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Assessment of Future Climate Change
Introduction to the Exercises

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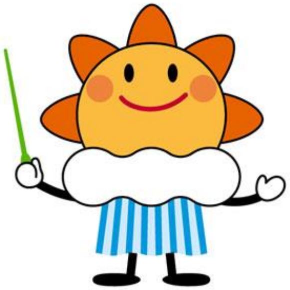

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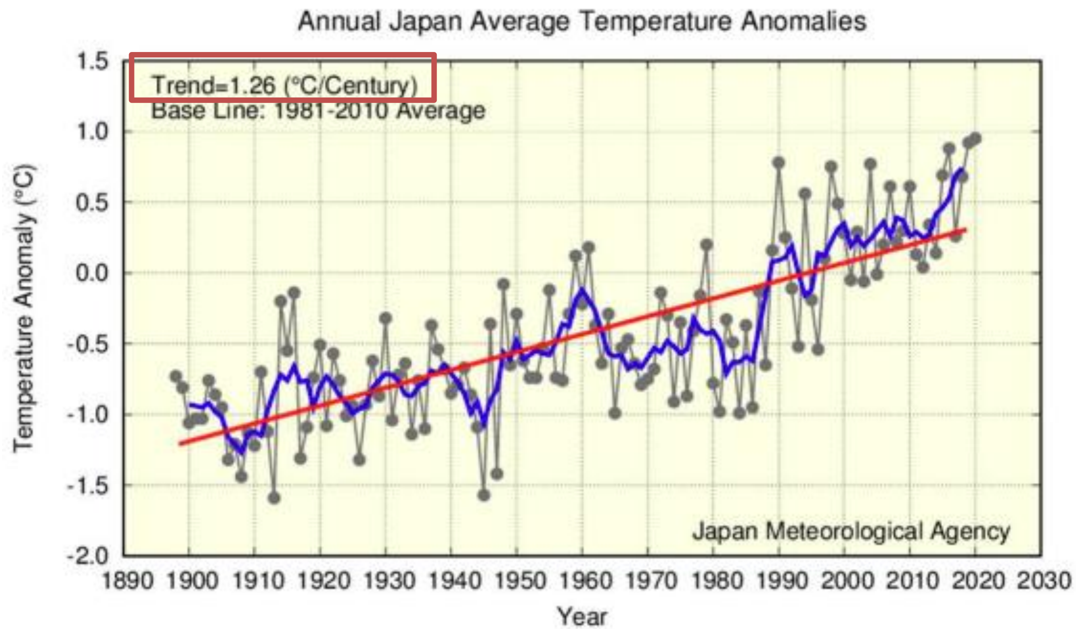
Description of a long-term trend

- JMA Climate Change Monitoring Report 2020
  - On a longer time scale, it is virtually certain that the annual mean surface temperature over Japan has risen at a rate of 1.26ºC per century (statistically significant at a confidence level of 99%).



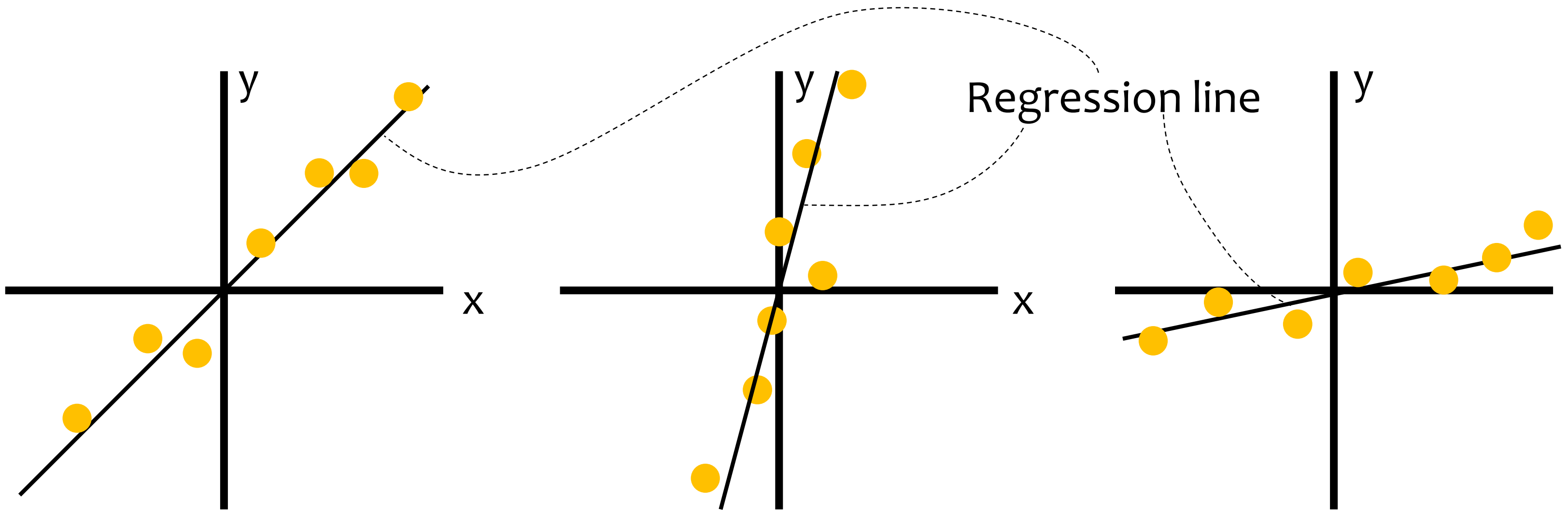
Long-term trend

Significant test

https://www.jma.go.jp/jma/en/NMHS/ccmr/5_Chapter2.pdf

Linear regression analysis

- When data has a linear relationship, a linear regression coefficient (a slope of a regression line) is data's trend.
- Since the slope is given by $\Delta y/\Delta x$, regression coefficients mean how much the variable y changes when the variable x changes.

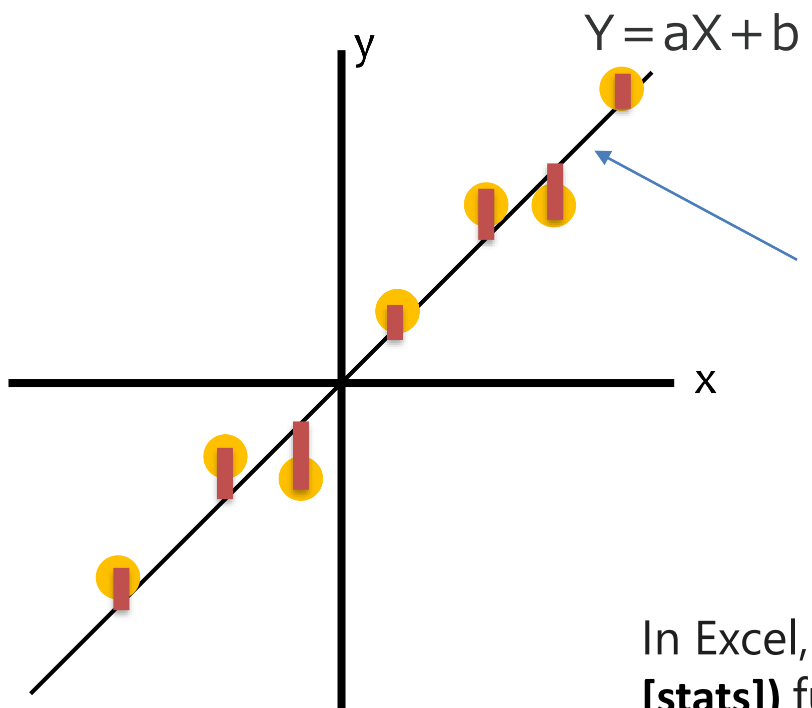


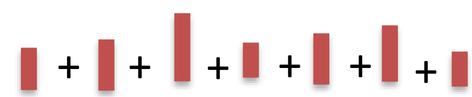
Regression coeff. ~ +1 | Regression coeff. ~ +0.5 | Regression coeff. ~ +3

Least-squares method

Least-squares method

- a standard approach in linear regression analysis, by minimizing the sum of the squares of the residuals between observed values and the fitted values.



Residuals = 

Find the optimal linear model that minimizes the residuals (the error of estimation)

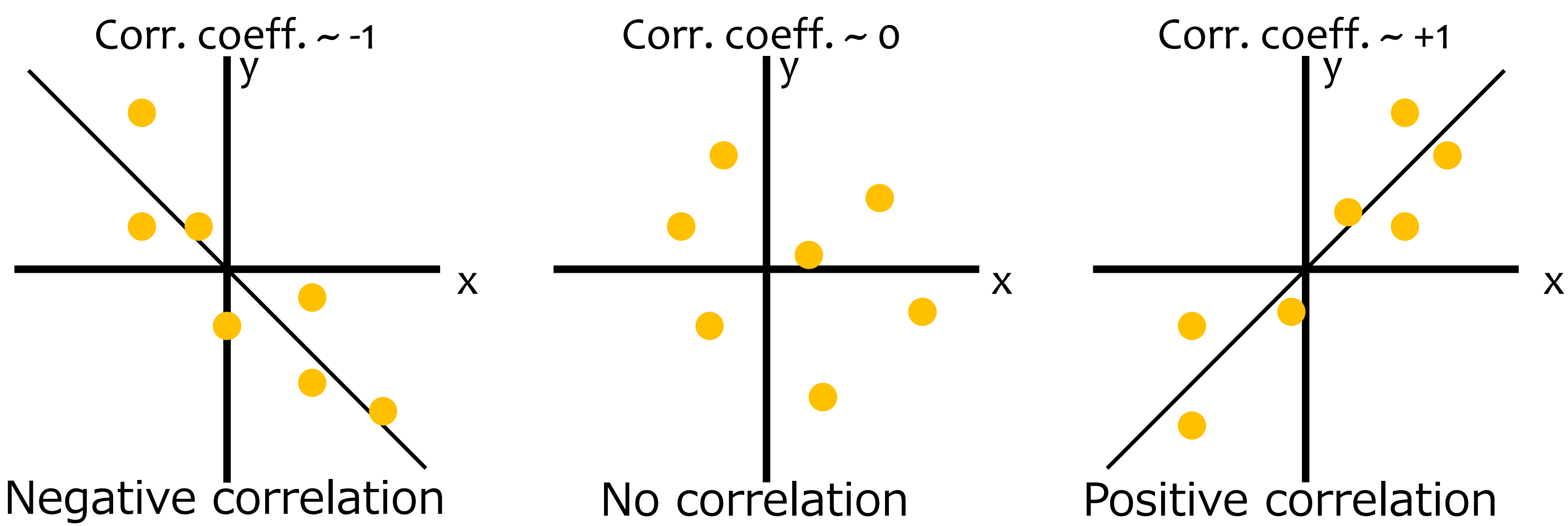
$$m = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sum (x-\bar{x})^2}$$

$$b = \bar{y} - m\bar{x}$$

In Excel, the **LINEST(known_y's, [known_x's], [const], [stats])** function returns the m-coefficients and the constant b.

Correlation analysis

- Correlation coefficient: How close they have a linear relationship
  - Correlation coefficient values are between -1 and +1.
  - The value close to +1 (or -1) means there is a clear positive (negative) linear relationship between the targeted data pair, and the value around zero means there is little (or weak) relation between them.



Pearson correlation coefficient

Pearson correlation coefficient

- The ratio between the covariance of two variables and the product of their standard deviations (normalizing the covariance to a value between -1 and 1)

$$\frac{\text{Covariance of x and y}}{\text{(Standard deviation of x) x (Standard deviation of y)}} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-\bar{y})^2}}$$

$$= \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}}$$

xi, yi: single value of dependent variable
X, Y: mean of all values of independent variable
n: population count

In Excel, the **CORREL(array1, array2)** function returns the correlation coefficient of two cell ranges.

Statistical test (Student's *t*-test)

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- Does the long-term trend (=correlation) exist?
  - Null hypothesis: "the true correlation coefficient is equal to 0 (no correlation)."
  - Check whether the sample data are inconsistent with the null hypothesis or not
  - if they are inconsistent, then reject the null hypothesis (no correlation) and conclude that "the true correlation coefficient is not 0 (correlation exists)".
  - If the underlying variables have a bivariate normal distribution, Since the sampling distribution of the specific correlation coefficient **T** (Pearson's correlation coefficient divided by the standard error) follows Student's t-distribution with degrees of freedom n-2, if t is significantly (e.g., 99%) unlikely to have occurred in the Student's t-distribution, the null hypothesis is rejected.

$$T = \frac{|r|\sqrt{n-2}}{\sqrt{1-r^2}}$$

Type I and type II errors

- Even if the null hypothesis is rejected at a confidence level of 95%, this does not means the decision is 100% correct.
- Type I error (false positive)
  - Rejecting the null hypothesis which is actually true in reality.
- Type II error (false negative)
  - Not rejecting the null hypothesis which is actually not true in reality.
- Neyman-Pearson lemma
  - Retaining a prespecified level of type I error, subsequently minimize type II error.
- Use the test with the most power at a prespecified confidence level
  - Usually, Student's *t*-test is the good choice.

		Decision about null hypothesis	
		reject	Don't reject
Null hypothesis is	Actually false	○	Type II error (false negative)
	Actually true	Type I error (false positive)	○

Type III error

- Type III error (Another definitions also exist)
  - Choosing the test falsely to suit the significance of the sample.
- The assumptions underlying a *t*-test are:
  - Normality (Samples from Normal Distribution)
  - Independent samples (No autocorrelation. Past values does not affect future one)
  - Homogeneity of variance (from past to future)
- In general, precipitation data does not have normality.
  - If you choose t-test for precipitation, type III error occurs.
  - You have to choose one of the nonparametric statistics, which does not require the assumptions of normality.
    - E.g., Kendall rank correlation coefficient

Kendall rank correlation coefficient

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- Kendall rank correlation coefficient measure the ordinal association between two measured quantities.

(Example)

x	2001	2002	2003	2004	2005
y	1300	1350	1200	1250	1400

2001 -> 2003
2001 -> 2004
2002 -> 2003
2002 -> 2004

(number of concordant pairs) = P = 6 (number of discordant pairs) = Q = 4

(number ways to choose) = ${}_nC_2 = \frac{n(n-1)}{2}$ The binomial coefficient

The Kendall τ coefficient is defined as: $\tau = \frac{P-Q}{\frac{n(n-1)}{2}} = \frac{6-4}{10} = 0.2$

When there are ties, the formula becomes more complicated! I recommend you use R software.

With the independence and larger samples of X and Y, it is common to use an approximation to the normal distribution, with mean zero and variance $\frac{2(2n+5)}{9n(n-1)}$

Therefore, we can conduct statistical test with a standard normal distribution with the modified τ.

$$\frac{\tau}{\sqrt{\frac{2(2n+5)}{9n(n-1)}}} \sim 0.49$$

To be precise, this value is incorrect because of its small sample size. You can calculate the exact value by using R software.

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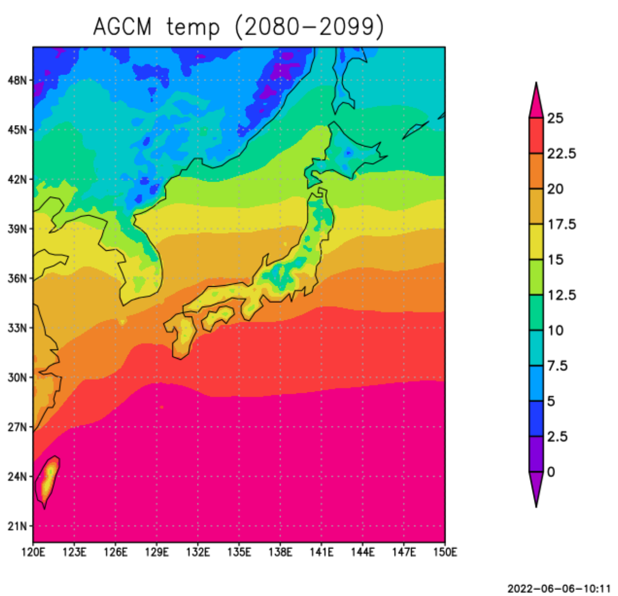
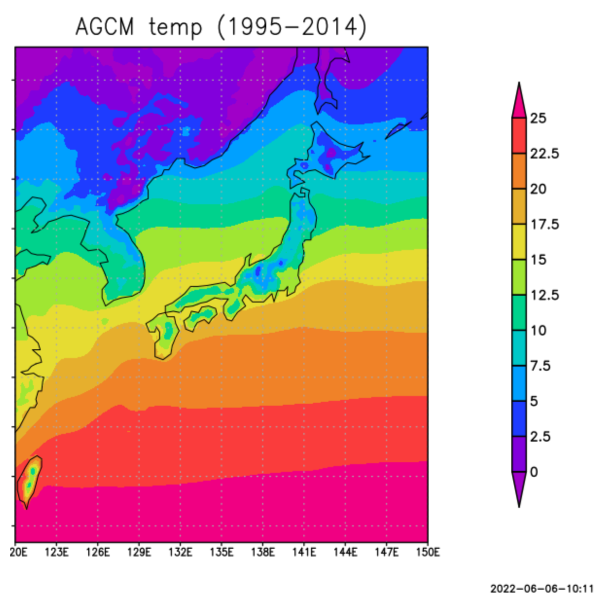
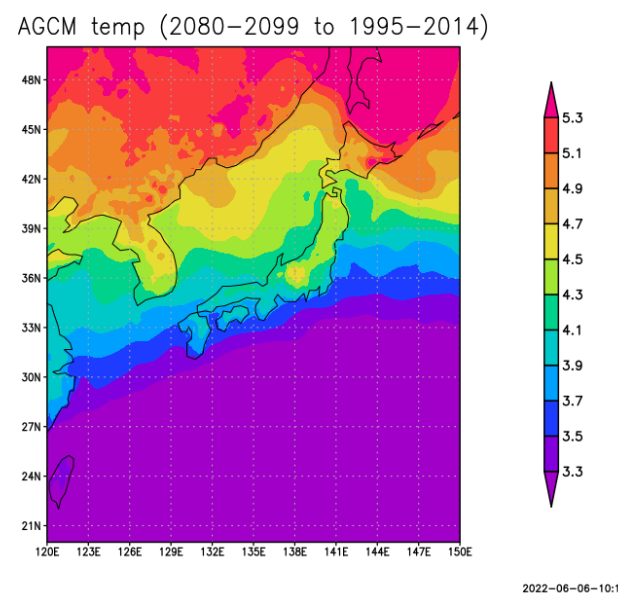
Description of future change

- In general, future changes of climate are described as the difference of climate model outputs between present and future.
  - In this training seminar, we use MRI-AGCM3.2 as the model.

Future (Climate model) − Present (Climate model) = Future change (F–P)



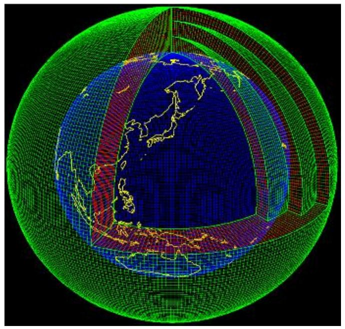




Projection by MRI-AGCM3.2S based on RCP8.5

About MRI-AGCM projection data

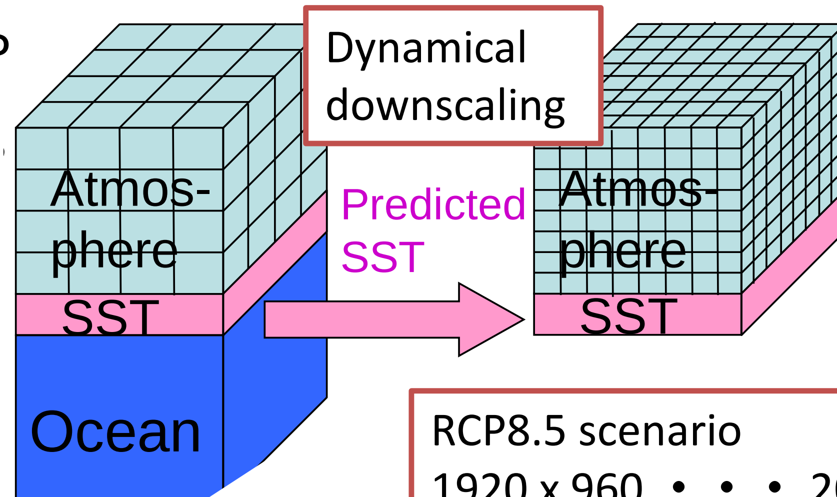
- MRI-AGCM3.2S, the model joining in the CMIP6 (HighResMIP).



MRI-AGCM projection Data

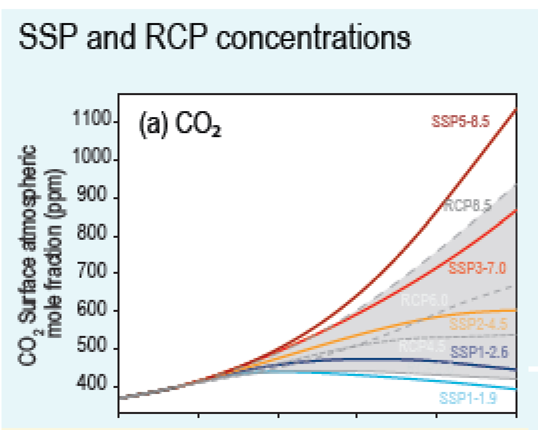
Atmosphere-Ocean Couple Model RCP8.5 Scenario	⇨	High resolution Atmosphere model experiment

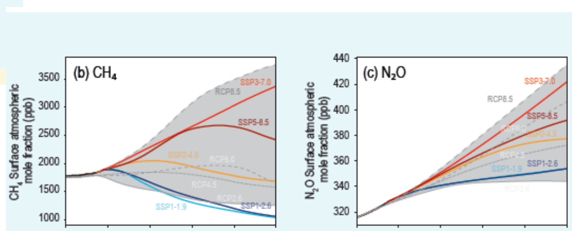
WCRP
CMIP5



20 km grid

RCP8.5 scenario
1920 x 960 ・・・ 20km mesh !!





AR6 WG1 Cross-Chapter Box 1.4, Figure 2

How to obtain MRI-AGCM projection data

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■ Data can be obtained from the WCRP website.

https://esgf-data.dkrz.de/search/cmip6-dkrz/

File Name	Content
tas_Amon_MRI-AGCM3-2-S_highresSST-future_r1i1p1f1_gn_207101-209012.nc tas_Amon_MRI-AGCM3-2-S_highresSST-future_r1i1p1f1_gn_209101-209912.nc	AGCM temperature (monthly, future) [K]
tas_Amon_MRI-AGCM3-2-S_highresSST-present_r1i1p1f1_gn_199001-200912.nc tas_Amon_MRI-AGCM3-2-S_highresSST-present_r1i1p1f1_gn_201001-201412.nc	AGCM temperature (monthly, present) [K]

File Name	Content
pr_Amon_MRI-AGCM3-2-S_highresSST-future_r1i1p1f1_gn_207101-209012.nc pr_Amon_MRI-AGCM3-2-S_highresSST-future_r1i1p1f1_gn_209101-209912.nc	AGCM precipitation (monthly, future) [kg m-2 s-1]
pr_Amon_MRI-AGCM3-2-S_highresSST-present_r1i1p1f1_gn_199001-200912.nc pr_Amon_MRI-AGCM3-2-S_highresSST-present_r1i1p1f1_gn_201001-201412.nc	AGCM precipitation (monthly, present) [kg m-2 s-1]

How to obtain MRI-AGCM projection data

- By using GrADS or OpenGrADS, time series of output values can be obtained easily.
  - However, the operation of GrADS or OpenGrADS is beyond the scope of this training seminar.
  - In this training seminar, simplified csv data prepared by lecturer will be provided for time saving.

COLA — Grid Analysis and Display System (GrADS) — George Mason University

OpenGrADS "Opening GrADS to a World of Extensions"

http://cola.gmu.edu/grads/
http://opengrads.org/

```
ga-> sdfopen temp/tas_Amon_MRI-AGCM3-2-S_highresSST-present_r1i1p1f1_gn_199001-200912.nc
ga-> set lon 139.75
ga-> set lat 35.69
ga-> set gxout print
ga-> set prnopts %7.3f 1 1
ga-> set time jan1995 dec2009
ga-> d tas
```

- Open a file
- Longitude and Latitude Setting
- Print format
- Set time range and Draw

```
ga-> sdfopen temp/pr_Amon_MRI-AGCM3-2-S_highresSST-present_r1i1p1f1_gn_199001-200912.nc
ga-> set lon 139.75
ga-> set lat 35.69
ga-> set gxout print
ga-> set prnopts %10.3e 1 1
ga-> set time jan1995 dec2009
ga-> d pr
```

Concerns when describing the future change

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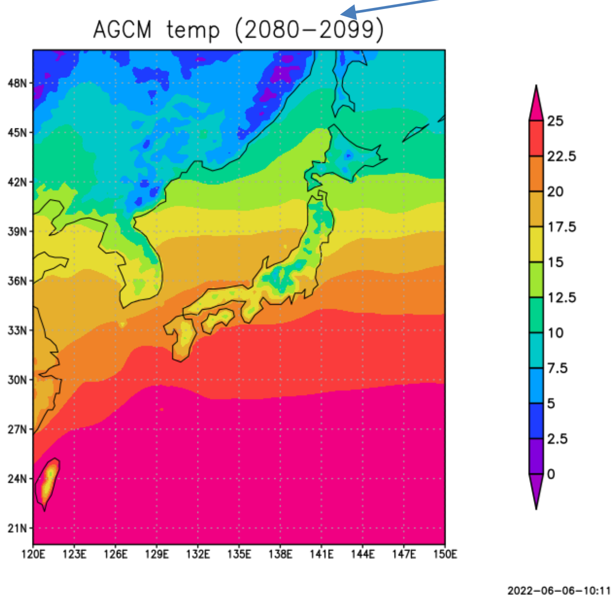
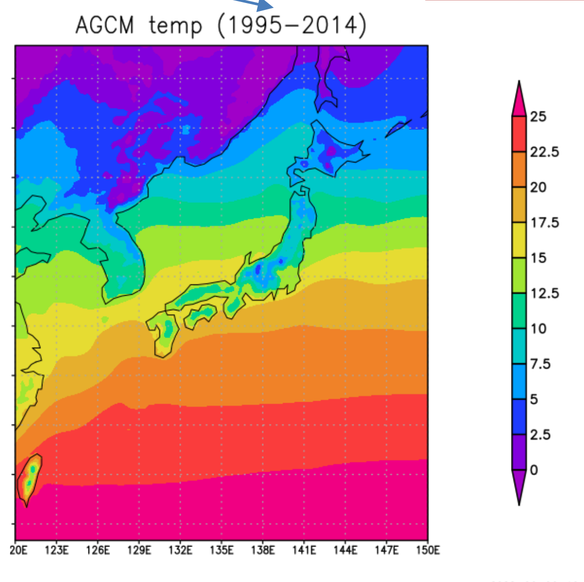
- In general, future changes of climate are described as the difference of climate model outputs between present and future.
  - There are several points to be included into consideration.

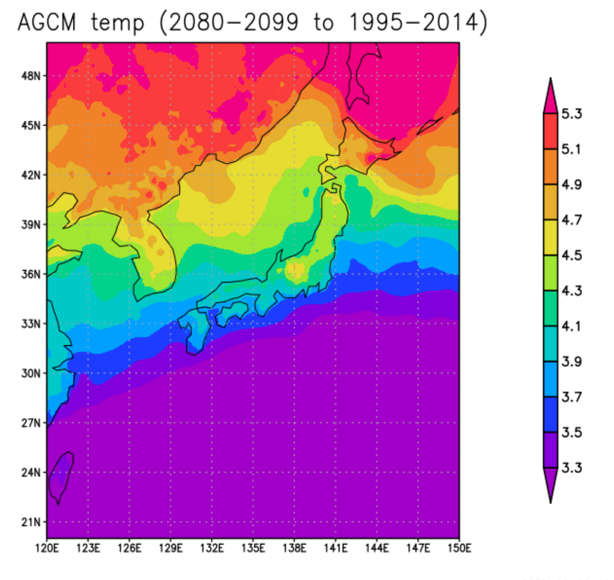
Future (Climate model) − Present (Climate model) = Future change (F–P)

Mean climate state?

Realistic?





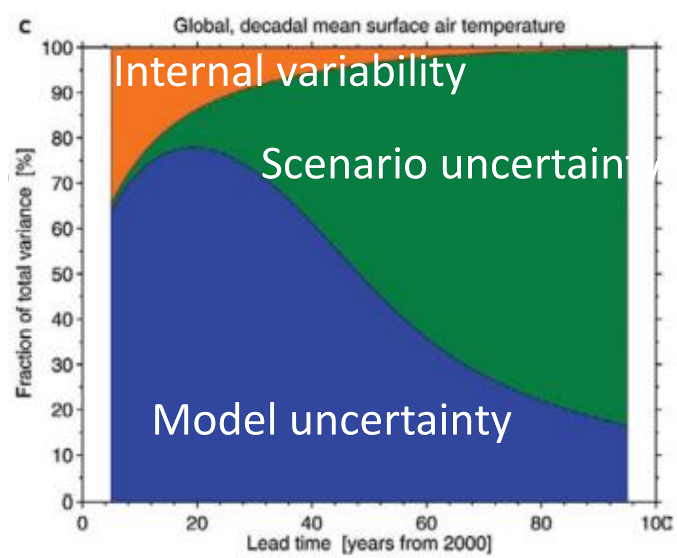


Projection by MRI-AGCM3.2S based on RCP8.5

Reliable?

Uncertainties in global warming projection

- Global warming projection contains many uncertainties. Therefore, we cannot say the results are correct projections without considering the uncertainties.
- Types of uncertainty
  - Natural climate variability
  - Regional scale
  - Incompleteness of climate model
  - Short period for calculation



(Hawkins and Sutton 2009)

Remarks on interpretation of key uncertainties

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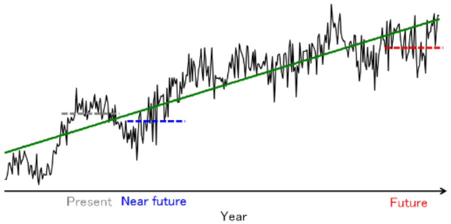
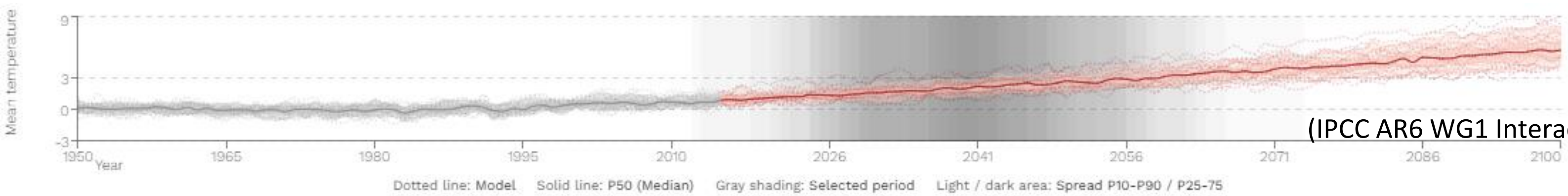
- The aim is to project climate change signals rather than natural climate variability.
  - Even state-of-the-art climate models cannot predict natural variability.
  - The 20-year average of results from the climate model are used for global warming projection.
- Uncertainties in regional-scale climate projections are greater than those in global-scale climate projections.
  - It is necessary to examine whether projected regional-scale climate change is consistent with broader-scale climate change.
- Uncertainties in near-future climate projections are larger than those in future climate projections.
  - As the level of greenhouse gas concentration in near-future projections is expected to be lower than that in future projections, less pronounced climate change signals may be dominated by natural variability.



http://ds.data.jma.go.jp/tcc/tcc/products/gwp/gwp8/html/section1_3.html

Remarks on interpretation of key uncertainties

- Uncertainties exist even in long-term trends.
  - Future climate projection uncertainties can be estimated via multi-model or multi-parameter experiments.
- The ability of models to project future climate conditions is limited.
  - Large-scale patterns averaged over a broader area provide a more meaningful picture than changes on a single-grid scale.
- Uncertainties in future projections depend on the variables used.
  - Detecting climatological trends for precipitation is more difficult than that for temperature because extreme rainfall events are rare by definition and occur on relatively limited spatial and temporal scales.
- Future projections depend on the greenhouse gas emissions scenario used.



(IPCC AR6 WG1 Interactive Atlas)

http://ds.data.jma.go.jp/tcc/tcc/products/gwp/gwp8/html/section1_3.html

Tackle the uncertainty (example)

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- Natural climate variability
  - Choose longer mean period than natural variability
    - In this training seminar, we choose 20-years mean
- Regional scale
  - Check the regional response as a part of the wider area
    - In this training seminar, we check the wider response by IPCC reports.
- Incompleteness of climate model (Model bias)
  - Check the reproducibility of the model
    - Take some bias correction method to correct the response
      - In this training seminar, we take a simple bias correction method.
- Short period for calculation
  - See the long-term climate change in the model
    - In this training seminar, we see the response at the end of 21st century.

Further explanation is in the following slide.

Comparing the regional response with the wider response: How to get the value from IPCC WG1 Interactive Atlas

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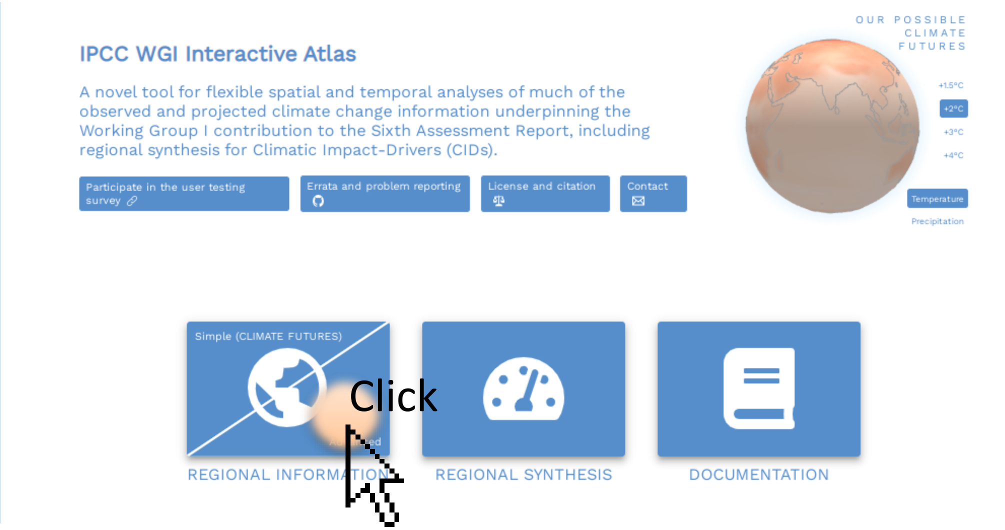
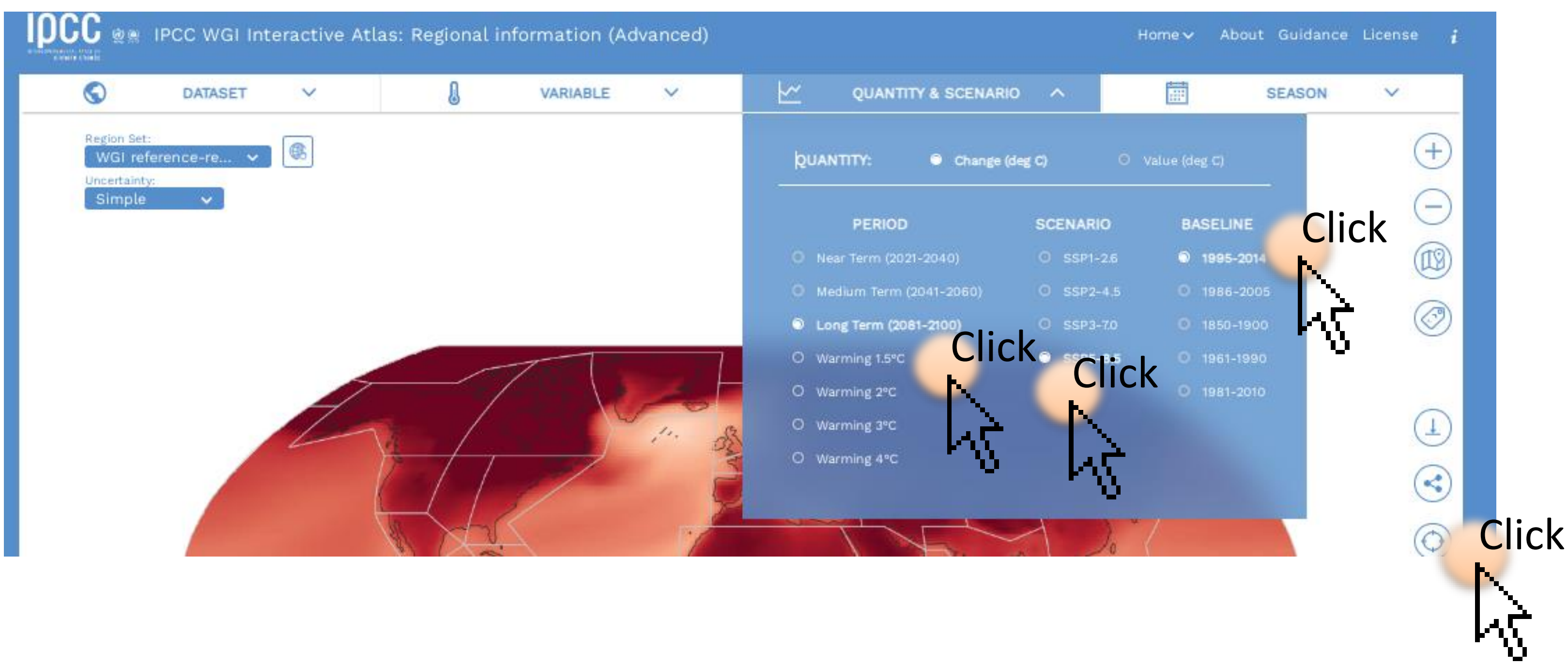


- Go to the website
  - https://interactive-atlas.ipcc.ch/
- Click “Advanced”
- Hover over “Quantity & Scenario”
- Click “Long Term (2081-2100)”
- Click “SSP8-8.5”
- Click “1995-2014”
- Click “Point Information”
- Click the point in your country/region



Checking reproducibility and correcting bias

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- Bias (systematic errors) in climate models is defined as certain tendency for errors in climate models.
  - E.g., the model tends to project warmer than observation (positive bias).
- The reproducibility can be judged by calculating the bias. Bias can be defined here as Simulation minus Observation.
  - Simulation is the forecast which is conducted by climate models.
  - Observation is the values which the model tries to reproduce.
- Simulation and Observation cannot be exactly the same result. Every model has its own bias.
  - Arising from simplified physics, parameterizations, rack of resolution and so on.
- Bias correction is the way to overcome the problem, which adjusts present simulation to observation. For example, a simple way (Delta method) is:
  - (Temp.) $\mathrm{Future}_{\mathrm{Bias\ corrected}} = \mathrm{Observation} + \mathrm{Future} - \mathrm{Present}$
  - (Precip.) $\mathrm{Future}_{\mathrm{Bias\ corrected}} = \mathrm{Observation} * \left(\frac{\mathrm{Future}}{\mathrm{Present}}\right)$