Simulating Climate Change Uncertainty in GoldSim

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With special thanks for the assistance from:

Victor Munoz for helping me understand Climate Change
Assaf Wunsch for demonstrating Power Query Data
Justin Eisner for creating our custom Python tools

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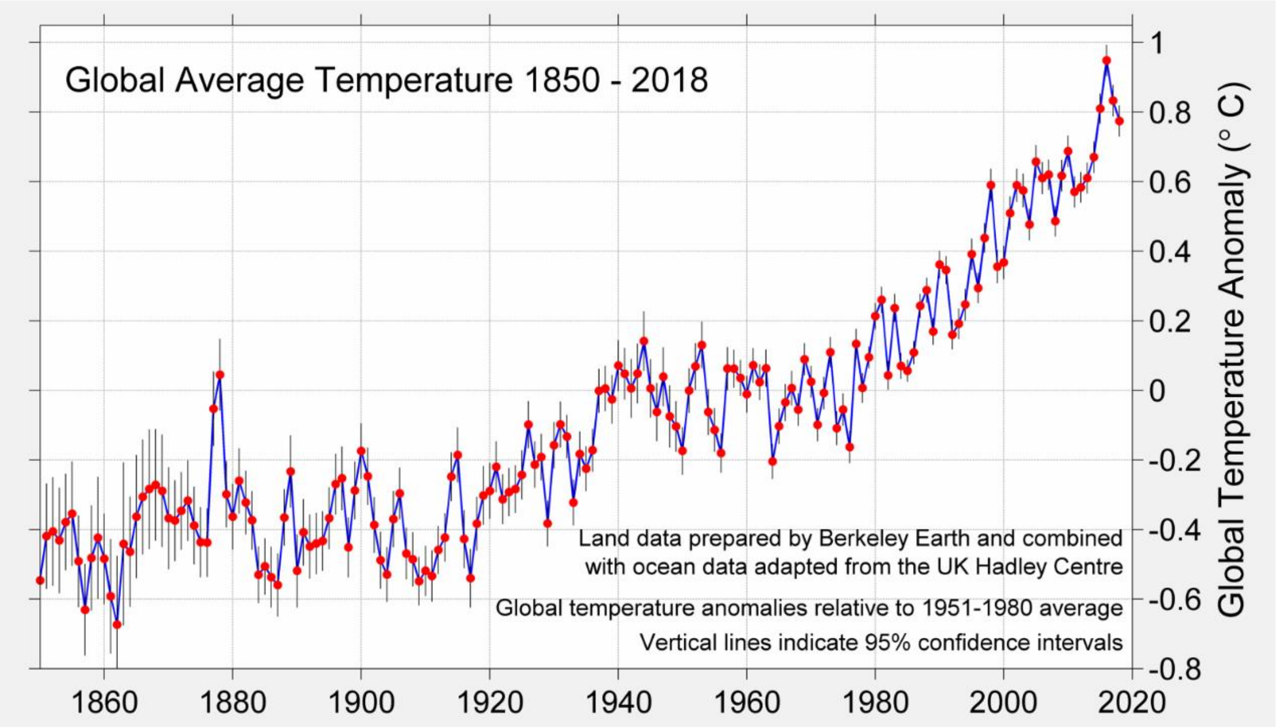
Why do we have to include climate change?

- SRK is primarily mining, and designing new mines needs to include long-term closure in the design
- Like other high risk industries, the mining industry understands:
  - ☑ Permanent and safe closure is needed
  - ☑ Risk-based approaches is needed
  - ☑ Agencies and industry group guidance and support (ie. GISTM for tailings)
  - ☑ Closure (for perpetuity) must include climate change
  - ☑ Best shot is to do right the first time
  - ☑ Redo’s are expensive when the source of funding is gone
  - ☑ Make it resilient to climate change risks

Climate Change Background

Lets go over the basics so we are all on the same page:

- Temperatures has increased historically beyond past conditions.
- Hydrologist used to assume
  Future conditions = Past conditions
- This is no longer a valid assumption for future conditions



Source: Victor Munoz (SRK Vancouver)

Temperature beyond historical => Predictive climate modeling

General Background- General Circulation Models

- Climate change predictions : **Assessment Reports** from the Intergovernmental Panel on Climate Change (IPCC)
- Best understanding of climate modeling at that time
  - Issued every 5 to 10 years (1990, 1995, 2001, 2007, 2022)
  - The General Circulation Models (GCM) **predict** future conditions up to 2100.
  - Include interaction of a host of climate influencing factors
  - Each can produce results for a single grid (i.e. *project* site)
  - 34 different GCMs are potentially available. Each has different methods and assumptions
  - Comparison of the different GCMs is the **Coupled Model Intercomparison Project** (CMIP)

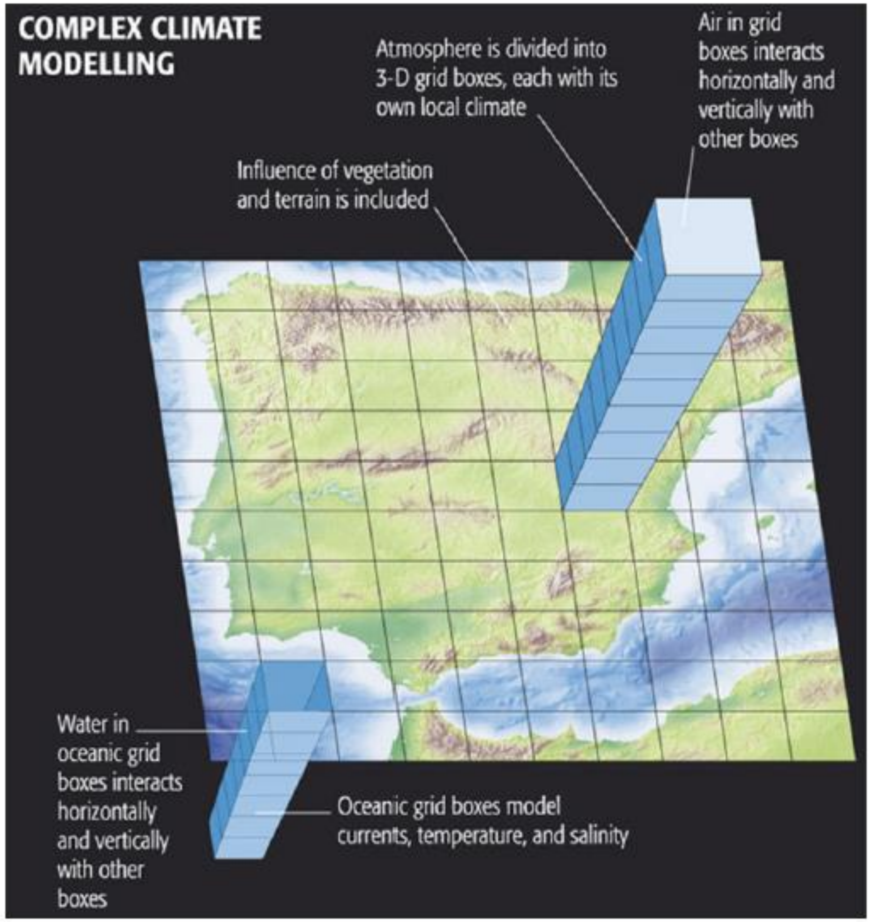
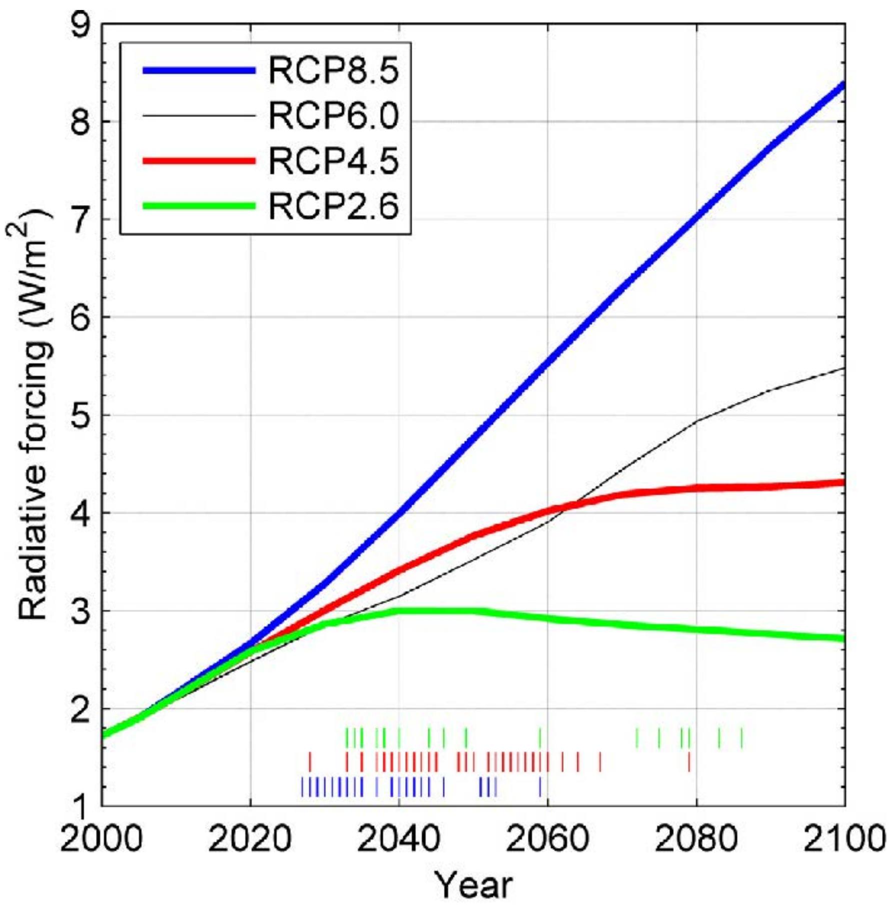


Fig. 18.5 A climate model showing the horizontal and vertical grids and the physical processes in a global circulation model (GCM) (From Mann and Kump, *Dire Predictions*, supported by the National Science Foundation, Public Domain)

Scenarios

- Each GCM incorporates a series of **Scenarios**
  - Estimates the heat in balance within the planet (radiative forcing) by the year 2100
- Different scenarios are paths we take to reach some heat level or **Representative Concentration Pathways** (RCPs)
- The RCP is an **indication** of the amount of temperature change expected

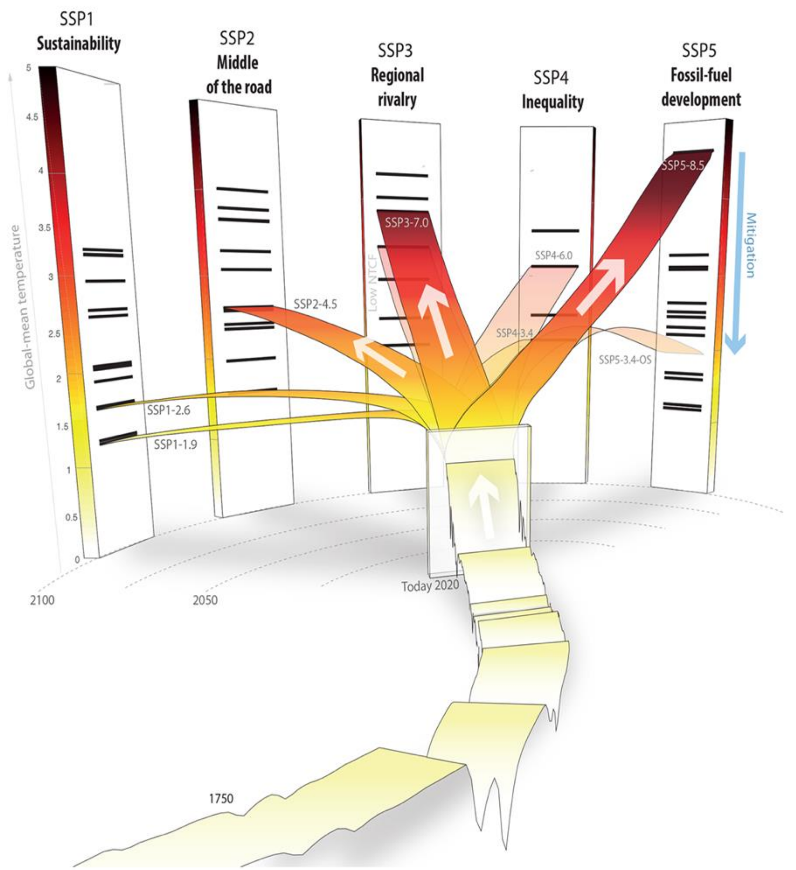


TL/DR ► RCP is an **END** condition for 2100 y how hot will it get in 2100

Shared Socioeconomic Pathways

- **Scenarios** also cover the way our society will address land use and greenhouse gases emissions
- Span a wide range of future outcomes through 2100

SSP1	**Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation**
SSP2	**Middle of the Road (Medium challenges to mitigation and adaptation)** • This future poses moderate challenges to mitigation and moderate challenges to adaptation • Population growth stabilizes toward the end of the century • Current social, economic, and technological trends continue • Global and national institutions make slow progress toward achieving sustainable development goals
SSP3	**Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)**
SSP4	**Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)**
SSP5	**Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)** • This future poses high challenges to mitigation and low challenges to adaptation • Global population peaks mid-century • Emphasis on economic growth and technological progress • Global adoption of resource and energy intensive lifestyles • Lack of environmental awareness



Source: *Climate Change 2021, Chen et al*

TL/DR ► SSP y how do we get there?

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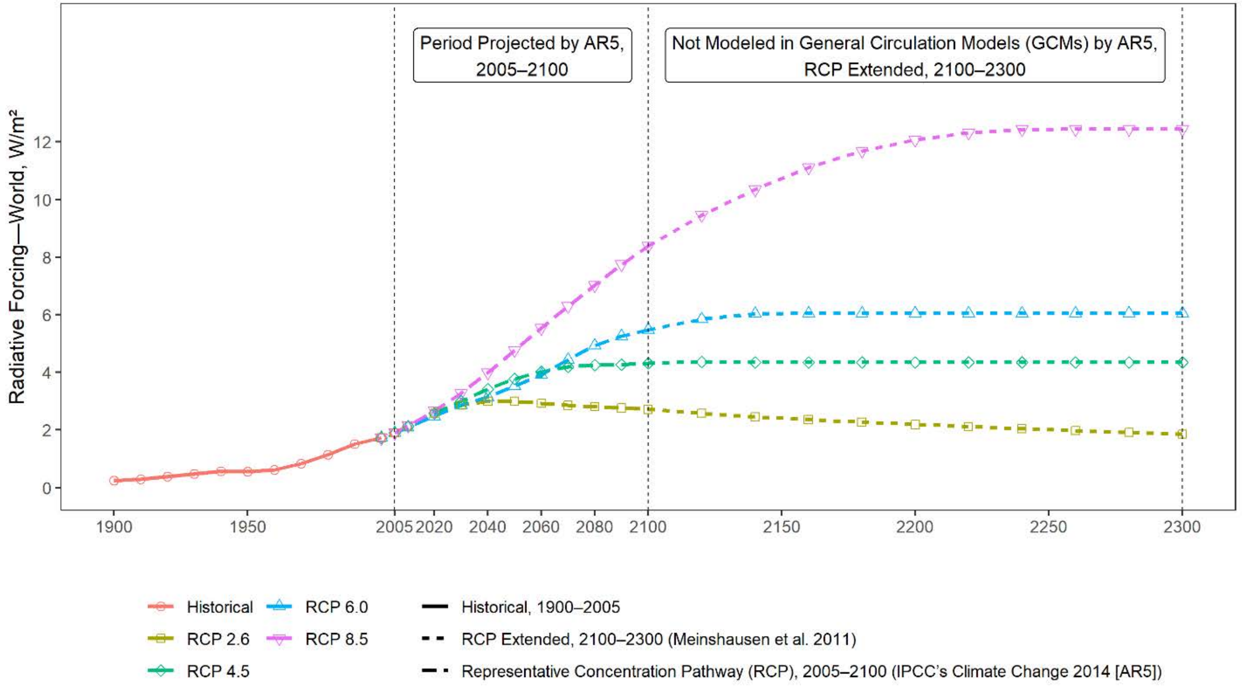
Projection Periods

- GCMs provide historical baseline results from 1900 through 2014 and projections out to 2100
- GCM model results often grouped in 30-year *chunks* for climate normals.
  - 2020's (2011-2039)
  - 2050's (2040-2069)
  - 2089's (2070-2099)
- GCMs don't predict past 2100, and should not be "straight lined" beyond that
  - No basis to believe these trends could continue for 100's of years

Projections beyond 2100 are not typically presented – so what does design for perpetuity mean?



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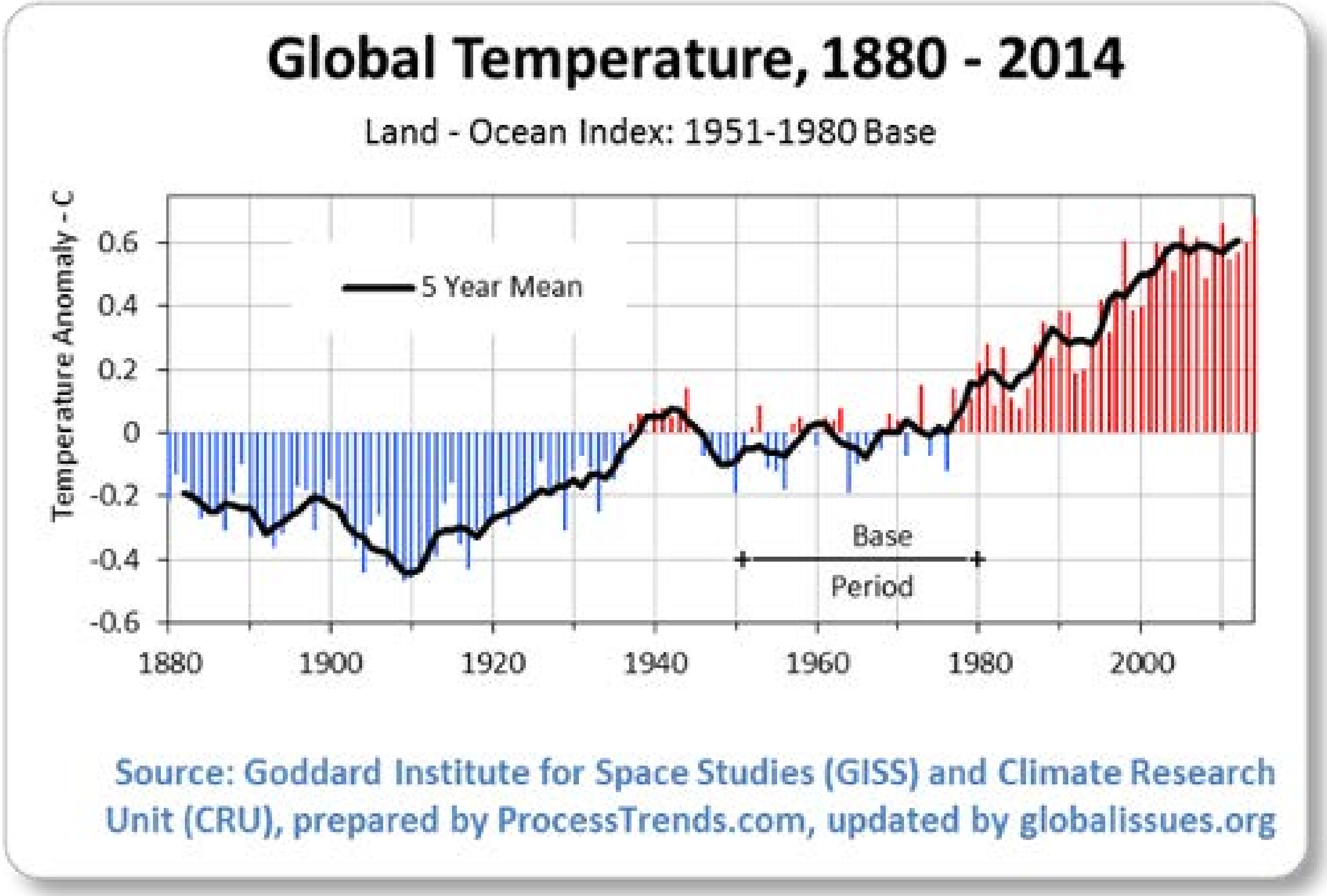
General background – Baseline and Anomaly

Baseline is the period to be compared with other future periods. In this case baseline (base) is considered between 1951 to 1980.

Anomaly is considered the difference with respect to a baseline period

Baseline values are typically annual averages against the 30-year baseline average as reported by the model



Temperature Anomalies are typically described as Δ Temperature from Baseline

ΔT_{avg} = Temperature – Baseline Temperature (± °C)

Precipitation Anomalies are typically described as relative change from baseline

$$\Delta P_{annual} = \frac{\text{Annual Precipitation} - \text{Baseline Precipitation}}{\text{Baseline Precipitation}} (\pm\%)$$

Background – TL/DR

- Terminology is important and we love our jargon

Concept	Meaning	It really means…
IPCC	Intergovernmental Panel on Climate Change	International body that produces the models used for climate change predictions
RCP	Heat balance of the planet in the year 2100	How hot will the planet get by 2100
SSP	5 different pathway to year 2100 of land use, population growth, greenhouse gas emissions, etc. for the whole planet	How will society respond to climate change
Baseline	Baseline temperature and precipitation	Climate in the end of the last century
Anomaly	Difference in precipitation or temperature from a baseline value	Change from baseline
AR{X}	Assessment Report Number {X}	Identify which climate study report (issued about every 5 yrs)
GCM	General Circulation Model	Single Climate Prediction Model
CMIP	Coupled Model Intercomparison Project	Comparison of multiple Climate Prediction Models
Projection Period	Multi-decade block to evaluate climate change anomalies within a window of time	Break down climate change into 20 to 30-year windows

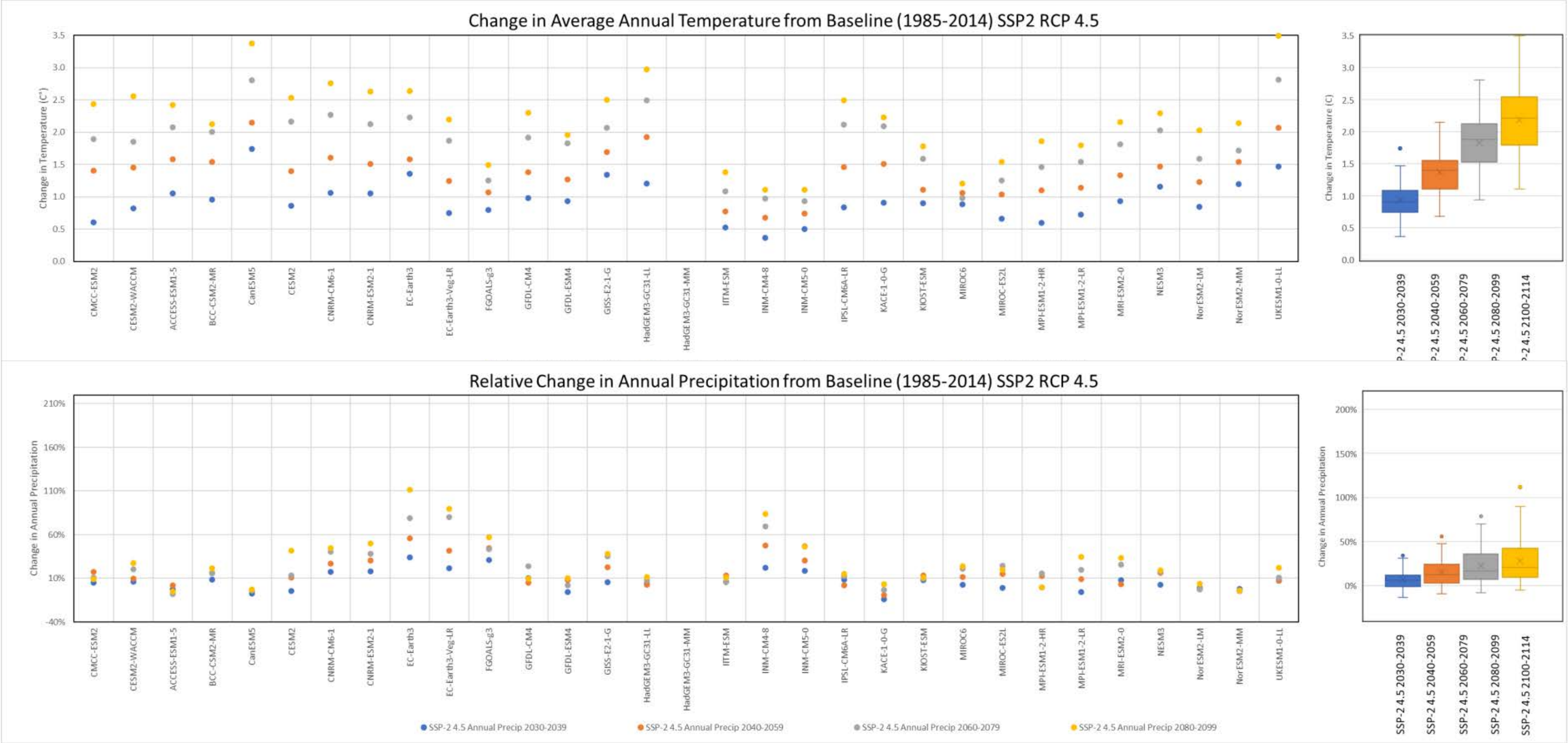
What anomaly to use to predict Climate Change

- We don’t know which GCM is the right one
  - Select the average anomaly for all the models
  - **Reasonably conservative** given the lack of knowledge of the future
- Especially appropriate if we will get a chance to observe conditions and correct our design

If we only have one chance to do it right (e.g. closure design for perpetuity <u>today</u>), we should be more conservative and explore the whole range of climate change response

Understanding the Uncertainty in the GCMs

- Must evaluate each Scenario separately   SSP-2 ≠ SSP-5 – cannot be combined
- For any given scenario, what is the range of the anomaly predictions for all the GCMs?



In the Box and whisker plot, 50% of the results (25% to 75%) will show up **in** the box, and any points outside ~3 sigma will show up outside the whiskers

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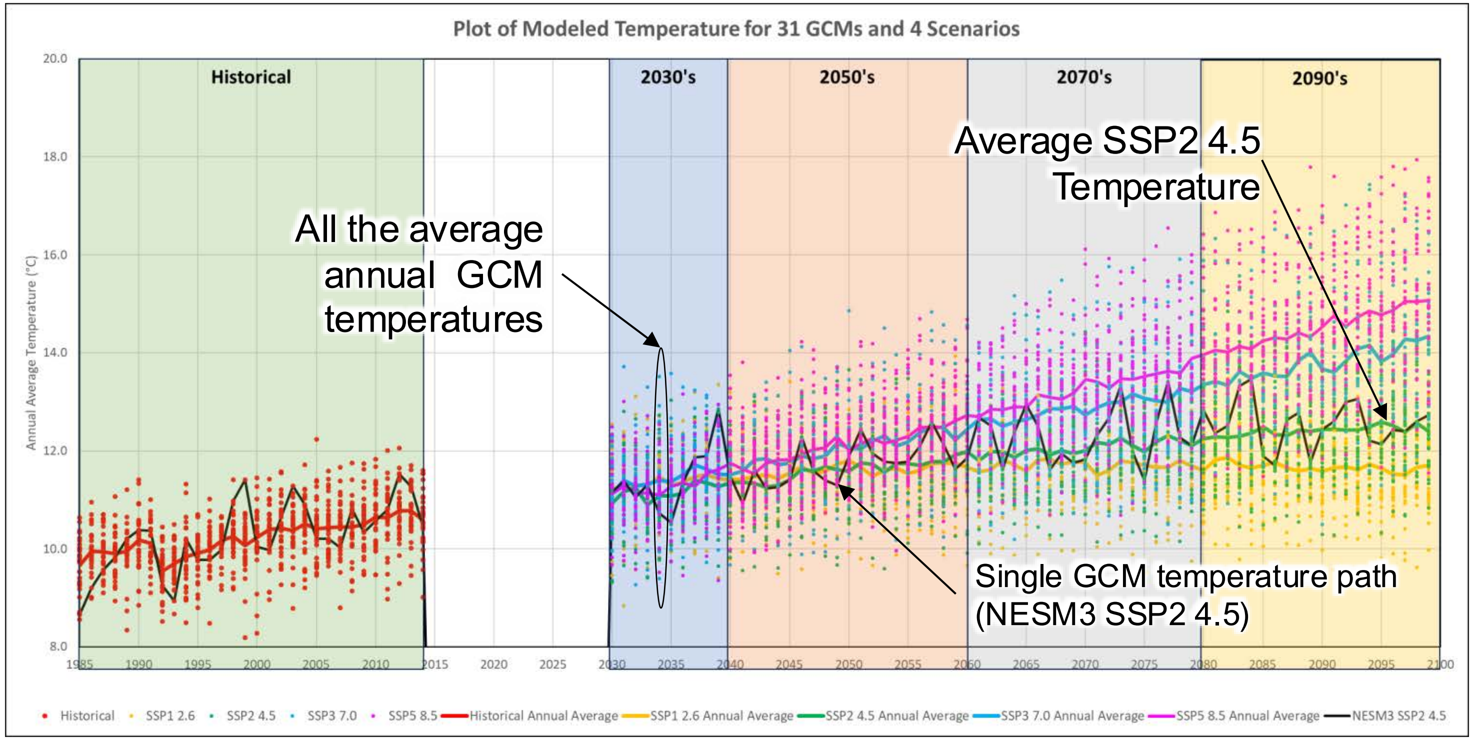
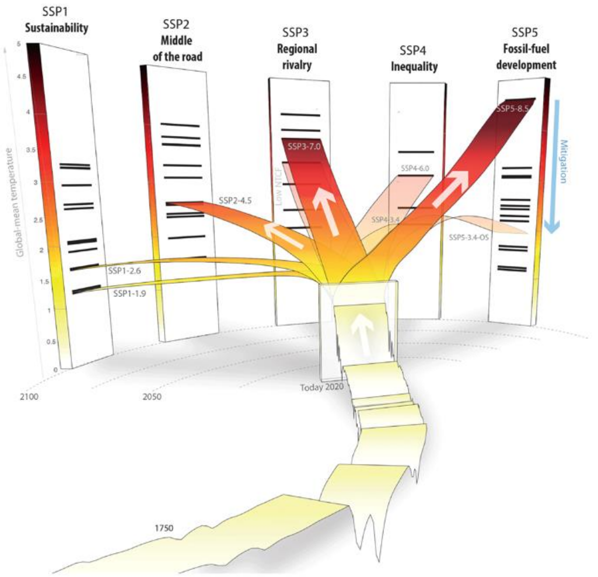
What does the Uncertainty look like?

- 4 Scenarios (SSP & RCP)
- Up to 34 Models within each Scenario
- Typically, 3-4 Projection Periods





Meinshausen, et al., 2020

- Every GCM has their own "Path" that is a function of individual assumptions and boundary conditions
- As each GCM is equally likely, the average of all the GCMs is a reasonable assumption

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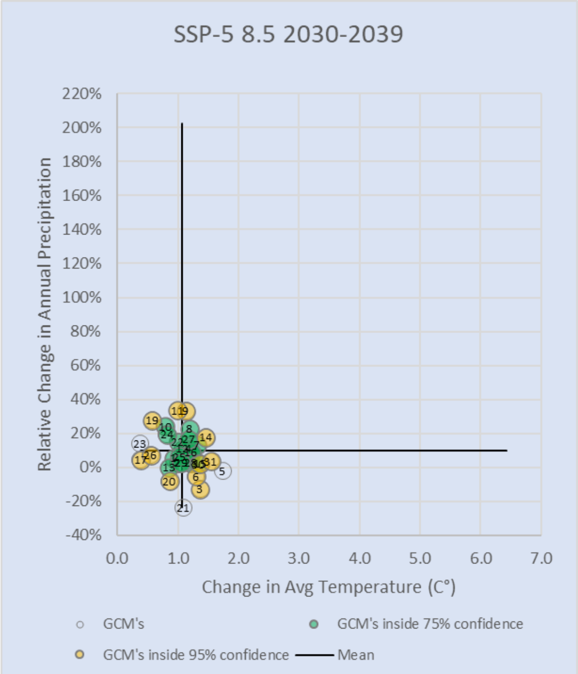
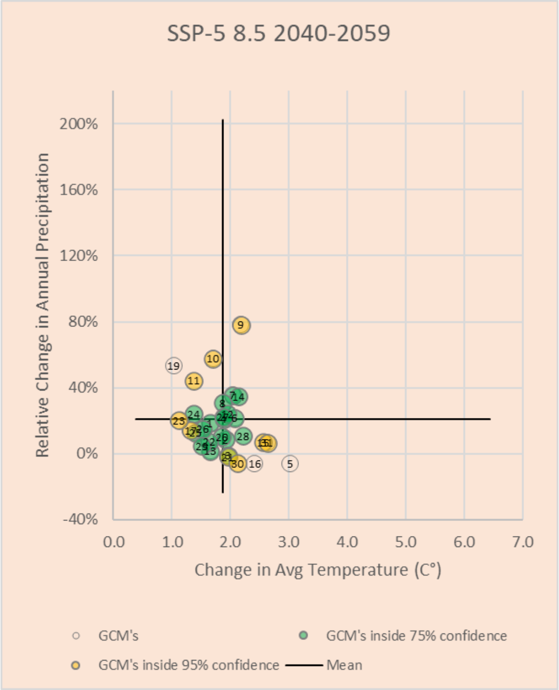
Scatter Plot of Relative Change through Time

Plotting Temperature and Precipitation anomalies for a single scenario through 4 Projection Periods

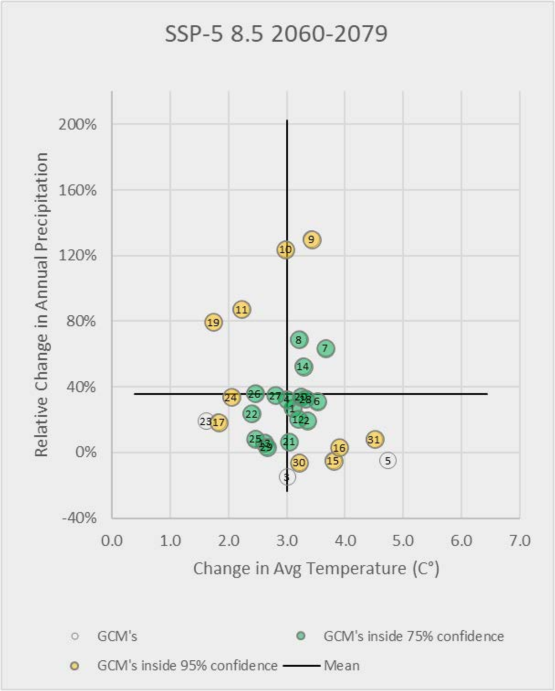
2030's



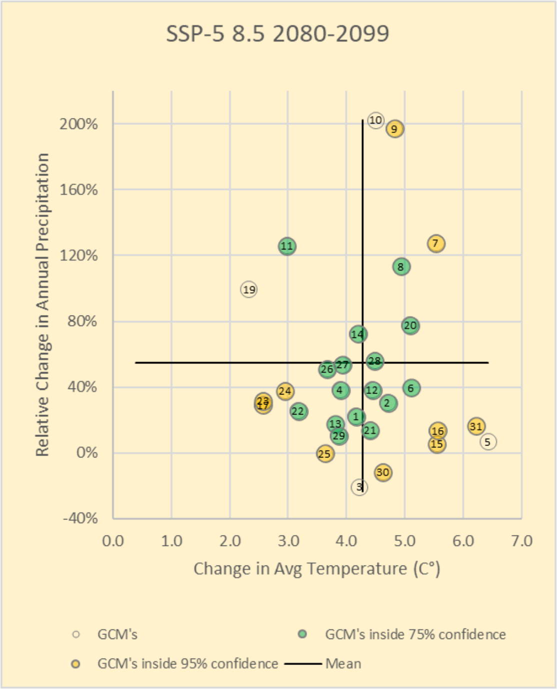
2050's



2070's



2090's



Any scenario is in fact a cloud of 25-34 different GCM results.

The cloud of uncertain expands as we include more models, more scenarios, and farther projections

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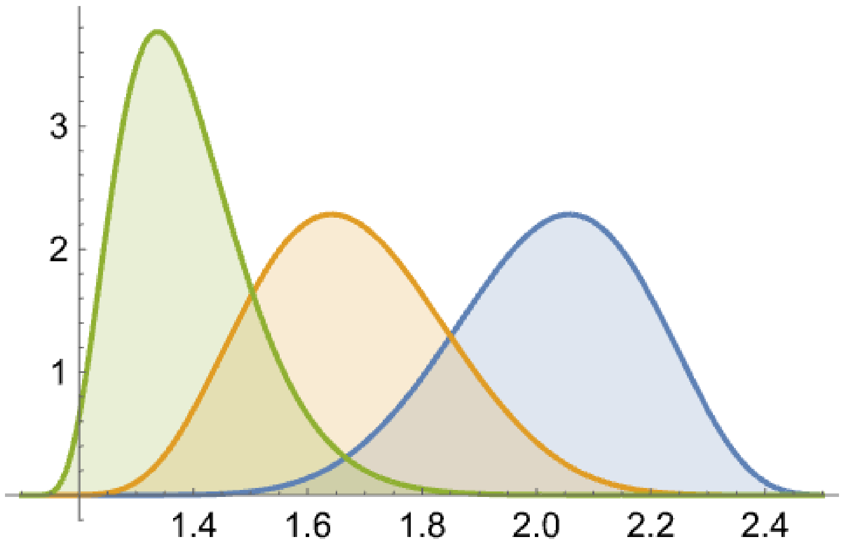
Making it happen in GoldSim

GoldSim

aka – Lets hit it with a Hammer of Monte-Carlo

WGEN distribution fitting

- Goldsim has a long history of using the WGEN model for a daily stochastic climate generator as others have described earlier
- The original WGEN model (Richardson & Wright, 1984) works with a static climate model – i.e. mean temperatures don't change
- GCMs are very complex, GoldSim climate simulation must be dynamic but simpler than that
- Original WGEN Precipitation model assumes the non-zero precipitation distribution is a 2-parameter gamma
  - Only needs mean and std deviation, very easy to fit
  - Sometimes, other distributions will fit better.



Johnson SB distribution
(Source: reference.Wolfram.com)

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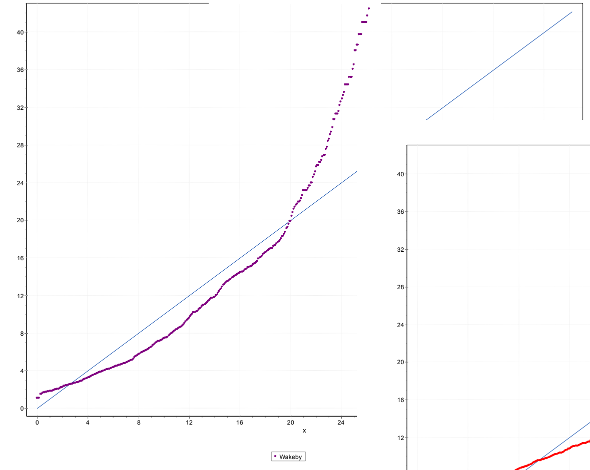
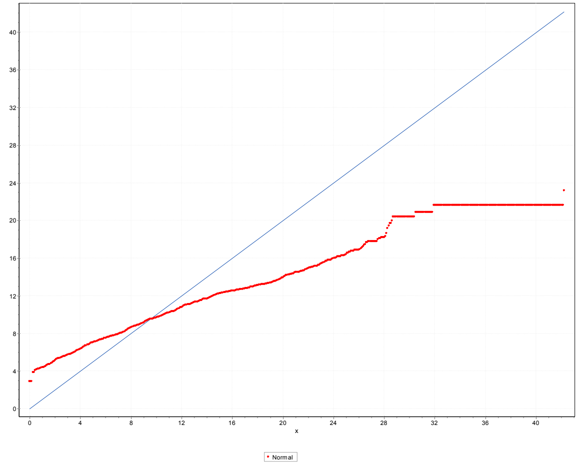
WGEN Distribution fittings

- Fit the distribution and plot Quantile-Quantile plots (Q-Q plots)
- Note that a straight 45° line means the shape of the distribution is correct (e.g. left skew, thickness of tails, etc.) and if it plots ON the line the scale is correct too

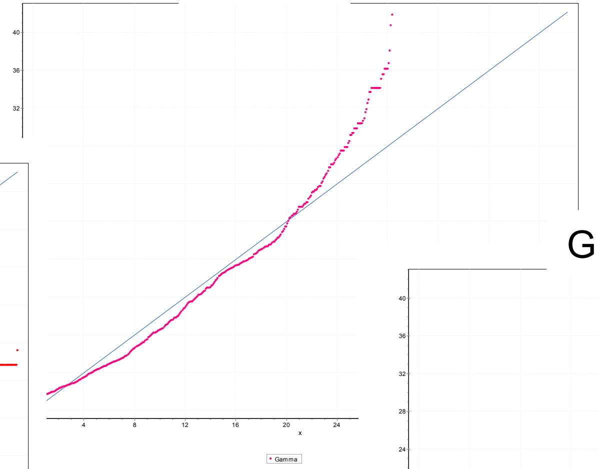
Wakeby



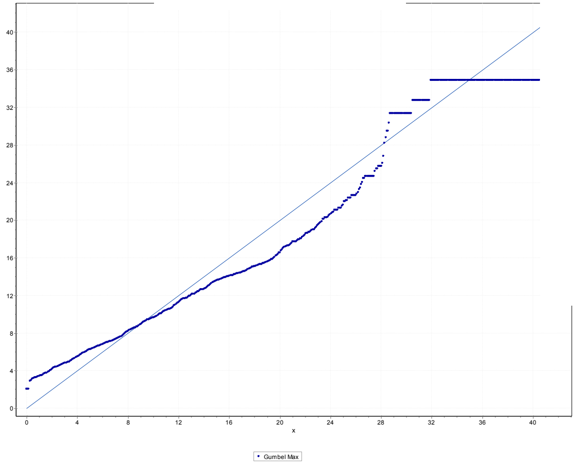
Normal



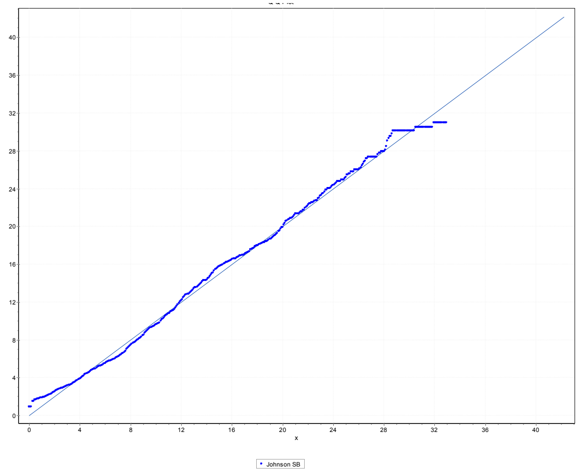
Gamma



Gumbel Max



Johnson SB



Generally, see one of these five give the best results

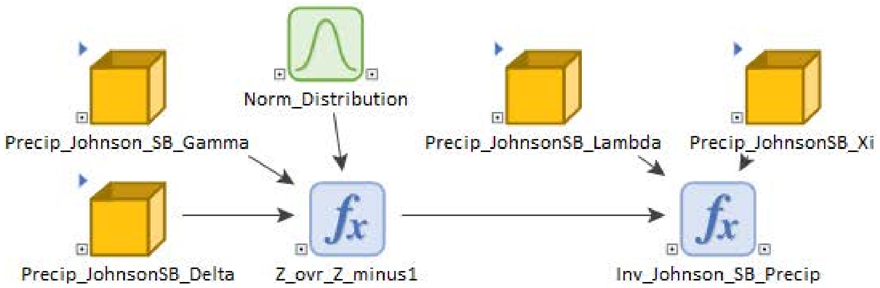
Adjusting WGEN for Climate Change Precipitation

- WGEN didn't account for change over time
- SRK incorporates multiple WGEN parameter sets for multiple prediction periods and can select different distributions over time
  - Similar to the Original WGEN, each set contains monthly tables for:
    - Probability of Rain day ($P_{wet\text{-}wet}$ and $P_{wet\text{-}dry}$)
    - If Rain day, Fitted parameters for non-zero precipitation distribution

    This is the Markov Chain Component

    - JohnsonSB distribution (transformed normal): Shape γ, Shape δ, Scale λ , Location ξ works very well and can be reproduced in GoldSim, but others work better in different locations

Simulate precipitation depth using the Johnson SB distribution, which uses a transformed Normal Distribution shape



Johnson SB Distribution

Probability Density Function

$$f(x) = \frac{\delta}{\lambda\sqrt{2\pi}\,z(1-z)} \exp\left(-\frac{1}{2}\left(\gamma + \delta \ln\left(\frac{z}{1-z}\right)\right)^2\right)$$

Cumulative Distribution Function

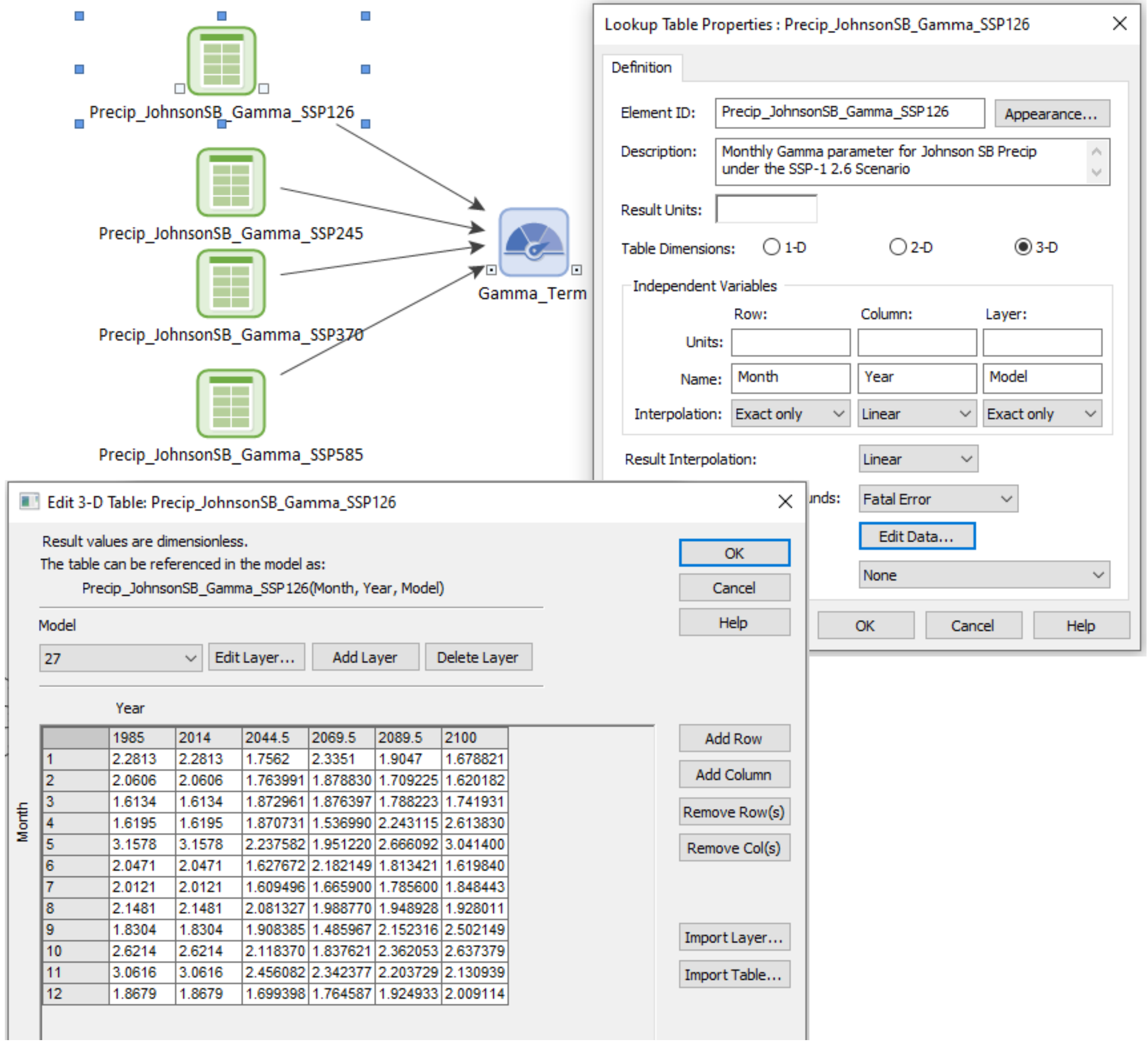
$$F(x) = \Phi\left(\gamma + \delta \ln\left(\frac{z}{1-z}\right)\right)$$

where $z \equiv \frac{x-\xi}{\lambda}$, and Φ is the Laplace Integral. (normal distribution)

Adjusting WGEN for Climate Change Precipitation

- However, each set ALSO contains:
  - 3D lookup tables for each climate scenario
  - Calendar year ‘hinge points’ to project trends
  - Separate layers for each GCM data set used
- GoldSim linearly interpolates between the hinge points according to the calendar year

KEY ASSUMPTION – adjusting distribution parameters between calendar years results in valid distributions

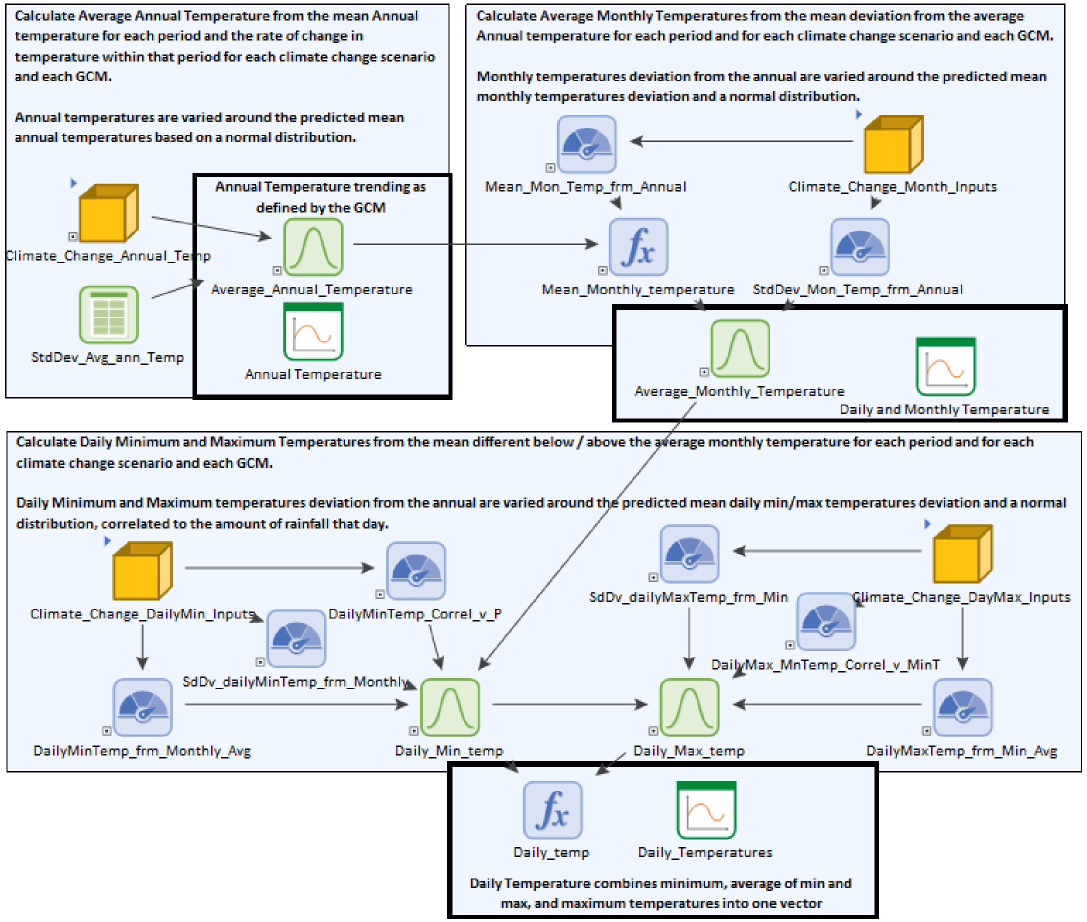


	1985	2014	2044.5	2069.5	2089.5	2100
1	2.2813	2.2813	1.7562	2.3351	1.9047	1.678821
2	2.0606	2.0606	1.763991	1.878830	1.709225	1.620182
3	1.6134	1.6134	1.872961	1.876397	1.788223	1.741931
4	1.6195	1.6195	1.870731	1.536990	2.243115	2.613830
5	3.1578	3.1578	2.237582	1.951220	2.666092	3.041400
6	2.0471	2.0471	1.627672	2.182149	1.813421	1.619840
7	2.0121	2.0121	1.609496	1.665900	1.785600	1.848443
8	2.1481	2.1481	2.081327	1.988770	1.948928	1.928011
9	1.8304	1.8304	1.908385	1.485967	2.152316	2.502149
10	2.6214	2.6214	2.118370	1.837621	2.362053	2.637379
11	3.0616	3.0616	2.456082	2.342377	2.203729	2.130939
12	1.8679	1.8679	1.699398	1.764587	1.924933	2.009114

Adjusting WGEN for Climate Change Temperature

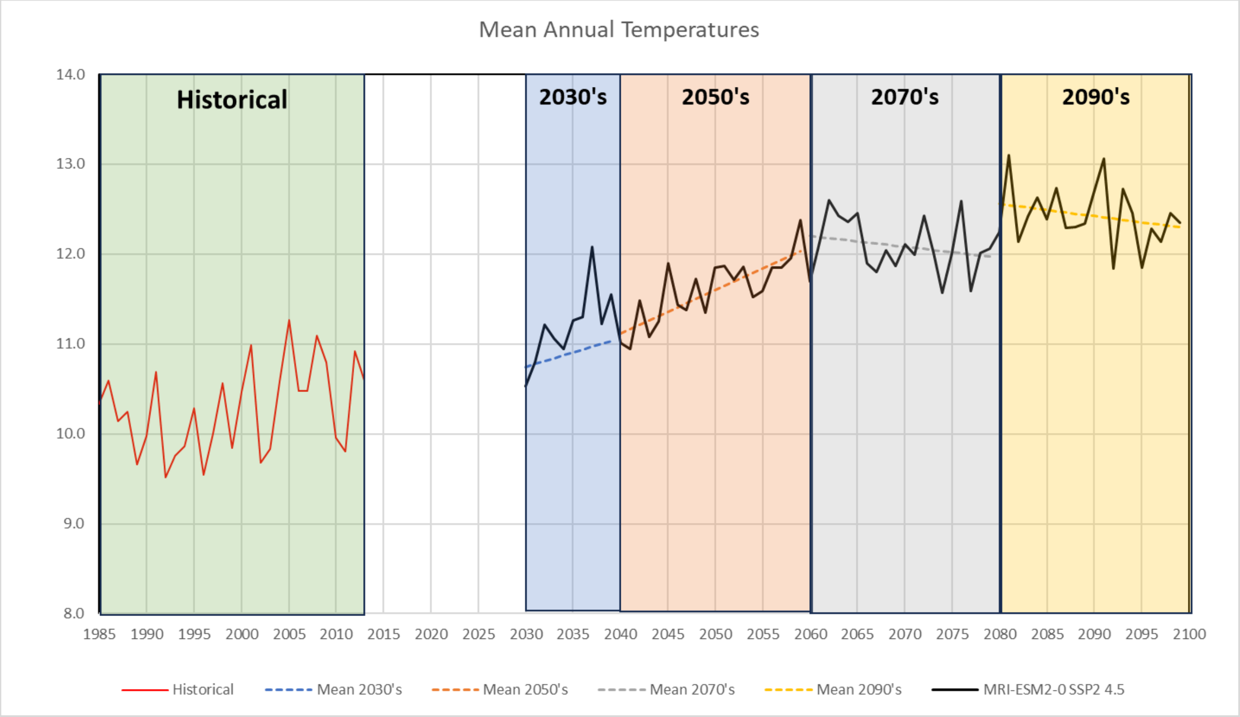
Dynamic temperature model

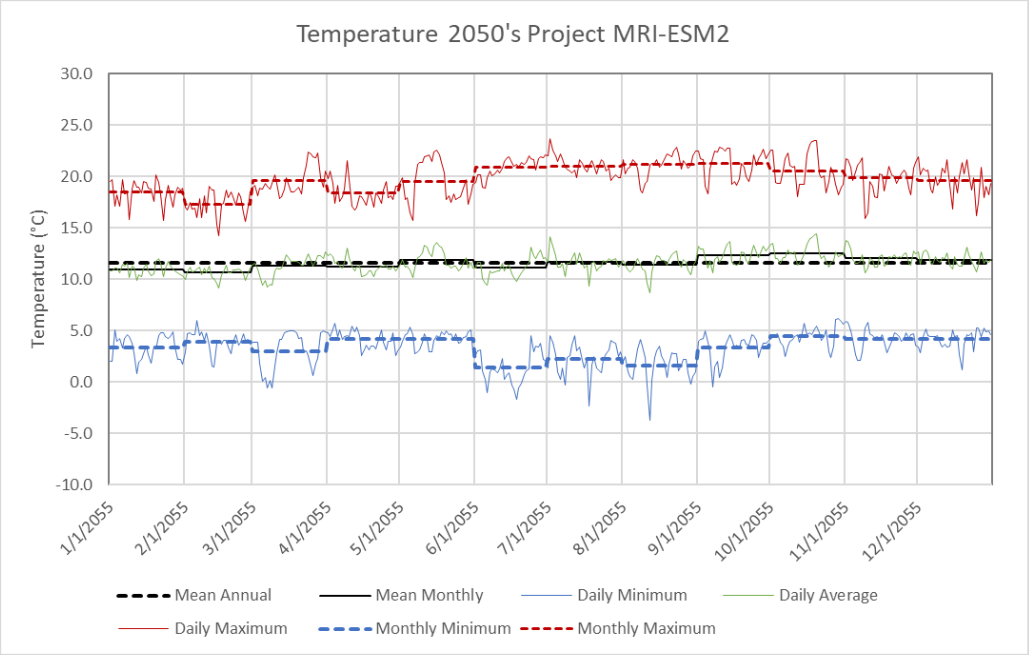
- Mean annual temperature is adjusted every year, and monthly and daily vary from that basepoint
- 3D Tables for
  - Mean Annual temperature and rate of change
  - Annual temperature offset from mean
  - Monthly offset from annual mean
  - Correlate precipitation to min and max temperature
  - Daily temperature (Mean – Min) offset
  - Daily temperature (Max – Mean) offset



Adjusting WGEN for Climate Change

- Model calculates mean annual Temperature from trend lines
- Generates an offset Δ°C from the mean
- Generates monthly temperature offset Δ°C from the annual

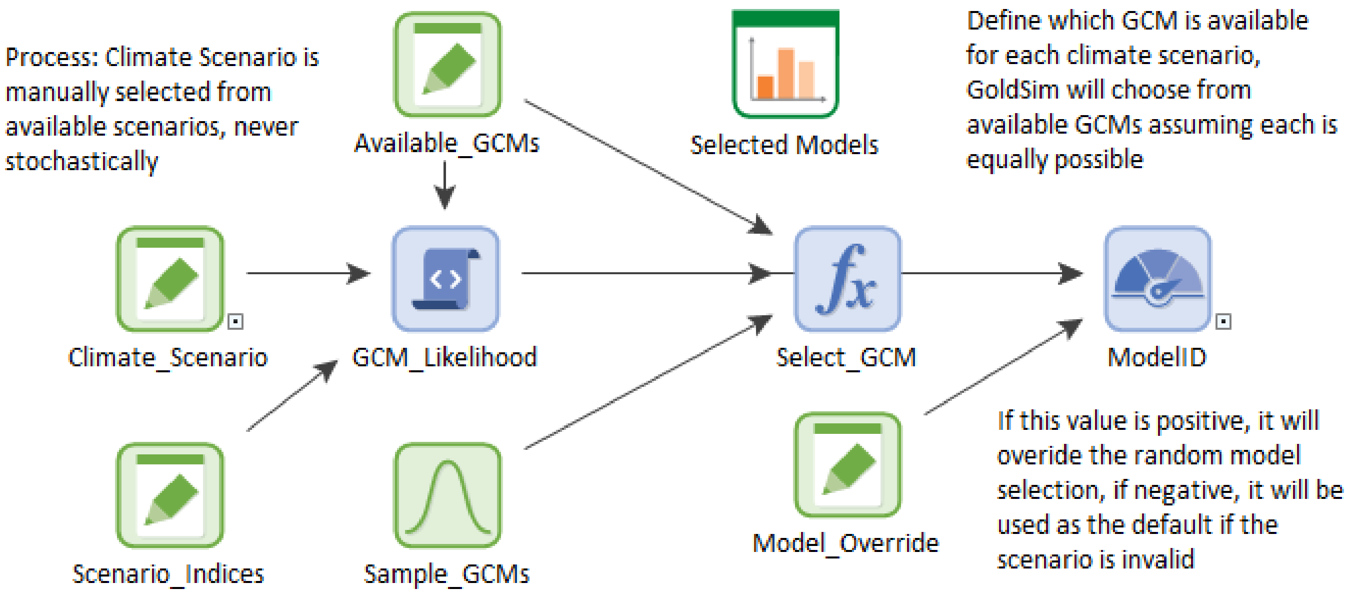


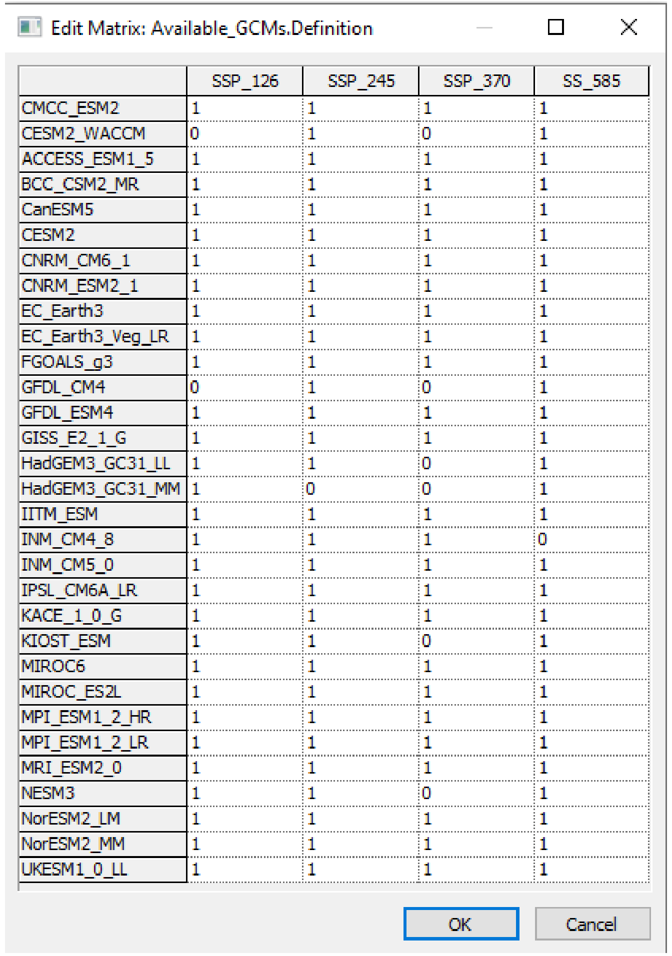


- Generates average daily temperature Δ°C from the monthly average
- Generates minimum daily temperature Δ°C below the average daily temperature
- Generates maximum daily temperature Δ°C above the daily minimum temperature

Adjusting WGEN for Climate Change

- As mentioned earlier, not every GCM is available for every scenario or parameter
- We may also not want to use some GCMs which are outliers in one scenario and valid in another
- Within each climate scenario, we define which of the models are valid
- GoldSim script dynamically develops a table (similar to the discrete distribution) that allows for any of the available models to be selected with equal likelihood





	SSP_126	SSP_245	SSP_370	SS_585
CMCC_ESM2	1	1	1	1
CESM2_WACCM	0	1	0	1
ACCESS_ESM1_5	1	1	1	1
BCC_CSM2_MR	1	1	1	1
CanESM5	1	1	1	1
CESM2	1	1	1	1
CNRM_CM6_1	1	1	1	1
CNRM_ESM2_1	1	1	1	1
EC_Earth3	1	1	1	1
EC_Earth3_Veg_LR	1	1	1	1
FGOALS_g3	1	1	1	1
GFDL_CM4	0	1	0	1
GFDL_ESM4	1	1	1	1
GISS_E2_1_G	1	1	1	1
HadGEM3_GC31_LL	1	1	0	1
HadGEM3_GC31_MM	1	0	0	1
IITM_ESM	1	1	1	1
INM_CM4_8	1	1	1	0
INM_CM5_0	1	1	1	1
IPSL_CM6A_LR	1	1	1	1
KACE_1_0_G	1	1	1	1
KIOST_ESM	1	1	0	1
MIROC6	1	1	1	1
MIROC_ES2L	1	1	1	1
MPI_ESM1_2_HR	1	1	1	1
MPI_ESM1_2_LR	1	1	1	1
MRI_ESM2_0	1	1	1	1
NESM3	1	1	0	1
NorESM2_LM	1	1	1	1
NorESM2_MM	1	1	1	1
UKESM1_0_LL	1	1	1	1

Climate Change Incorporation into GoldSim Water Balance Workflow

- Identify Climate Change Scenarios to incorporate in the Study
  - Typically, SSP-2 RCP 4.5 and SSP-5 RCP 8.5
  - Also see SSP-1 RCP 2.6 and SSP-3 RCP 7.0
- Download all available files from CIMP
  - Daily data from baseline to 2099, at least Tmin,Tmax, Tavg, Precip
  - 1950-2099, 34 models, 4 scenarios ► up to 7.4 million lines of data
- Determine Projection Periods (capture critical points in time)
- Use Microsoft Power Query to format data files
  - Time series - baseline through 2099
  - By GCM, by Scenario (including historical) ► up to 170 files

Climate Change Incorporation into GoldSim Water Balance Workflow (cont)

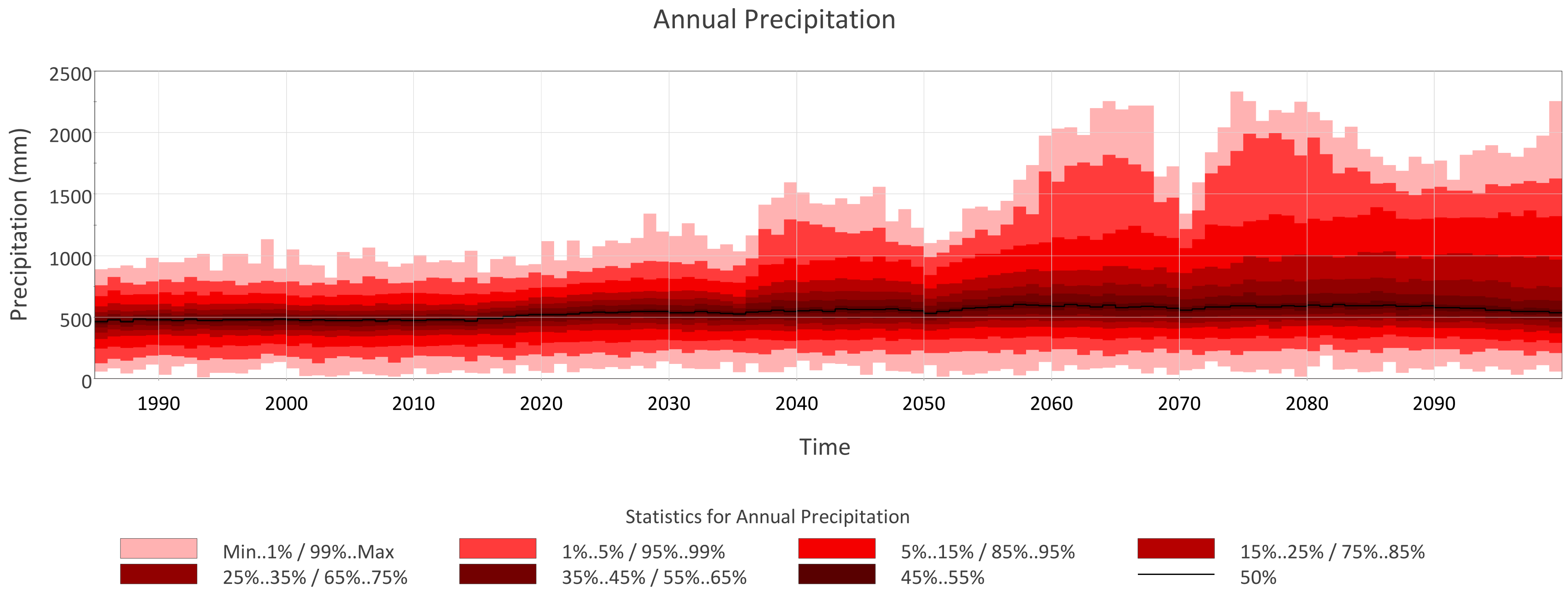
- Evaluate precipitation probability distributions (which is the most appropriate fit? – one distribution to rule them all?)
- Using custom python tool, develop WGEN parameters for each GCM used for each projection period
  - 4-6 monthly precipitation parameters (depends on distribution)
  - 3 annual and 2 monthly temperature parameters
  - 6 parameters for daily minimum and maximum temperatures
  - Export to text or Excell file for import into GoldSim 3D table
  - 12 months x 4-5 hinge point years x 25-34 models
    - (rows x columns x layers)
  - 2 to 4 3D lookup tables each, one for each scenario included

GoldSim Modeling Process

- User selects a climate scenario:
  - Optimistic: SSP-1 RCP 2.6
  - Middle of the road: SSP-2 RCP 4.5 or SSP-3 RCP 7.0
  - Pessimistic: SSP-5 RCP 8.5
- Begin simulation:
  - Each realization: Randomly select GCM
    - Each Year: Stochastically generate mean annual temperature and monthly tables of precipitation and temperature parameters
      - Each Month: Stochastically generate mean monthly temperature and extract daily temperature and precipitation parameters
        - Each Day: Stochastically generate daily precipitation depth, minimum, maximum and average temperature

Generate Cloud of temperature and Precipitation Results

- Stochastic results for SSP-2 4.5 climate predictions, using 7 of the 31 available GCMs for a site in South America



Summary

- Because future IS uncertain, results are not fixed values but ranges.
- Climate Projections out to year 2099 using the WGEN stochastic climate generator in GoldSim that captures a large part of the uncertainty
- For simplicity, these ranges **can** be presented as median value; however, we may need to ncorporate more uncertainty for highly conservative designs
- The climate change model produces daily precipitation and temperature that can be fed into the hydrologic models
  - Rainfall-runoff (GR4J, AWBM, etc.)
  - Snowpack/snowmelt (CemaNeige, Snow 17)
- These models can then feed the water balance model to predict long-term climate that incorporates the full range of climate change predicted