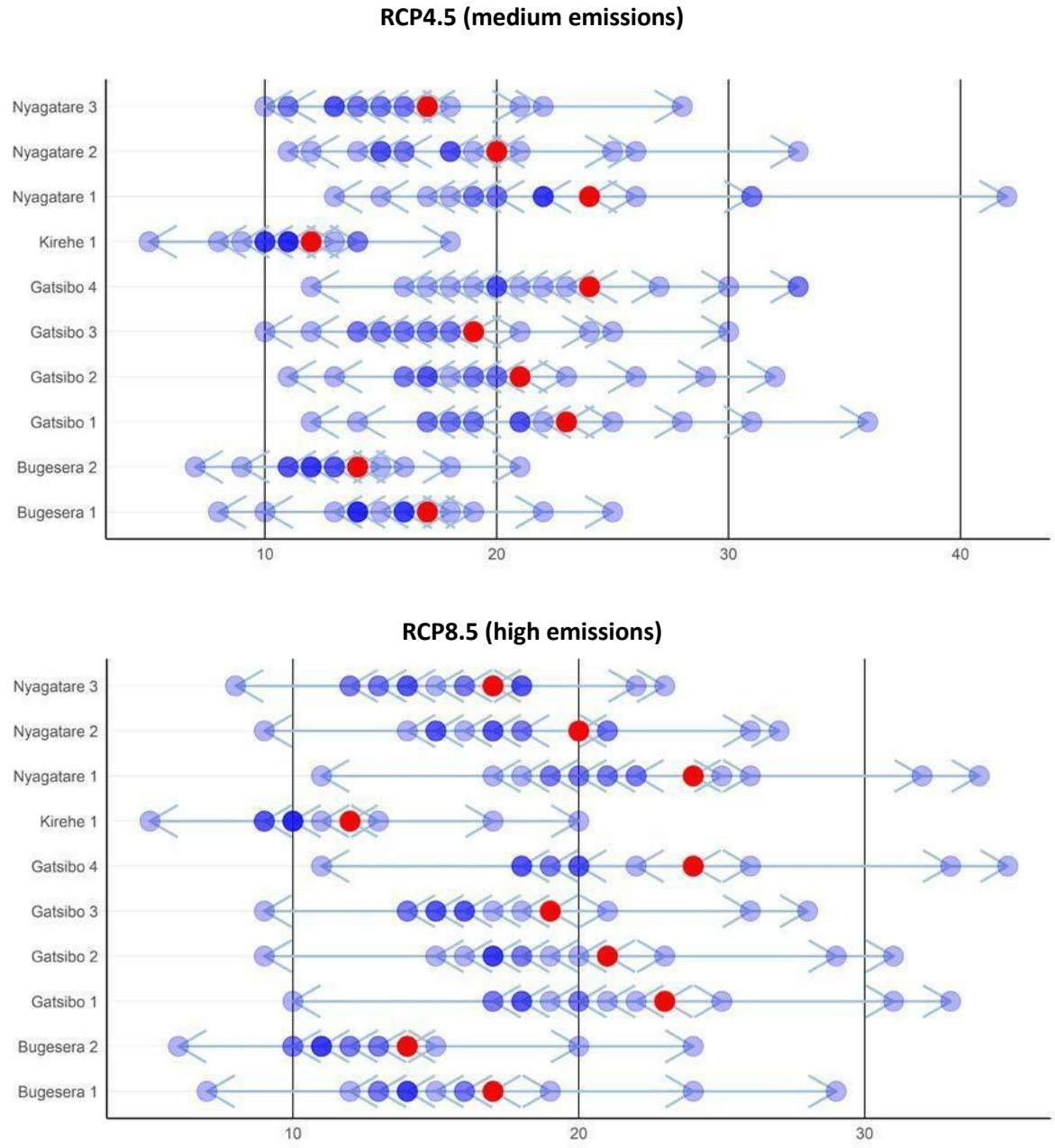


Table 3.3. Summary statistics of projected changes in June precipitation. Colour scheme corresponds to likely increases or decreases in precipitation using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline	Future					
			Mean	Min	33%	50%	66%	Max
RCP4.5	**Nyagatare 3**	17.0	15.8	10.0	13.7	15.0	16.3	28.0
	Bugesera 2	14.0	13.0	7.0	12.0	12.5	13.3	21.0

		Gatsibo 3		19.0	17.8	10.0	15.7	17.0	18.3	30.0
		Nyagatare 2		20.0	18.4	11.0	15.7	18.0	19.3	33.0
		Gatsibo 2		21.0	19.7	11.0	17.0	19.0	20.3	32.0
		Kirehe 1		12.0	11.1	5.0	10.0	11.0	11.3	18.0
		Bugesera 1		17.0	15.6	8.0	14.0	15.5	16.0	25.0
		Gatsibo 1		23.0	21.4	12.0	18.7	21.0	22.3	36.0
		Nyagatare 1		24.0	22.6	13.0	19.7	22.0	22.7	42.0
		Gatsibo 4		24.0	22.4					12.0
20.0		21.5		24.0	33.0	8.0	14.0	15.0	16.7	
RCP8.5		**Nyagatare 3**		17.0	15.5					23.0
		Bugesera 2		14.0	13.0	6.0	11.0	12.0	13.7	24.0
		Gatsibo 3		19.0	17.5					28.0
		Nyagatare 2		20.0	18.0	9.0	15.3	16.0	18.7	27.0
		Gatsibo 2		21.0	19.4					31.0
		Kirehe 1		12.0	11.2	9.0	16.3	17.0	19.3	5.0
10.0										10.0
12.0	20.0	7.0	14.0	15.0	16.7	9.0	17.0	18.0	20.7	
										Bugesera 1
17.0		10.0	18.3	20.0	22.7					15.9
29.0										
		11.0	20.0	21.0	23.3					**Gatsibo 1**
23.0										21.1
33.0		10.0	13.7	15.0	16.3					
										Nyagatare 1
24.0		22.1		34.0						
		Nyagatare 3		17.0	15.8					28.0

Figure 3.10. Projected changes for the precipitation in November. Project locations are sorted by baseline moisture index. Red circle indicates the baseline precipitation and blue circles precipitation projected for the 2050s.

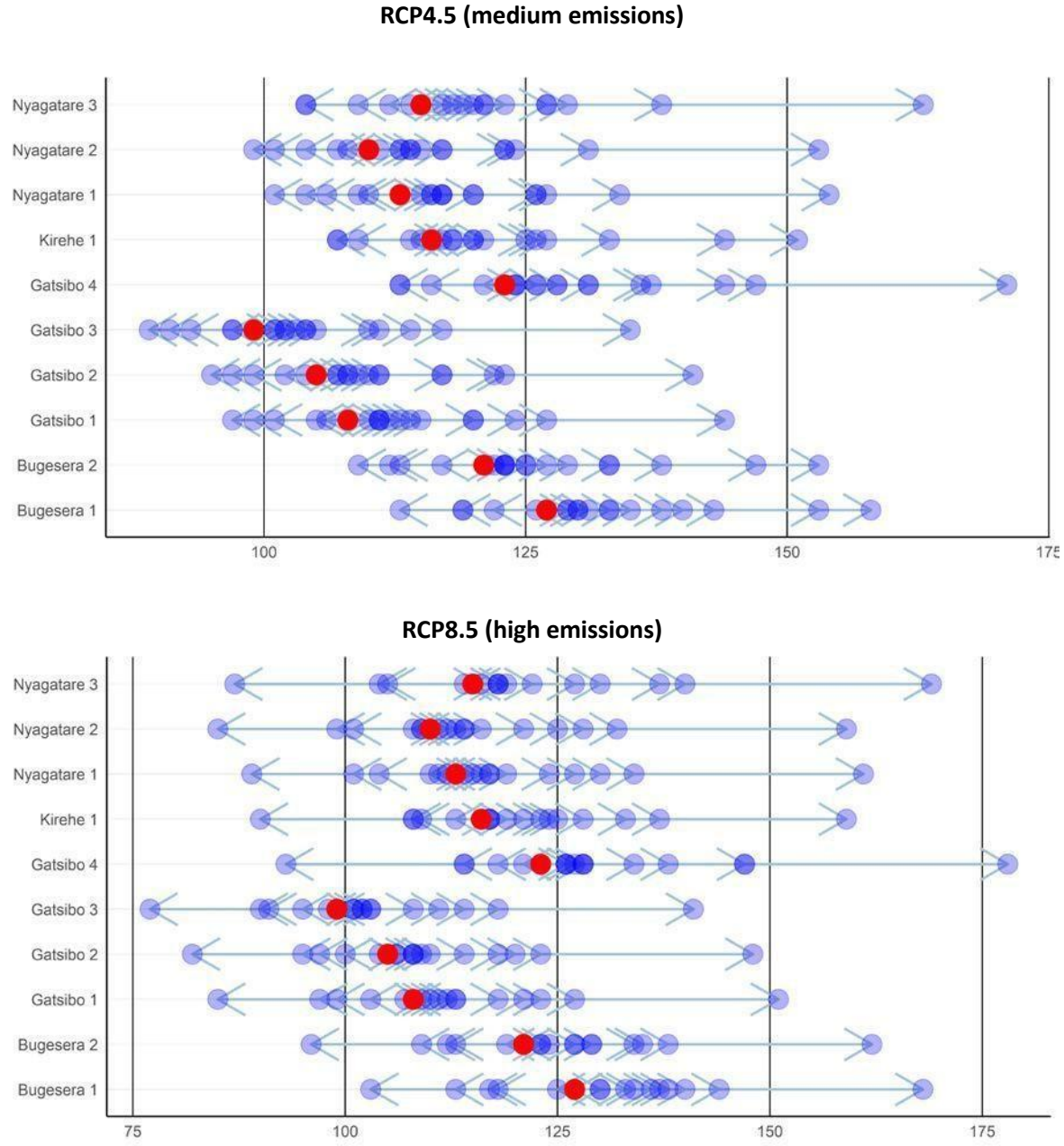


Table 3.4. Summary statistics of projected changes in November precipitation. Colour scheme corresponds to likely increases or decreases in precipitation using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline	Future					
			Mean	Min	33%	50%	66%	Max
RCP4.5	**Nyagatare 3**	115.0	121.2	104.0	116.3	119.5	121.7	163.0
	Bugesera 2	121.0	126.4	109.0	123.0	124.0	127.7	153.0

	Gatsibo 3	99.0	104.2	89.0	101.0	102.5	104.3	135.0
	Nyagatare 2	110.0	115.9	99.0	112.3	114.0	117.0	153.0
	Gatsibo 2	105.0	110.4	95.0	107.0	108.5	111.0	141.0
	Kirehe 1	116.0	121.6	107.0	116.7	119.0	122.3	151.0
	Bugesera 1	127.0	132.3	113.0	129.0	130.5	133.7	158.0
	Gatsibo 1	108.0	113.3	97.0	110.7	111.5	114.3	144.0
	Nyagatare 1	113.0	118.6	101.0	115.7	117.0	120.0	154.0
	Gatsibo 4	123.0	130.0	113.0	124.0	127.0	131.0	171.0
RCP8.5	**Nyagatare 3**	115.0	120.8	87.0	115.3	118.0	121.0	169.0
	Bugesera 2	121.0	124.8	96.0	121.7	124.0	128.3	162.0
	Gatsibo 3	99.0	103.2	77.0	99.7	102.0	103.0	141.0
	Nyagatare 2	110.0	115.1	85.0				
109.7	113.0	115.3	159.0		106.0	108.0	109.7	148.0
	Gatsibo 2	105.0	109.2	82.0	117.0	119.0	123.7	159.0
	Kirehe 1	116.0	120.5	90.0	127.0	130.0	135.3	168.0
	Bugesera 1	127.0	130.6	103.0	108.3	111.0	113.0	151.0
	Gatsibo 1	108.0	112.2	85.0				
	Nyagatare 1	113.0	117.7	89.0	112.7	116.0	118.3	161.0
	Gatsibo 4	123.0	129.0		126.0	127.0	128.0	178.0
93.0								

Figure 3.11. Projected changes for the precipitation in December. Project locations are sorted by baseline moisture index. Red circle indicates the baseline precipitation and blue circles precipitation projected for the 2050s.

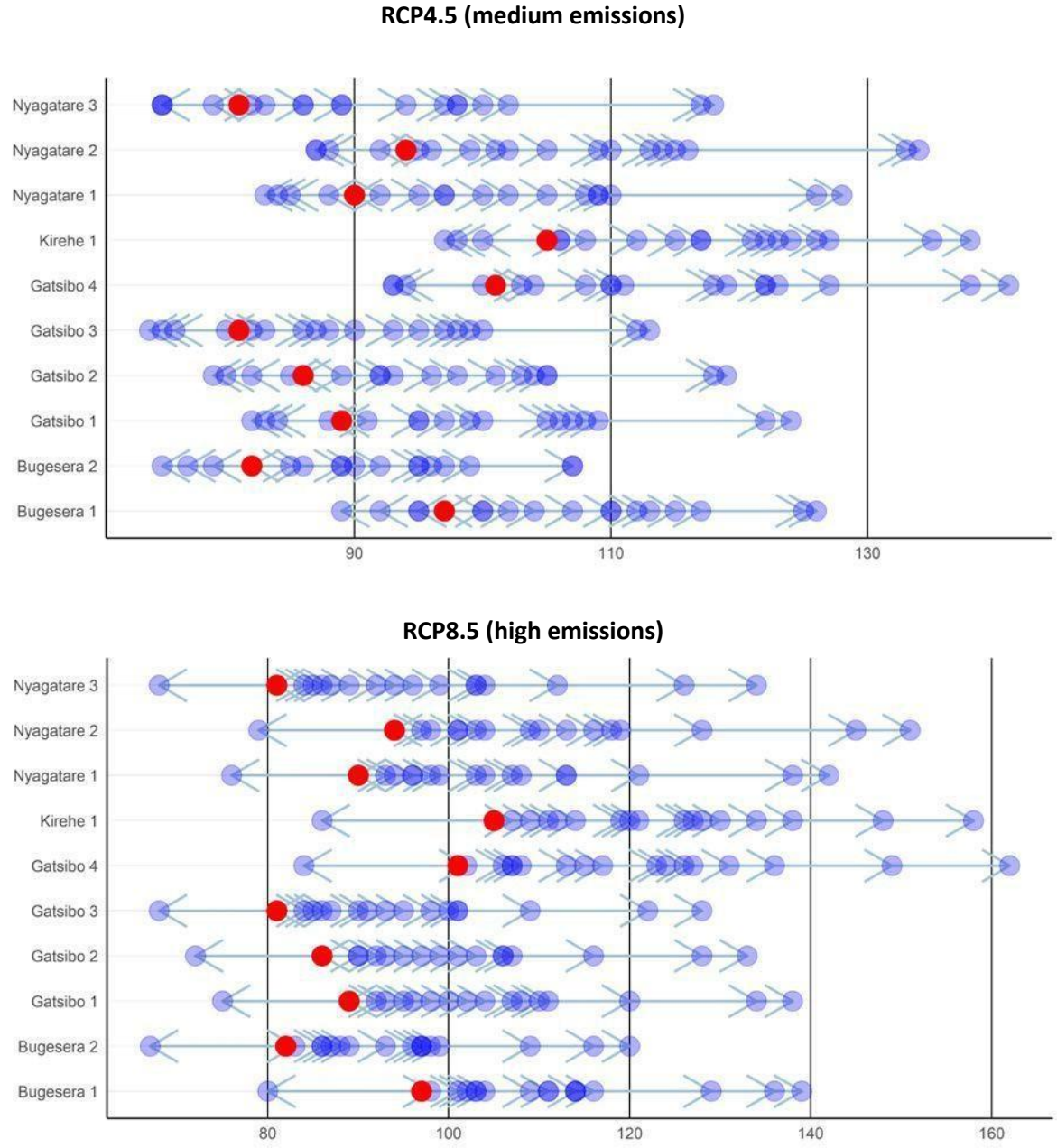


Table 3.5. Summary statistics of projected changes in December precipitation. Colour scheme corresponds to likely increases or decreases in precipitation using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline		Future				
RCP4.5	**Nyagatare 3**	81.0	91.3	75.0	85.0	89.0	97.3	118.0
	Bugesera 2	82.0	90.1	75.0	85.7	89.5	95.0	107.0

	Gatsibo 3	81.0	90.4	74.0	85.0	89.0	95.7	113.0
	Nyagatare 2	94.0	105.3	87.0	98.0	103.5	111.0	134.0
	Gatsibo 2	86.0	95.9	79.0	91.0	94.5	101.7	119.0
	Kirehe 1	105.0	116.2	97.0	110.7	117.0	122.3	138.0
	Bugesera 1	97.0	106.1	89.0	100.0	105.5	110.7	126.0
	Gatsibo 1	89.0	99.1	82.0	93.7	98.0	105.3	124.0
	Nyagatare 1	90.0	100.4	83.0	94.0	98.5	106.0	128.0
	Gatsibo 4	101.0	113.1	93.0	106.7	110.5	120.0	141.0
RCP8.5	**Nyagatare 3**	81.0	96.7	68.0	87.7	94.0	101.7	134.0
	Bugesera 2	82.0	94.6	67.0	88.3	96.0	97.0	120.0
	Gatsibo 3	81.0	95.2	68.0	88.0	93.0	99.3	128.0
	Nyagatare 2	94.0	110.9	79.0	101.7	109.0	115.0	151.0
	Gatsibo 2	86.0	100.8	72.0	93.7	99.0	105.0	133.0
	Kirehe 1	105.0	122.8	86.0	115.7	121.0	127.7	158.0
	Bugesera 1	97.0	110.8	80.0	103.3	111.0	114.0	139.0
	Gatsibo 1	89.0	104.2	75.0	96.7	102.0	107.7	138.0
	Nyagatare 1	90.0	105.4	76.0	96.7	103.0	107.7	142.0
	Gatsibo 4	101.0	119.8	84.0	109.7	117.0	125.3	162.0
			Mean	**Min**	**33%**	**50%**	**66%**	**Max**

Figure 3.12. Projected changes for the precipitation in January. Project locations are sorted by baseline moisture index. Red circle indicates the baseline precipitation and blue circles precipitation projected for the 2050s.

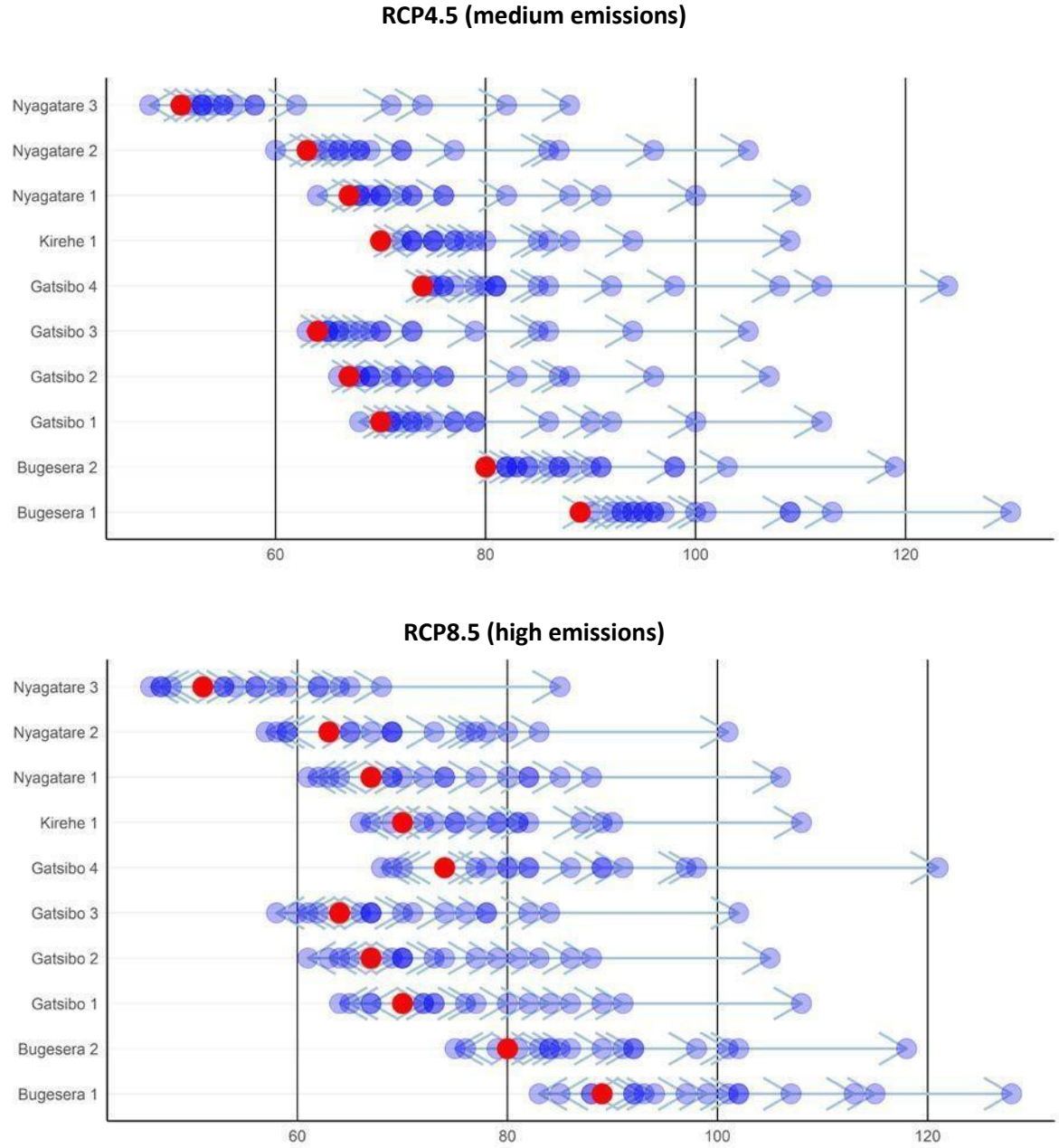


Table 3.6. Summary statistics of projected changes in January precipitation. Colour scheme corresponds to likely increases or decreases in precipitation using the Mastrandea et al. likelihood scale (see methods). Locations are sorted by baseline moisture index.

RCP	Location	Baseline			Future				
RCP4.5	**Nyagatare 3**	51.0	80.0	59.7	48.0	53.0	55.0	58.0	88.0
	Bugesera 2	64.0		89.9					
	Gatsibo 3			73.8	82.0	84.0	87.0	90.3	119.0

				63.0	66.7	69.5	73.0	105.0
	Nyagatare 2	63.0	73.0	60.0	66.0	68.0	72.0	105.0
	Gatsibo 2	67.0	76.9	66.0	70.3	73.0	76.0	107.0
	Kirehe 1	70.0	79.9	70.0	75.0	77.0	79.3	109.0
	Bugesera 1	89.0	99.2	89.0	94.0	95.5	98.0	130.0
	Gatsibo 1	70.0	80.0	68.0	73.0	76.0	79.0	112.0
	Nyagatare 1	67.0	77.1	64.0	70.0	72.5	76.0	110.0
	Gatsibo 4	74.0	86.7	74.0	78.3	81.0	85.3	124.0
RCP8.5	**Nyagatare 3**	51.0	57.8	46.0	53.3	56.0	61.0	85.0
	Bugesera 2	80.0	89.2	75.0	84.0	86.0	91.7	118.0
	Gatsibo 3	64.0	71.9	58.0	67.0	70.0	75.3	102.0
	Nyagatare 2	63.0	70.9	57.0	65.7	69.0	75.0	101.0
	Gatsibo 2	67.0	75.2	61.0	70.0	73.0	78.3	105.0
	Kirehe 1	70.0	79.4	66.0	75.0	79.0	81.0	108.0
	Bugesera 1	89.0	98.8	83.0	92.3	97.0	101.7	128.0
	Gatsibo 1	70.0	78.0	64.0	72.3	76.0	81.3	108.0
	Nyagatare 1	67.0	75.2	61.0	69.3	74.0	79.0	106.0
	Gatsibo 4	74.0	84.2	68.0	78.7	82.0	88.0	121.0
			Mean	**Min**	**33%**	**50%**	**66%**	**Max**

4. Methods

A national level climate analysis was conducted with mid-21st century bioclimatic raster layers obtained from AFRICLIM (Table 5.1; Platts *et al.* 2015) and monthly precipitation data obtained from WorldClim 1.4 (Table 5.2; Hijmans *et al.* 2005). Future data were centred on 2050 (averages for 2041-2060) and corresponded to the most recent General Circulation Model (GCM) climate projections that were used in the Fifth Assessment IPCC report. The resolution of grid layers was 2.5 minutes, a compromise between the highest resolution of 0.5 minutes and data processing time, but also reflecting potential pitfalls in statistical downscaling where densities of weather station data are scarce. RCPs were introduced in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5, including RCP 2.6 W m^{-2}, RCP 4.5 W m^{-2}, RCP 6.0 W m^{-2} and RCP 8.5 W m^{-2}; Table 1.1). WorldClim was selected as a frequently-used open-access and high resolution downscaled climate data set, whereas AFRICLIM was selected as a data set that had also used regional climate models.

Representative Concentration Pathways (RCPs) use more realistic greenhouse gas concentration inputs for running climate models than those provided by previous scenario sets (Moss *et al.* 2010, Jubb *et al.* 2013). The four RCPs (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W m^{-2}, respectively). Radiative forcing is the extra heat that the lower atmosphere will retain because of additional greenhouse gases (Jubb *et al.* 2013). The full range of emissions scenarios is included within the range of the RCPs, including one mitigation scenario leading to a very low forcing level (RCP 2.6), two medium stabilization scenarios (RCP 4.5 and RCP 6.0) and one very high baseline emission scenario (RCP8.5). The RCP 8.5 pathway arises from little effort to reduce emissions and represents a failure to curb warming by 2100. RCP 2.6 sees emissions peak early, then fall due to active removal of atmospheric carbon dioxide; this scenario had no counterpart scenario in the fourth assessment report of the IPCC (Jubb *et al.* 2013).

In a more detailed climate change analysis for the Eastern Province, 10 locations were selected that were furthest apart in environmental space. The selection was achieved with the *BiodiversityR::environmentalThin* function with default settings for the number of random runs (10) and number of principal component analysis axes (representing at least 95% of variation). The function was applied to a point data set representing the centres of all grid cells covering Eastern Province and a bioclimatic data set including all the bioclimatic variables included in AFRICLIM. The subset of bioclimatic variables used for the Dumbbell charts was informed by a Variance Inflation Factor analysis of the full AFRICLIM data set.

Throughout the analyses, the likelihood scale recommended for the fifth Assessment Report of the IPCC (Mastrandea *et al.* 2011) was adopted. Thresholds of 33% (ranges of 0-33% are interpreted as **unlikely**) and 66% (ranges of 66-100% are interpreted as **likely**) were obtained with the *stats::quantile* function for location-specific data sets extracted from (bio)climatic raster layers. For counts of climate models, thresholds were calculated with the *base::floor* and *base::ceiling* functions for the total number of GCMs multiplied by 1/3 and 2/3 respectively.

All analyses shown in this report was done with customized scripts that ran in R version 3.5.1. Maps depicting the study areas were made with Quantum GIS 2.18.23.

Table 5.1. Abbreviations of models available from AFRICLIM.

Driving GCMs	Regional models				
	CCCma-CanRCM4_r2	CLMcom-CCLM4-8-17_v1	DMI-HIRHAM5_v2	KNMI-RACMO22T_v1	SMHI-RCA4_v1
CCCma-CanESM2	cccc				ccsm
CNRM-CERFACS-CNRM-CM5		cncl			cnsm
CSIRO-QCCCE-CSIRO-Mk3-6-0					cssm
ICHEC-EC-EARTH		iccl	icdm	ickn	icsm
IPSL-IPSL-CM5A-MR					ipsm
MIROC-MIROC5					mism
MOHC-HadGEM2-ES		mocl		mokn	mosm
MPI-M-MPI-ESM-LR		mpcl			mpsm
NCC-NorESM1-M					ncsm
NOAA-GFDL-GFDL-ESM2M					nosm

Table 5.2. Mid-21st century GCM datasets obtained from WorldClim 1.4 and analysed in this report, including direct access hyperlinks used for downloading them (June 2018).

GCM	Code	RCP 4.5	RCP 8.5
ACCESS1-0	AC	pr	pr
BCC-CSM1-1	BC	pr	pr
CCSM4	CC	pr	pr
CESM1-CAM5-1-FV2	CE	pr	
CNRM-CM5	CN	pr	pr
GFDL-CM3	GF	pr	pr
GFDL-ESM2G	GD	pr	
GISS-E2-R	GS	pr	pr
HadGEM2-AO	HD	pr	pr
HadGEM2-CC	HG	pr	pr
HadGEM2-ES	HE	pr	pr
INMCM4	IN	pr	pr
IPSL-CM5A-LR	IP	pr	pr
MIROC-ESM-CHEM	MI	pr	pr
MIROC-ESM	MR	pr	pr
MIROC5	MC	pr	pr
MPI-ESM-LR	MP	pr	pr
MRI-CGCM3	MG	pr	pr
NorESM1-M	NO	pr	pr