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Analyzing hydrological and crop responses to climate change scenarios of an ungauged catchment in Kenya

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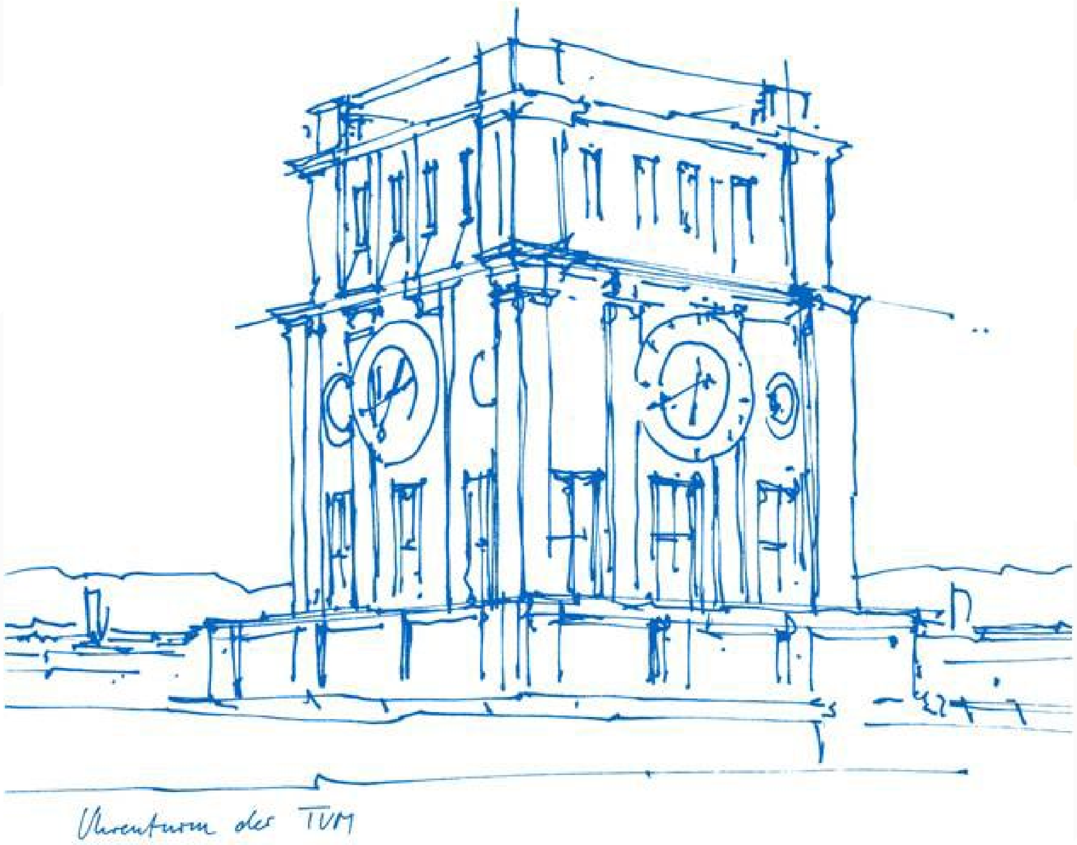

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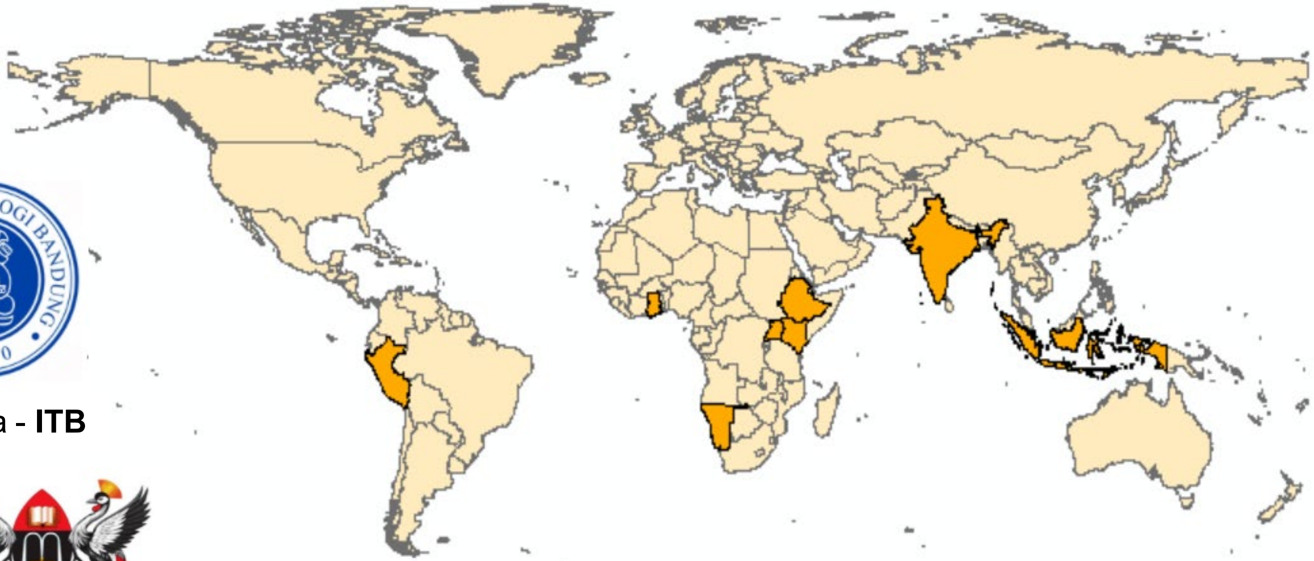

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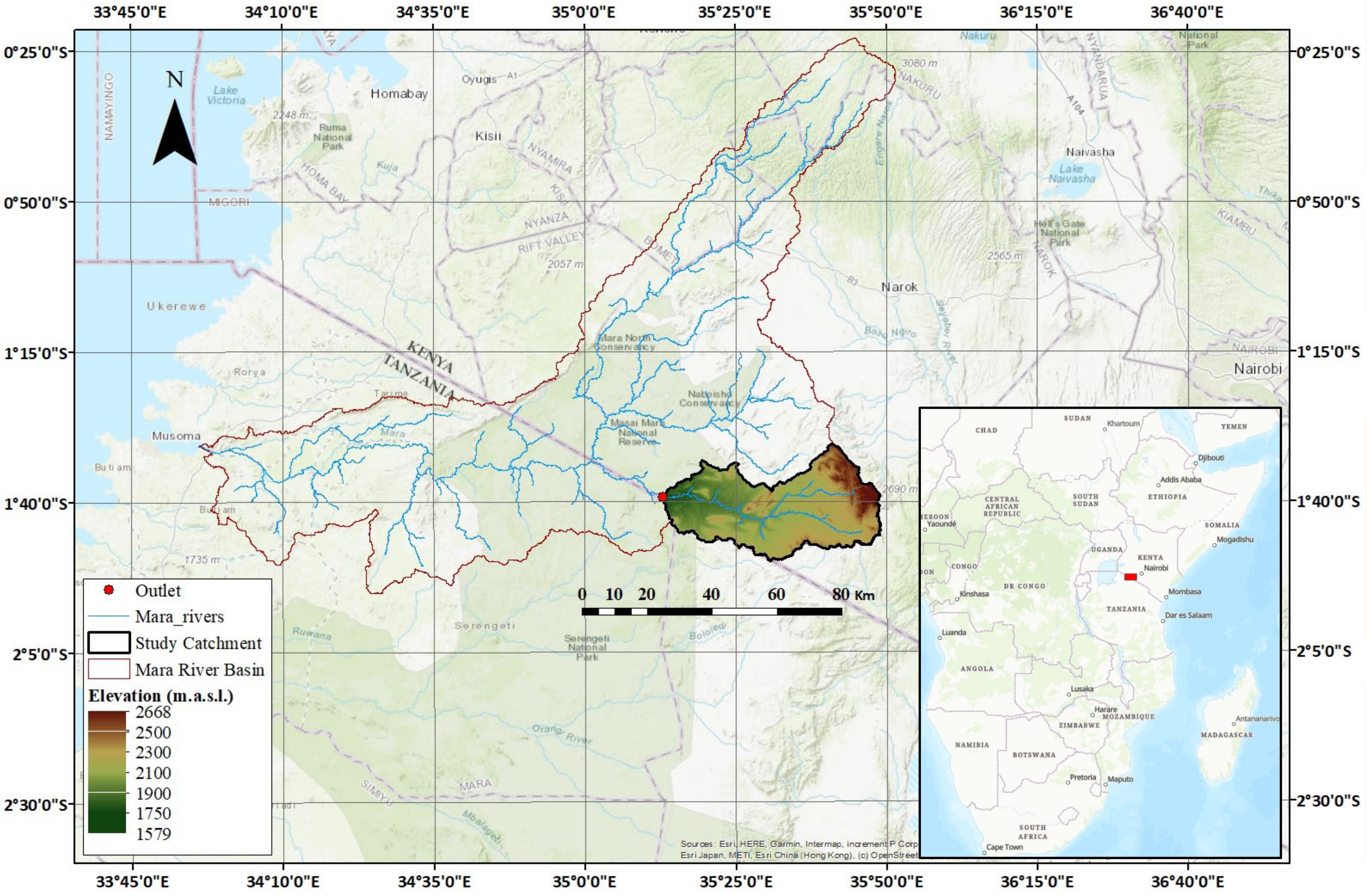
Study area

- Sand River Basin (SRB) ~ 1435 km^2.
- Subbasin of the Mara River Basin (MRB) ~ 13750 km^2
- Semiarid agro ecological zone.
- Mean annual temperature is 18° C with a mean maximum and minimum of 25° C and 12° C, respectively.
- Two rainy seasons:
  - Long rains: March to May (130 mm/month)
  - Short rains: October to January (75 mm/month)
- Land cover: Range-grassland (53%), Forest (32%) and Cropland (15%)
- Ungauged catchment



SWAT+ model set up

Data used

	Data type	Dataset	Source
Model set up	Temperature, precipitation	W5E5	ISIMIP Repository
Model set up	Topography	Digital Elevation Model	USGS Earth Explorer SRTM 1 Arc-Second Global
Model set up	Land use	Landsat 8	USGS Earth Explorer
Model set up	Soil	Soil map	Soil and Terrain Database for Kenya (KENSOTER) version 2.0 and Southern Africa (SOTERSAF). SOTER-based soil parameter estimates by taxo-transfer rules (SOTWIS)
Model set up	Crop management	Planting date Fertilizer application	Food and Agriculture Organization of the United Nations (FAO) Crop Calendar Ministry of Agriculture, Livestock, Fisheries and Cooperatives of Kenya
Model evaluation	Evapotranspiration	GLEAM MOD16A2 SSEBop TerraClimate Wapor	https://www.gleam.eu https://lpdaac.usgs.gov/products/mod16a2v006 https://ssebop.users.earthengine.app/view/ssebop-v101 https://www.climatologylab.org/terraclimate.html https://wapor.apps.fao.org/home/WAPOR_2
Model evaluation	Temperature, precipitation	CHIRPS (precipitation) ERA5 (precipitation) IMERG (precipitation) TAMSAT (precipitation) KMD (precipitation, temperature)	https://www.chc.ucsb.edu/data https://gpm.nasa.gov/ https://research.reading.ac.uk/tamsat/data-access/ https://research.reading.ac.uk/tamsat/data-access/ Kenyan Meteorological Department (KMD)
Model evaluation	Soil moisture	GLDAS Noah V2.1	https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_M_2.1
Climate change analysis	Climate projections	GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL	Global Circulation Models (GCMs) from ISIMIP Repository

Model set up: Decision tables

Name	Conds	Alts	Acts							
pl_hv_Narok	5	5	5							
var	**obj**	**obj_num**	**lim_var**	**lim_op**	**lim_const**	**alt1**	**alt2**	**alt3**	**alt4**	**alt5**
jday	hru	0	null	-	75	=	-	-	-	-
jday	hru	0	null	-	214	-	=	-	-	-
jday	hru	0	null	-	289	-	-	=	-	-
jday	hru	0	null	-	61	-	-	-	=	-
year_rot	hru	0	null	-	1.00	-	-	-	-	=
act_typ	**obj**	**obj_num**	**name**	**option**	**const**	**const2**	**fp**	**outcome**		
plant	hru	0	plant_corn120	corn120	0.00	1.00	null	y n n n n		
harvest_kill	hru	0	grain_harv	corn120	0.00	1.00	grain	n y n n n		
plant	hru	0	plant_ptbn	ptbn	0.00	1.00	null	n n y n n		
haverst_kill	hru	0	grain_harv	ptbn	0.00	1.00	grain	n n n y n		
rot_reset	hru	0	reset_1	null	1.00	1.00	null	n n n n y		

Two cropping seasons:

- 1st Cropping season: Maize from March to August
- 2nd Cropping season: Beans from October to January

Fertilizer application:

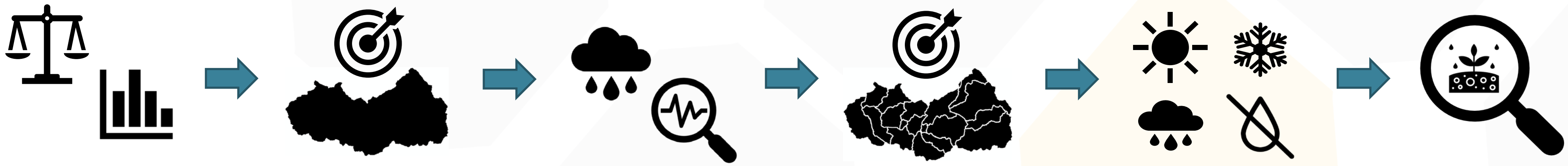
- At planting
- Diamonium phosphate (DAP)

Name	Conds	Alts	Acts					
fert_DAP	2	2	2					
var	**obj**	**obj_num**	**lim_var**	**lim_op**	**lim_const**	**alt1**	**alt2**	
jday	hru	0	null	-	75	=	-	
jday	hru	0	null	-	289	-	=	
act_typ	**obj**	**obj_num**	**name**	**option**	**const**	**const2**	**fp**	**outcome**
fertilize	hru	0	18_46_00_fert	18_46_00	130.00	1.00	broadcast	y n
fertilize	hru	0	18_46_00_fert	18_46_00	20.00	1.00	broadcast	n y

Methodology

Model evaluation: Applied strategies for developing a robust hydrological model for climate change analysis (Krysanova et al., 2020; Schaffhauser et al., 2023):

Sensitivity Analysis → Calibration → AETs Evaluation → Multi-site Calibration/Validation → Robustness Check → Cross-validation



Climate Change impact assessment:

- Climate change scenarios: SSP126 (low) – SSP370 (medium) – SSP585 (high)
- Future periods: Near future (2025-2054) and Far future (2070-2099)

Meteorological responses: Temperature, Precipitation

Hydrological responses: Surface runoff, Evapotranspiration

Crop responses: Temperature and water stress, Yield

Results

Results: Model evaluation

- Statistical metrics results for simulating evapotranspiration products. In bold: basin-scale calibration results using the reference data (W5E5).

NSE (Min. – Max.)

	GLEAM	MOD16A2	SSEBop	TerraClimate	WaPOR
W5E5	**0.77**	**-0.30**	**-0.40**	**0.66**	**-1.29**
CHIRPS	0.54	0.05	-1.50	0.33	-2.69
ERA5	0.57	0.26	-2.29	0.33	-3.11
IMERG	0.55	-0.14	-1.26	0.28	-2.31
TAMSAT	-0.46	-0.54	-1.52	0.24	-1.97
KMD	0.68	0.22	-1.54	0.39	-1.74

R^2 (Min. – Max.)

	GLEAM	MOD16A2	SSEBop	TerraClimate	WaPOR
W5E5	**0.77**	**0.22**	**0.49**	**0.66**	**0.18**
CHIRPS	0.60	0.29	0.48	0.34	0.19
ERA5	0.57	0.36	0.44	0.37	0.32
IMERG	0.68	0.31	0.49	0.28	0.31
TAMSAT	0.16	0.21	0.11	0.27	0.08
KMD	0.72	0.46	0.54	0.42	0.33

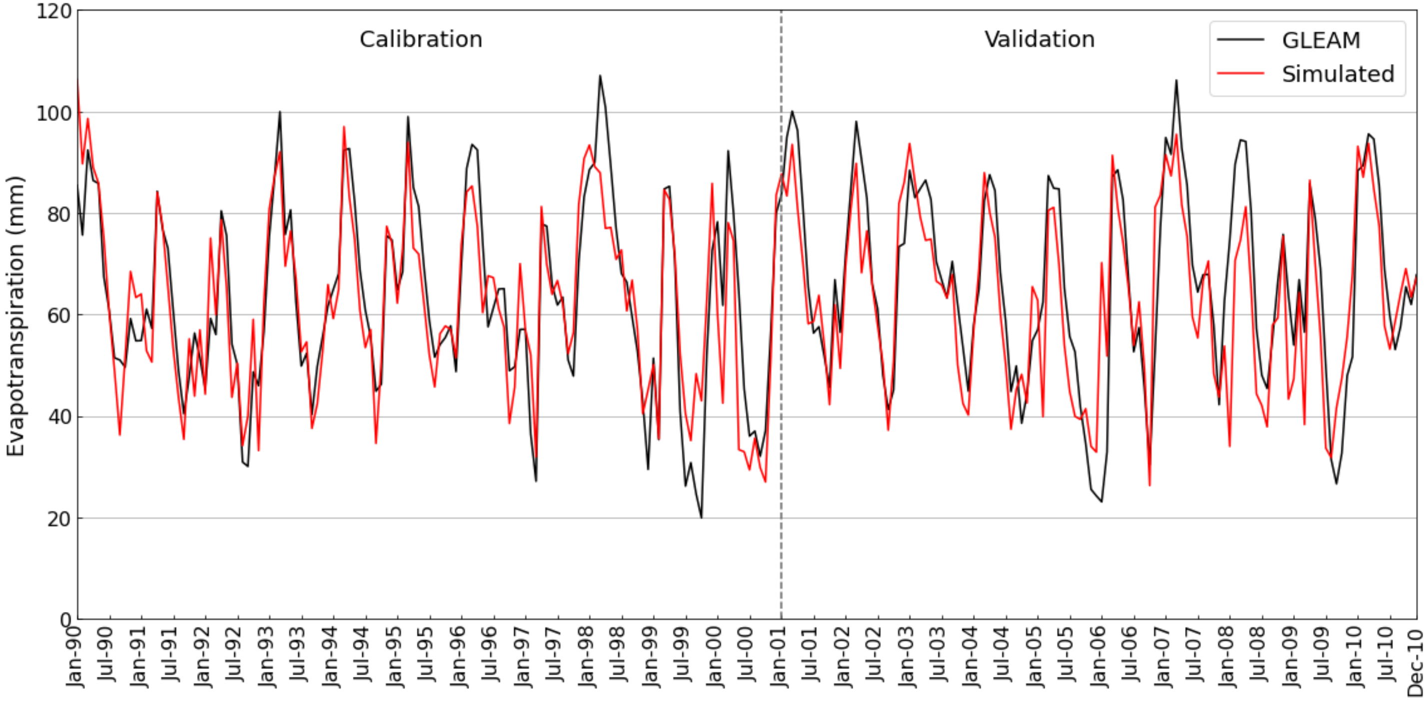
Pbias (Min. Negative % – Max. Positive %)

	GLEAM	MOD16A2	SSEBop	TerraClimate	WaPOR
W5E5	**-1.60**	**-15.67**	**54.90**	**1.73**	**24.69**
CHIRPS	-6.93	-15.69	84.86	-0.94	43.27
ERA5	0.49	-8.96	99.61	6.96	48.79
IMERG	-10.03	-18.49	78.71	-4.24	40.34
TAMSAT	-15.63	-23.56	67.58	-10.20	13.34
KMD	-5.81	-14.66	87.10	0.26	35.72

NSE > 0.50, R^2 > 0.60, Pbias ≤ ±25 %
(Moriasi et al., 2007; Thieming et al., 2013; and Kouchi et al., 2017)

Results: Model evaluation

- Comparison between GLEAM and simulated monthly evapotranspiration for the calibration (1990-2000) and validation (2001-2010) periods and robustness check results



	NSE	KGE	R^2	Pbias
Calibration	0.78	0.87	0.77	-1.19
Validation	0.68	0.81	0.71	-4.64
Robustness check				
Warm	0.75	0.78	0.75	-1.14
Cold	0.68	0.85	0.73	-4.53
Wet	0.73	0.83	0.73	-0.23
Dry	0.7	0.82	0.73	-5.54

NSE > 0.50, KGE > 0.50, R^2 > 0.60, Pbias ≤ ±25 %
(Moriasi et al., 2007; Thieming et al., 2013; and Kouchi et al., 2017)

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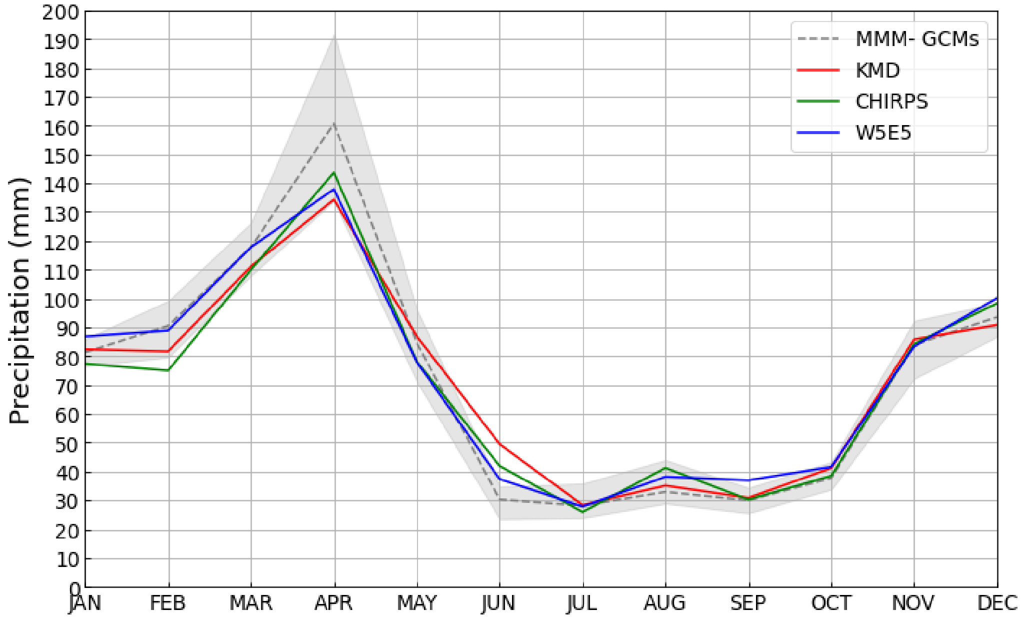
Results: Outliers check

❑ Pbias results of mean annual precipitation and evapotranspiration for the period 1991-2014.

Variable	Reference	Pbias (%)				
		GFDL-ESM4	IPSL-CM6A-LR	MPI-ESM1-2-HR	MRI-ESM2-0	UKESM1-0-LL
Precipitation	KMD	+4.17	+4.61	+5.23	+0.49	+17.5
	CHIRPS	+2.2	+2.64	+3.26	-1.4	+15.3
	W5E5	-2.48	-2.07	-1.49	-5.94	+9.97
Evapotranspiration	GLEAM	-1.80	-4.55	-2.42	-4.16	+7.13

Pbias ≤ ±25 %
(Krysanova et al., 2018)

❑ Comparison of mean monthly precipitation



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Climate Change Analysis

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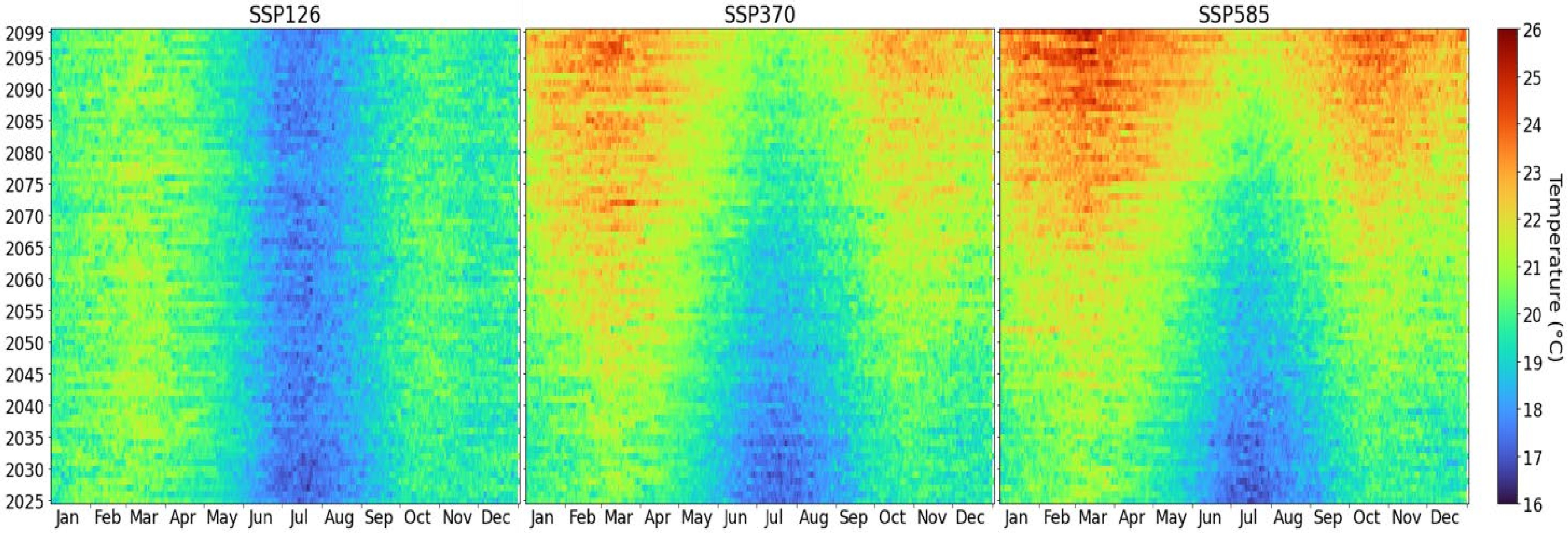
Results: Temperature

❑ Daily average temperature projections according three climate change scenarios



- SSP370 and SSP585:
  - → Temperature increases by 4° C
  - → Jan-May and Sep-Dec temperature ranges 23° C to 26° C from 2070

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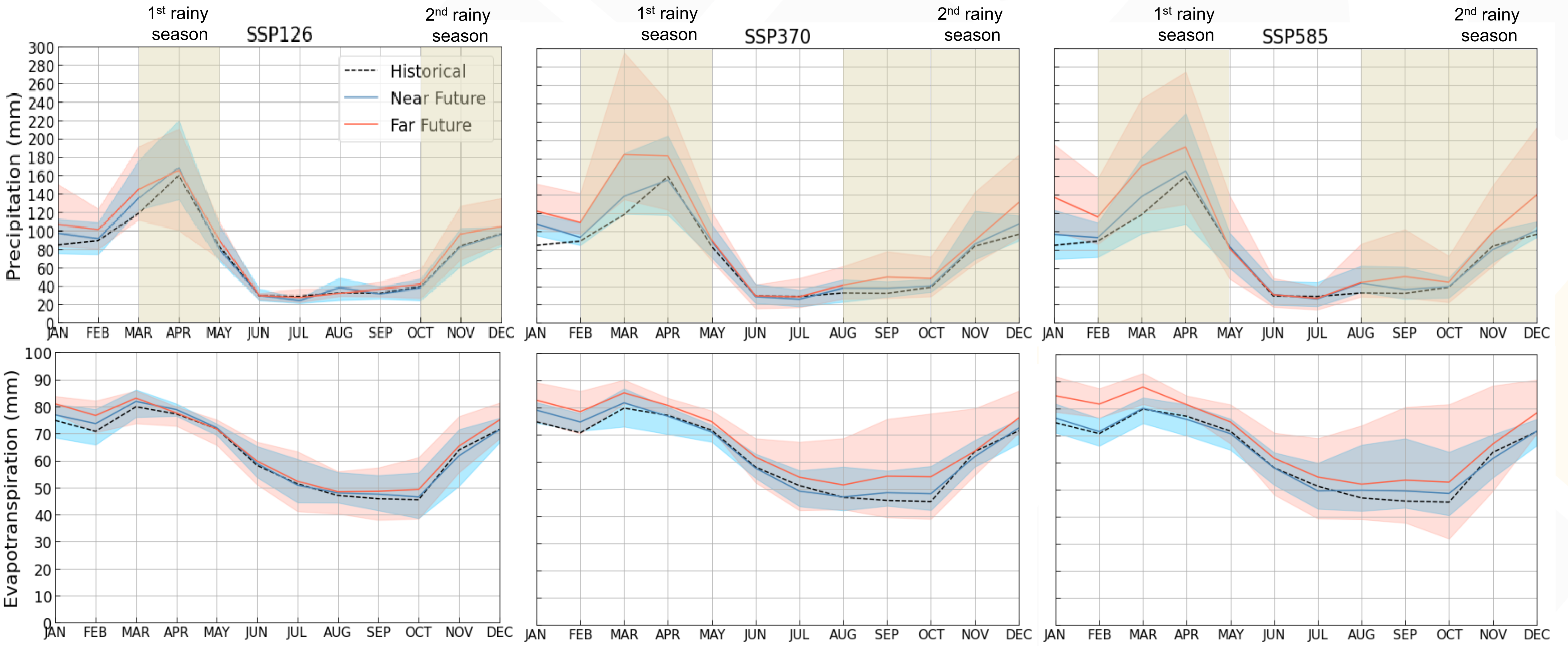
Results: Hydrological responses



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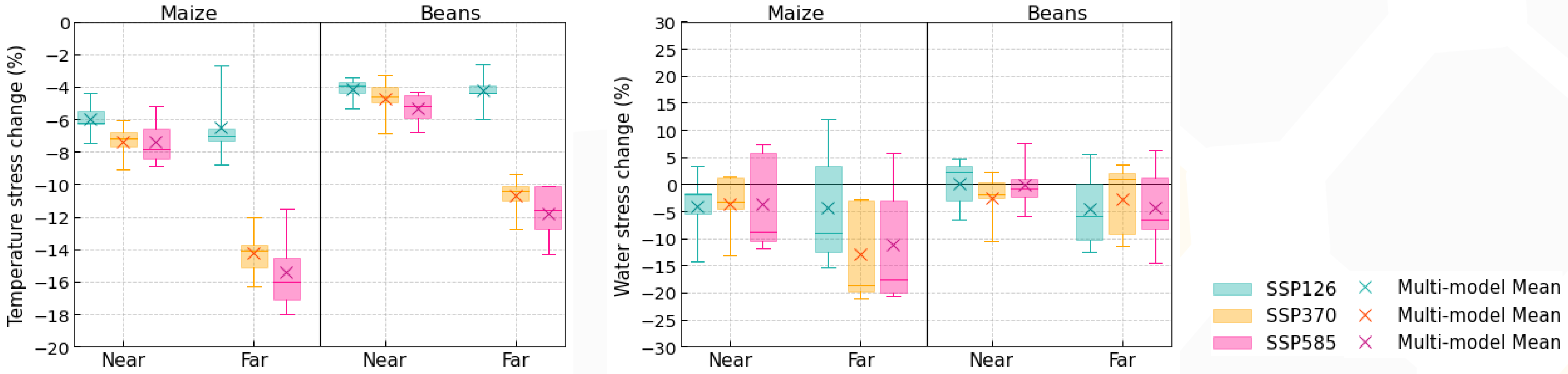
Results: Crop responses

❑ Projected changes of temperature stress, water stress and days to maturity (DTM) for each future period



- Temperature stress:
  - → Overall decrease, more pronounce in far future under SSP370 and SSP585
  - → Optimal T° for maize and beans ~ 25° C

- Water stress:
  - → Less water stress in maize compared to beans under SSP370 and SSP585
  - → High variability in far future period

Results: Crop responses

- Crop yield projections. Absolute values are presented in kg/ha, relative changes respect to the historical baseline (1985-2014) are shown as percentage (in brackets).

	Near future (2025 - 2054)		**Far future (2070 - 2099)**	
	1st cropping season Maize	2nd cropping season Beans	1st cropping season Maize	2nd cropping season Beans
SPP126				
Crop yield	1661.7 (+0.6)	530.2 (+2.9)	1683 (+1.9)	566.5 (+9.9)
SPP370				
Crop yield	1660 (+0.5)	550.7 (+6.9)	1764.6 (+6.9)	575.3 (+11.6)
SPP585				
Crop yield	1651 (0)	540.4 (+4.9)	1717.6 (+4)	604.2 (+17.3)

Conclusions

- Higher increases in temperature are expected in the far future period under the medium and high emission scenarios.
- Despite the high variability in projected rainfall, there is an overall increasing trend more pronounce in the far future period. Rainy seasons are expected to onset earlier.
- Decreases in temperature and water stress would lead to higher crop yield. However, analysis on crop responses at specific phenological stages and CO_2 concentrations are recommended.
- Further analysis of possible flood/drought events in the region are recommended.

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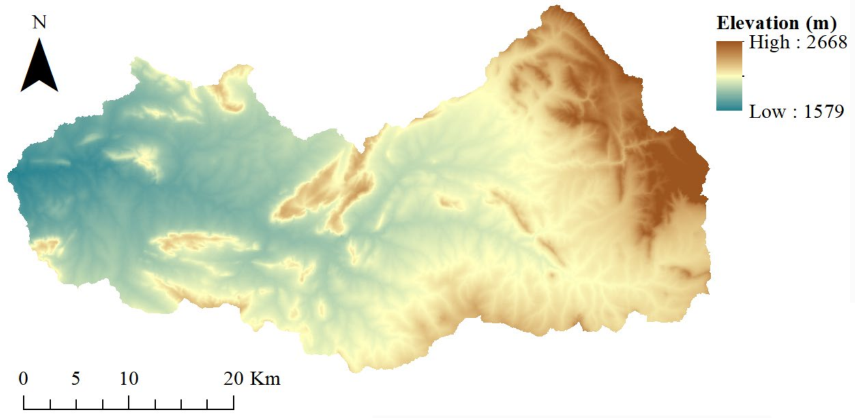
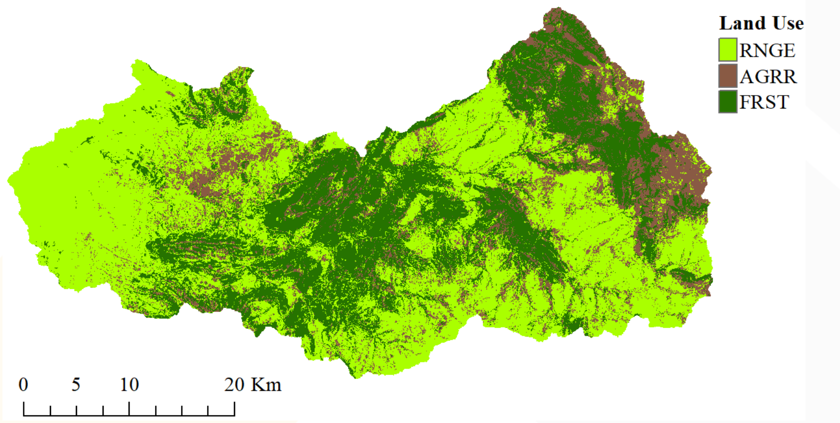
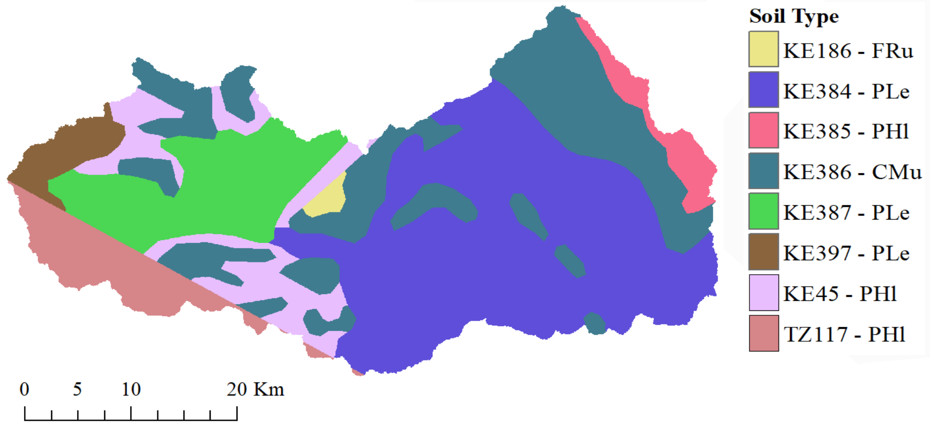
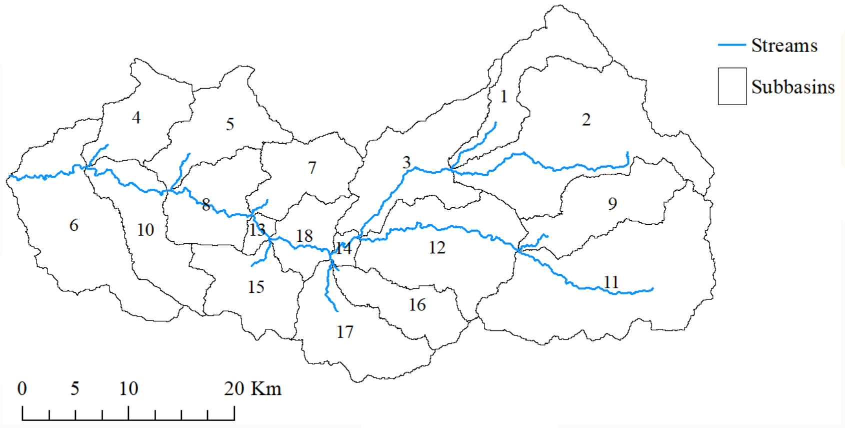
Model set up

- Land use cover:
  - → Range-grassland (53%)
  - → Forest (32%)
  - → Cropland (15%)
- 12 Subbasins, 688 HRUs
- 8 soil types









2. Model evaluation: AET products

AET RS product	Spatial resolution	Temporal resolution	Calibration period	Validation period
GLEAM	25 km	Monthly	1990-2000	2001-2010
MOD16A2	1 km	Monthly	2004-2011	2012-2019
SSEBop	1 km	Monthly	2004-2011	2012-2019
Terra Climate	4 km	Monthly	1990-2000	2001-2010
WaPOR	250 m	Monthly	2009-2014	2015-2019

Precipitation RS product	Description	Spatial Resolution	Temporal Resolution	Provider
CHIRPS	Combines satellite-derived infrared data and station observations	5 km	Daily	Climate Hazards Group at the University of California
IMERG	Combines data from various satellite sources, including passive microwave sensors and infrared imagers, to estimate global precipitation at high spatial and temporal resolutions.	20 km	Daily	NASA's Global Precipitation Measurement (GPM) mission
ERA5	Global atmospheric reanalysis dataset	25 km	Daily	European Centre for Medium-Range Weather Forecasts (ECMWF)
TAMSTAT	Tropical Applications of Meteorology using Satellite data and ground-based observations. Combines data from various sources, including geostationary and polar-orbiting satellites, weather stations, and climate models	4 km	Daily	University of Reading, Climate Division of the National Centre for Atmospheric Science (NCAS) and the National Centre for Earth Observation (NCEO)
KMD	Estimates data from TAMSAT (Tropical Applications of Meteorology using Satellite data and ground-based observations) and CHIRPS (Climate Hazard Group InfraRed Precipitation).	10 km	Daily	The Enhancing National Climate Services (ENACTS) initiative from Columbia Climate School and Kenyan Meteorological Department

AET	ET Scheme
SSEBop	P-M equation. Surface energy balance. Combines ET fractions generated from remotely sensed MODIS thermal imagery, with reference ET using a thermal index approach.
MODIS16A	P-M equation Replacing NDVI with EVI and adding a calculation of soil evaporation to the previously proposed RS-PM method. Soil moisture scalar.
WaPOR	P-M equation
GLEAM	Priestly Taylor ETA = ETo x Stress Module based on Vegetation Optical Depth + Intercepted ET
TerraClimate	P-M formula. Soi water balance approach

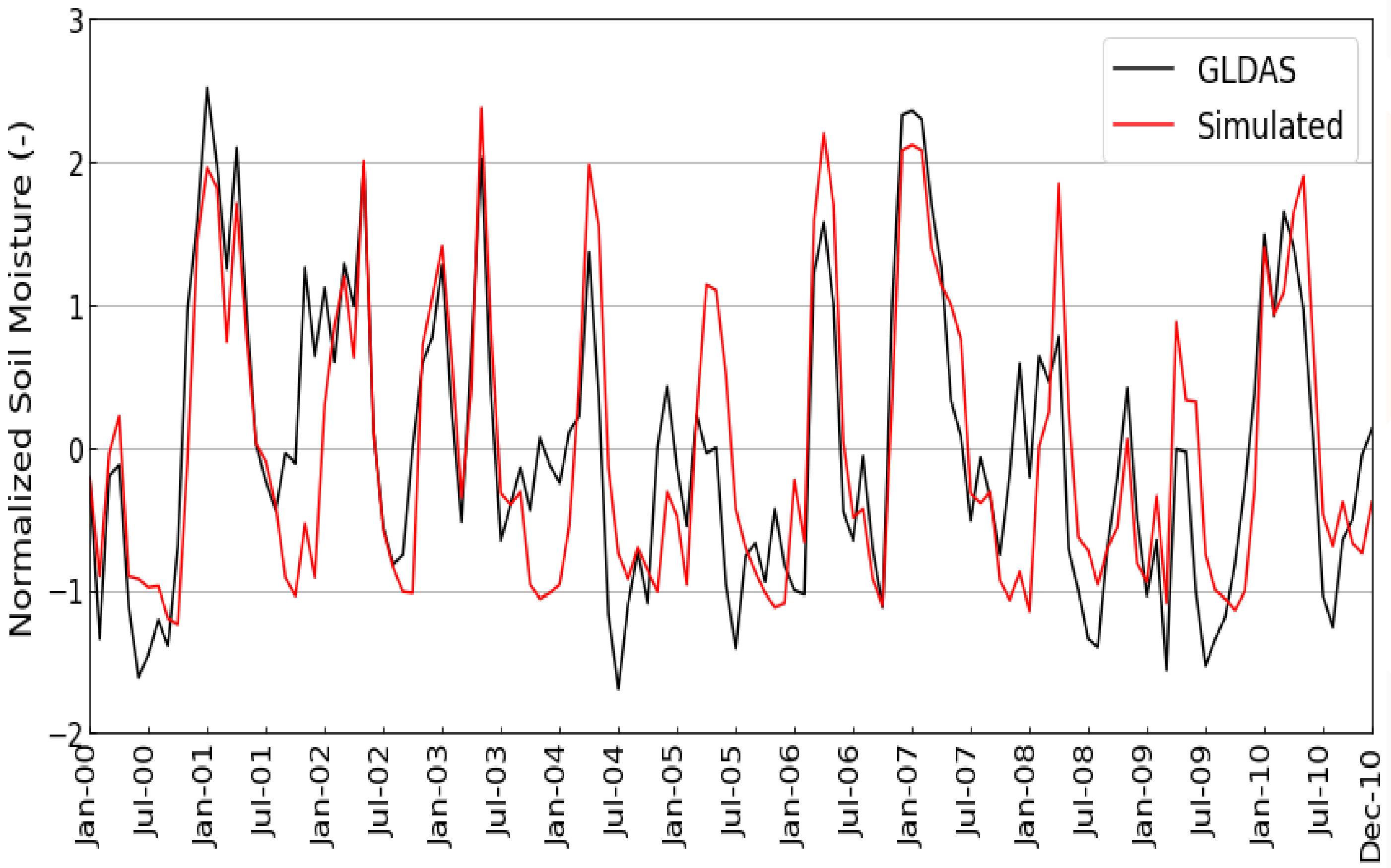
Results: Sensitivity analysis

- Ranking of most sensitive parameters for evapotranspiration

Parameter	Description	GLEAM	MOD16A2	SSEBop	TerraClimate	WaPOR
v_awc	Soil available water storage capacity	7	2	7	4	7
v_bd	Bulk density	1	4	2	5	4
v_canmx	Maximum canopy storage	2	1	1	1	1
p_cn2	SCS runoff curve number for soil moisture condition II	5	9	4	3	5
v_cn3_swf	Soil water factor for curve number condition III	4	7	5	9	9
v_epco	Plant uptake compensation factor	6	5	9	7	3
v_esco	Soil evaporation compensation coefficient	3	6	3	2	2
r_k	Soil hydraulic conductivity	9	8	6	8	6
v_perco	Soil percolation coefficient	8	3	8	6	8

"p_" means a percentage change (initial or existing parameter value is multiplied by % given value within the range).
"r_" means a relative change (initial or existing parameter value is multiplied by 1+ given value within the range).
"v_" means a replacement (initial or existing parameter value is to be replaced by a given value).

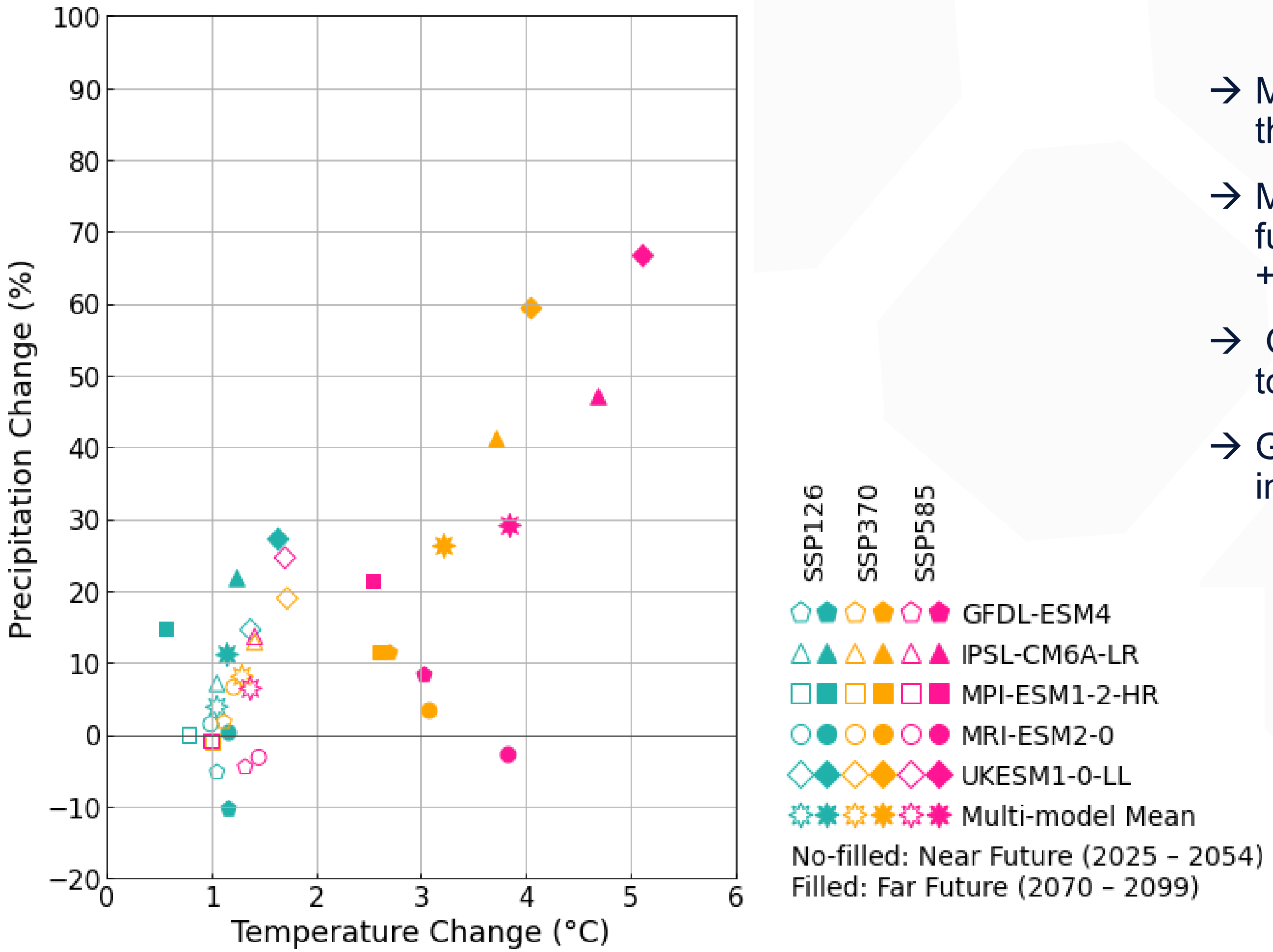
Results: Cross-validation



NSE = 0.64
Pearson = 0.82
NRMSE = 0.14

Results – Climate Assessment

- Mean annual meteorological changes of five GCMs compared to their historical baseline (1985-2014).



→ Most of the GCMs showing a decline in precipitation correspond to the near future period (2025-2054).

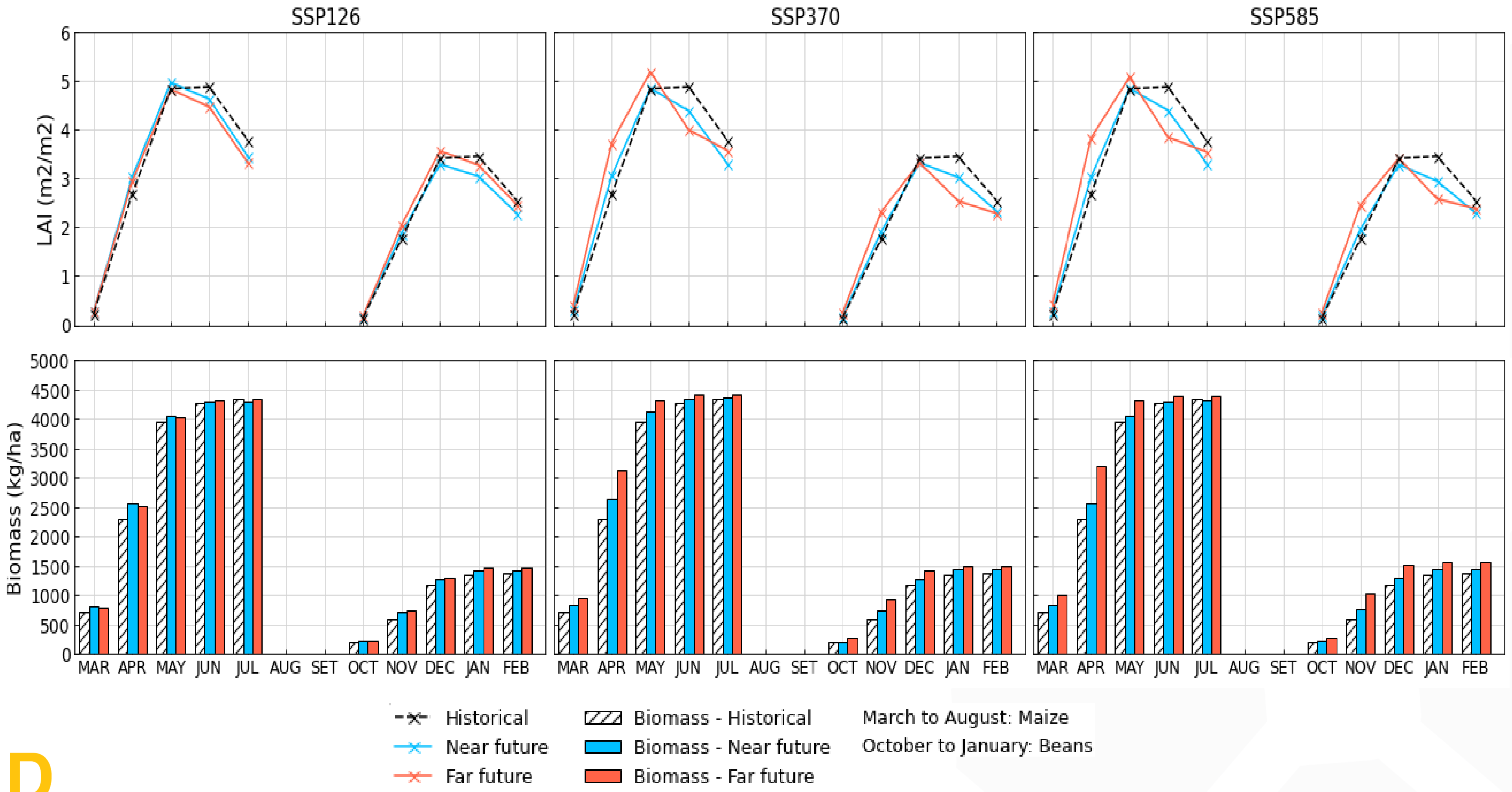
→ MMMs show increases in precipitation more pronounce in the far future period: SSP126, SSP370 and SSP585 increase by +11.3%, +26.3% and +29.2%, respectively.

→ GCMs in the SSP126 temperature change ranges between +0.6° C to +1.6° C.

→ GCMs in SSP370 and SSP585 scenarios show temperature increases above 2.5° C.

Results: Crop responses

- Mean monthly responses of leaf area index (LAI) and biomass to climate changes scenarios compared to the historical baseline



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Muchas gracias!

Asante Sana