Event attribution methods and approaches

Yukiko Imada (AORI, the Univ. of Tokyo)

A member of EPESC WG3 and RIfS GEP EA WG

On behalf of the Japanese EA team

Various EA methods to date

Various types of EA

Probabilistic (risk-based) EA	Attribution for likelihood. Usually based on AGCM/CGCM large ensemble simulations. LESFMIP can be also used.
Storyline EA	Attribution for severity. Usually based on historical and pseudo-non-warming simulations using high-resolution regional climate models.
Statistical EA	A kind of probabilistic (risk-based) EA but based on statistical equations obtained from the observation or existing simulations. Adopted by WWA, Climate Central, WAC Japan etc.
Analogue EA	Attribution for both likelihood and severity. Find and compare analogues from the observation or existing simulations. Adopted by ClimaMeter.
Conditional EA	Attribution for dynamical fields (extreme circulation). Utilize initialized large ensemble simulations.
EA for unseen events	e.g., Ensemble boosting method: Select a subsamples in which a causal circulation field is likely to develop and increase the number of members by adding the initial perturbations.

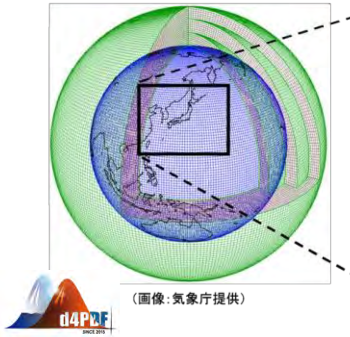
Multiple EA systems in Japan

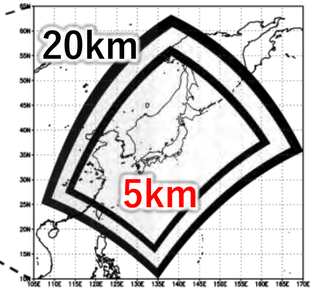
Imada et al.

Risk-based EA with extend d4PDF

Global model (MRI-AGCM60)

Regional model (NHRCM)



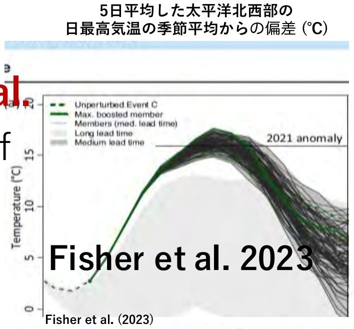


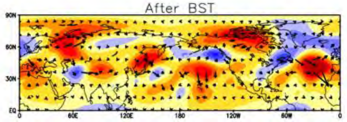
Imada et al.

Ensemble boosting System for dynamical EA (trial)

d4PDF x Ensemble boosting Higuchi et al.

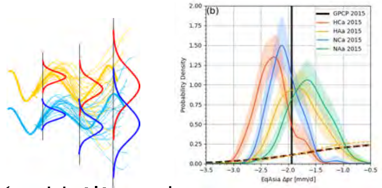
- ✓Increase the number of members which promise the growth of a specific circulation pattern
- ✓Capture unprecedented events





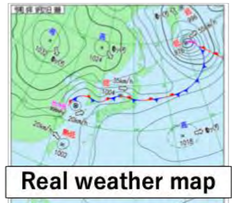
Coupled EA

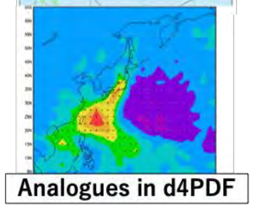
Hasegawa et al.



- ✓ Utilize the assimilation system of seasonal forecasts.
- ✓ Consider the effects of air-sea interaction

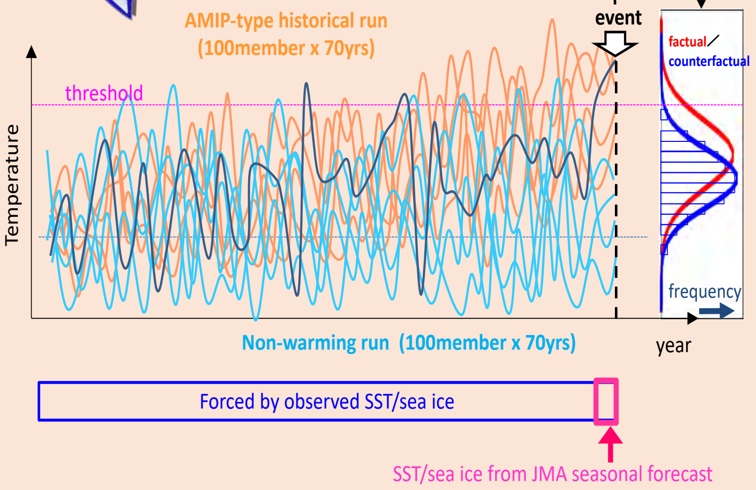
Analogue EA





Rapid EA

Predictive EA

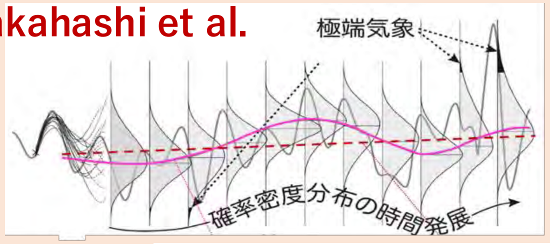


Imada et al.

Lower boundary condition is replaced by seasonal forecasted SST and sea ice.

Statistical EA

Takahashi et al.

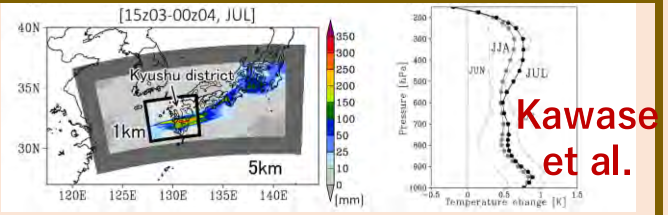


Gaussian $$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

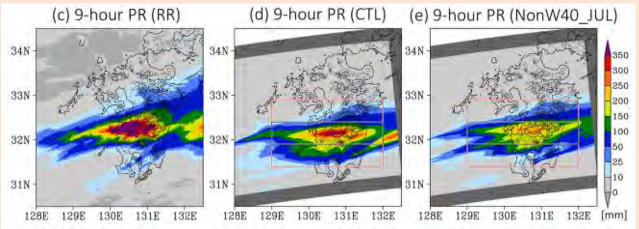
GEV $$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$$

μ(t), σ(t), ξ(t)をd4PDFから予め推定

Storyline EA (pseudo-non-warming experiment)



Kawase et al.

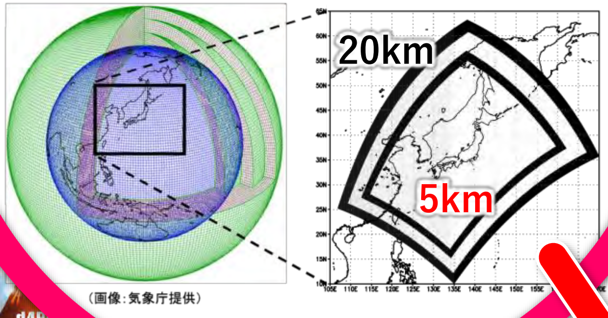


Multiple EA systems in Japan

Imada et al.

Risk-based EA with extend d4PDF

Global model (MRI-AGCM60) | Regional model (NHRCM)

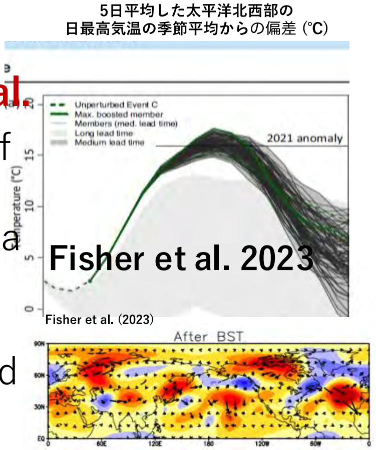


Imada et al.

Ensemble boosting System for dynamical EA (trial)

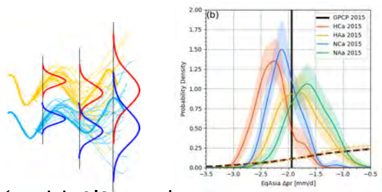
d4PDF x Ensemble boosting Higuchi et al.

- ✓Increase the number of members which promise the growth of a specific circulation pattern
- ✓Capture unprecedented events



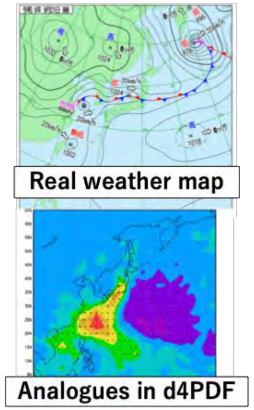
Coupled EA

Hasegawa et al.



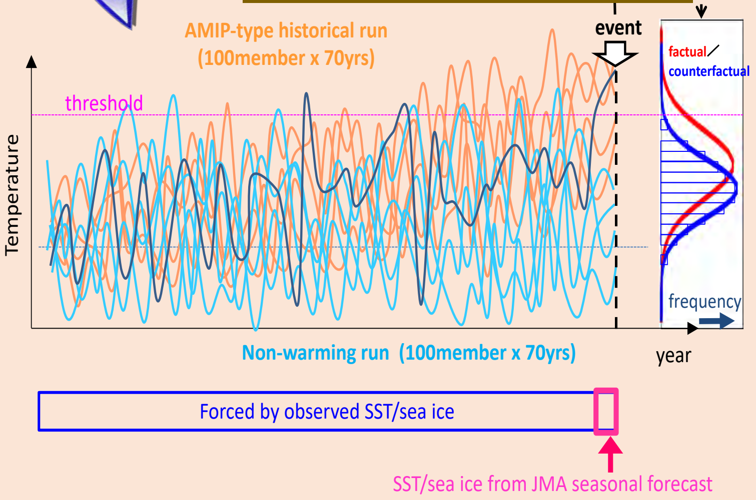
- ✓ Utilize the assimilation system of seasonal forecasts.
- ✓ Consider the effects of air-sea interaction

Analogue EA



Rapid EA

Predictive EA

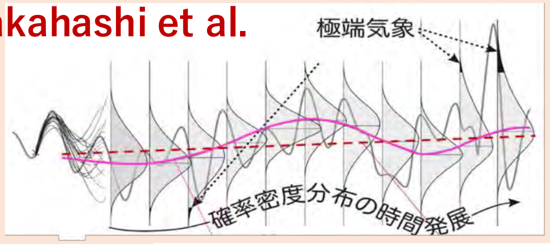


Imada et al.

Lower boundary condition is replaced by seasonal forecasted SST and sea ice.

Statistical EA

Takahashi et al.



Gaussian

$$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

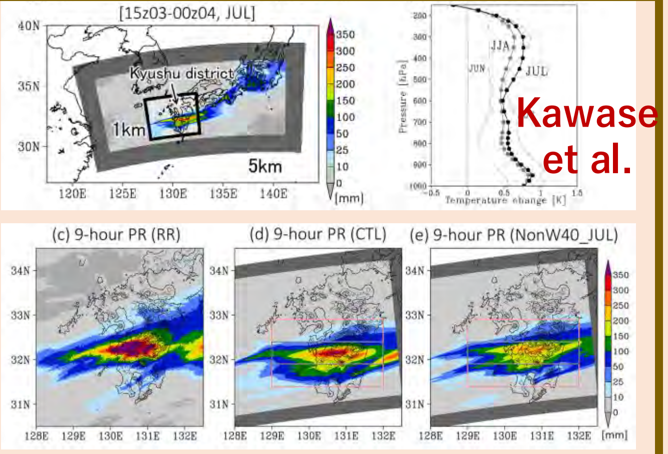
GEV

$$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$$

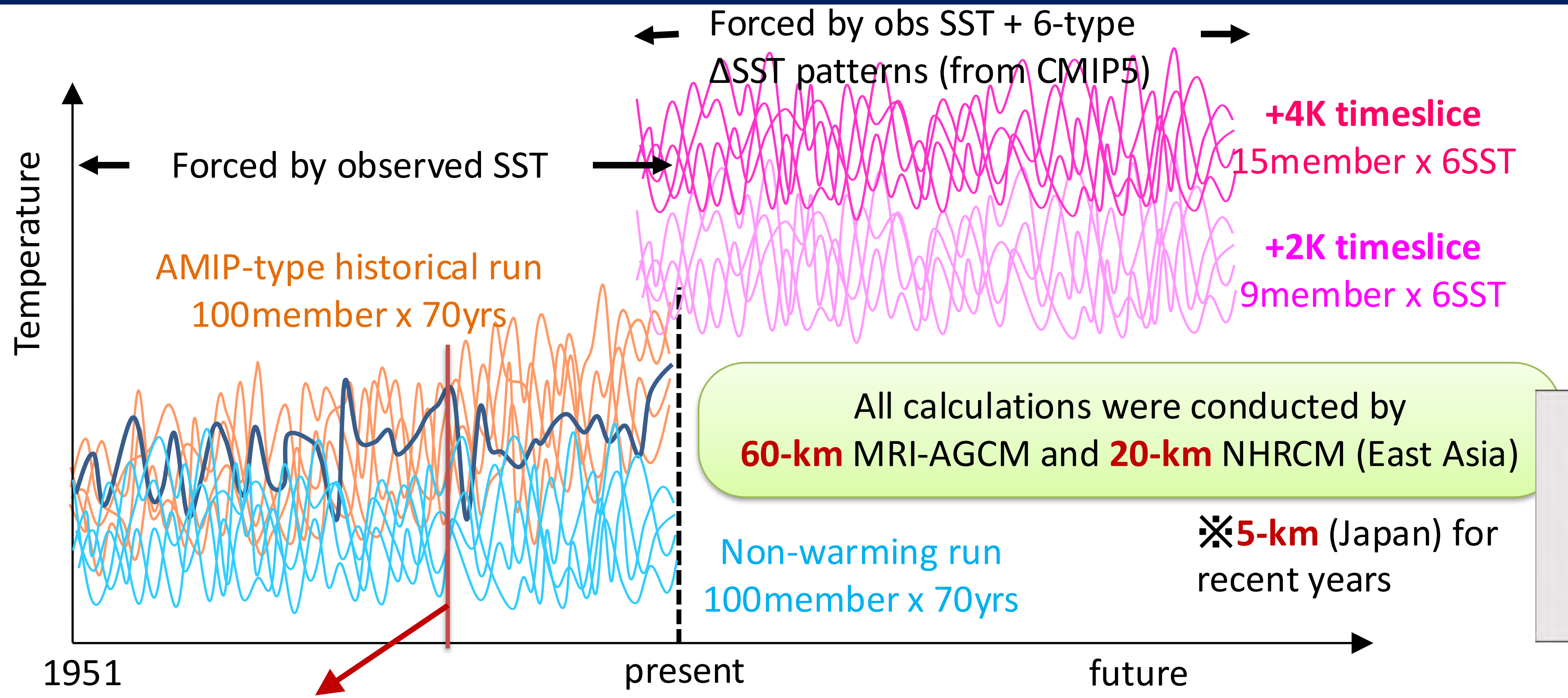
μ(t), σ(t), ξ(t)をd4PDFから予め推定

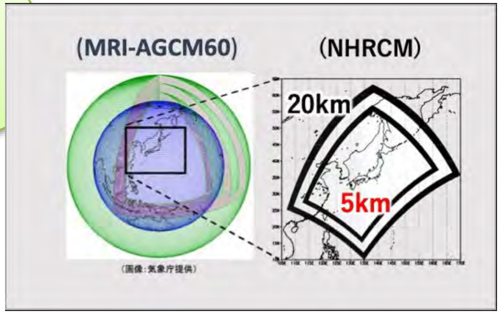
Storyline EA (pseudo-non-warming experiment)

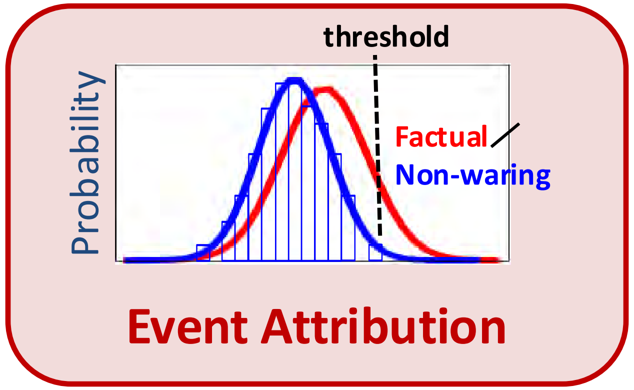
Kawase et al.



Basic strategy of risk-based Event Attribution in Japan





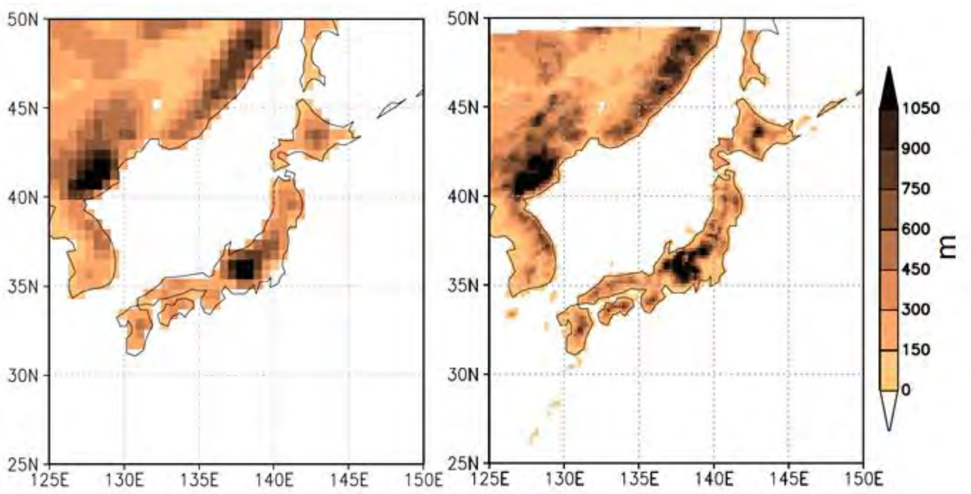


- High performance for East Asian climate due to dynamical downscaling
- The database is updated annually.
- Conduct irregular emergency calculation when an extreme event occurs (1-2 months for calculation and analysis)
- Prescribed by the observed SST and Sea Ice. -> Calculation cannot be started before we obtain the observed variables.

Points to note about EA in Japan

★Japan-specific issues

- **Required resolution**
  - ✓ The 20-km resolution is minimum requirement to distinguish the four main Japanese islands and climate features depend on the topography.
  - ✓ Limited available datasets: d4PDF, GFDL high-resolution ensemble runs



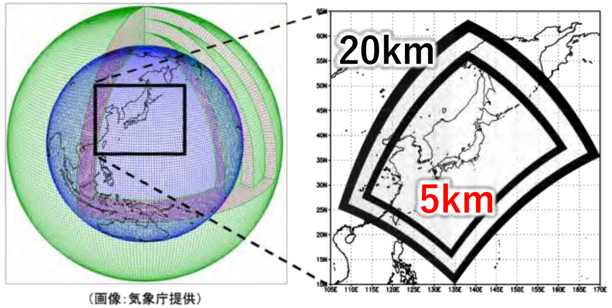
- **Impacts of tropical oceans**
  - ✓Japanese extreme climate cannot be discussed without the impacts of natural variability in the tropical oceans (ENSO, Indian Ocean, etc...)
  - ✓La Nina brings hotter summer / El Nino brings hotter winter / warmer IO brings heavy rainfall to the western Japan
  - ✓Before reporting the impact of global warming, we have to explain what is different from the normal year by considering the impact of oceanic natural variability.
  - ✓The unique SST pattern of each year should be considered in EA.

Multiple EA systems in Japan

Risk-based EA with extend d4PDF

全球モデル
（MRI-AGCM60）

領域モデル
（NHRCM）

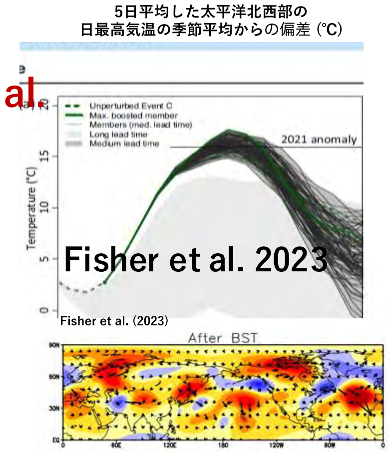


Imada et al.

Ensemble boosting System for dynamical EA (trial)

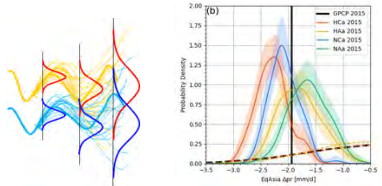
d4PDF x Ensemble boosting Higuchi et al.

✓ Increase the number of members which promise the growth of a specific circulation pattern
✓ Capture unprecedented events



Coupled EA

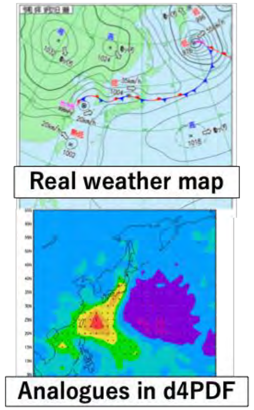
Hasegawa et al.



✓ Utilize the assimilation system of seasonal forecasts.
✓ Consider the effects of air-sea interaction

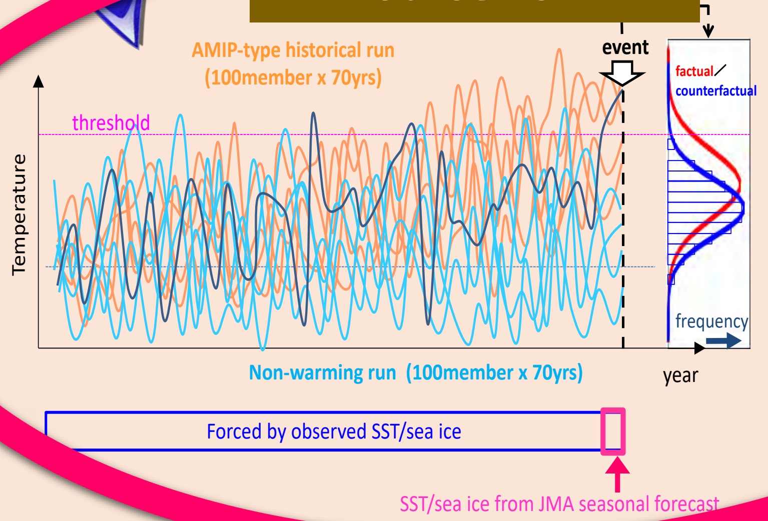
Imada et al.

Analogue EA



Rapid EA

Predictive EA

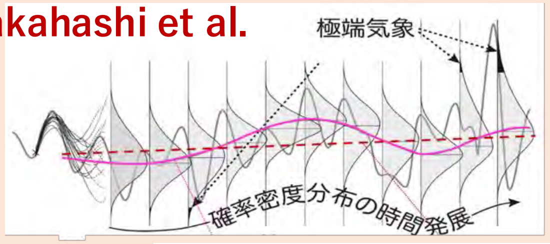


Imada et al.

Lower boundary condition is replaced by seasonal forecast of SST and ice

Statistical EA

Takahashi et al.

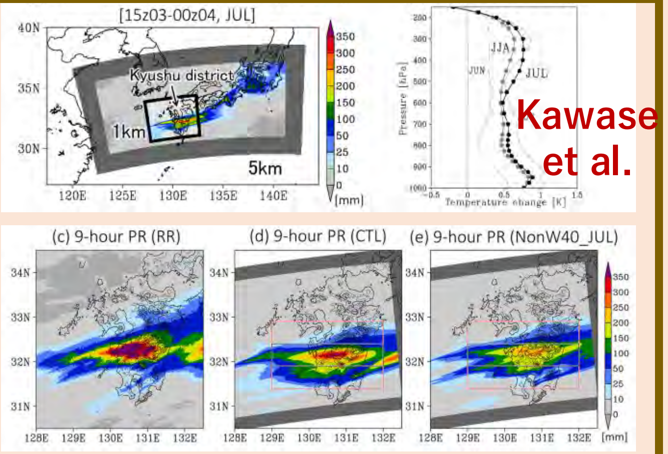


Gaussian
$$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

GEV
$$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$$

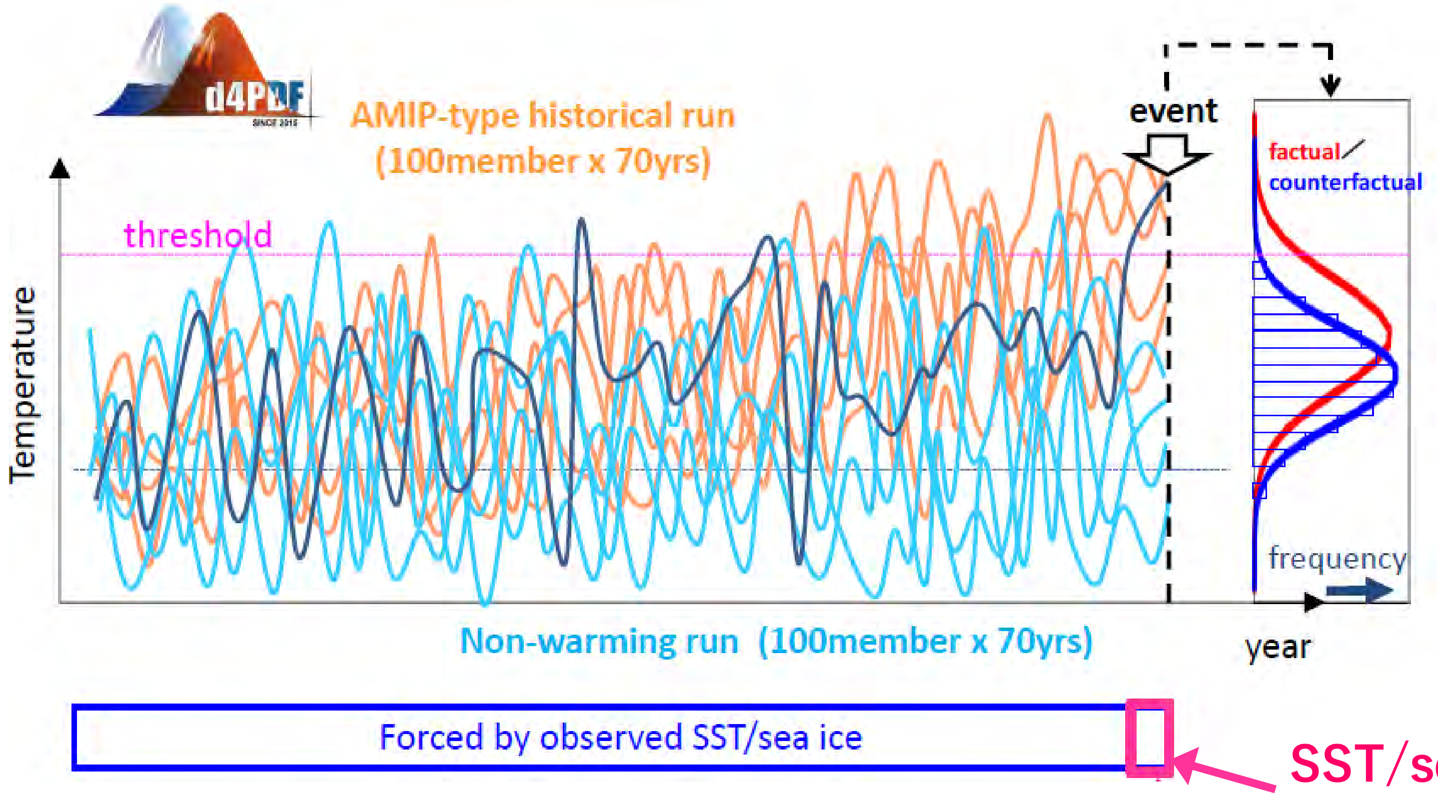
μ(t), σ(t), ξ(t)をd4PDFから予め推定

Storyline EA（pseudo-non-warming experiment）

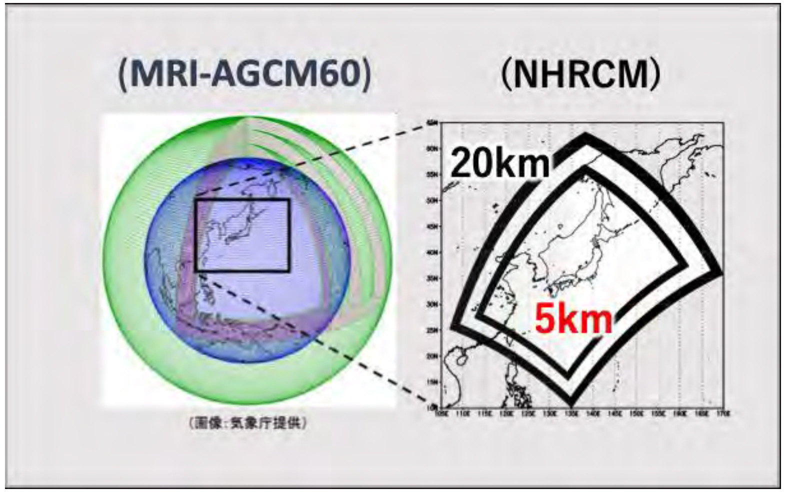


Kawase et al.

Operational EA in Japan: Predictive EA



Dynamical downscaling
60km ➔ 20km ➔ 5km



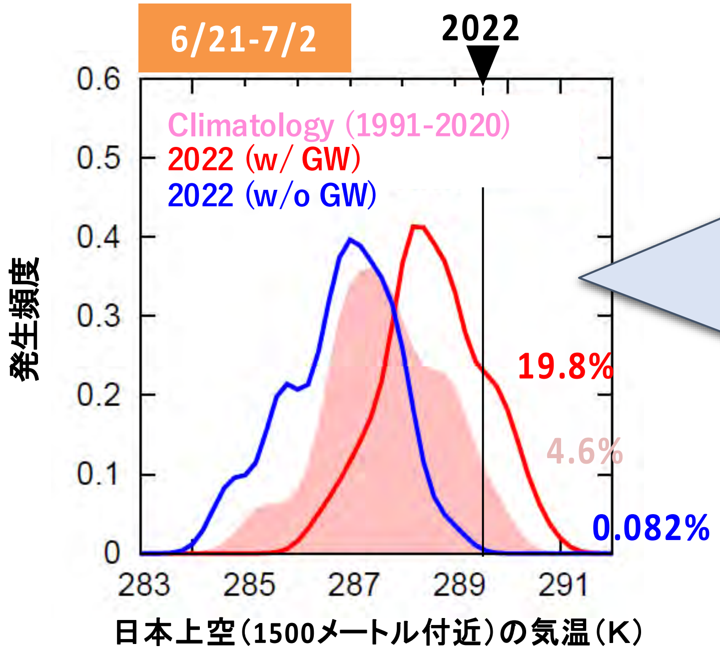
SST/sea ice from JMA seasonal forecast
(a kind of two-tier seasonal prediction)

- ✓ d4PDF-type AGCM large ensemble simulations
- ✓ Utilize JMA's seasonal prediction as BCs (SST, sea ice) instead of the observation.
- ✓ Prepare high-resolution large-ensemble prediction in advance before the season of extreme events

Operational EA in Japan: Predictive EA

Examples

Heatwaves 2022 (6/21-7/2)	Heatwaves 2023 (7/23-8/10)	Heatwaves 2024 (7/1-31)



Risk Ratio≒240

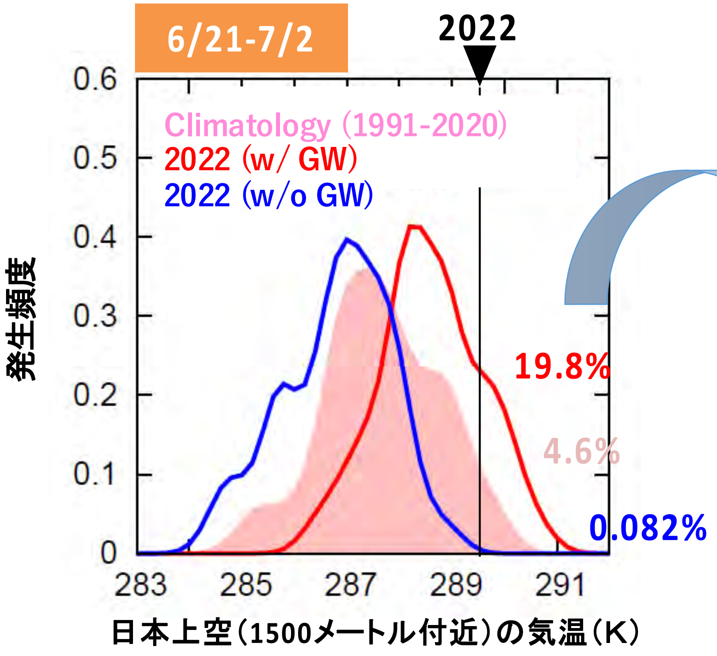
At the press release, we reported that...

- "In the normal years, the probability of this event was **4.6%** (return period: 22 years). **But in the 2022 early summer, it raised up to 19.8% (return period: 5 years) because of the impact of La Nina.** Without human induced climate change, this value would drop to **0.082%** (return period: 1216 years)
- Probability Ratio: about 240

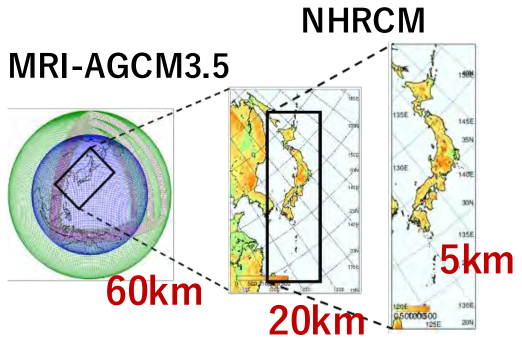
Operational EA in Japan: Predictive EA

Downscaled outputs

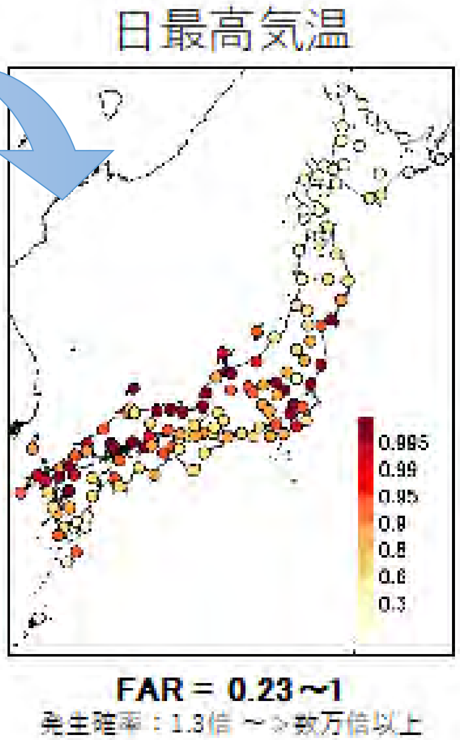
Heatwaves 2022 (6/21-7/2)

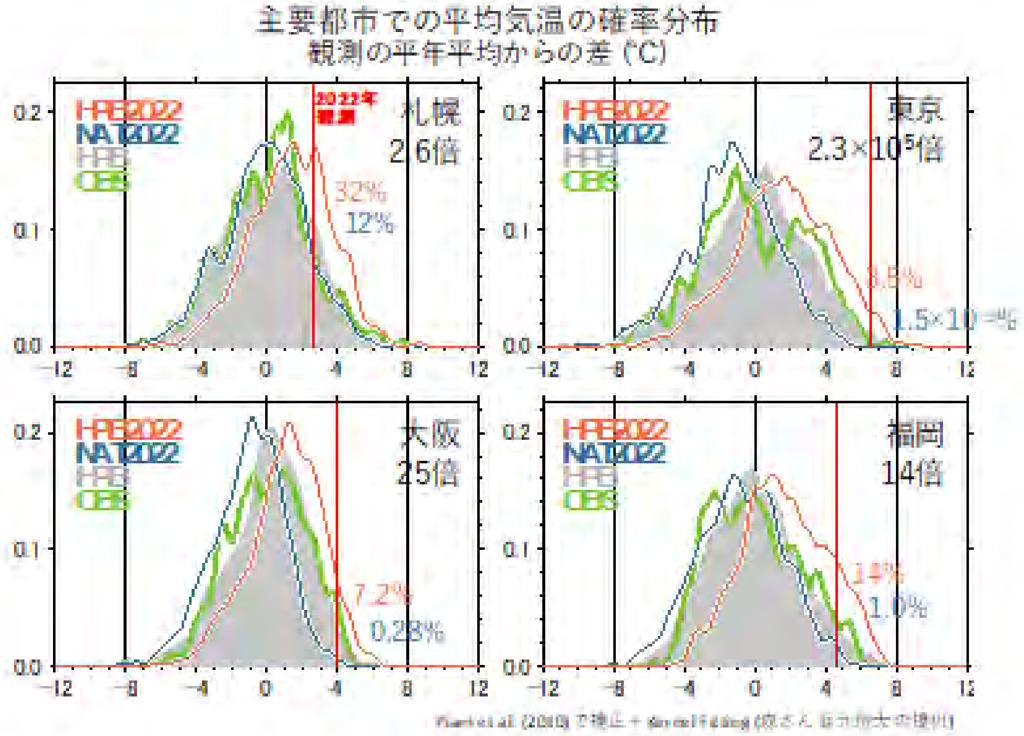


Risk Ratio≒240



Results of dynamical downscaling





Providing city-by-city information

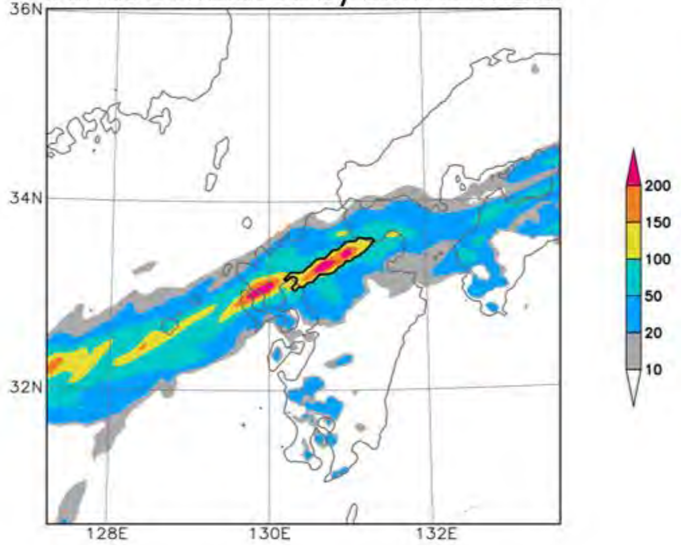
Ito et al. (2023)

Operational EA in Japan: Predictive EA

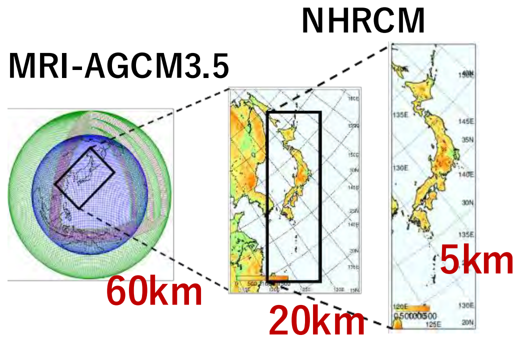
Downscaled outputs

Heavy rainfall in 2023 (7/1-31)

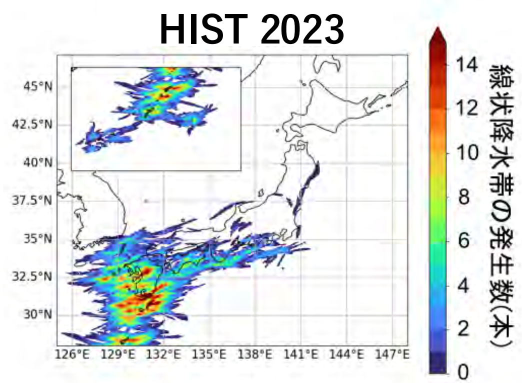
(a) A sample of quasi-stationary convective bands simulated by 5km NHRCM

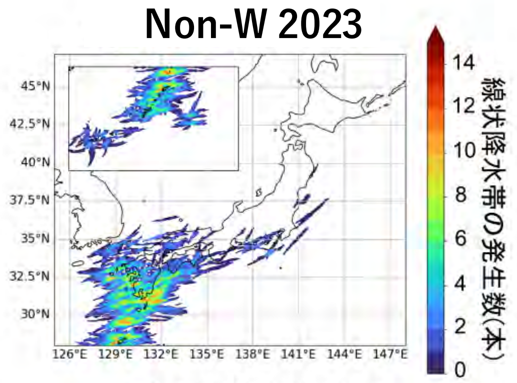


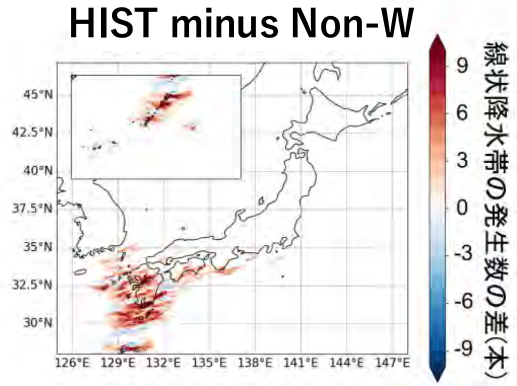
Watanabe et al. (2024)

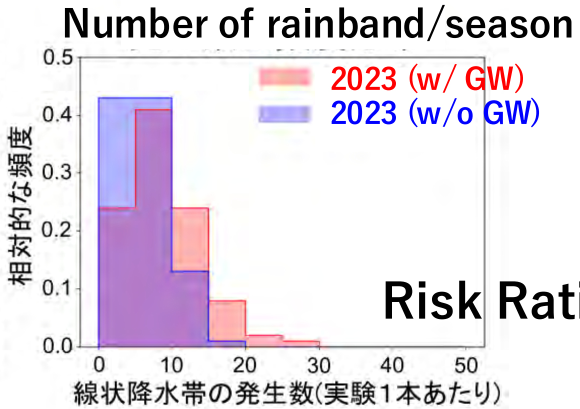


Results of dynamical downscaling









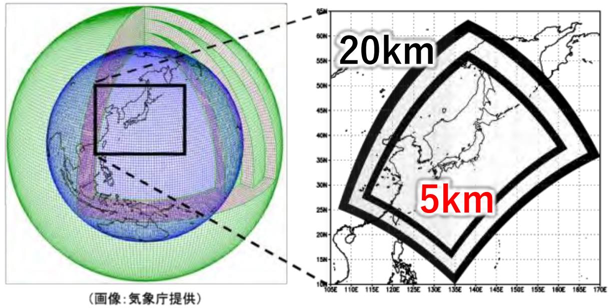
Risk Ratio≒1.5

Multiple EA systems in Japan

Imada et al.

Riskbased EA with extend d4PDF

全球モデル（MRI-AGCM60）　領域モデル（NHRCM）

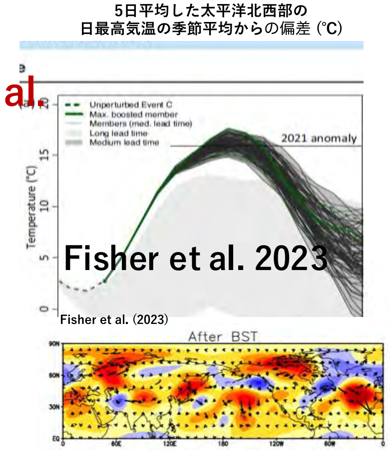


Imada et al.

Ensemble boosting System for dynamical EA (trial)

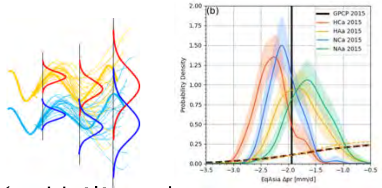
d4PDF x Ensemble boosting　Higuchi et al.

- ✓ Increase the number of members which promise the growth of a specific circulation pattern
- ✓ Capture unprecedented events



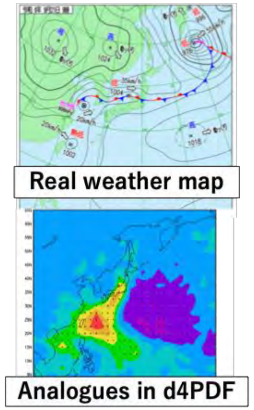
Coupled EA

Hasegawa et al.



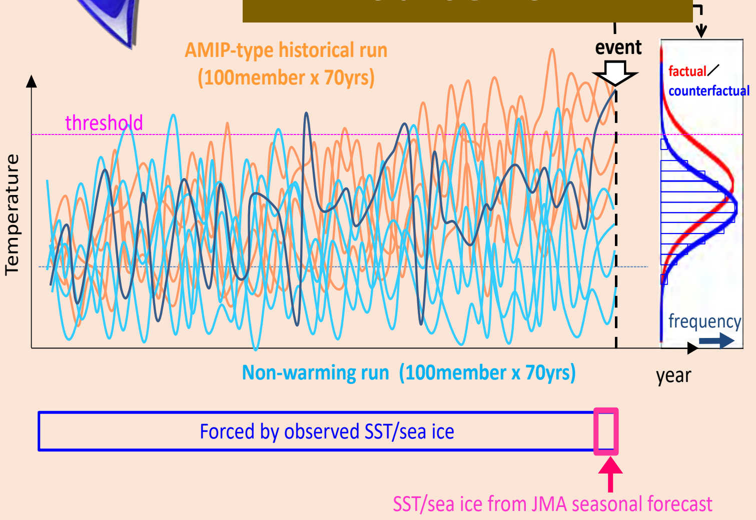
- ✓ Utilize the assimilation system of seasonal forecasts.
- ✓ Consider the effects of air-sea interaction

Analogue EA



Rapid EA

Predictive EA

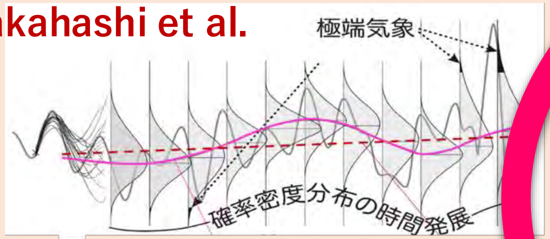


Imada et al.

Lower boundary condition is replaced by seasonal forecasted SST and sea ice.

Statistical EA

Takahashi et al.

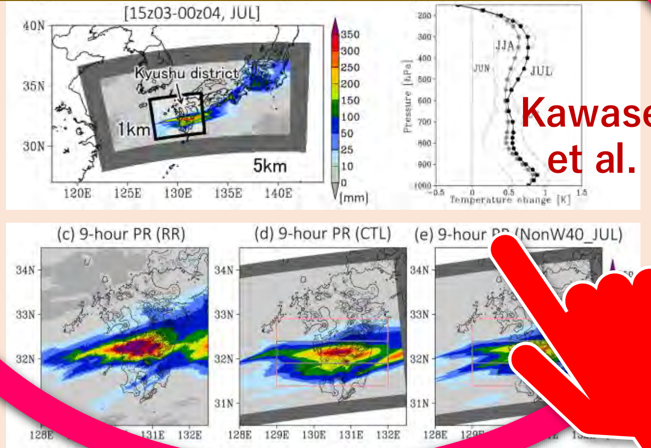


Gaussian　$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$

GEV　$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$

μ(t), σ(t), ξ(t)をd4PDFから予め推定

Storyline EA (pseudo non-warming experiment)



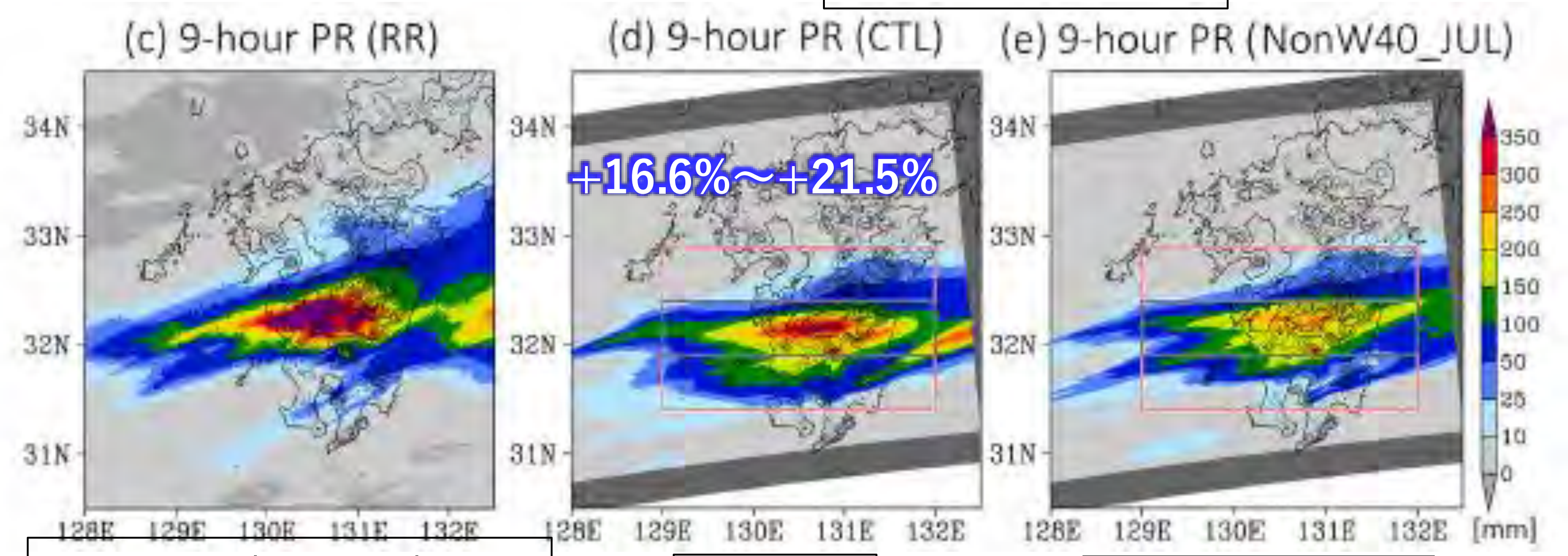
Kawase et al.

Operational EA in Japan: Storyline EA

- ✓ **<u>CTL</u>**: Specific extreme events are simulated by the high-resolution regional climate model simulation with realistic initial and boundary conditions based on the reanalysis data.
- ✓ **<u>NonW</u>**: The impact of global warming is quantitatively excluded from the boundary conditions estimated by the reanalysis data or global climate simulations (pseudo-global non-warming (PGnW) simulation).

Example: Heavy rainfall in 2020 in western Japan

1km NHRCM



Mesoscale Reanalysis (JMA)

CTL

NonW (PGnW)

Kawase et al. 2022, BAMS

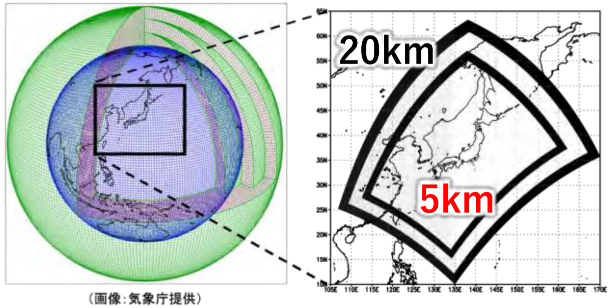
Multiple EA systems in Japan

Imada et al.

Riskbased EA with extend d4PDF

全球モデル (MRI-AGCM60)

領域モデル (NHRCM)



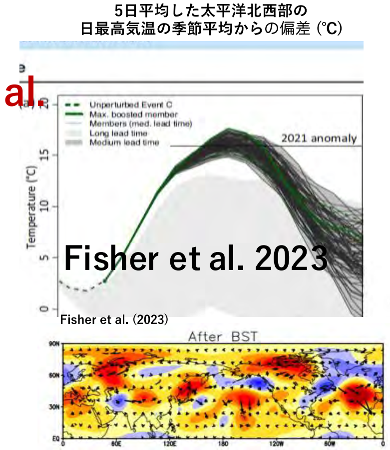
Imada et al.

Ensemble boosting System for dynamical EA (trial)

d4PDF x Ensemble boosting

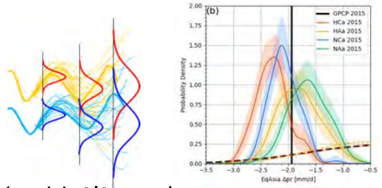
Higuchi et al.

- ✓ Increase the number of members which promise the growth of a specific circulation pattern
- ✓ Capture unprecedented events



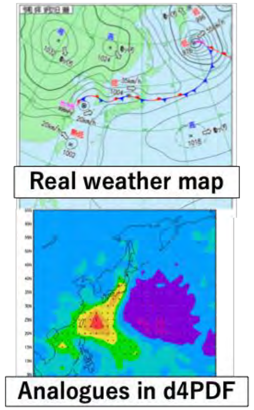
Coupled EA

Hasegawa et al.



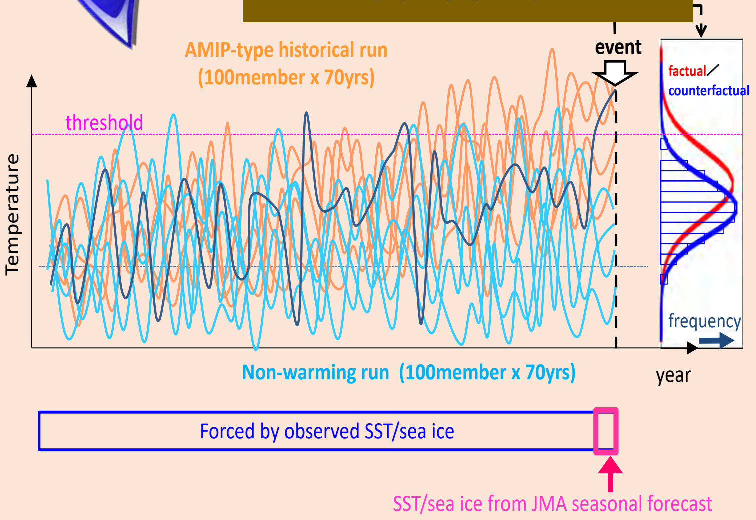
- ✓ Utilize the assimilation system of seasonal forecasts.
- ✓ Consider the effects of air-sea interaction

Analogue EA



Rapid EA

Predictive EA

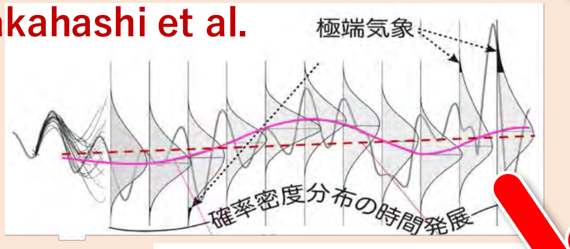


Imada et al.

Lower boundary condition is replaced by seasonal forecasted SST and sea ice.

Statistical EA

Takahashi et al.



Gaussian

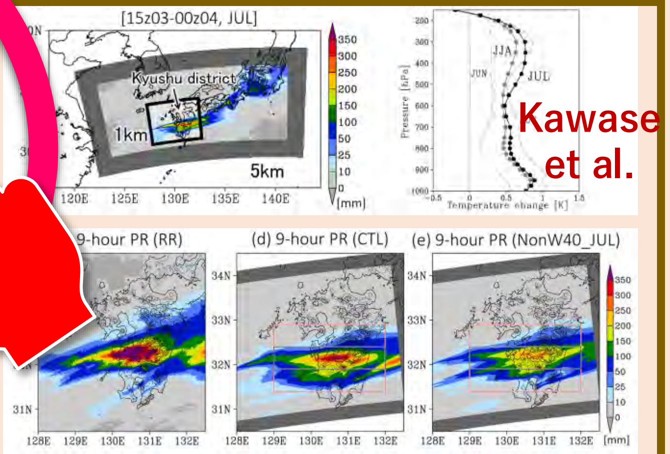
$$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

GEV

$$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$$

μ(t), σ(t), ξ(t)をd4PDFから子…推定

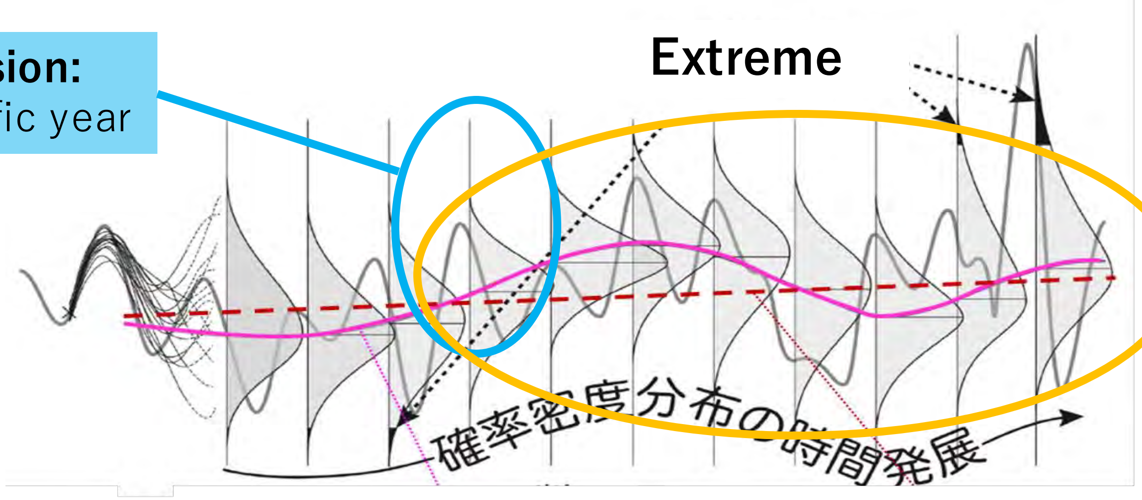
Storyline EA (pseudo-non-warming experiment)



Kawase et al.

Operational EA in Japan: Statistical EA

Japanese version:
PDFs for a specific year



WWA-like method:
PDFs averaged for several years

Gaussian

$$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

GEV

$$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$$

μ ：location parameter（～mean）
σ ：scale parameter（～standard deviation）
ξ ：shape parameter（～skewness）

※ ξ = 0 of GEV: **Gumbel distribution**

Estimate parameters μ, σ, ξ as a function of the specific SST pattern

Takahashi et al. (2025)

Operational EA in Japan: Statistical EA

◻ STEP1

Estimate the impact of oceanic natural variability on μ and σ using non-warming large ensemble experiment

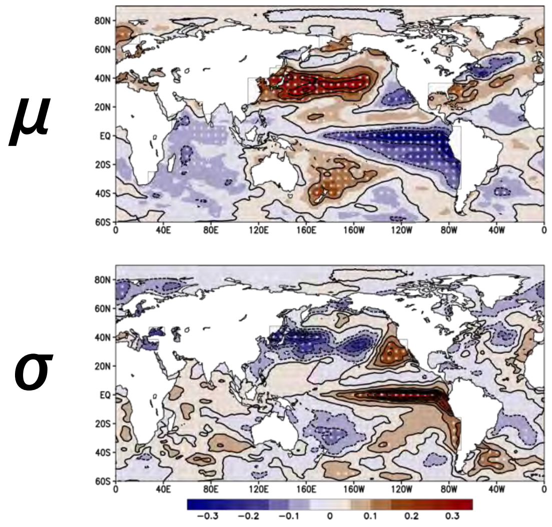
◻ STEP2

Estimate the impact of anthropogenic warming on $\Delta\mu$ and $\Delta\sigma$ from the difference between HIST and Non-warming simulations.

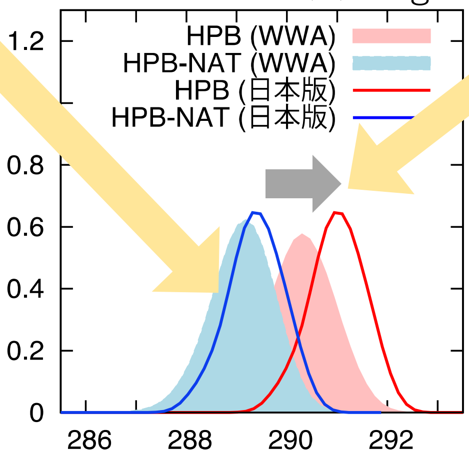
Reconstruct the PDF using $\mu(t_{target})$ and $\sigma(t_{target})$

Shift PDF with $\Delta\mu$ ($\Delta\sigma$)

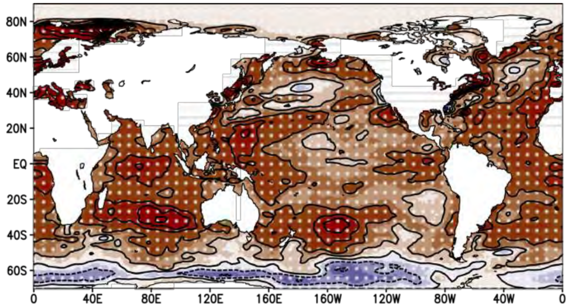
Temporal regression of SST on μ(t) and σ(t) (Non-warming run)



※Image



Regression of SST on $\Delta\mu$(t) (5-year running mean)



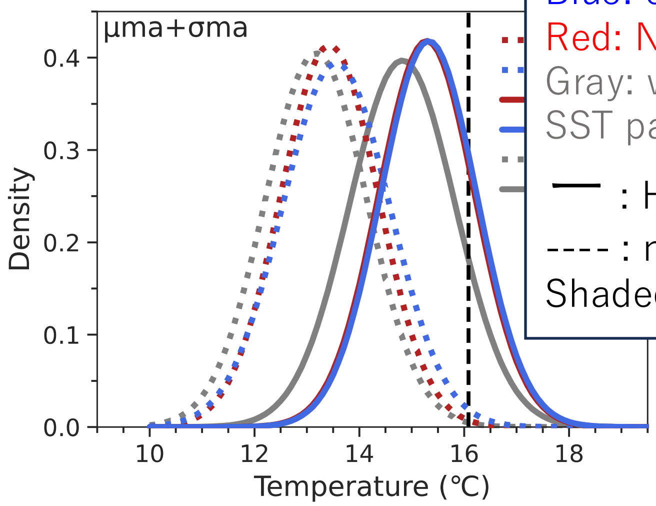
SST warming pattern related to Japanese temperature

Takahashi et al. (2025)

Operational EA in Japan: Statistical EA

Hot extreme events in Japan

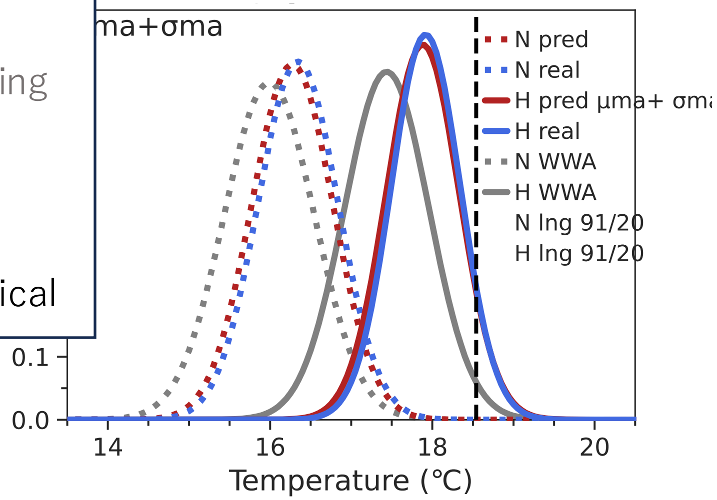
2022 early summer



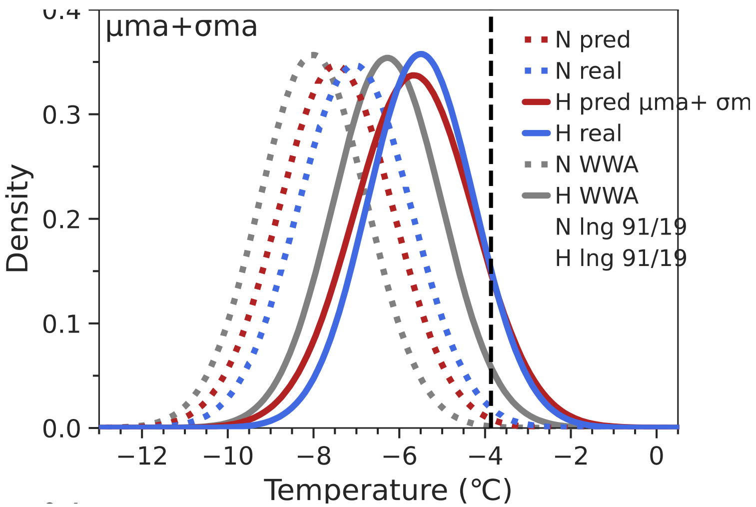
Blue: original
Red: New
Gray: w/o considering SST pattern

— : HIST
---- : non-W
Shaded: climatological

July 2018



December 2019-February 2020 hot winter



Probability exceeding a threshold

	HIST	NAT	HIST	NAT	HIST	NAT
d4PDF-base	20.25%	0.69%	7.2%	0%	9.46%	0.8%
New method	**19.07**	**0.22**	**7.1**	**0**	**9.95**	**0.32**
w/o considering SST pattern	10.58	0.14	1.73	0	2.86	0.05

Takahashi et al. (2025)

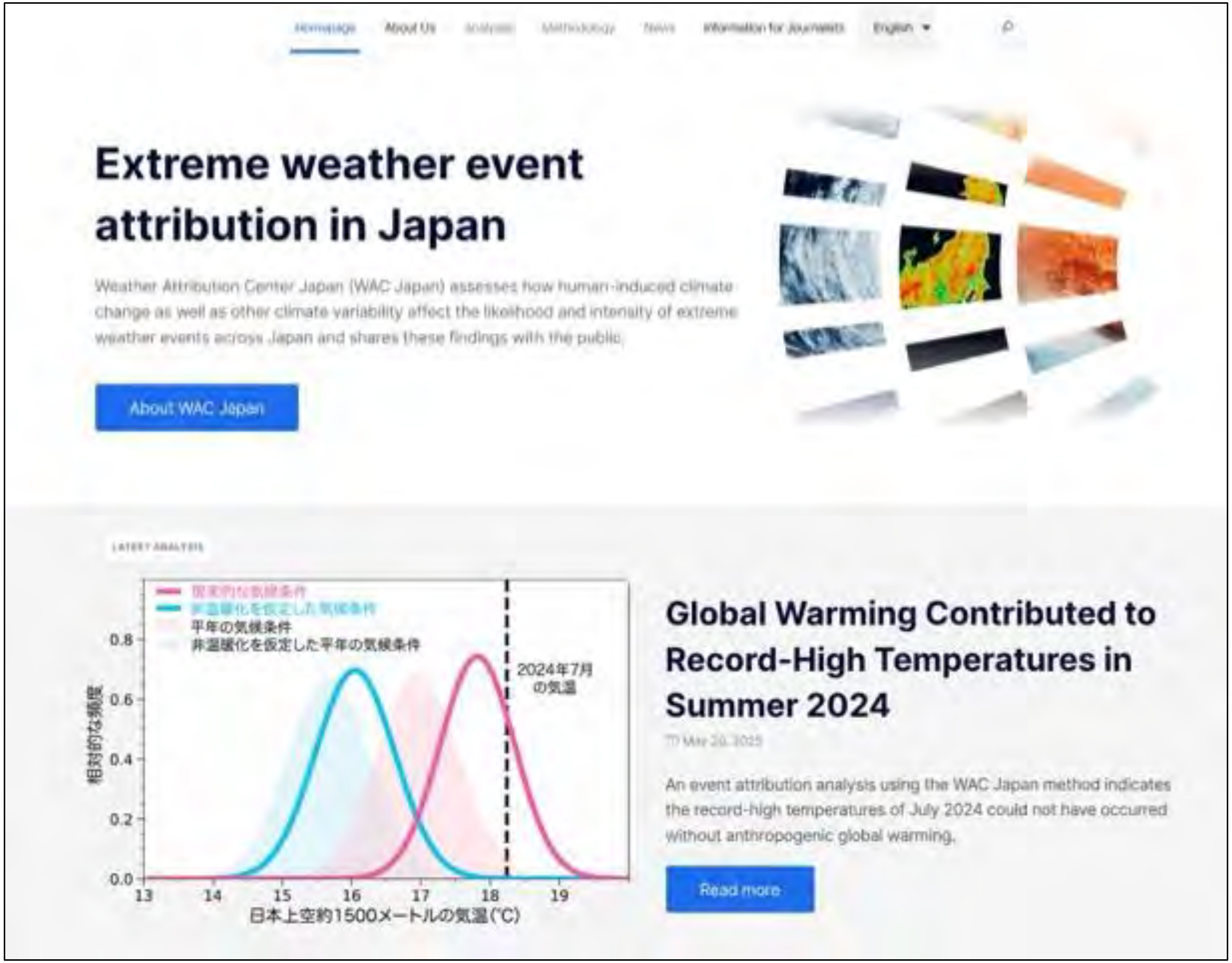


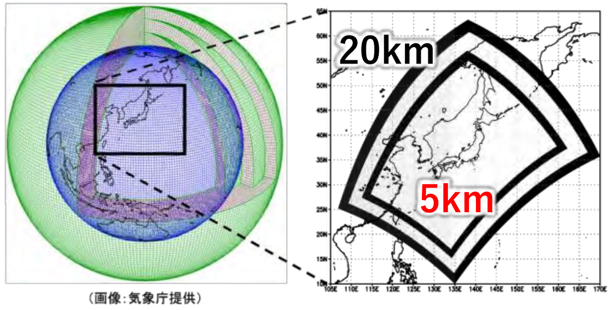
Image of the Weather Attribution Center Japan (WAC Japan) website

- Rapidly releasing highly reliable analyses on our website within a few days after the occurrence of an event.
- A unique statistical method designed for the distinct meteorological features of Japan
- Currently performed manually / Automation planned for the future

Multiple EA systems in Japan

Riskbased EA with extend d4PDF

全球モデル（MRI-AGCM60）　領域モデル（NHRCM）

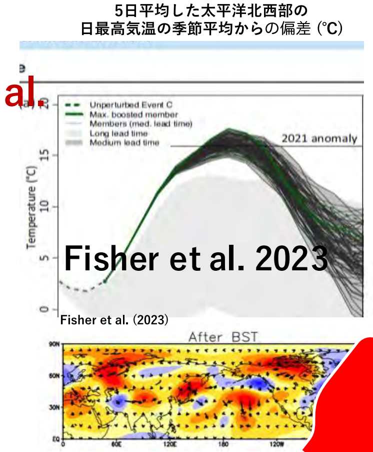


Imada et al.

Ensemble boosting System for dynamical EA (trial)

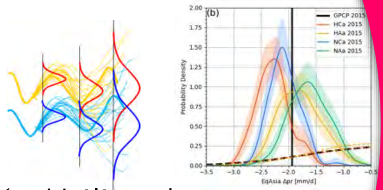
d4PDF x Ensemble boosting　Higuchi et al.

- ✓ Increase the number of members which promise the growth of a specific circulation pattern
- ✓ Capture unprecedented events



Coupled EA

Hasegawa et al.

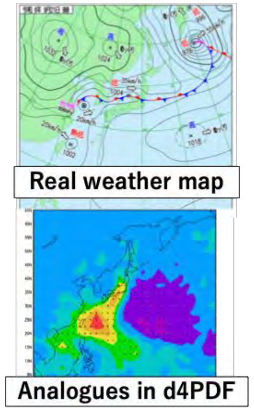


- ✓ Utilize the assimilation system of seasonal forecasts.

Consider the effects of air-sea interaction

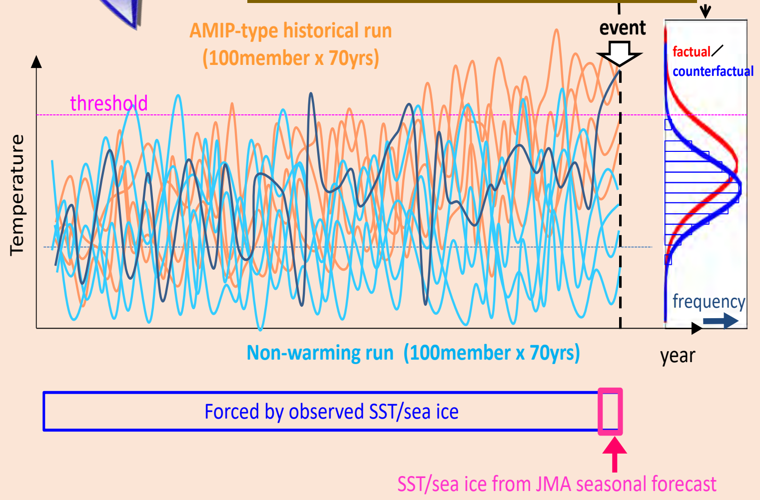
Analogue EA

Imada et al.



Rapid EA

Predictive EA

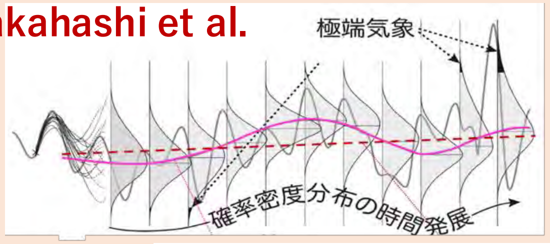


Imada et al.

Lower boundary condition is replaced by seasonal forecasted SST and sea ice.

Statistical EA

Takahashi et al.



Gaussian

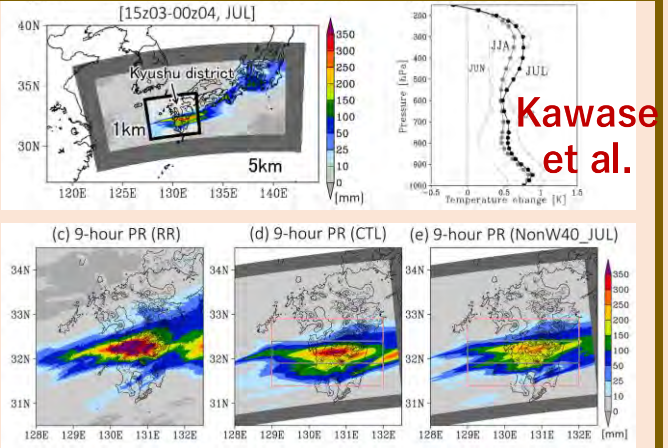
$$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

GEV

$$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$$

μ(t), σ(t), ξ(t)をd4PDFから予め推定

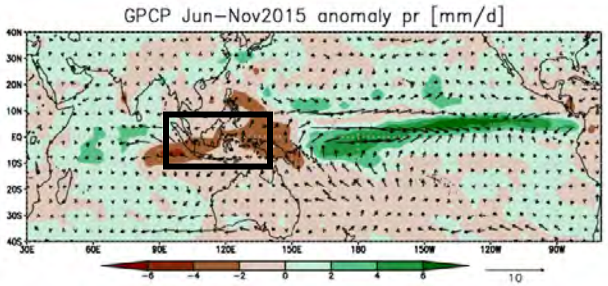
Storyline EA（pseudo-non-warming experiment）



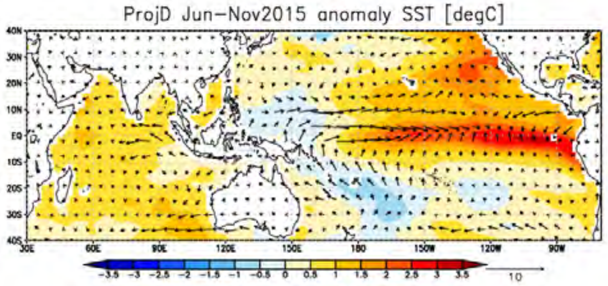
Kawase et al.

EA with Coupled GCM

- 100-member **HIST** and **NAT** simulations
- Comparison:
  - **MIROC6 CGCM**
    Observed T and S are assimilated
  - **MIROC6 AGCM**
    Prescribed by observed SST and sea ice

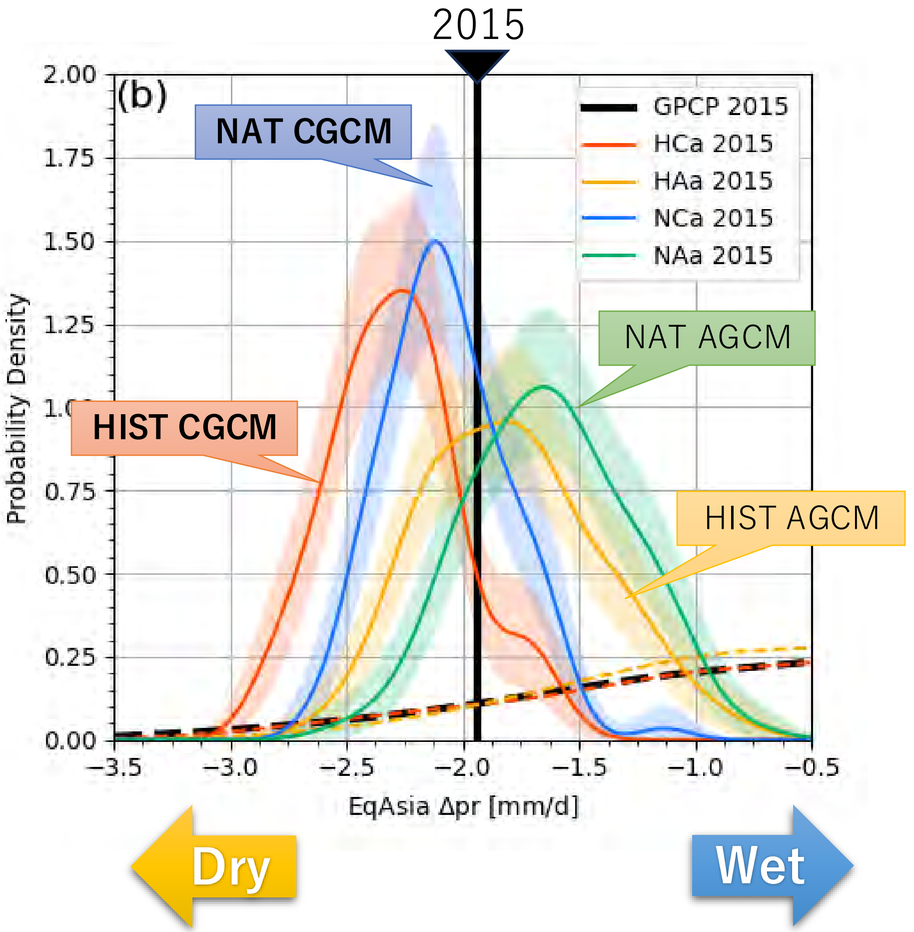


GPCP Anom



SST Anom

EA for the 2015 draught event in equatorial Asia



Hasegawa et al. (in prep.)

2025 draught event in the maritime continents	HIST			NAT	
	Obs	Hist C Assm	Hist AGCM	Nat C Assm	Nat AGCM
%	---	87.6	38.5	70.4	21.4

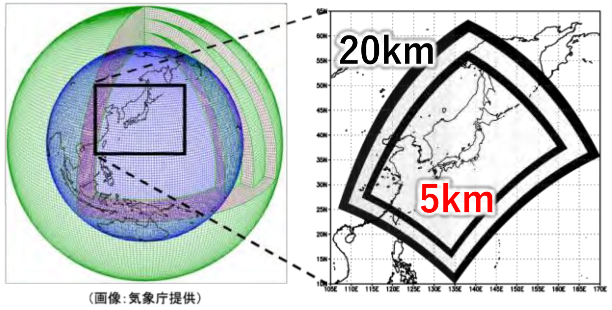
	CGCM assim	AGCM
FAR	0.20	0.44

Multiple EA systems in Japan

Riskbased EA with extend d4PDF

全球モデル (MRI-AGCM60)

領域モデル (NHRCM)

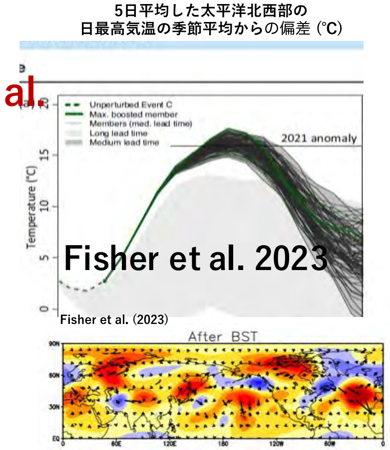


Imada et al.

Ensemble boosting System for dynamical EA (trial)

d4PDF x Ensemble boosting Higuchi et al.

- ✓ Increase the number of members which promise the growth of a specific circulation pattern
- ✓ Capture unprecedented events



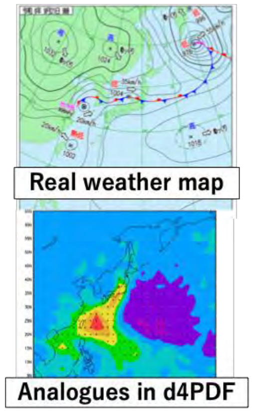
Coupled EA

Hasegawa et al. ➡ d4PDF

- ✓ Utilize the assimilation system of seasonal forecasts.
- ✓ Consider the ... of air-sea in...

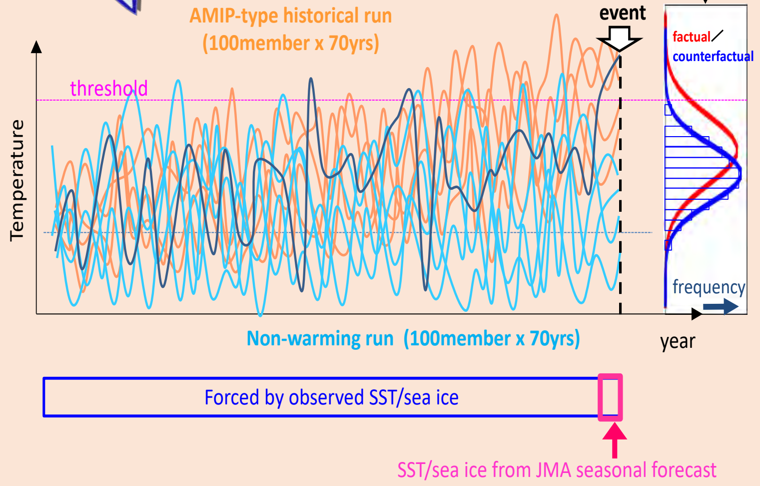
Analogue EA

Imada et al.



Rapid EA

Predictive EA

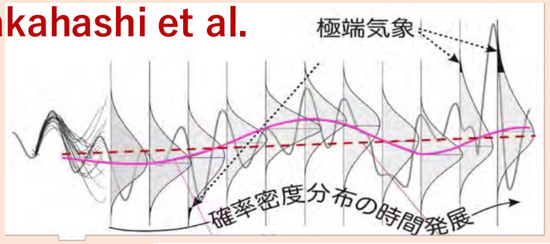


Imada et al.

Lower boundary condition is replaced by seasonal forecasted SST and sea ice.

Statistical EA

Takahashi et al.



Gaussian

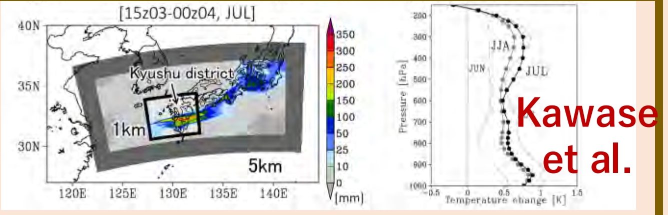
$$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

GEV

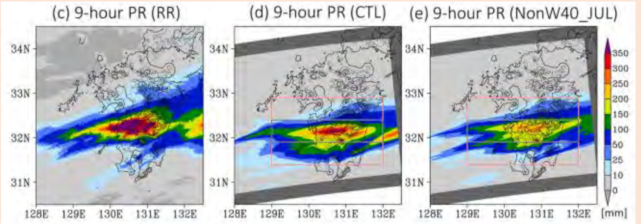
$$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$$

μ(t), σ(t), ξ(t)をd4PDFから予め推定

Storyline EA (pseudo-non-warming experiment)

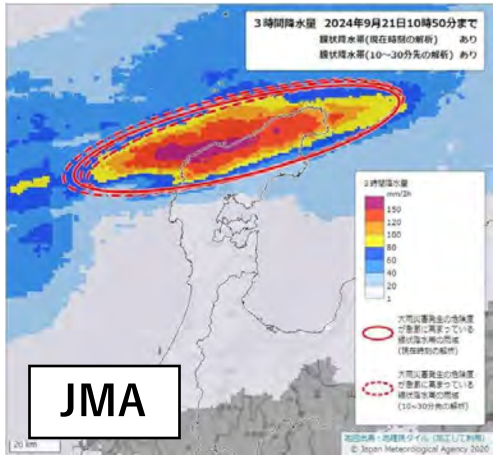


Kawase et al.



Analogue EA (2024 heavy rainfall case in Japan)

21 Sep, 2024



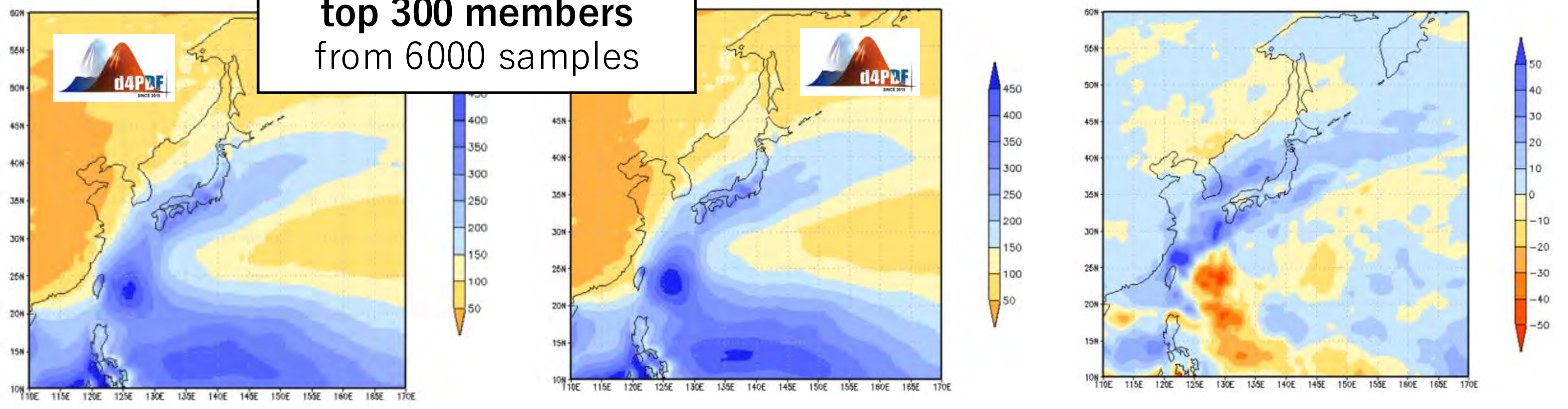
気象庁 キキクル

HIST

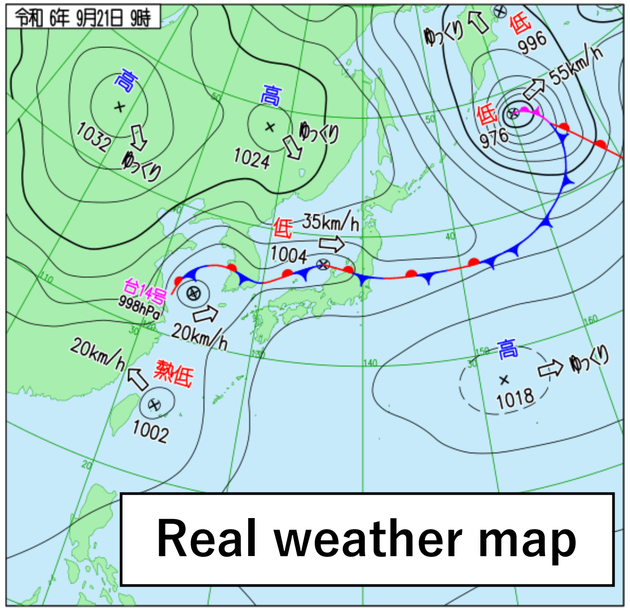
Analogues
top 300 members
from 6000 samples

NAT

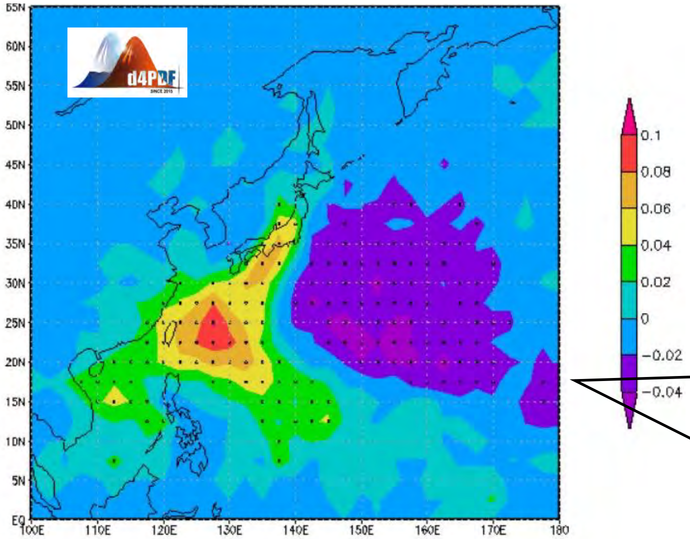
HIST minus NAT



A 5% increase in rainfall
in the focus area



Reg(heavy rain index, TC density)



*Total 6000 yrs for HIST and NAT

Enough analogues in d4PDF

(typhoon density regressed onto heavy rainfall in the focus area)

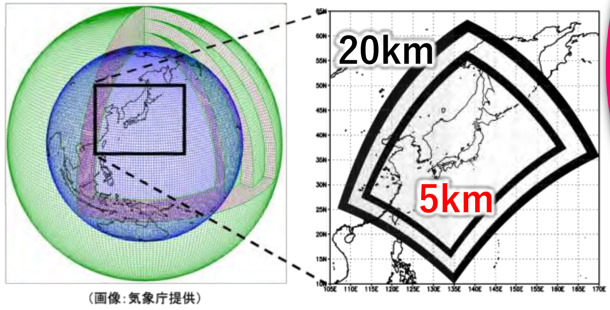
Obara et al. (in prep.)

Multiple EA systems in Japan

Imada et al.

Riskbased EA with extend d4PDF

全球モデル（MRI-AGCM60）　領域モデル（NHRCM）

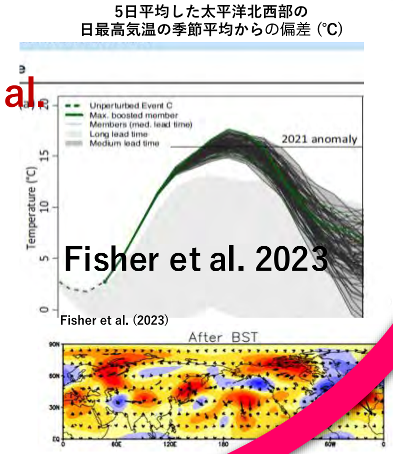


Imada et al.

Ensemble boosting System for dynamical EA (trial)

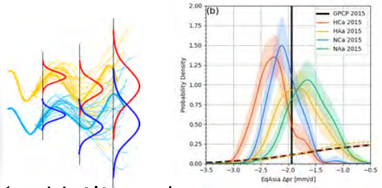
d4PDF x Ensemble boosting　Higuchi et al.

- ✓ Increase the number of members which promise the growth of a specific circulation pattern
- ✓ Capture unprecedented events



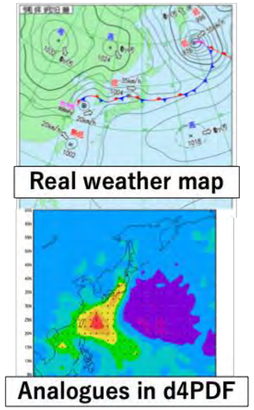
Coupled EA

Hasegawa et al.



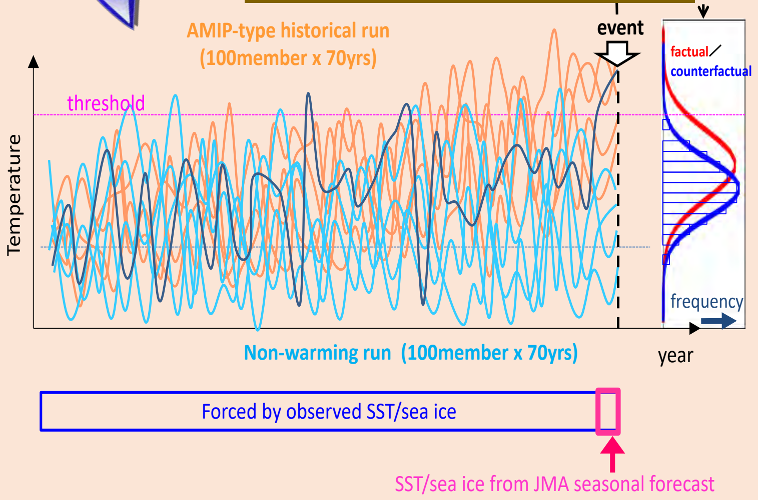
- ✓ Utilize the assimilation system of seasonal forecasts.
- ✓ Consider the effects of air-sea interaction

Analogue EA



Rapid EA

Predictive EA

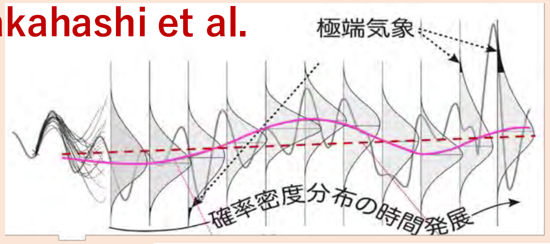


Imada et al.

Lower boundary condition is replaced by seasonal forecasted SST and sea ice.

Statistical EA

Takahashi et al.

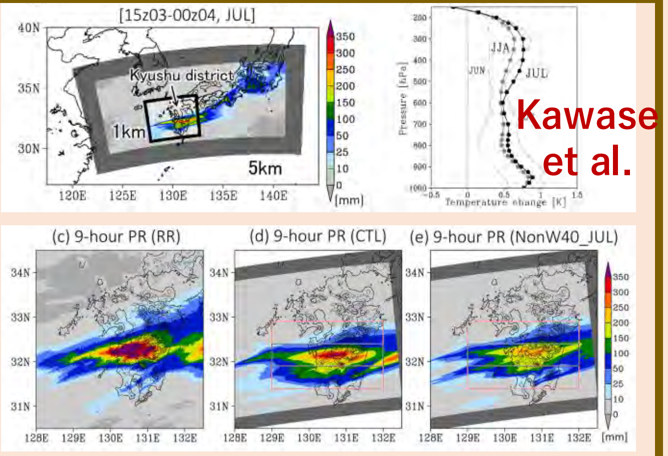


Gaussian　$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$

GEV　$P(x) = \exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]$

μ(t), σ(t), ξ(t)をd4PDFから予め推定

Storyline EA（pseudo-non-warming experiment）

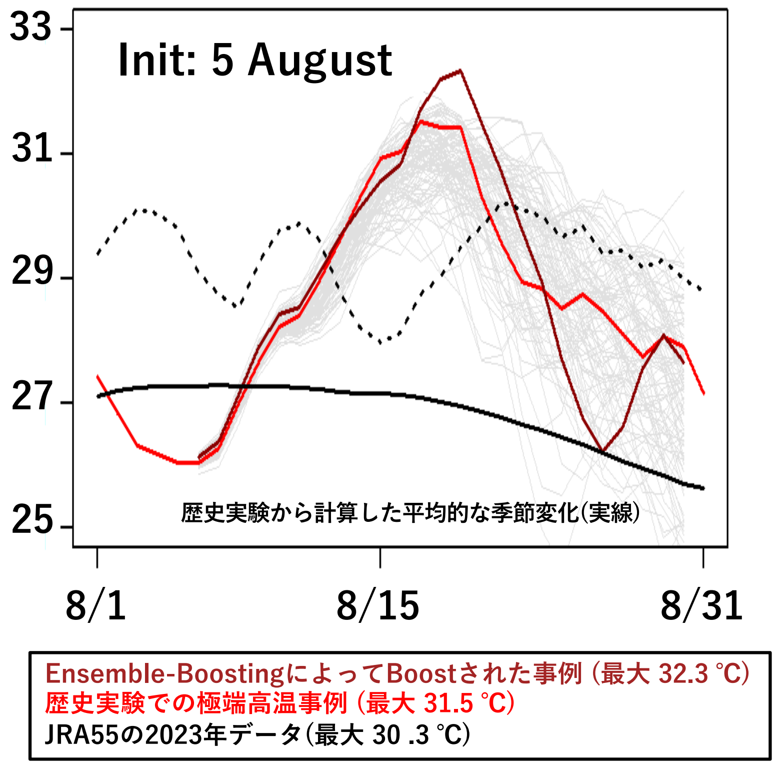


Kawase et al.

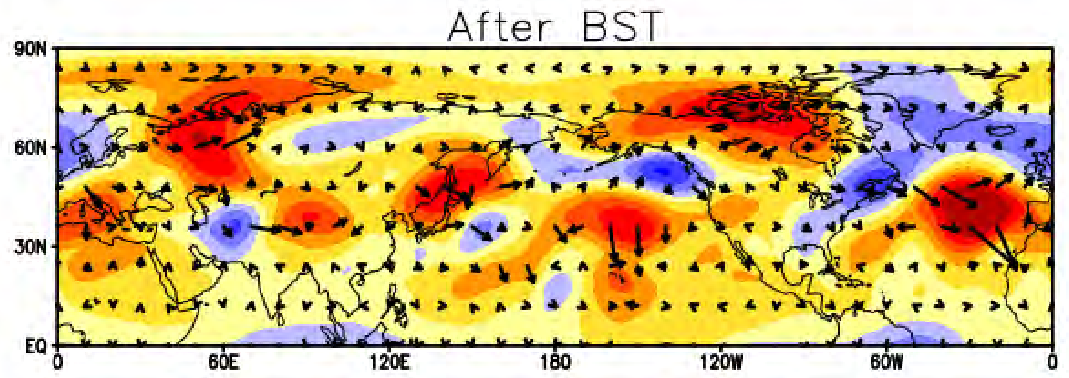
EA for unseen event: Ensemble boosting

August heatwaves in Japan

Land surface daily maximum temperature averaged over Japan



- **Ensemble boosting simulations** (Fisher et al. 2023) **for the Japanese unseen high temperature event**
- Select a subsamples in which a causal circulation field is likely to develop and increase the number of members by adding the initial perturbations.
- Capture the unseen high temperature extremes
- Provides insight into the background circulation patterns when Japan experiences an unseen heatwaves



Z200 anomalies associated with maximum daily temperature of boosting experiment

Higuchi et al. (in prep.)

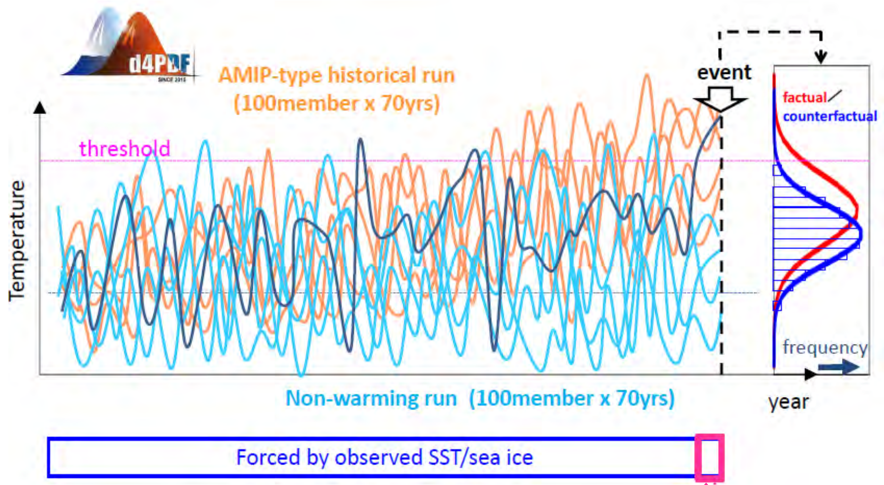
Summary　～Next step?

- Wider variety of EA methods
  - In addition to the original risk-based and storyline approaches, operational methods conducted by WWA, ClimateCentral, ClimaMeter, BoM, WAC Japan, etc…
- How to evaluate the uncertainty induced by different methods?
- Each method may focus on different aspects of extreme events and provide different types of information. How can we synthesize these insights and deliver them effectively to users?

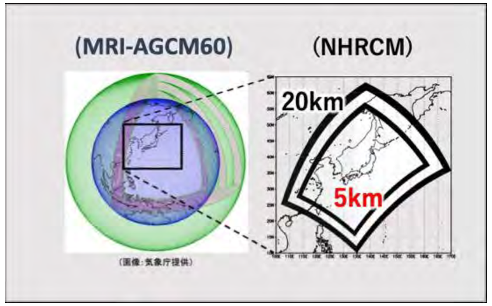
➢ Multiple methods to one common extreme event
  - Choice of the event?
  - Definition of the event?

Predictive EA simulations can be regarded as high-resolution large-ensemble seasonal prediction!

A kind of Two-tier seasonal prediction



SST/sea ice from JMA seasonal forecast



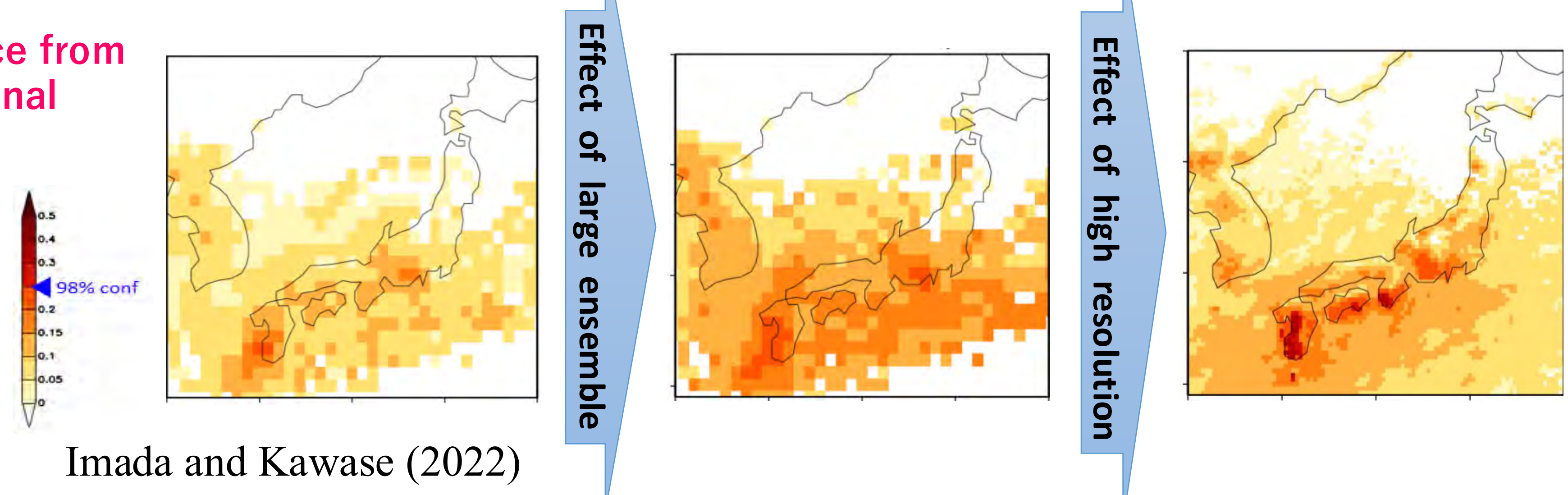
Dynamical downscaling
60km ➔ 20km ➔ 5km

Expected maximum ACC skill

Perfect model ACC estimated from d4PDF

Maximum prediction skill for heavy rainfall frequency

60km, 10 member | 60km, 100 member | 20km, 100 member



Imada and Kawase (2022)

Backups

Recent active rapid EA in the world: World Weather Attribution

World Weather Attribution

Home About Analyses News Peer reviewed research

Extreme downpours increasing in Southern Spain as fossil fuel emissions heat the climate

Latest analyses

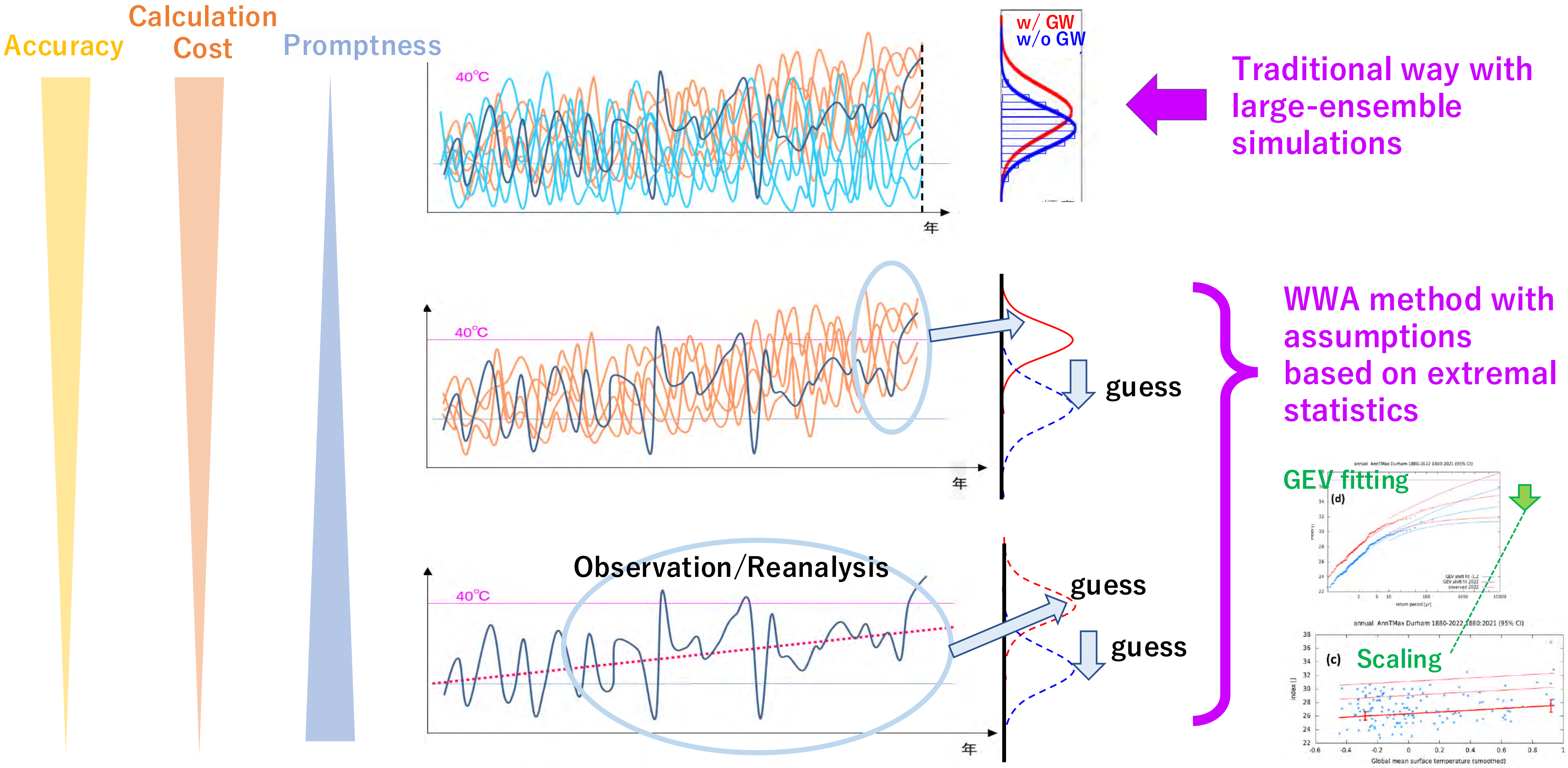
Heatwave

Heatwaves can be particularly dangerous to humans, and occur all over the world with increasing intensity.

Extreme rainfall

Rainfall events from a major storm or hurricane, or intense localised downpours can lead to flooding in any type of location.

Recent active rapid EA in the world: World Weather Attribution



Recent active rapid EA in the world: World Weather Attribution

Another advantage of the WWA method:

Estimation of uncertainty based on

◆Multi- data source (obs/reanalysis or CMIP)

◆Multi- method

◆Multi- model

Example:
2022 UK Heatwaves
Zachariah et al. 2022

Probability Ratio （P_{HIST}/P_{NAT}）

Reanalysis

Multi-model

Synthesis

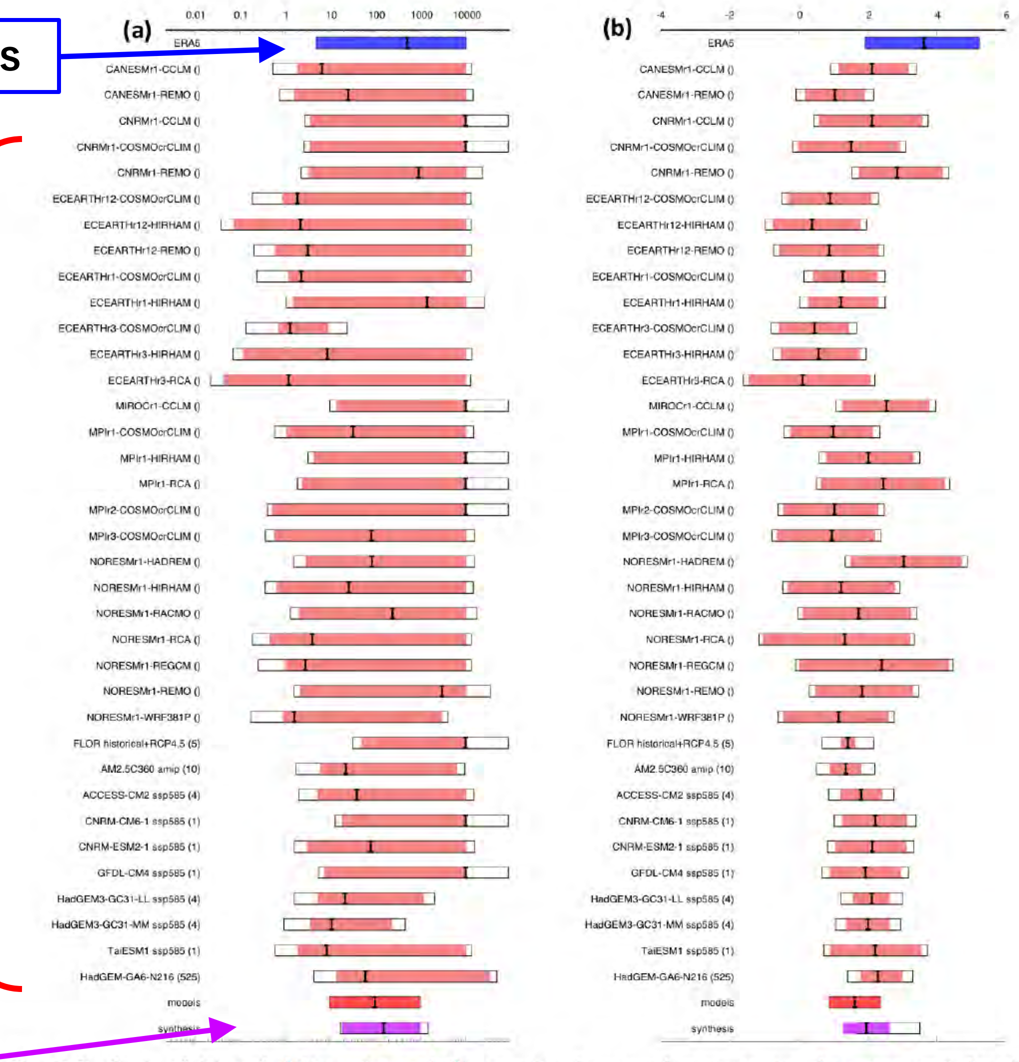
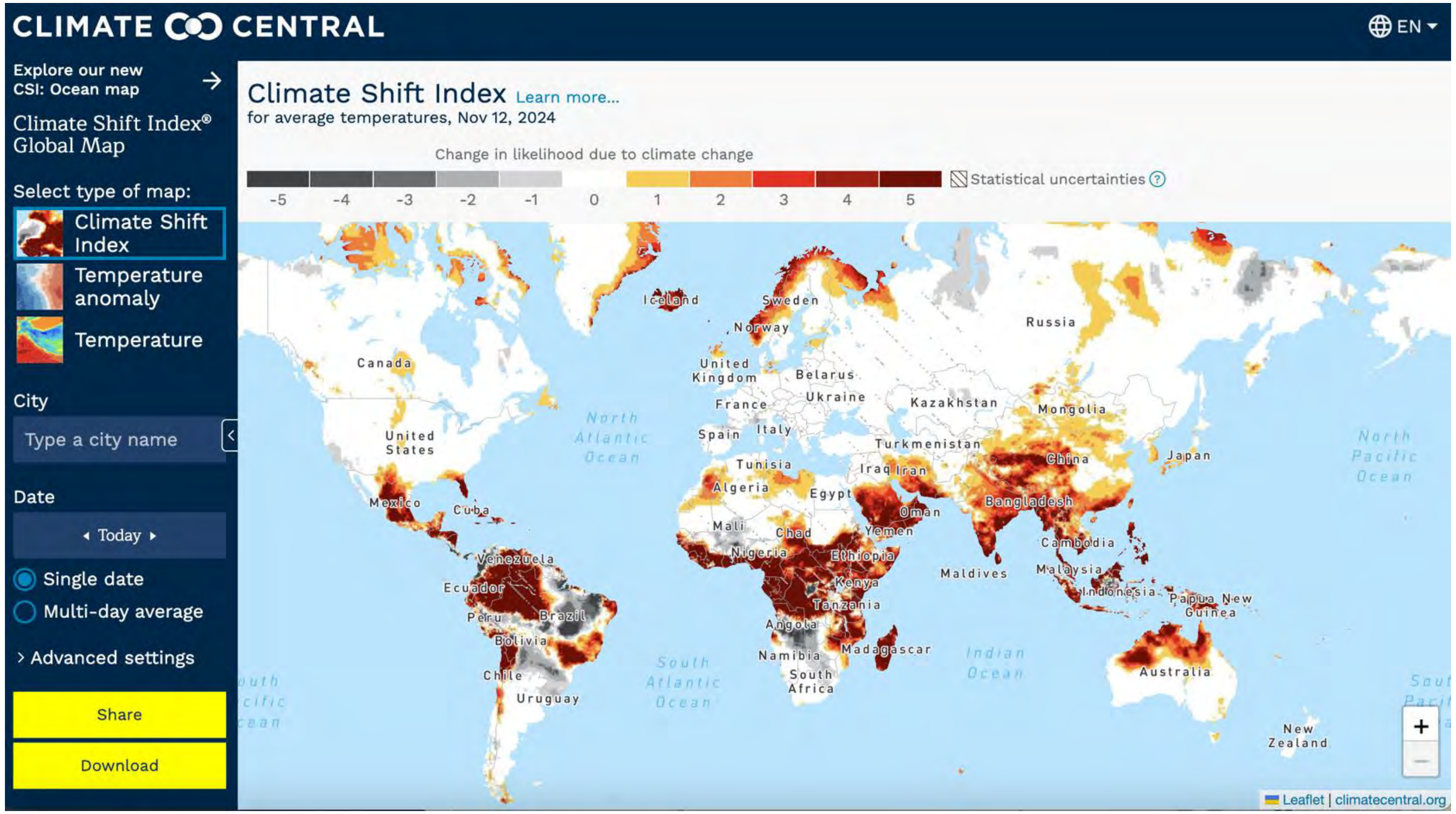


Fig. 6 Synthesis of (a) probability ratios and (b) intensity changes when comparing the return period and magnitudes of the 2022 maximum of 1-day maximum daily temperature event in the current climate and a 1.2°C cooler climate.

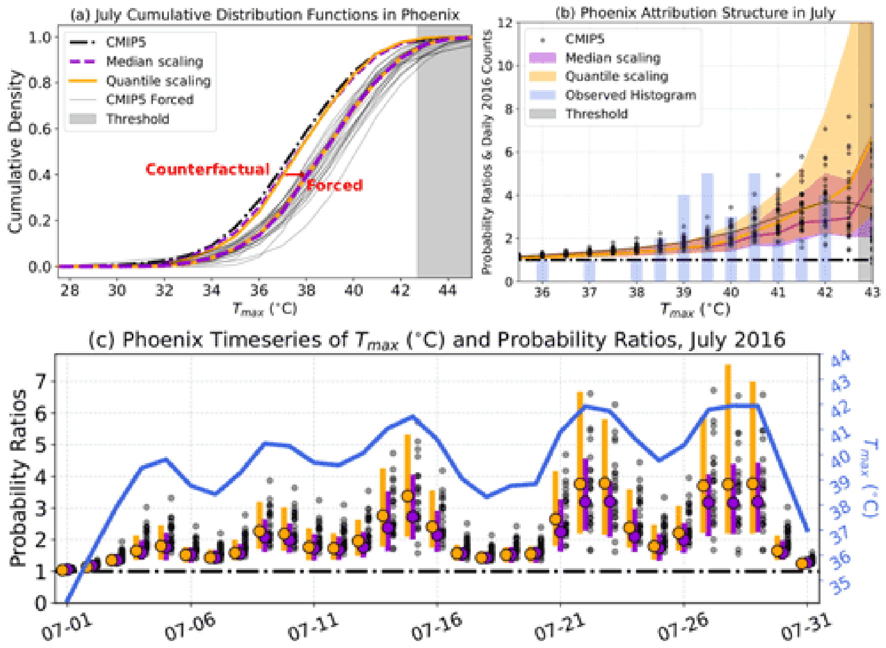
Recent active rapid EA in the world: Climate Central

Climate Shift Index

Daily temperature attribution system



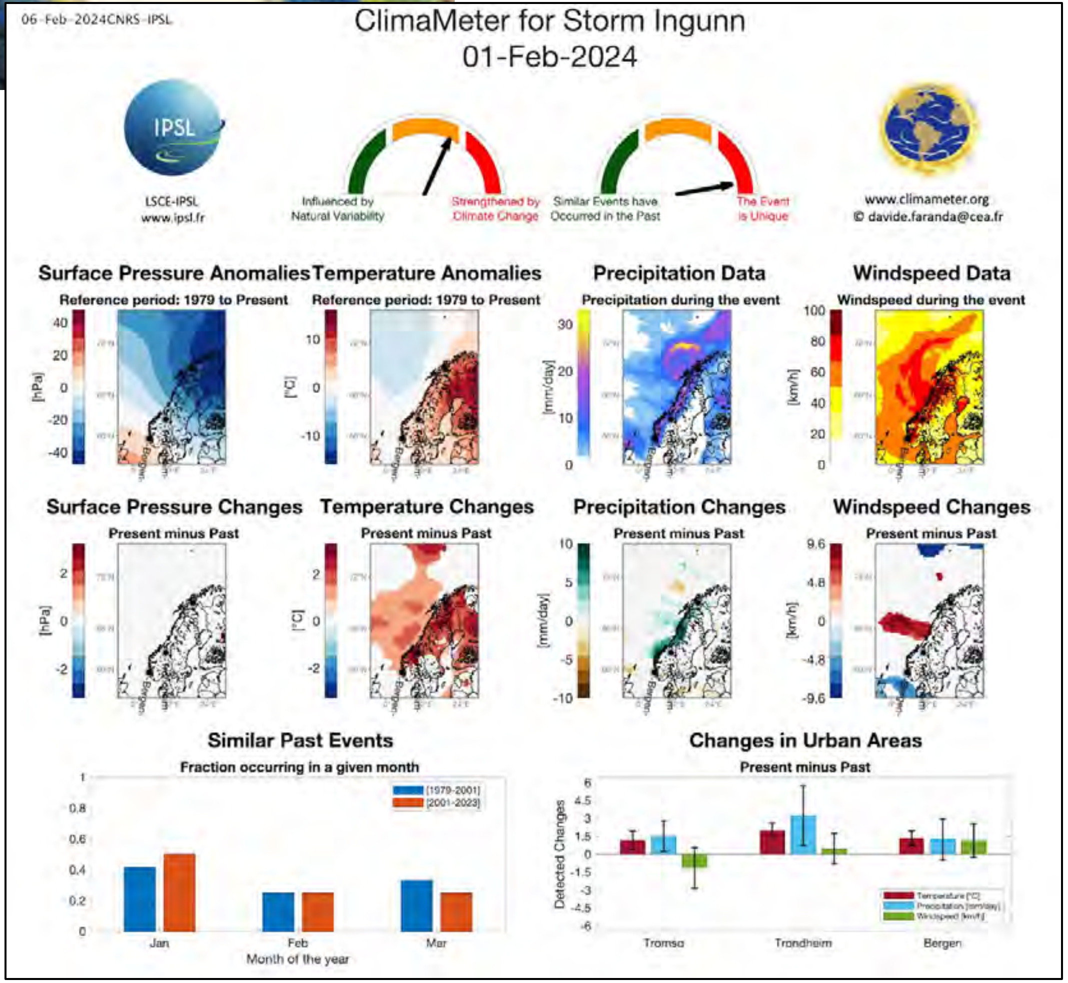
- Pre-prepared CDFs of daily maximum temperatures under the HIST and NAT climate conditions for each month for all grids.
- Calculate Risk Ratio by applying daily Tmax.



Recent active rapid EA in the world: ClimaMeter

ClimaMeter is an experimental rapid framework for understanding extreme weather events in a changing climate based on looking at similar past weather situations.

- Divide historical observation/reanalysis data into the past and present periods.
- The events that are similar to the target event are extracted from the two periods and compared.
- To determine how much natural variability affected the results, ClimaMeter verifies whether the AMO, PDO or ENSO phases were significantly different on average during the two sets of analogue events.

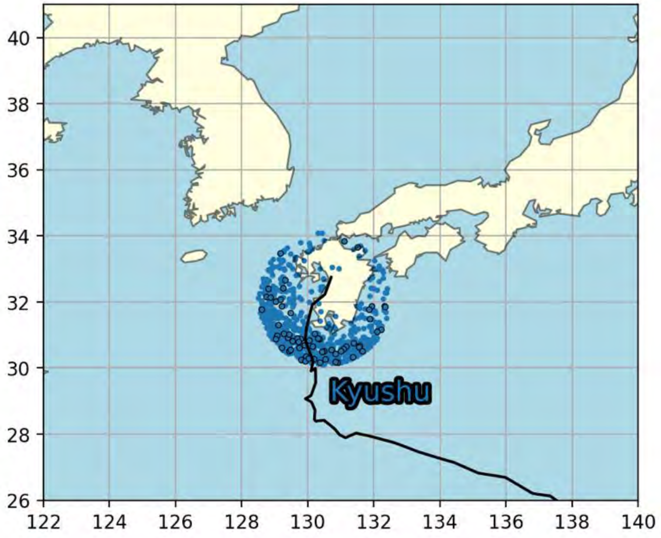


A kind of analogue method?

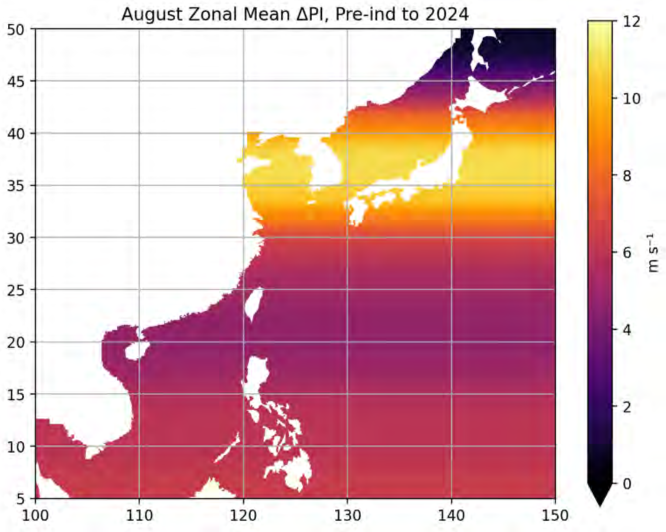
Recent active rapid EA in the world: Imperial College

台風10号のEA

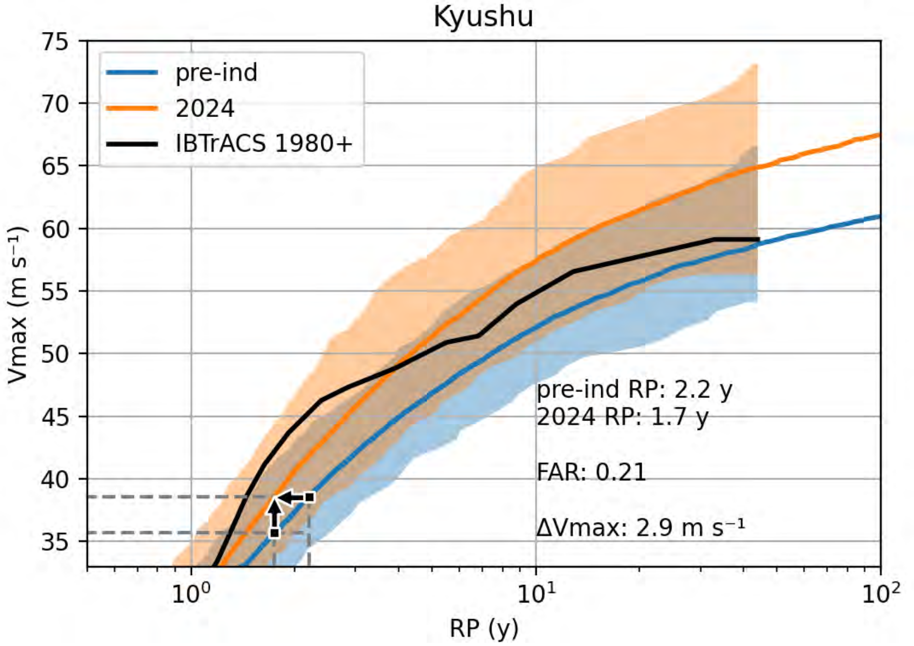
- Imperial College Storm Model (IRIS)（CHIPSタイプ）を利用
- 数千メンバー
- −1.3℃で非温暖化実験
- 九州に接近した台風のみを抽出して属性を比較（アナログ法の一種）



九州に接近した台風を解析



温暖化による最大風速の変化（東西平均）



最大風速の再現期間