User-Oriented Metrics and Evaluations

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AGCI ESM Evaluation Workshop

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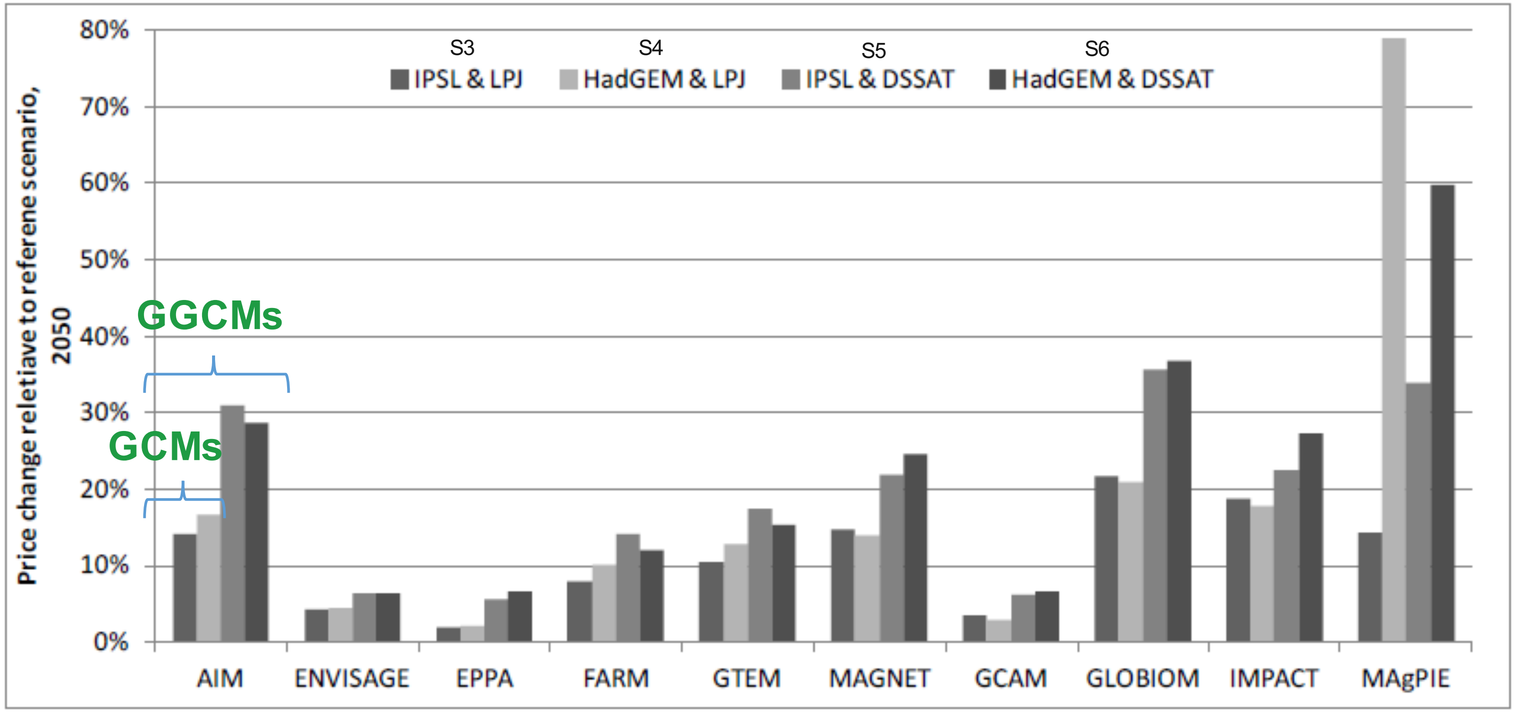
Global Economics Model Results

Effects of climate change on agricultural prices

(2050 RCP8.5 relative to results without climate change in 2050)



Source: Model results as of February 15, 2013

Note: All changes relative to the reference scenario for the same year.

AgMIP Global Economics Model Intercomparison

10 Global Economics Models, 2 GCMs, 2 crop models

Von Lampe et al., *Agricultural Economics, 2013*

Baseline from SSP2

Uncertainty for Global Prices: Economics Models > Crop models > Climate models

ESM evaluation provides physical confidence in model outputs that are at the heart of applications

Societal impact applications are most concerned with:

- Direct evaluation of a relatively small subset of near-surface 2D fields that are of primary interest
- Understanding of these variables' changing distributions
- Indicators of performance and proxies for primary variables of interest
- Stakeholders' own backyards

Outline

The VIACS Community of ESM output users

How ESM output is often applied

Priority Evaluation Requests

Key Challenges for ESM-VIACS Connections

Ideas to Better Serve VIACS Applications and Downstream Stakeholders

The Vulnerability, Impacts, Adaptation, and Climate Services (VIACS) Advisory Board for CMIP6

Building bridges between the Modeling and Applications communities




Co-Chairs: Alex Ruane[1,2] and Claas Teichmann[3]

[1]NASA Goddard Institute for Space Studies, New York City
[2]Columbia University Center for Climate Systems Research
[3]Climate Service Center, HZG, Hamburg

Vulnerability, Impacts, Adaptation

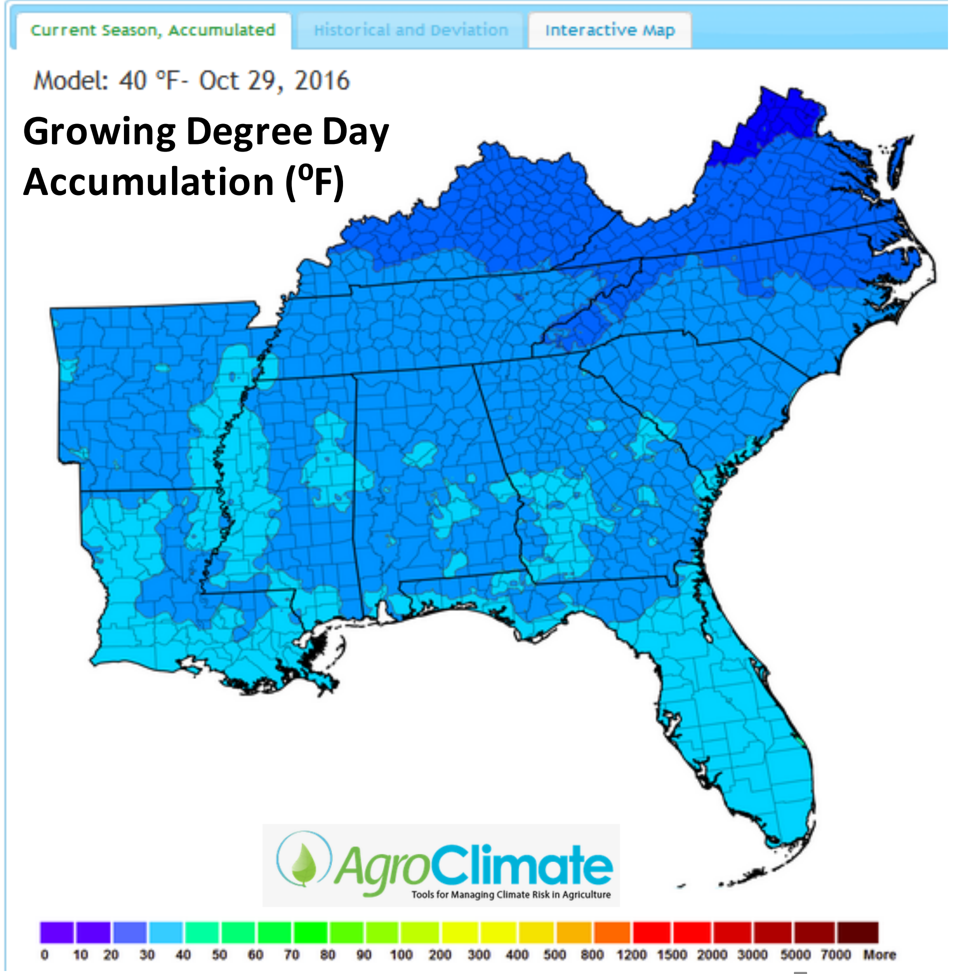
Charged with understanding how climate changes affect natural and human systems (largely basic research)

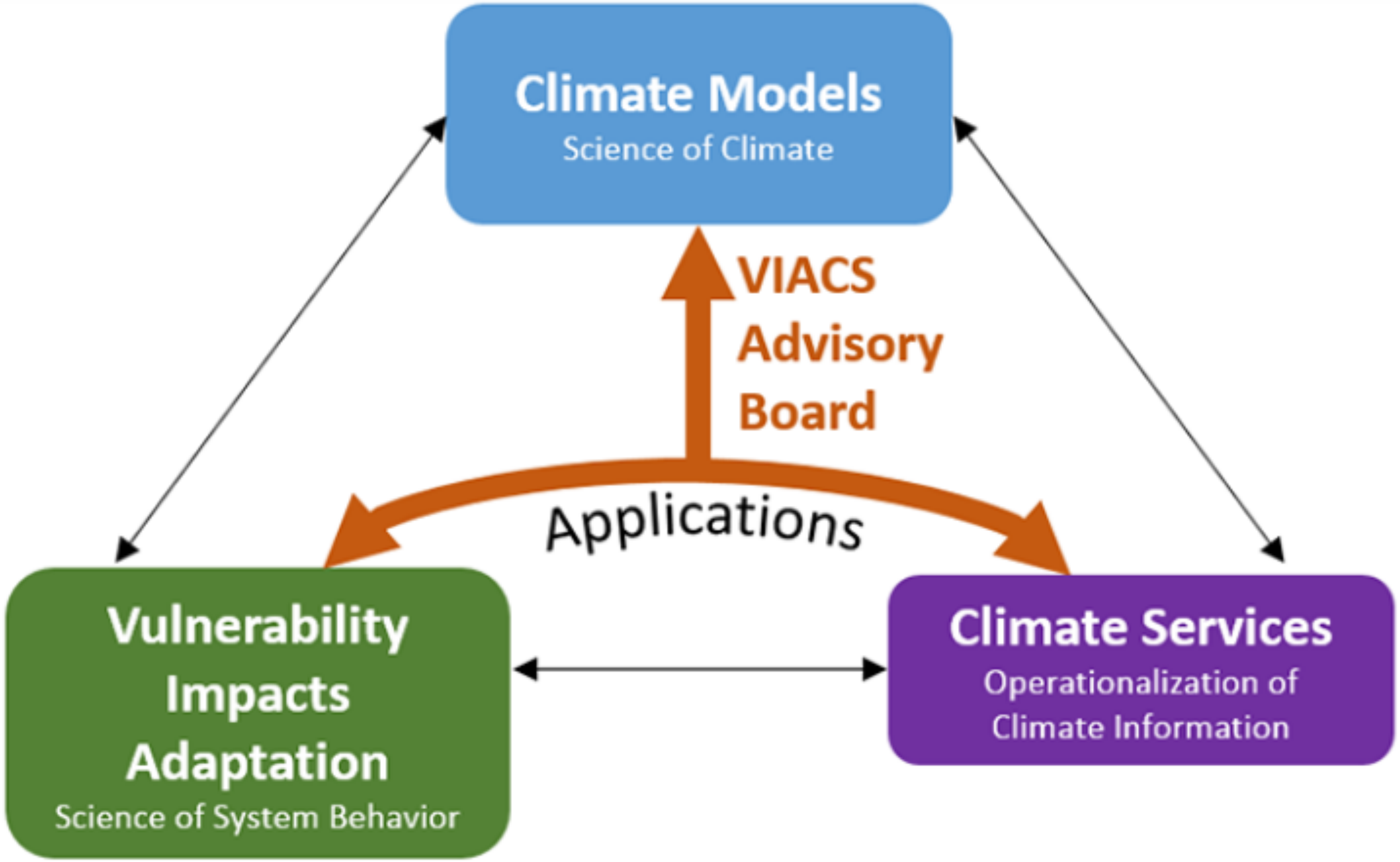
- **VIA Sectors:**
  - Agriculture
  - Forestry
  - Energy
  - Water Resources and Hydrology
  - Oceans/Fisheries
  - Coastal
  - Biomes/Ecology
  - Urban
  - Health
  - Infrastructure/Transportation
- **Projects and Programs:**
  - TGICA, CORDEX, ICONICS
  - WCRP Working Group on Regional Climate
  - ISI-MIP, AgMIP, WaterMIP
  - Others…

Climate Services

Operationalizes climate and VIA information as user-oriented products and tools.

- **Climate Service Organizations:**
  - Public Agencies
  - Private Organizations
  - Academic Institutions
- **Projects and Programs:**
  - Climate Services Partnership
  - Global Framework for Climate Services
  - Others…




Climate Models
Science of Climate
VIACS
Advisory
Board
Applications
Vulnerability
Impacts
Adaptation
Science of System Behavior
Climate Services
Operationalization of
Climate Information

VIACS Advisory Board Members

Name	Community	Institution
Alex Ruane (co-chair)	*Agriculture/AgMIP*	NASA Goddard Institute for Space Studies, USA
Claas Teichmann (co-chair)	*Climate Services*	Climate Service Center, Hamburg, Germany
Nigell Arnell	*WaterMIP*	University of Reading, UK
Tim Carter	*TGICA*	Finnish Environment Institute (SYKE), Finland
Kristie Ebi	*ICONICS/Health*	University of Washington, USA
Katja Frieler	*ISI-MIP*	Potsdam Institute for Climate Impacts Research, Germany
Clare Goodess	*WGRC*	University of East Anglia, UK
Bruce Hewitson	*CORDEX*	University of Cape Town, South Africa
Radley Horton	*Urban/Coastal*	Columbia University, USA
Sari Kovats	*Health*	London School of Hygiene and Tropical Medicine, UK
Heike Lotze	*Oceans/Fisheries*	Dalhousie University, Canada
Linda Mearns	*ICONICS*	National Center for Atmospheric Research, USA
Antonio Navarra	*Climate Services*	Istituto Nazionale di Geofisica e Vulcanologia, Italy
Dennis Ojima	*Land Ecosystems*	Colorado State University, USA
Keywan Riahi	*Energy/IAMs*	International Institute for Applied Systems Analysis, Austria
Cynthia Rosenzweig	*PROVIA/AgMIP*	NASA Goddard Institute for Space Studies, USA
Matthias Themessl	*Climate Services*	Climate Change Centre Austria, Austria
Katharine Vincent	*Climate Services*	Kulima Integrated Development Solutions, South Africa

Endorsed by CMIP6 and PROVIA

PROVIA

About the VIACS Advisory Board

Geosci. Model Dev., 9, 3493–3515, 2016
www.geosci-model-dev.net/9/3493/2016/
doi:10.5194/gmd-9-3493-2016

Geoscientific Model Development
Open Access
EGU

The Vulnerability, Impacts, Adaptation and Climate Services Advisory Board (VIACS AB v1.0) contribution to CMIP6

Alex C. Ruane[1], Claas Teichmann[2], Nigel W. Arnell[3], Timothy R. Carter[4], Kristie L. Ebi[5], Katja Frieler[6], Clare M. Goodess[7], Bruce Hewitson[8], Radley Horton[9], R. Sari Kovats[10], Heike K. Lotze[11], Linda O. Mearns[12], Antonio Navarra[13], Dennis S. Ojima[14], Keywan Riahi[15], Cynthia Rosenzweig[1], Matthias Themessl[16], and Katharine Vincent[17]

- **Motivation, initial activities, and plans for VIACS Advisory Board**

VIACS Advisory Board Engagement with CMIP6 Variable Design

900+ CMIP5 Variables assessed for VIACS applications

- Necessary variables for most applications already exist
- Determined priorities – strong desire for more validation and quality assessment studies
- Identified complete sets needed to allow particular applications (e.g., ocean ecosystems requires many unique variable sets)
- Variables queued up for download from the CMIP6 Data Request according to community (e.g., several AgMIP packages)

				Variable Set Requests/Categorization			
							FISH-MIP
				AgMIP	CSP	Arctic	FISH-MIP
Variable Category	Time Resolution	Long Name	Units				
2(e) Monthly land biogeochemistry, soil and land cover data							
CMOR Table Lmon: Monthly Mean Land Fields, Including							
Physical, Vegetation, Soil, and Biogeochemical Variables							
@Lmon	monthly mean	Moisture in Upper Portion of Soil Column	kg m-2	2	2	0	0
	monthly mean	Total Soil Moisture Content	kg m-2	1	1	0	0
	monthly mean	Soil Frozen Water Content	kg m-2	2	2	0	0
	monthly mean	Surface Runoff	kg m-2 s-1	2	2	0	0
	monthly mean	Total Runoff	kg m-2 s-1	2	2	0	2
	monthly mean	Precipitation onto Canopy	kg m-2 s-1	3	3	0	0
	monthly mean	Evaporation from Canopy	kg m-2 s-1	3	3	0	0
	monthly mean	Water Evaporation from Soil	kg m-2 s-1	3	3	0	0
	monthly mean	Transpiration	kg m-2 s-1	3	3	0	0
	monthly mean	Water Content of Soil Layer	kg m-2	1	1	0	0
	monthly mean	Temperature of Soil	K	3	3	1	0
	monthly mean	Tree Cover Fraction	%	4	4	0	0
	monthly mean	Natural Grass Fraction	%	4	4	0	0

VIACS Advisory Board Engagement with CMIP6 Variable Design

60+ new variables requested (and more continuously coming in)

- Requirement of different time periods or heights
- Need for low-frequency reports of high-frequency statistics, e.g.:
  - monthly output file showing number of hours where precipitation exceeded a given heavy rain threshold
  - separation of variables by wet and dry days
- Interest in tile information, if simulated (e.g., agricultural tile of broader grid box)

Photo: constructionweekonline.com

Time resolution	Name (plus description as needed)	Units	Additional notes
New variables requested by the agricultural sector (for Historical, DECK, and ScenarioMIP experiments, as well as requests for experiments within AerChemMIP, C4MIP, DAMIP, DCPP, GeoMIP, LUMIP, and VolMIP).			
Monthly	Surface concentration of ozone	ppm	Also for use ecosystem and health sectors
Daily, monthly	Cropland tile maximum temperatures	K	Tile contains information from agricultural fraction of land in a given GCM grid box.
Daily, monthly	Cropland tile minimum temperatures	K	
Daily, monthly	Cropland tile precipitation	$kg\,m^{-2}\,s^{-1}$	
Daily, monthly	Cropland tile minimum relative humidity	%	
Daily, monthly	Cropland tile wind speed	$m\,s^{-1}$	
Monthly	Number of precipitation days where accumulation was above $1\,kg\,m^{-2}$	No.	These two variables combine to describe the intensity of rainfall when it does occur.
Monthly	Average precipitation accumulation on days where accumulation was above $1\,kg\,m^{-2}$	$kg\,m^{-2}$	

VIACS Advisory Board Engagement with CMIP6 MIP Application

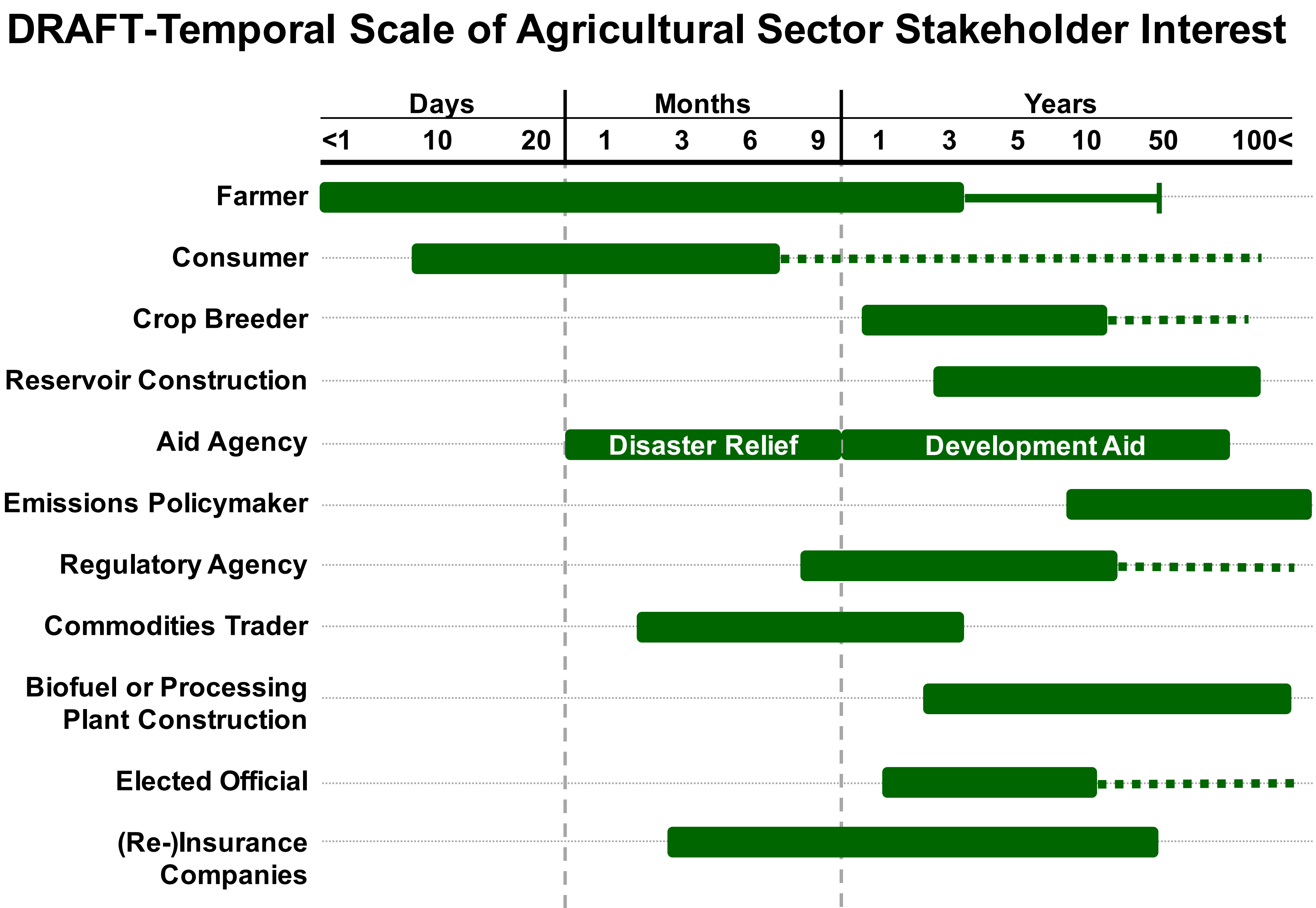
188 MIP Experiments assessed for VIACS applications

- Determined priorities for various application packages
- Identified specific experiments within MIPs that VIACS community is interesting in exploring for broader implications

- Historical and ScenarioMIP experiments most widely sought, followed by Decadal Climate Prediction Project (DCPP) and HighResMIP
- Nearly all MIPs had at least one experiment that generated VIACS interest

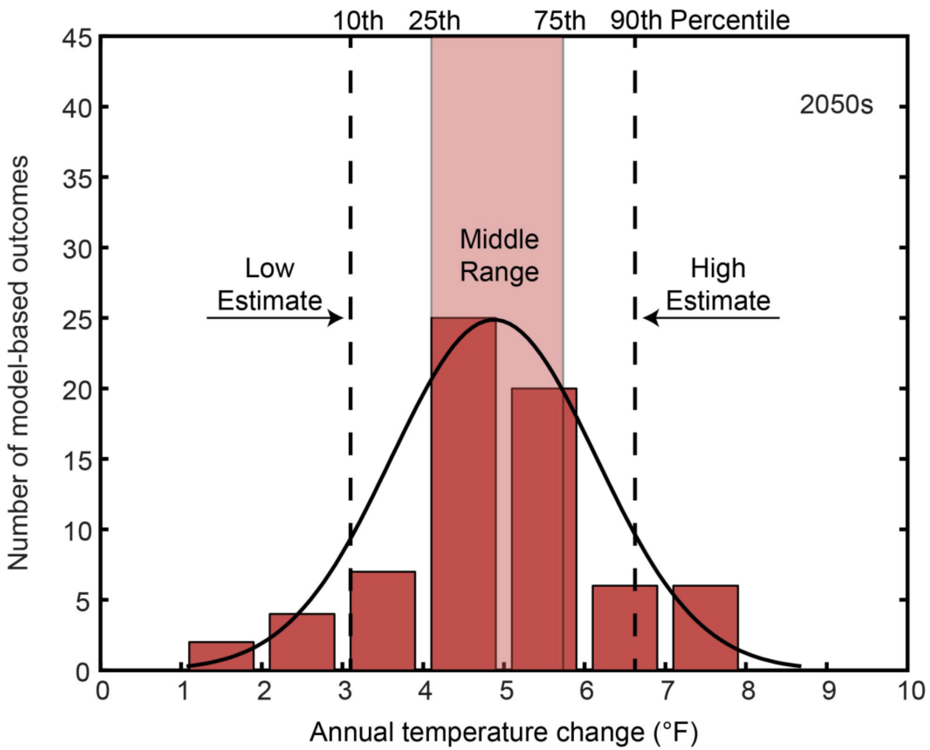
CMIP6 MIP Experiments that you plan on exploring (see full names of MIPs in next tab):					AgMIP
Experiment group	Experiment short name	Experiment Description / Design			
@EXPT			188		
Diagnostics, Evaluation, and Characterization of Klima (DECK)-1	AMIP	observed SSTs and sea ice prescribed	24	0	1,2,3
DECK-2	control	coupled atmosphere/ocean pre-industrial control run	26		1,2,3
DECK-3	1pctCO2	impose 1%/yr increase in CO2 to quadrupling*	25		1
DECK-4	abrupt4xCO2	Abruptly quadruple CO2, then hold fixed**	24		1
DECK-5	historical	emission- or concentration-driven simulation of the recent past (~165 years)	26		1,2,3,4,5
AerChemMIP-1	RFDOC-01	Perturbation from 1850 control using PD aerosol and ozone precursor emissions (all aerosols interact with radiation)	23		1, 5
AerChemMIP-1	RFDOC-02	Perturbation from 1850 control using PD aerosol and ozone precursor emissions (only BC aerosols interact with radiation)	21		0

Understanding Stakeholder Needs


DRAFT-Temporal Scale of Agricultural Sector Stakeholder Interest
Days
Months
Years
<1
10
20
1
3
6
9
1
3
5
10
50
100<
Farmer
Consumer
Crop Breeder
Reservoir Construction
Aid Agency
Disaster Relief
Development Aid
Emissions Policymaker
Regulatory Agency
Commodities Trader
Biofuel or Processing Plant Construction
Elected Official
(Re-)Insurance Companies

Stakeholders want:

- Credibility of climate data established in observational period
- Highest possible resolution *(must be connected to value of added detail)*
- Single answer *(but accepting of probabilistic information for risk management framework)*
- Basic understanding of process used to make scenarios
- Sustained engagement



Model-based range of outcomes (distribution) for 2050s temperature change in New York City relative to the 1971 - 2000 base period. Based on 35 global climate models and 2 representative concentrations pathways. The 10th, 25th, 75th, and 90th percentiles of the distribution are presented.

New York City Panel on Climate Change, 2013

Climate Risk Information:

- Start with the questions: "When has climate or weather affected you in the past? What changes in climate do you notice in recent years?"
- Characterize in current system
- Project changes in future system
- Envision future changes in climate (including new threats) and place in context of socioeconomic development and technological change

Huge diversity in tailored metrics requested

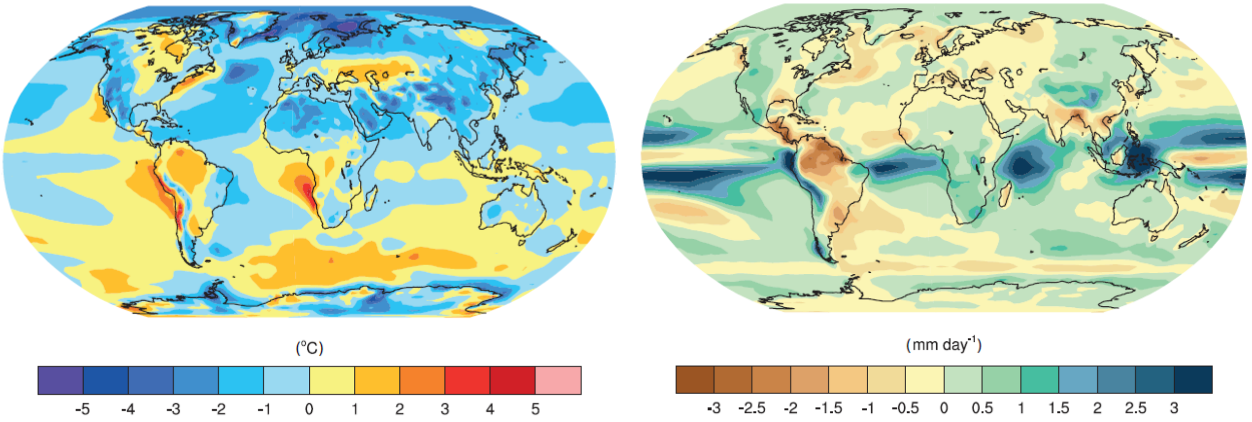
- E.g., chill hours for blueberries, killing degree days for wheat, consecutive dry days, extreme temperatures for airport runway closure, critical overwinter temperatures for pests, temperature-humidity indices for health, heavy downpours for flash flooding, wind speed at turbine height…
- Most are statistics or close derivatives of temperature, rainfall, wind, humidity, and precipitation distributions

How ESM Outputs are Often Applied

Raw ESM output rarely used directly for VIACS analysis due to resolution, biases, sampling of internal variability, and efficiency

ESM outputs are often evaluated through the following lenses:

- Further downscaling
  (dynamical or empirical)
- Bias-correction / scenario generation
  (depends heavily on change statistics and target observational dataset)
- Weather generators
  (produce synthetic climate series based on core statistics to examine extremes)
- ESM subsets
  (to eliminate heavily biased models and/or focus resources)
- Climate emulators (e.g., MAGICC, HECTOR)
  (reduced form representation of models for integrated assessment models)

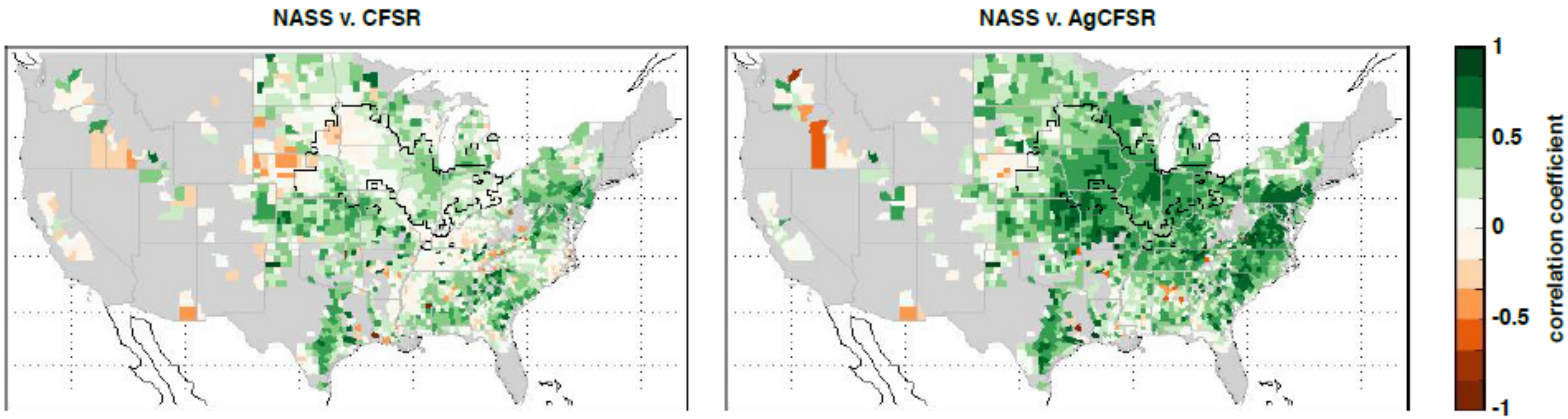


Multi-model mean annual biases for Temperature (left) & Precipitation (right) (Flato et al., 2013)

Bias-correction also often needed for Reanalysis

Many “climate forcing datasets” used for impacts research

Glotter et al. (2016) improvements in simulation of corn:



Above: 1980-2010 Correlations between National Agricultural Statistics Service (NASS) County-level production and that simulated by pDSSAT using CFSR (left) and AgCFSR (right) climate data (from Glotter et al., 2016). Note dramatic improvement in correlations over major agricultural regions including the US Corn Belt (outlined in black).

AgCFSR features bias corrections applied to CFSR for mean precipitation and temperature; diurnal Temperature Range, solar radiation, and number of rainy days

Selecting a Climate Scenario Approach

Depends on sector(s) examined

- Some can be considered as individual points (e.g., urban; single agricultural region; infrastructure)
- Some require spatial covariance across ESM gridcells (e.g., widespread extreme events; global food prices; basin water resources; species suitability; vector-borne diseases)
- Multi-disciplinary studies must target most needy applications (may lower quality of individual sectors assessments)

Climate scenario detail only useful if impact model/analysis is responsive

- Depends heavily on quality of impacts model
- Often less concerned with energy and water budget closure
- Off-season biases may not matter
- Many sub-seasonal characteristics only matter on aggregate unless extreme threshold surpassed
- Likewise, changes in highly uncertain variables can swamp more certain information

(e.g., changes in downward SW radiation at the surface could dominate agricultural responses)

Many approaches -- nearly all seek to impose climate changes on observed conditions

(beware big %changes from dry GCM month imposed on wet observations)

Selecting a subset of models

Ideally we could find top performing models by filtering out those performing poorly
Paraphrasing Dennis Lettenmeier – "once you start eliminating models eventually you have none"

Subset to create more accurate weighted projections (e.g., Giorgi and Mearns, 2002)

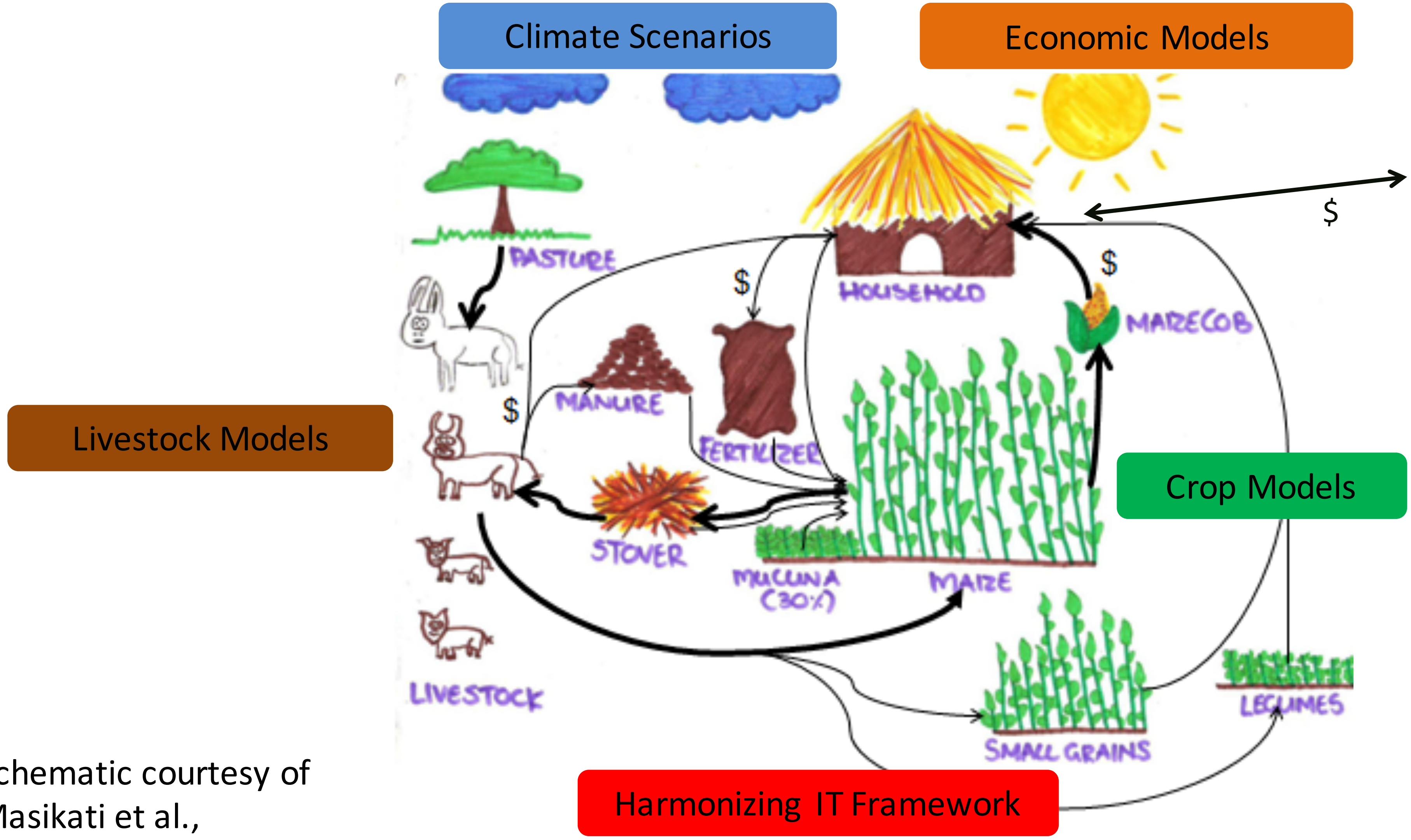
- Often based on historical simulation performance for a key metric

Subset to conserve resources for other parts of impacts assessments

Selected GCMs determined by some combination of:

- Availability
  - CMIP outputs with desired variables
  - CMIP outputs with bias correction applied (BCSD, NEX, ISIMIP)
- Performance in key atmospheric phenomenon (e.g., monsoons)
- Equilibrium Climate sensitivity
- Spatial resolution
- Reputation of models and modeling groups (publication and inclusion in past CMIPs)
- Representation of broader ESM ensemble in region of interest

Resource Constraints for Regional Integrated Assessment of Future Agricultural Systems



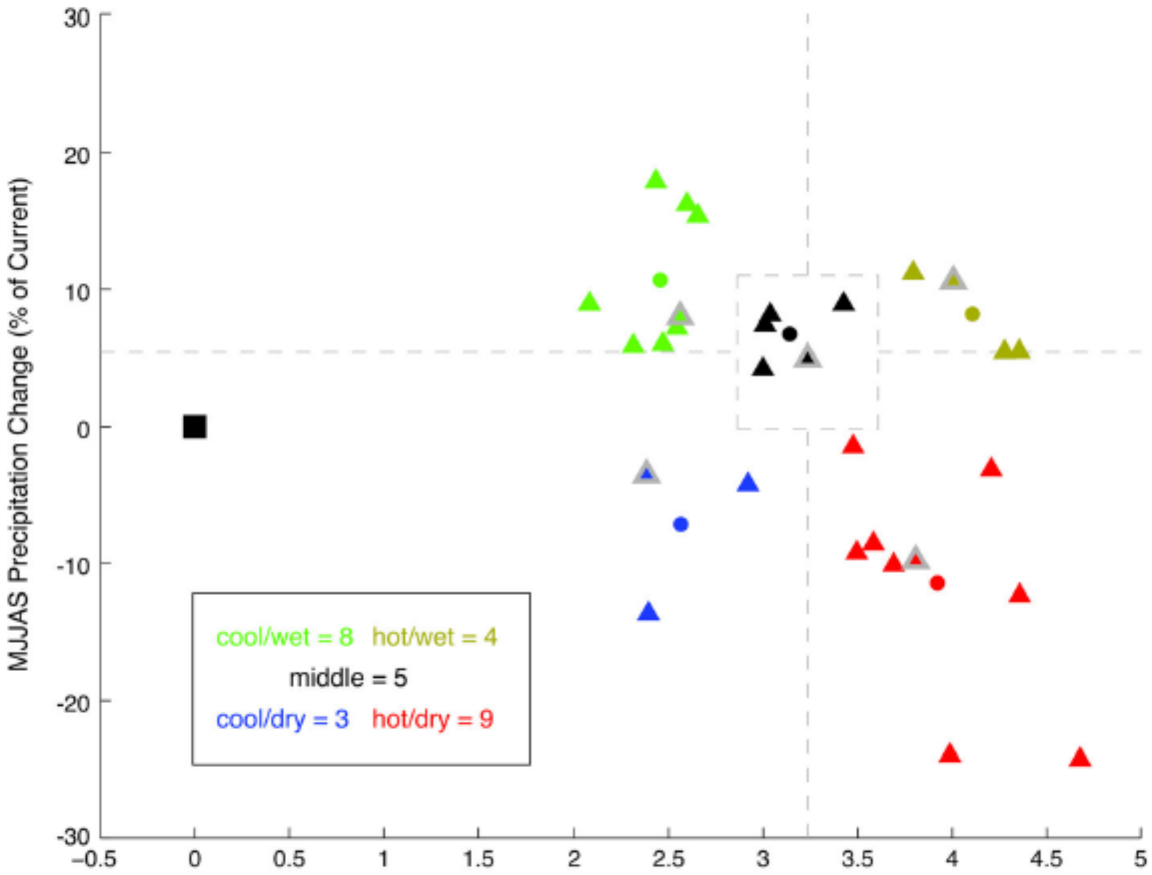
29 Climate Models
~150 farms
2 crop models
4 crop/livestock species
2 future scenarios
2 adaptation packages
30 year simulations
===================

- > 4 million simulated years

Lots of pressure to reduce climate models in order to focus on future policies and adaptations

Schematic courtesy of Masikati et al., AgMIP CLIP team
Artist: Amina Homann

Subset example for Regional Integrated Assessment of Future Agricultural Systems (Ruane and McDermid, 2017)

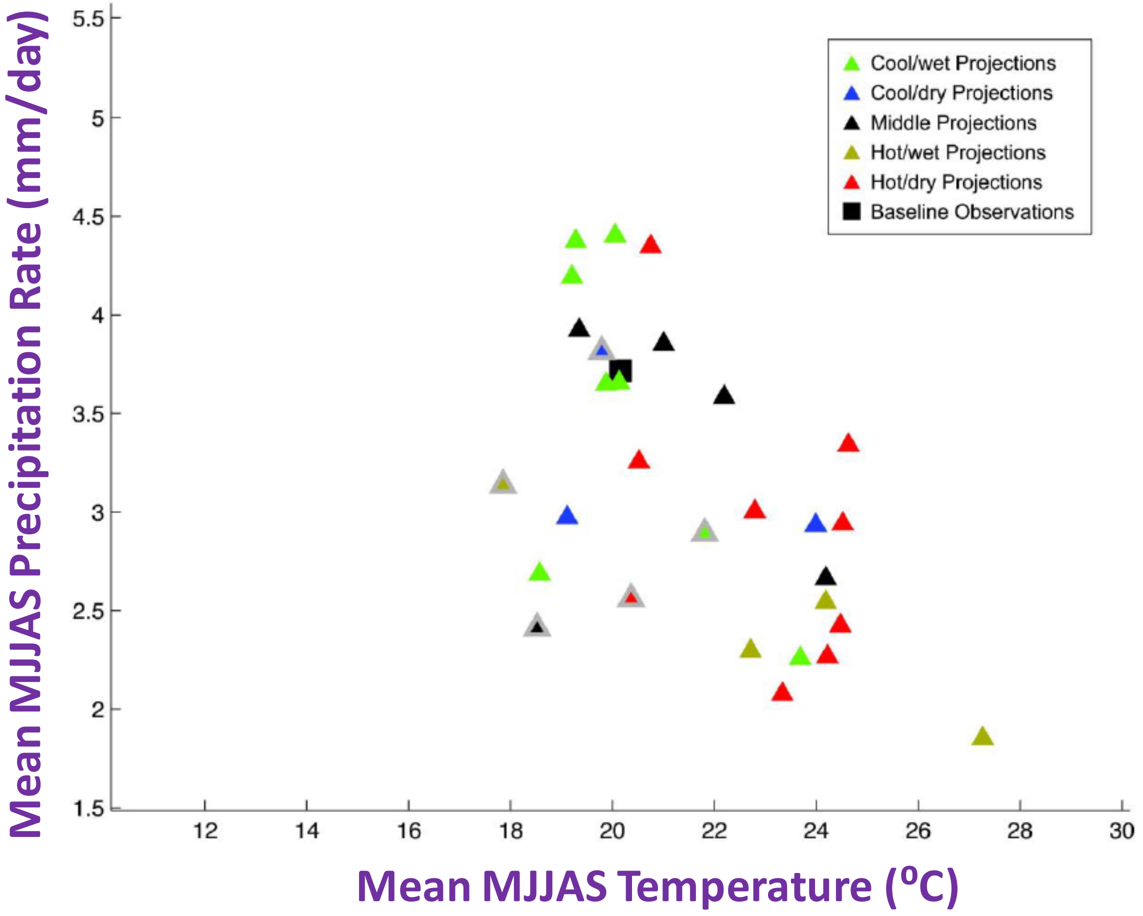


Ames, Iowa – Climate Model Projections and subset selection for Corn Season

Fig. 1 Basic definition of the quadrants and Ames, Iowa, Maize season examples from 29 GCMs for Mid-Century RCP8.5. Each triangle is colored by its quadrant and represents one of the 29 GCMs, and the square represents the baseline condition (no change from observed average of 20.2 °C and 3.7 mm/day). *Dots* represent the mean of GCMs within any given quadrant, and the selected representative GCMs are denoted with a gray outline

See also Semenov and Stratonovitch (2015) for Giorgi Regions Change Heat Map

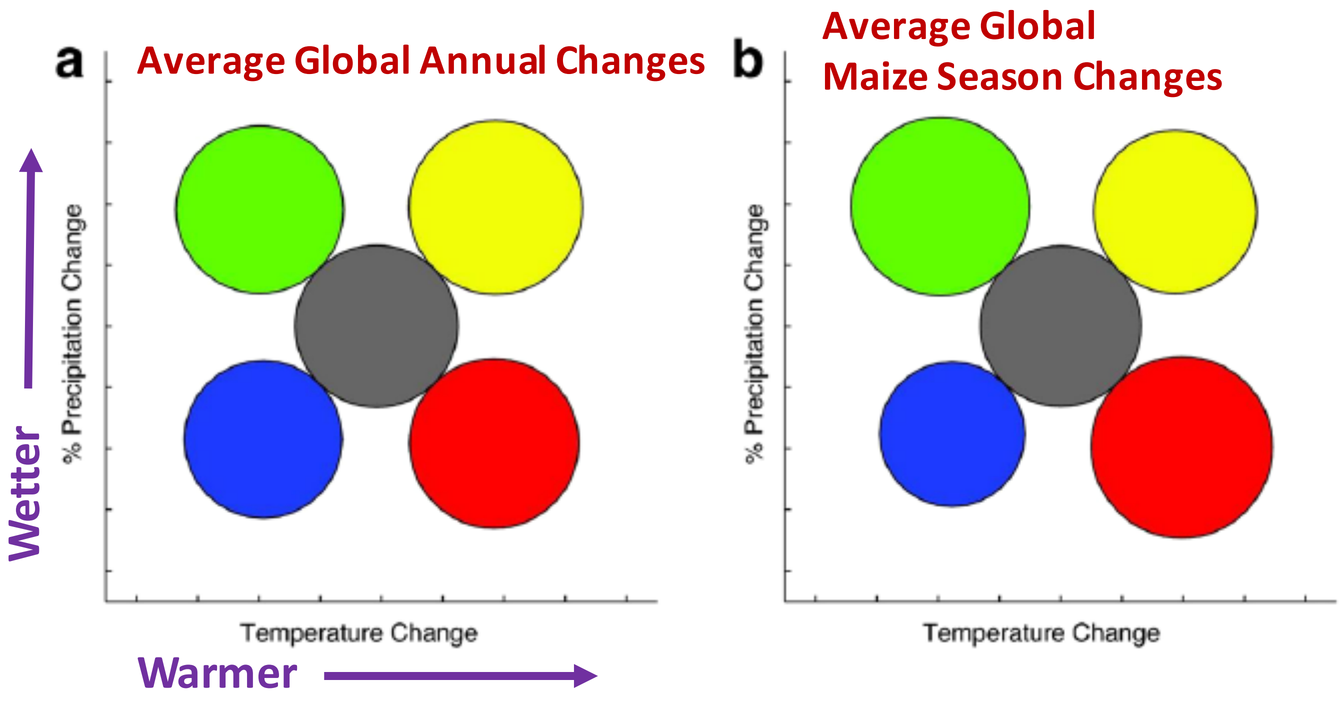
Subset example for Regional Integrated Assessment of Future Agricultural Systems (Ruane and McDermid, 2017)



Ames, Iowa – Model mean conditions in historical simulation

No strong connection between future quadrants or selected model and historical bias

Skewness in ensemble spread (Ruane and McDermid, 2017)

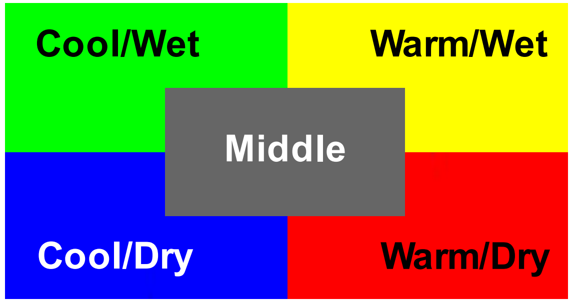


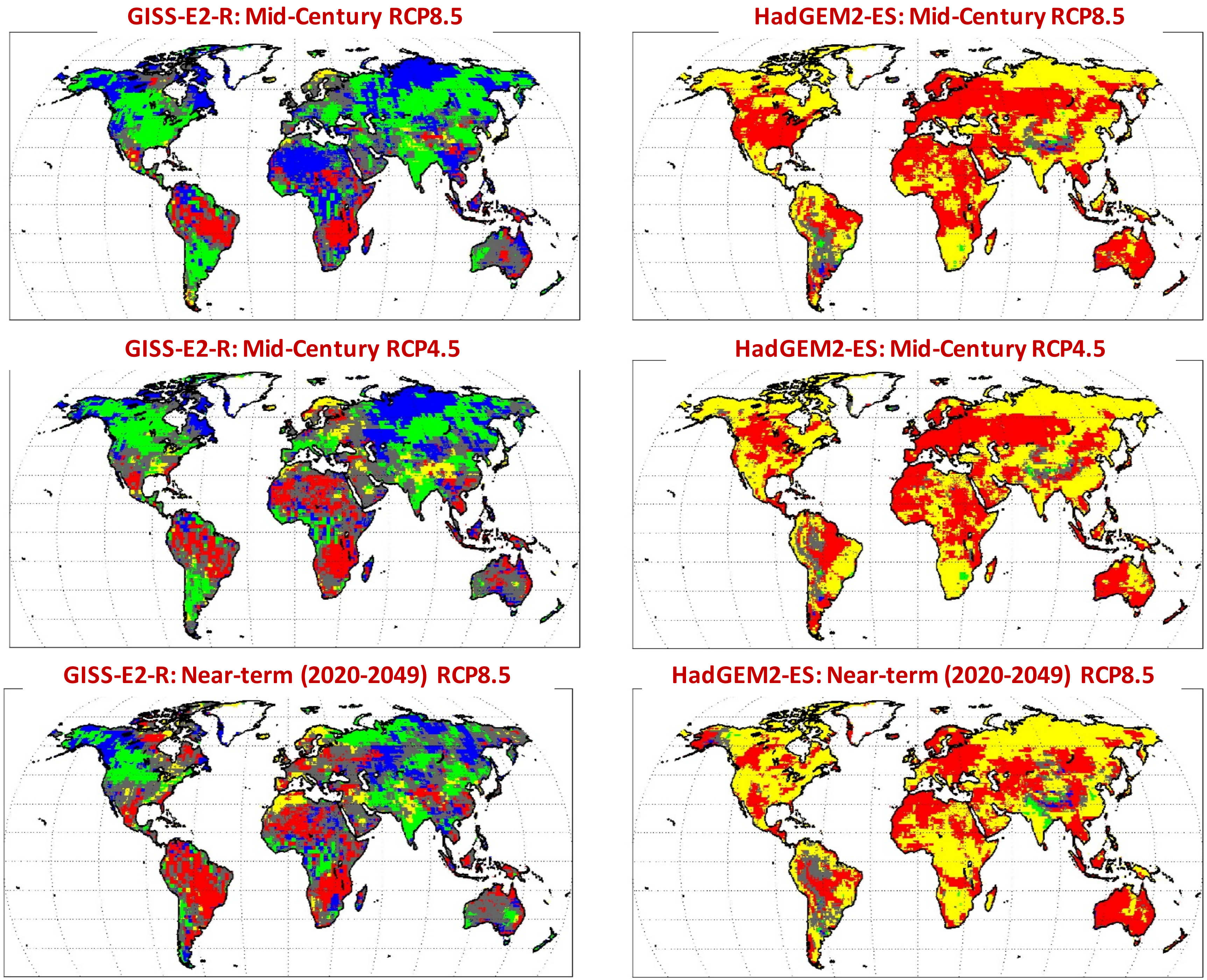
Projections for Maize season skew toward cool/wet and hot/dry axis

Size of circle represents fraction of models in each quadrant

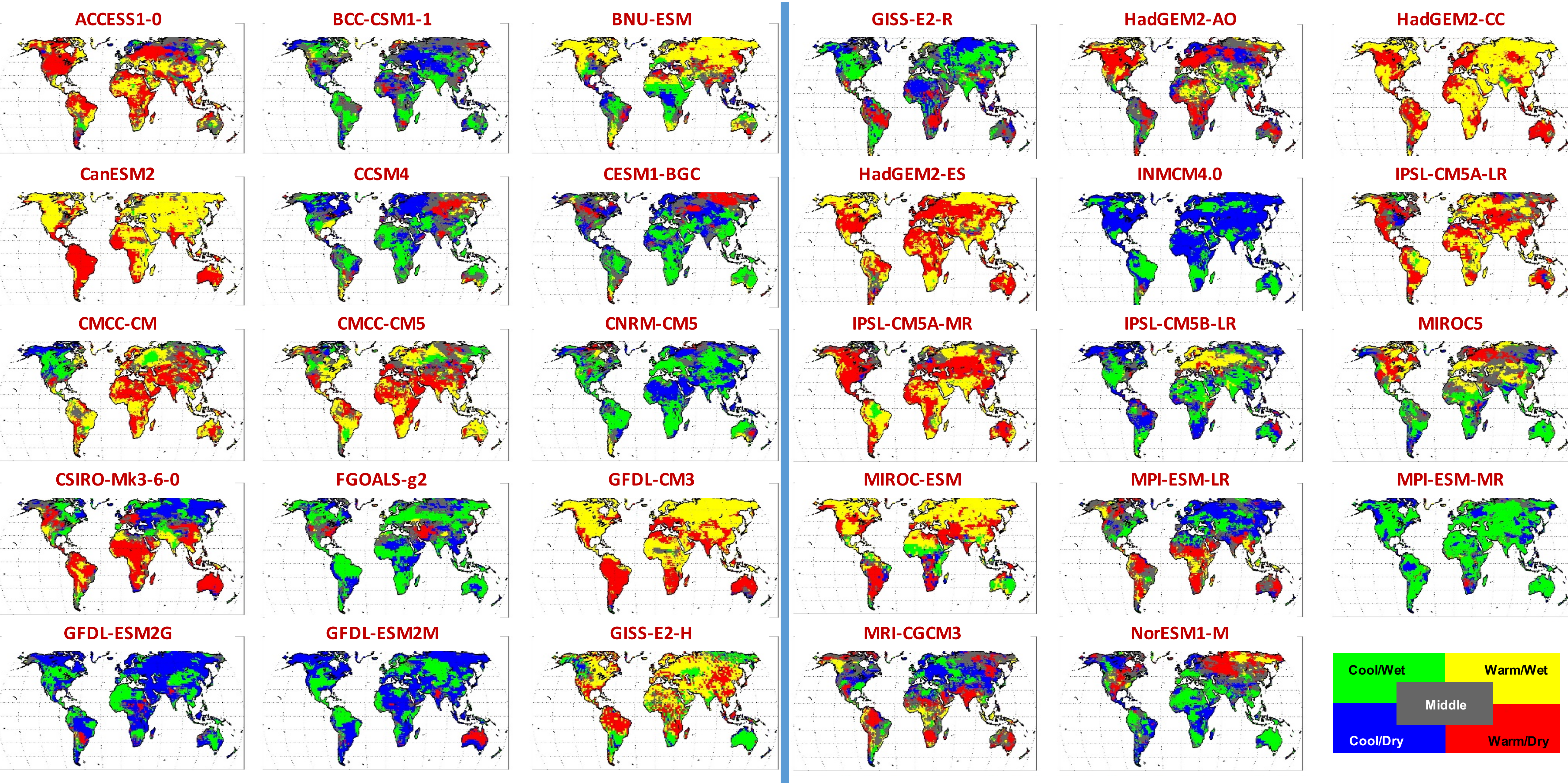
GCM location amidst ensemble is fairly robust

(Ruane and McDermid, 2017)





Atlas of relative GCM projections for T and P (Ruane and McDermid, 2017)



Priority Evaluation Requests

VIACS researcher priorities:

Regional patterns, seasonal progression and monsoons

- Evaluate ESMs in key circulation patterns (e.g., Sperber et al., 2013, for monsoons)
  - Onset, withdrawal, total precipitation, spatial extent, false starts, and break periods
- Connects with local interests and phenology

Modes of variability

- Less concerned about predictability of individual modes, more interested in overall distribution of extreme events (return periods)

Enhanced evaluation of extreme events

- Metrics of duration, frequency, extent, magnitude of extremes (SREX)
- Low-frequency outputs of high-frequency variables

Regime shifts

- When is future so different than present that our scenario generation or bias-correction methods break down? (e.g., rainy season shifts dramatically; massive land-surface or vegetation change)

Key Challenges for ESM-VIACS Connections

Key challenges for ESM-VIACS Connections

Improved VIACS models and analyses to make use of improved outputs

Incorporate offline VIA results for ESM development

- Benchmarking of global crop models and vegetation models' croplands (Müller et al., 2017)
- Review of agricultural land representation in ESMs (McDermid et al., in press)

ESM expert guidance and VIACS translation needed:

- Do we eliminate models for any purposes?
- How to handle requests that require output variables we do not trust?
  (e.g., sea-level rise in AR5 without ice sheet dynamics;
  solar radiation changes; localized extreme events)

Technical facilitation:

- Output access and processing for those with limited resources
- Interactive exploration of potentially huge number of tailored metrics that will be requested

Suggestions to Better Serve VIACS Applications and Downstream Stakeholders

Suggestions to Better Serve VIACS Applications and Downstream Stakeholders

- Produce low-frequency outputs of high-frequency statistical quantities
  - Facilitates large initial condition ensembles to explore internal variability
  - Daily histogram values for temperature and precipitation *(and perhaps RHmin)*
  - Hourly values for extreme thresholds (hot, cold, and wet)
  - Likely more efficient to count in model rather than post-process due to huge amount of output that would be required

- Online data holdings and workflows to facilitate access where computational resources are limited (ESMValTool, PMP, FACE-IT)
  - Common post-processing (e.g., regridding)
  - Ideally could allow customizable metrics (e.g., growing degree days with specified base temperature; number of extreme heat events in specified growing season; percentage of total precipitation falling in heaviest 5% of events)

- “Consumer reports” for ESMs listing known, VIACS-relevant biases
- Demonstration papers for CMIP6 MIPs: VIACS leader and MIP leader model application

- Version guidance:
  - Which versions/simulations are promoted for projection?
  - Which were included for diagnostic purposes

Thanks!

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Extra Slides

Sperber et al. (2013) Monsoon Metrics

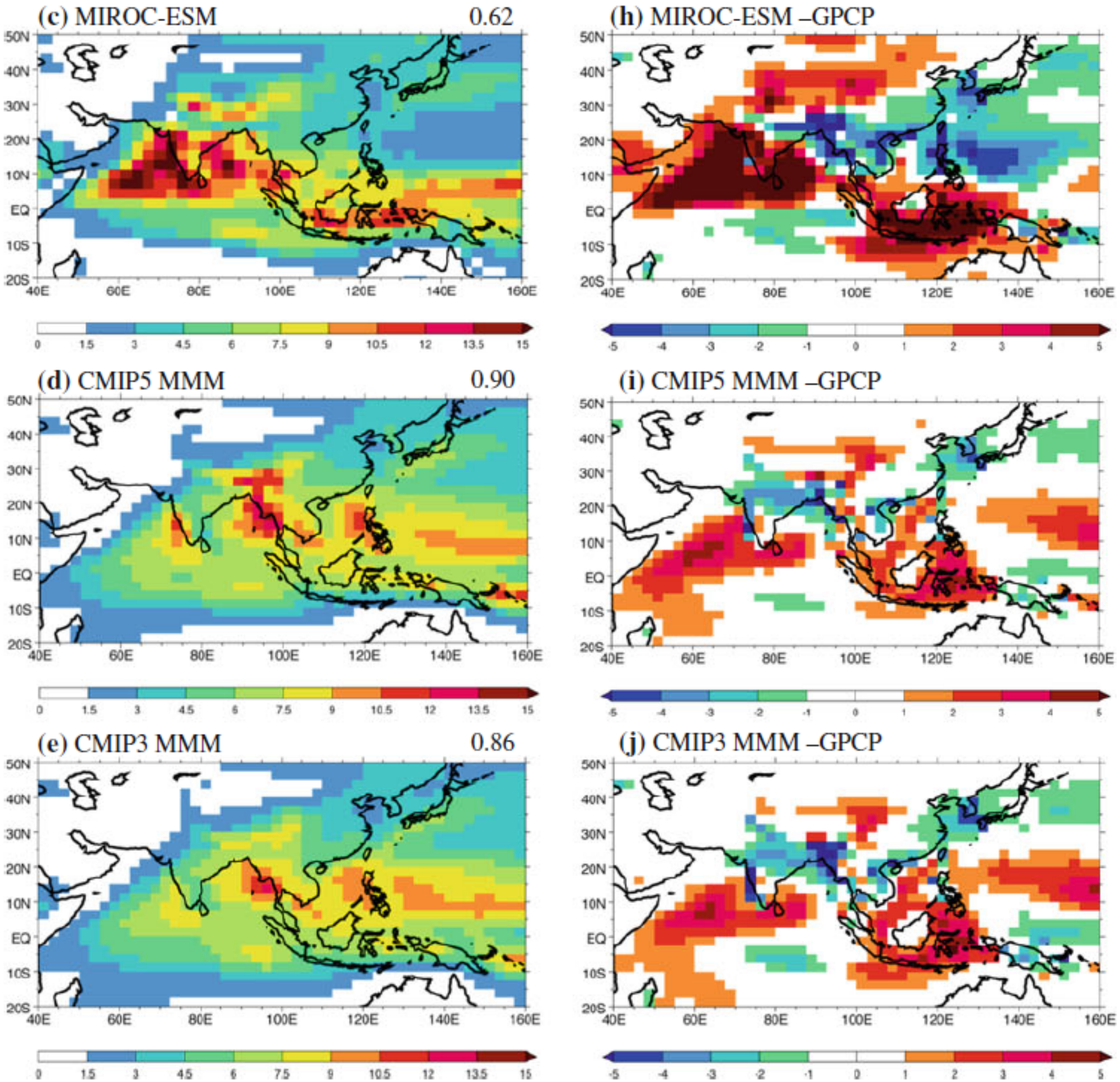
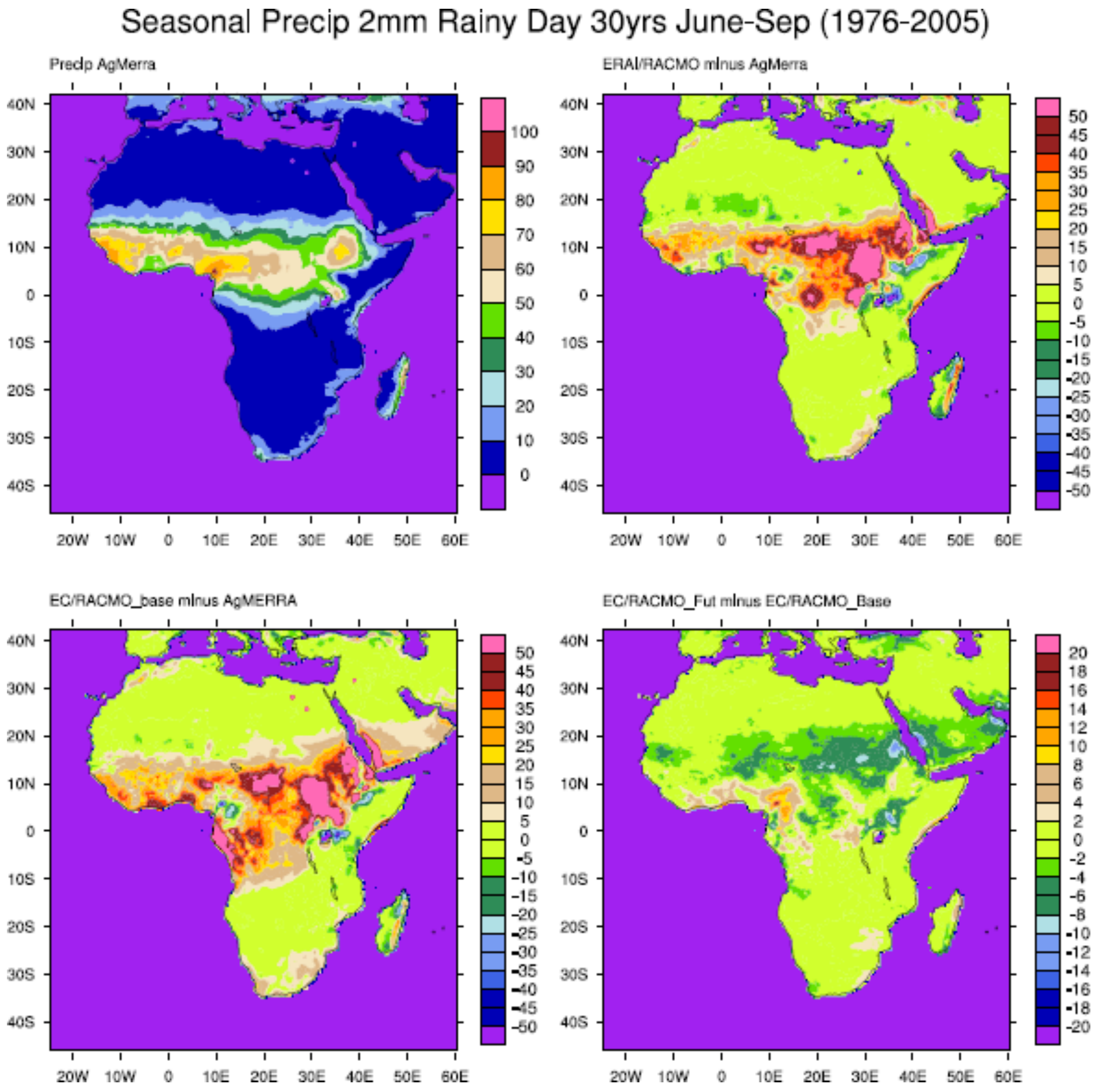


Table 3 continued

Model	Indian Monsoon		East Asian Monsoon	
	AIR/N3.4	Pr	Pr	850 hPa
HadGEM2-CC	−0.335	−0.068	**0.787**	0.935
HadGEM2-ES	−0.344	0.216	**0.839**	0.949
ukmo-hadcm3	−0.374	0.323	0.758	0.947
ukmo-hadgem1	−0.446	0.154	0.744	0.912
ingv-sxg	−0.455	0.313	0.513	0.925
INM-CM4	−0.033	0.110	−0.047	0.816
inm-cm3.0	−0.258	−0.073	0.520	0.850
IPSL-CM5A-LR	**−0.700**	**0.611**	0.450	0.708
IPSL-CM5A-MR	**−0.763**	**0.636**	0.532	0.749
ipsl-cm4	−0.554	0.347	0.675	0.787
MIROC-ESM	0.088	0.061	0.596	0.694
MIROC-ESM-CHEM	−0.104	0.045	0.687	0.882
MIROC4h	−0.327	**0.529**	0.723	0.921
MIROC5	−0.321	0.010	0.567	0.946
miroc3.2 (hires)	0.080	−0.009	0.643	0.915
miroc3.2 (medres)	−0.329	0.234	0.719	0.928
MPI-ESM-LR	−0.291	0.401	0.283	0.899
echam5/mpi-om	−0.573	**0.560**	0.230	0.817
echo_g	−0.554	0.113	0.664	0.914
MRI-CGCM3	−0.274	0.338	**0.819**	0.937
mri-cgcm2.3.2	−0.424	0.107	0.570	0.931
NorESM1-M	**−0.690**	**0.522**	**0.811**	**0.959**

Above: Spatial skill scores (AIR = All India Rainfall)
Left: Summer precipitation comparison

Grounding downscaled simulations to understand methodological biases



AgMERRA (1980-2009)

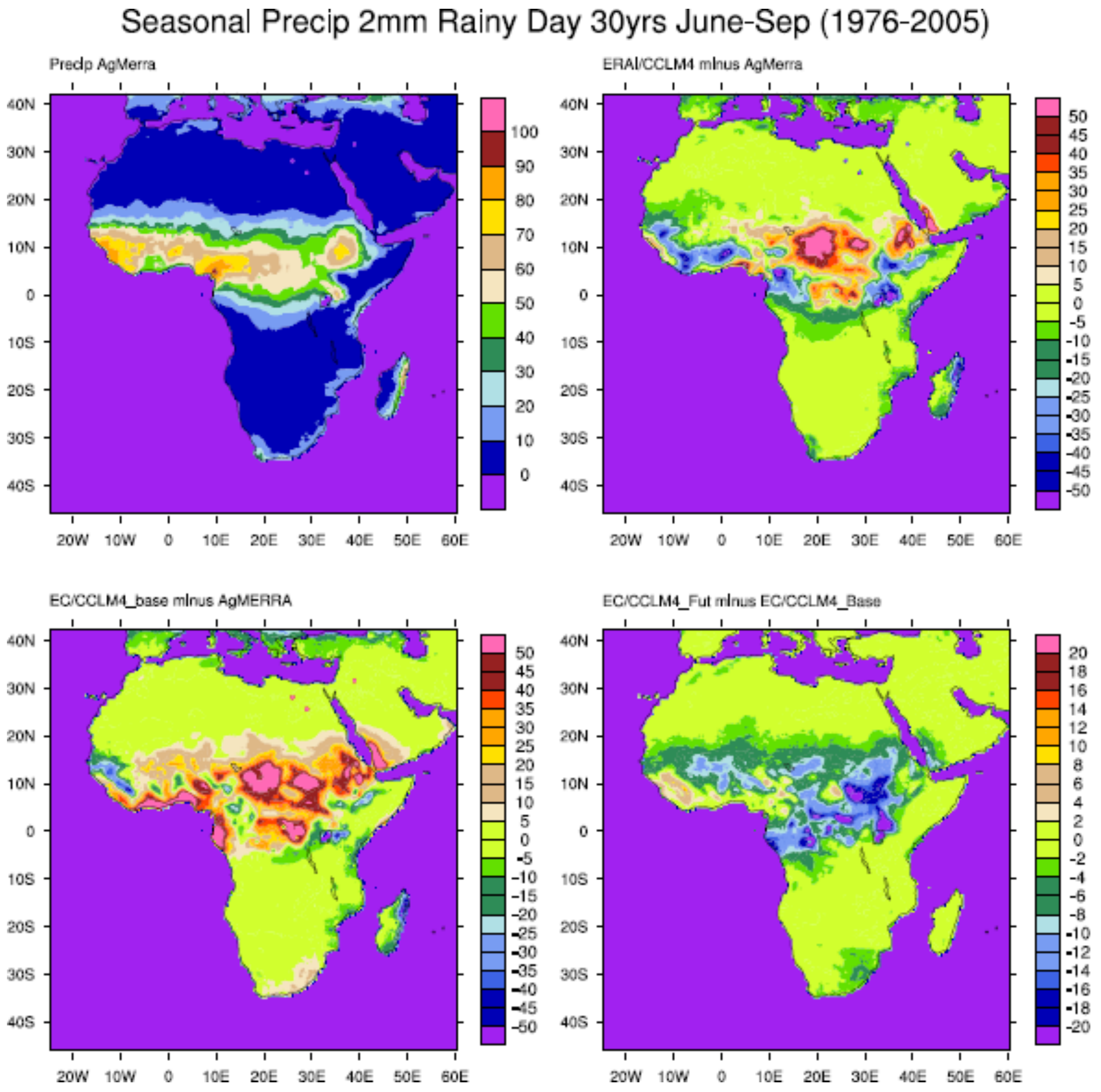
RACMO RCM driven by ERA Interim minus AgMERRA

RACMO RCM driven by **EC_EARTH**: Base minus AgMERRA

RACMO RCM driven by EC_EARTH: Future minus Base

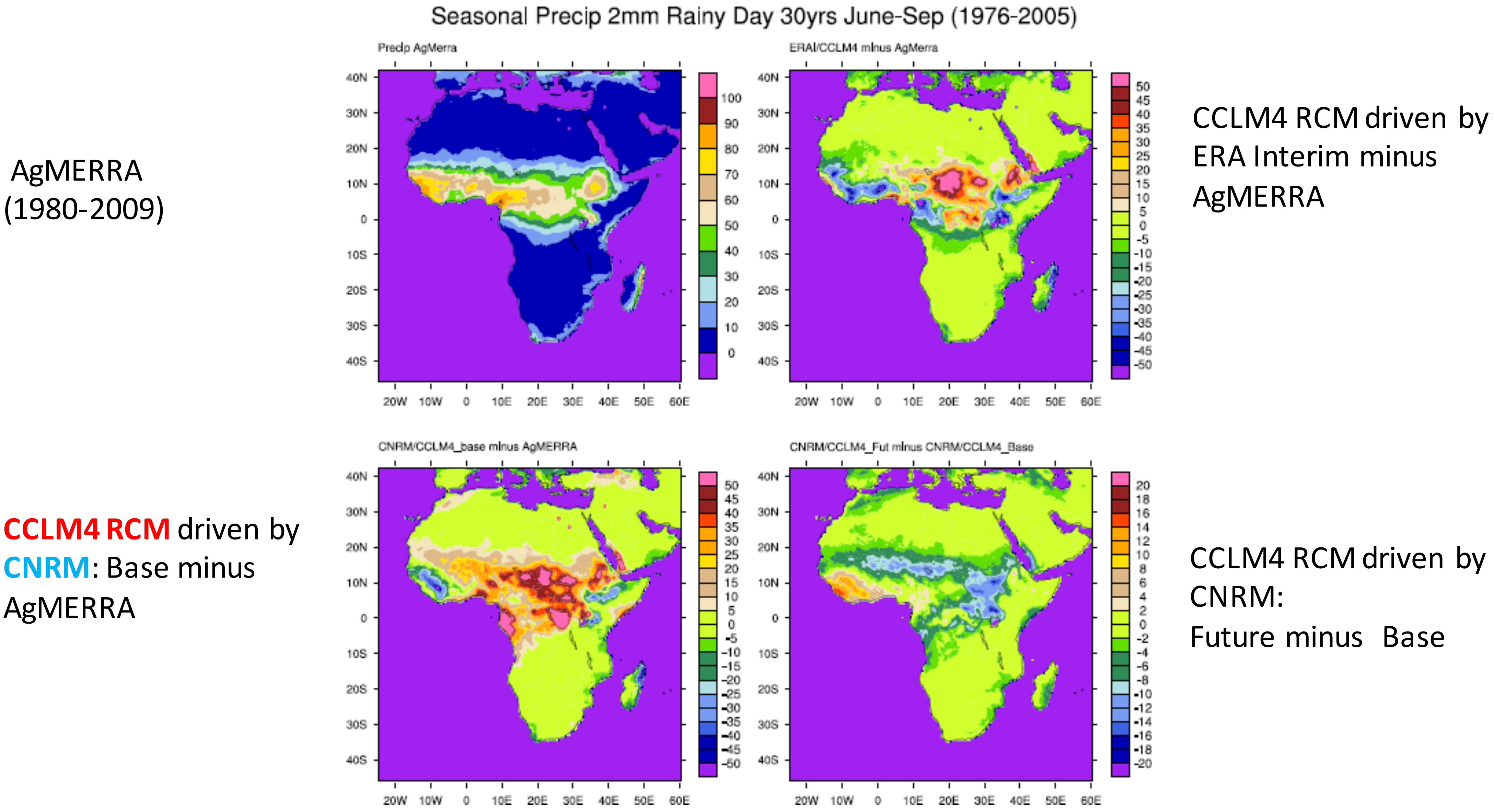
AgMERRA (1980-2009)

CCLM4 RCM driven by ERA Interim minus AgMERRA



CCLM4 RCM driven by **EC_EARTH**: Base minus AgMERRA

CCLM4 RCM driven by EC_EARTH: Future minus Base

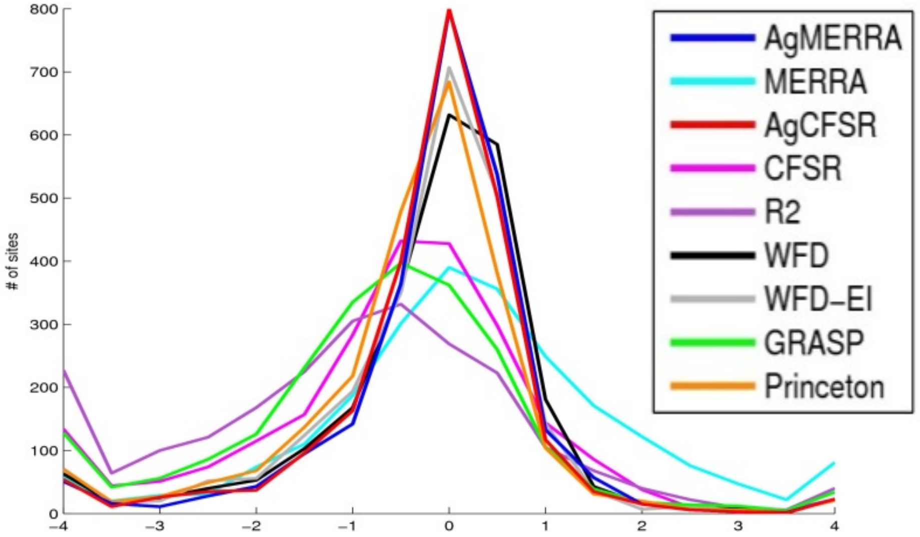


Seasonal Precip 2mm Rainy Day 30yrs June-Sep (1976-2005)
Precip AgMerra
ERAI/CCLM4 minus AgMerra
CNRM/CCLM4_base minus AgMERRA
CNRM/CCLM4_Fut minus CNRM/CCLM4_Base
AgMERRA
(1980-2009)
CCLM4 RCM driven by
ERA Interim minus
AgMERRA
CCLM4 RCM driven by
CNRM: Base minus
AgMERRA
CCLM4 RCM driven by
CNRM:
Future minus Base

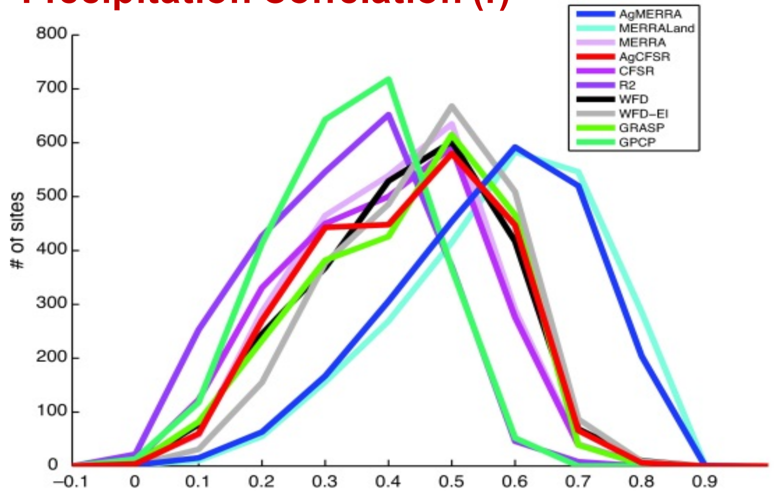
AgMERRA: Historical Climate Dataset for Agricultural Model Applications

Ruane et al., 2014

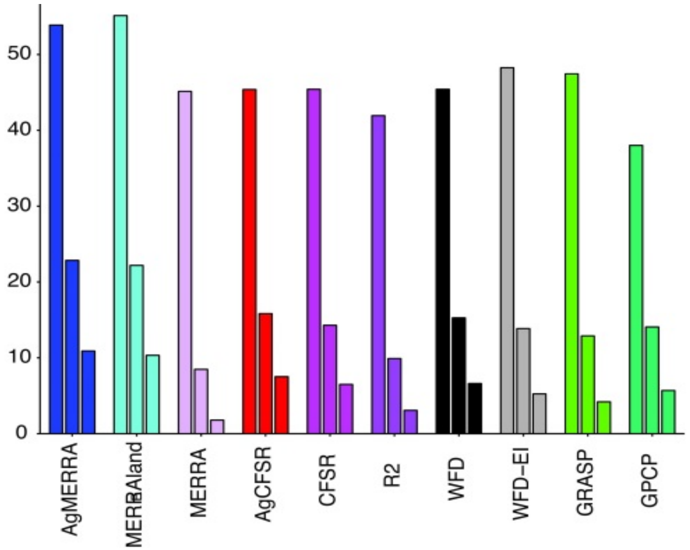
Avg of Tmax and Tmin Biases (ºC)



Precipitation Correlation (r)



Threat score for 1, 25, and 50mm precipitation events (%)



AgMERRA (1980-2010) features:

- Temperature and rainfall bias correction
- Improved solar radiation (NASA/GEWEX SRB)
- Improved precipitation variability (MERRA-land)
- Fine spatial patterns of rainfall from satellites
- An adjustment to diurnal temperature range
- Relative humidity at Tmax

AgMERRA better captures rainfall distribution and actual sequence of extreme events

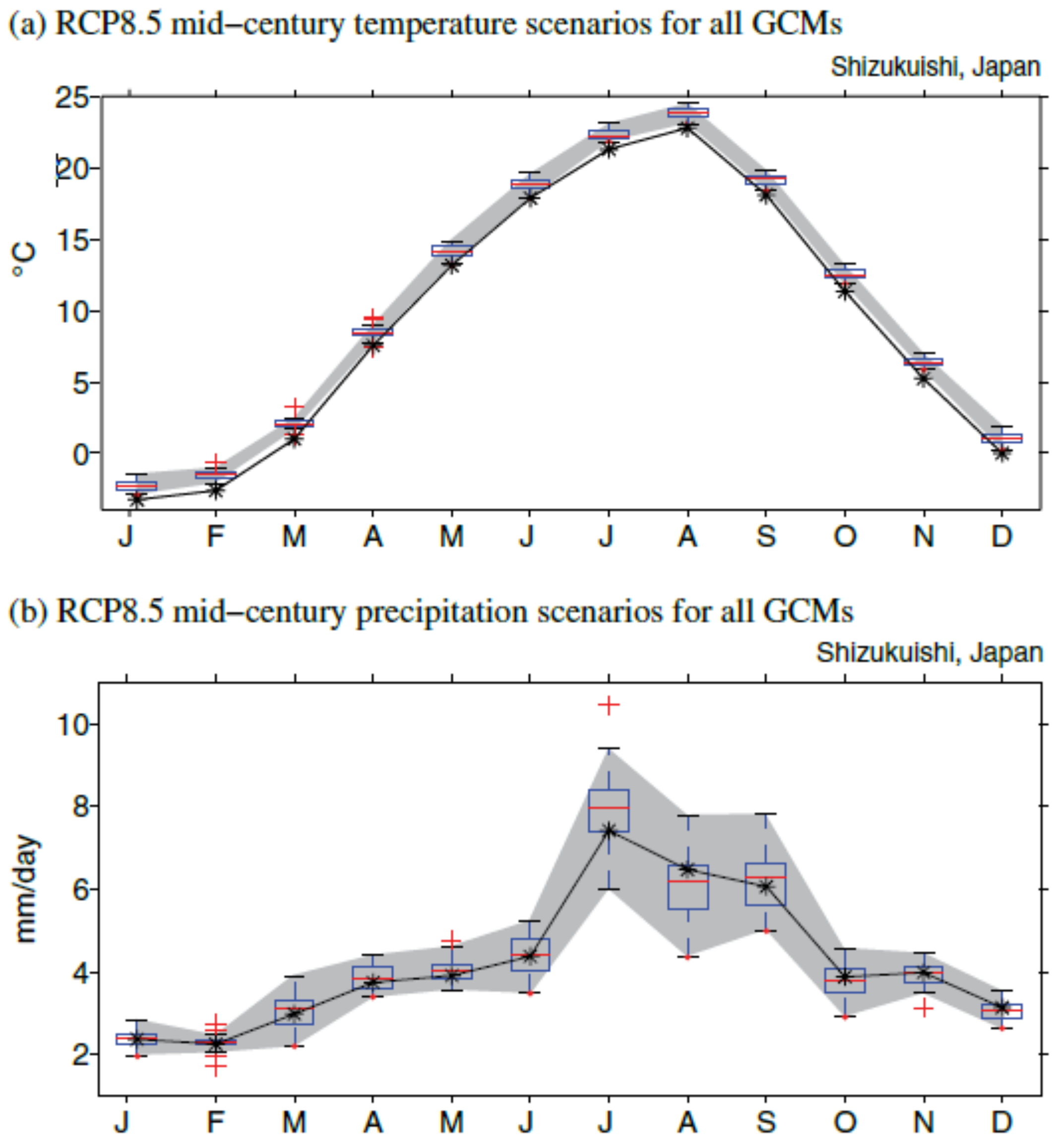
Climate Scenarios Methods

Nearly all connect climate changes to observed conditions while de-emphasizing mean biases

Scenario generation approaches require core sets of outputs:
- **Delta method** (monthly mean changes imposed on observed time series)
- **Stretched distributions** (adjust observed distribution to impose mean and variability changes)
- **Quantile mapping** (adjust model distribution to better reflect observed characteristics)
- **Spatial disaggregation** (use high-resolution information to estimate finer spatial patterns)
- **Constructed analogues** (use large-scale conditions to identify historical proxies)
- **Trend-maintaining quantile mapping** (ISIMIP)

New developments and approaches frequently developed

Simple Climate Scenario Generation

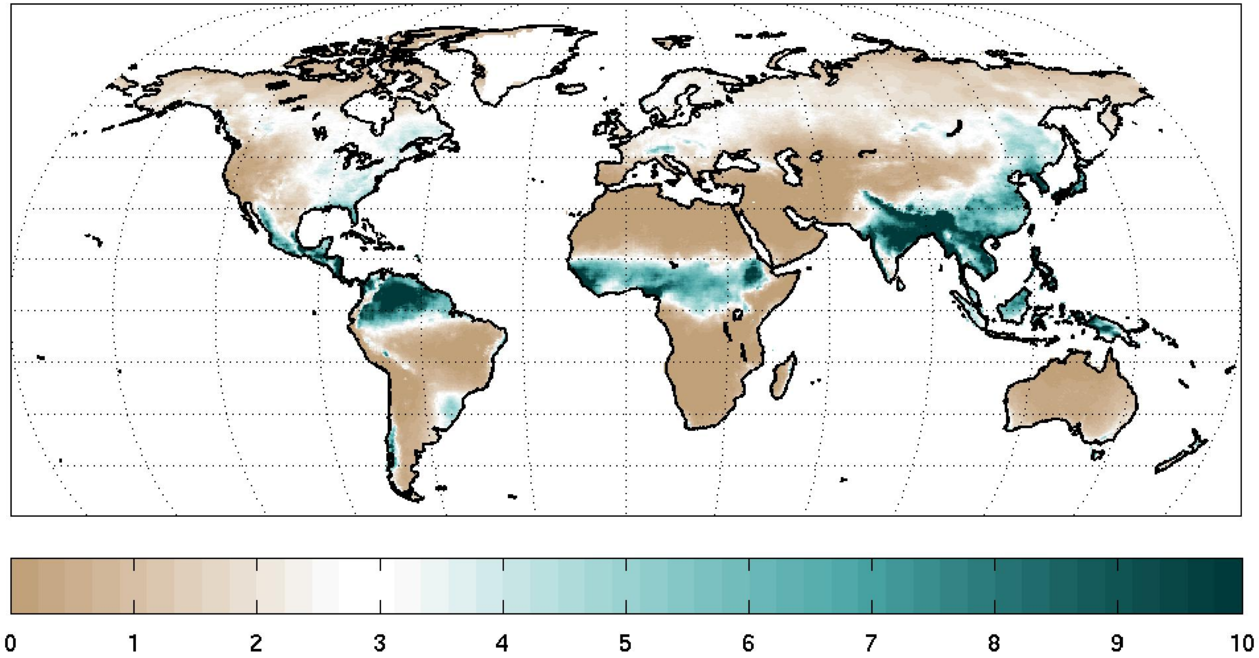


(Ruane et al., 2015)

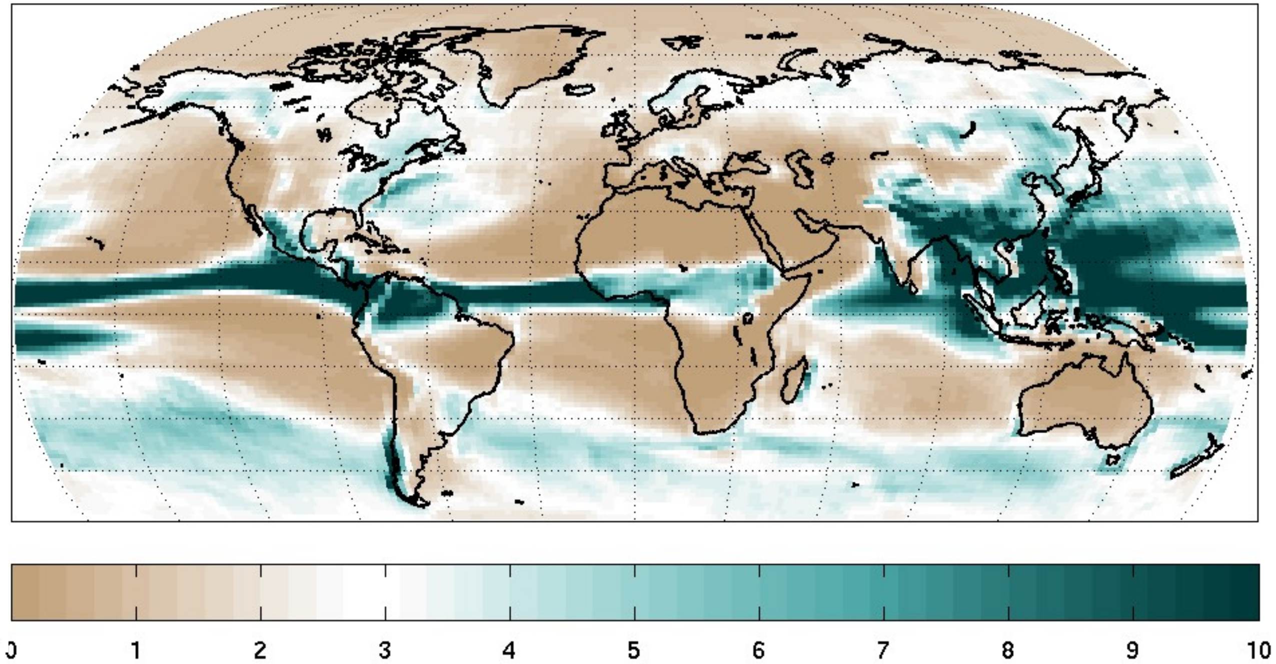
Goddard Institute for Space Studies
New York, N.Y.

Monsoons

AgMERRA 1980-2009 Mean July Precipitation



HadGEM2-ES1980-2009 Mean July Precipitation



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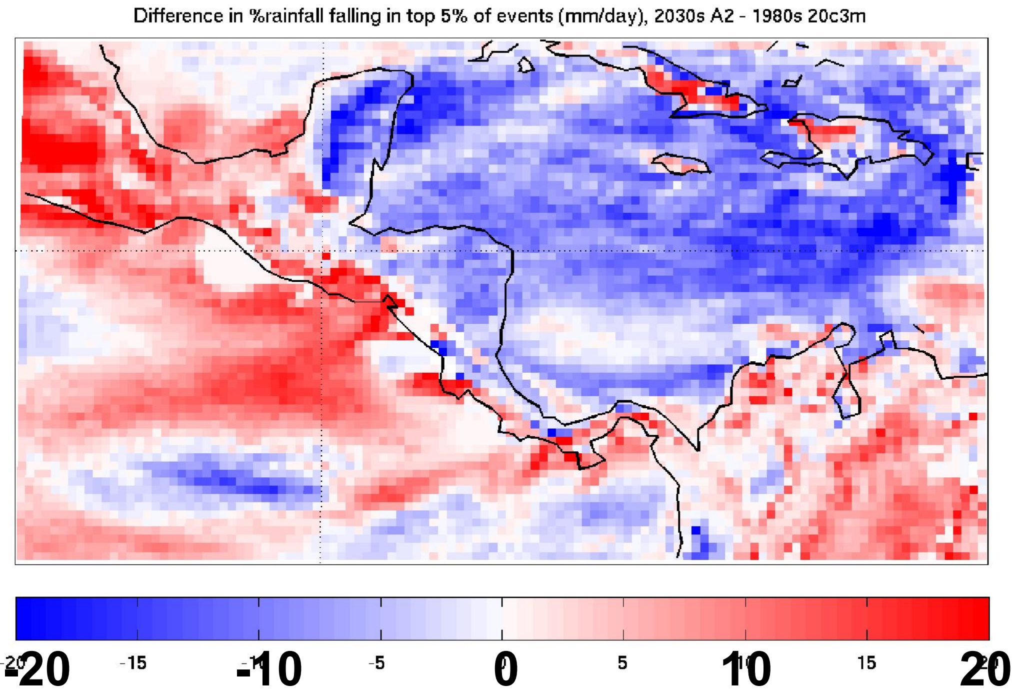
Extreme rainfall patterns changing



- **Shifts in the percentage of rainfall falling in rainiest 5% of days**
- **Areas with decreasing rainfall and increased extreme characteristics are vulnerable**

(Ruane et al., as yet unpublished)

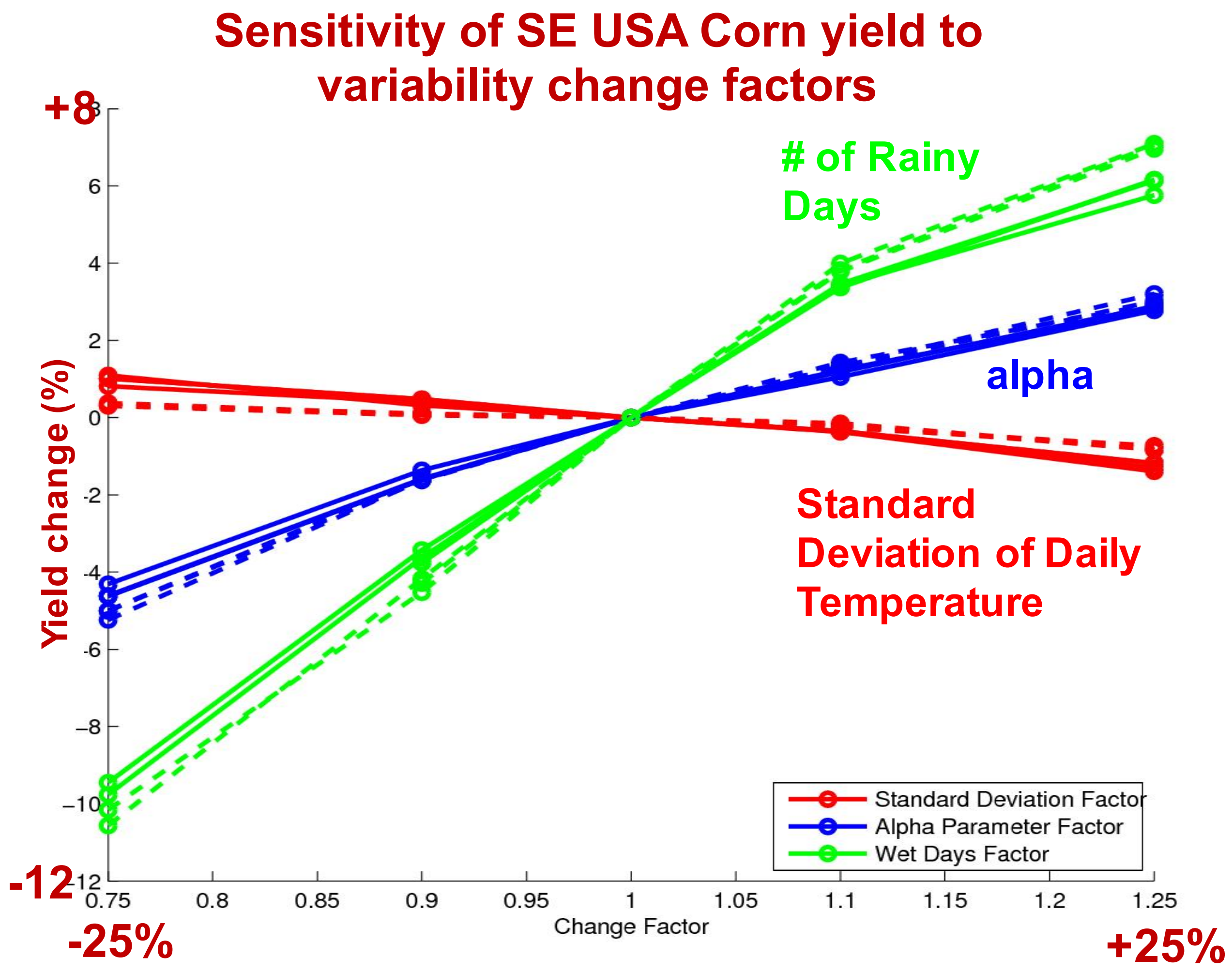
NPCC2 Quantitative Extreme Event Projections (Horton et al., 2015)

			2020s			2050s		
		Baseline (1971-2000)	Low-estimate	Middle range	High-estimate	Low-estimate	Middle range	High-estimate
Heat waves and cold weather events	Number of days/year with maximum temperature at or above 90°F	18	24	26 to 31	33	32	39 to 52	57
	Number of heat waves/year	2	3	3 to 4	4	4	5 to 7	7
	Average heat wave duration (in days)	4	5	5 to 5	5	5	5 to 6	6
	Number of days/year with minimum temperature at or below 32°F	72	50	52 to 58	60	37	42 to 48	52
Intense Precipitation	Number of days/year with rainfall at or above 2 inches	3	3	3 to 4	5	3	4 to 4	5

Based on 35 GCMs and two Representative Concentration Pathways. Baseline data are from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) United States Historical Climatology Network (USHCN), Version 2 (Menne et al., 2009). Shown are the low-estimate (10th percentile), middle range (25th percentile to 75th percentile), and high-estimate (90th percentile) 30-year mean values from model-based outcomes. Heat waves are defined as three more consecutive days with maximum temperatures at or above 90°F.

Corn Sensitivity to Climate Variability Changes

- **Use stretched distribution approach to impose particular statistical qualities on observed series**
- **Solid lines include interactions between changes in mean and variability**
- **Note that as alpha parameter decreases, rainfall is more extreme.**



(Ruane et al., as yet unpublished)