# Future changes in the intensity and duration of marine heatwaves: Insights from coupled model initial-condition Large Ensembles

Clara Deser (NCAR)

US CLIVAR and ICTP Summer School on Marine Heatwaves
27 July 2023, Trieste

*Deser et al. 2023: In review at Journal of Climate*

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- Background Warming
- Change in Variability

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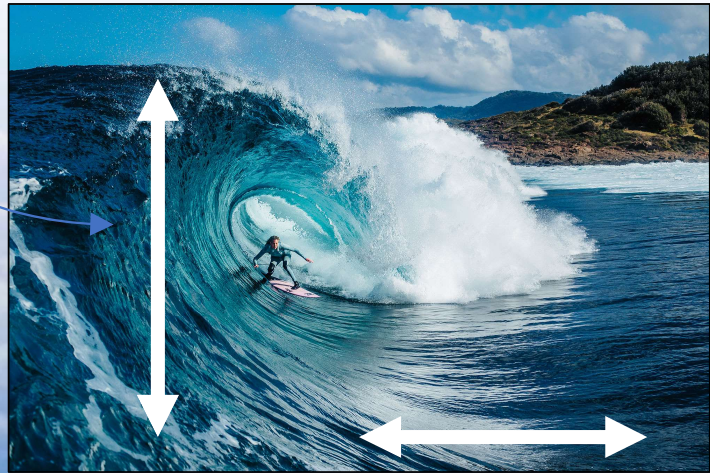

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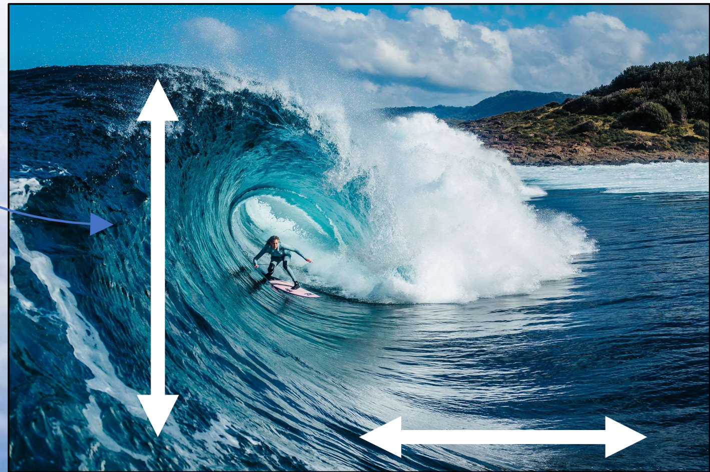
Unravel with climate model initial-condition Large Ensembles.



# Initial-condition Large Ensembles

*US CLIVAR Working Group on Large Ensembles*

nature climate change

30 March 2020
Deser et al.

PERSPECTIVE
https://doi.org/10.1038/s41558-020-0731-2

Check for updates

## Insights from Earth system model initial-condition large ensembles and future prospects

C. Deser[1,2] ✉, F. Lehner[1,2], K. B. Rodgers[2,3,4], T. Ault[2,5], T. L. Delworth[2,6], P. N. DiNezio[2,7], A. Fiore[2,8], C. Frankignoul[2,9], J. C. Fyfe[2,10], D. E. Horton[2,11], J. E. Kay[2,12,13], R. Knutti[2,14], N. S. Lovenduski[2,12,15], J. Marotzke[2,16], K. A. McKinnon[2,17], S. Minobe[2,18], J. Randerson[2,19], J. A. Screen[2,20], I. R. Simpson[1,2] and M. Ting[2,8]

*What are they? Why are they useful?*
*How large do they need to be?*
*How are they best designed?*
*Emerging applications and future directions?*

# Initial-condition Large Ensembles in a nutshell

CMIP5 & 6 Models
Global, Coupled

Spatial resolution
~ 1° latitude/longitude

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- **Large** ensemble size (30-100 members for each model).
- **Different** initial conditions for each member.
- **Same** radiative forcing protocol for each member.
- Each simulation follows a **different random sequence of internally-generated variability**, superimposed upon a **common forced** response (after initial condition memory is lost).

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➢ Lots of samples of internal variability for robust estimation of the evolving characteristics of the forced response.

Forced response:

1) Background climate change
2) Changes in variability (including extremes)

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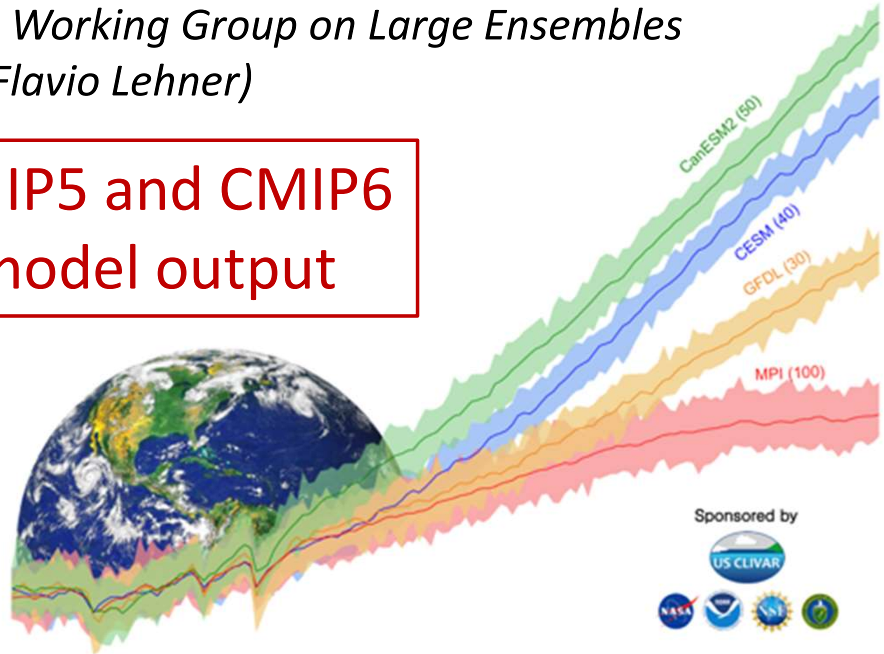
> 1) Background climate change ≈ ensemble mean (*t*)
> 2) Changes in variability (including extremes)
>
> Internal variability (*t*) in each member ≈ deviation from ensemble mean (*t*)

# MULTI-MODEL LARGE ENSEMBLE ARCHIVE

*US CLIVAR Working Group on Large Ensembles*
*(credit to Flavio Lehner)*

CMIP5 and CMIP6 model output




**https://www.cesm.ucar.edu/community-projects/mmlea**

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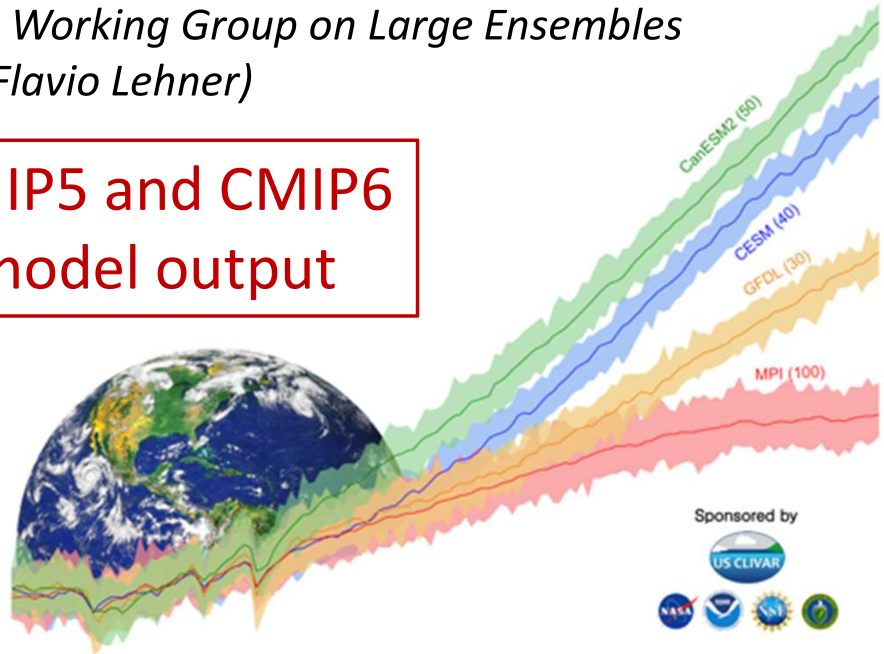


Expansion to 16 models and 11 variables coming soon!
(credit to Nicola Maher)

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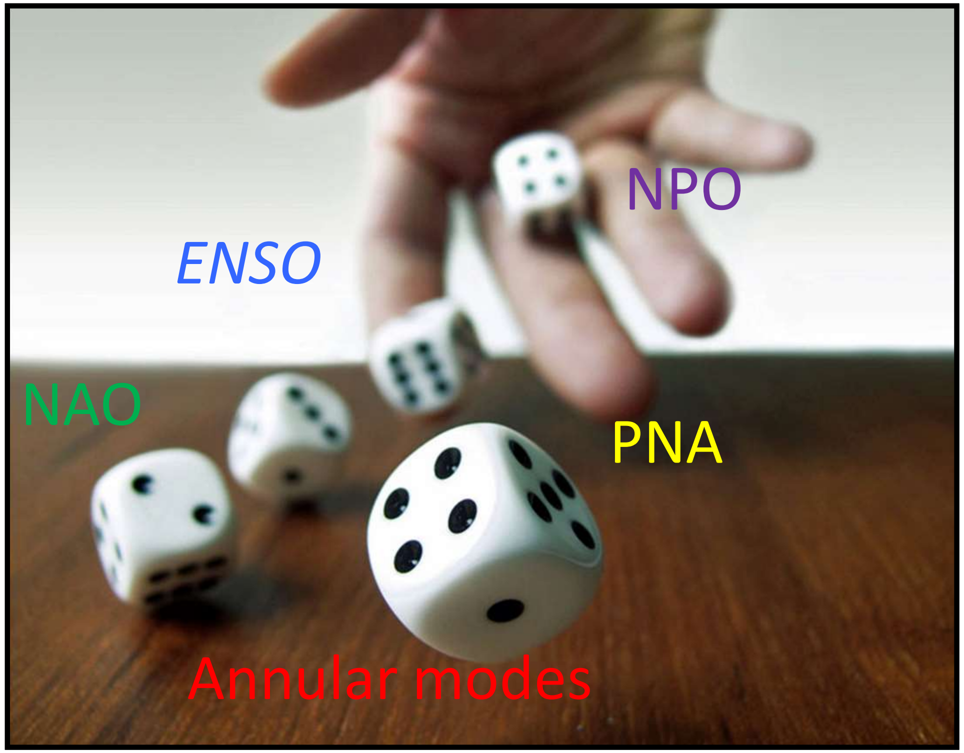


**Lots of random variability, which means it is essential to have a large number of samples for robust assessment.**

**Null hypothesis for any apparent *model bias in variability* and any apparent *change in variability* due to radiative forcing (e.g.,solar, GHG, volcanoes …) should be "sampling fluctuations".**

# Guiding Questions

1. How well do models simulate present-day characteristics of marine heatwaves?

2. How will marine heatwaves change in the future?

3. What role does ENSO play?

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CESM2 100-member Large Ensemble (1850-2100)

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Monthly “SST” 1950-2020

(anomalies relative to the 1950-2020 mean seasonal cycle, then linearly detrended)

90$^{th}$ percentile threshold computed for each month separately.

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Monthly "SST" 1950-2020
(anomalies relative to the 1950-2020 mean seasonal cycle, then linearly detrended)
$90^{th}$ percentile threshold computed for each month separately.

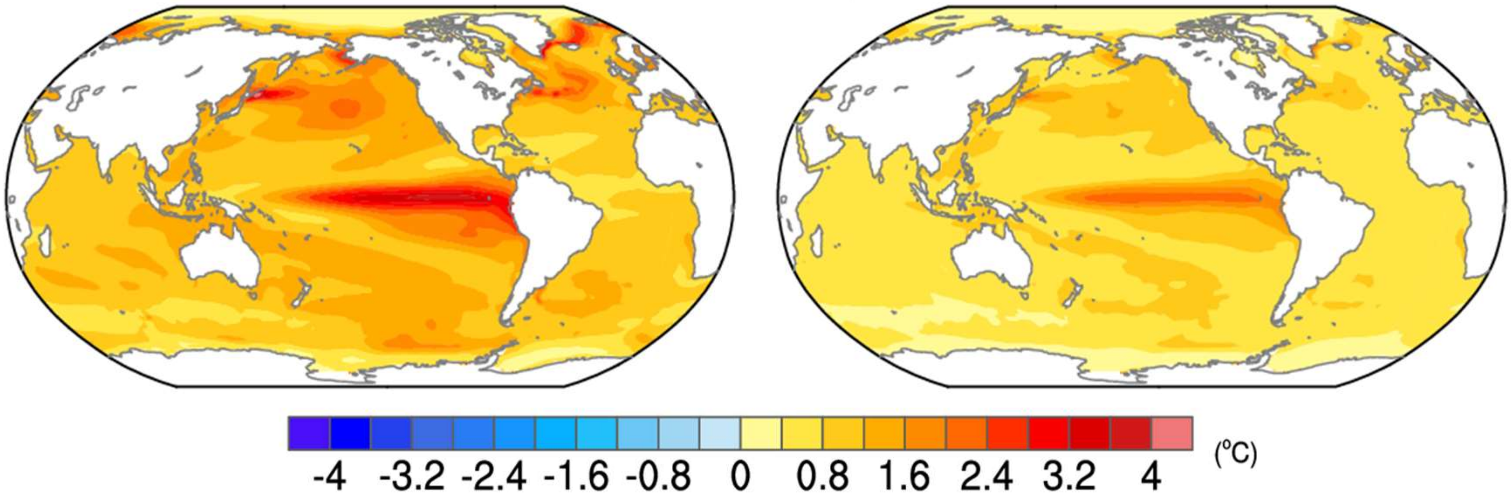
71 years x 12 months x 0.10 = 85 heatwave months per member on average
(8500 across the entire ensemble)

# CESM2 100-member Large Ensemble

## Average Intensity of all Marine Heatwaves during 1950-2020

Ensemble member with the maximum value

Ensemble member with the minimum value




85 samples

**Spread is due to inadequate sampling of random internal variability!**

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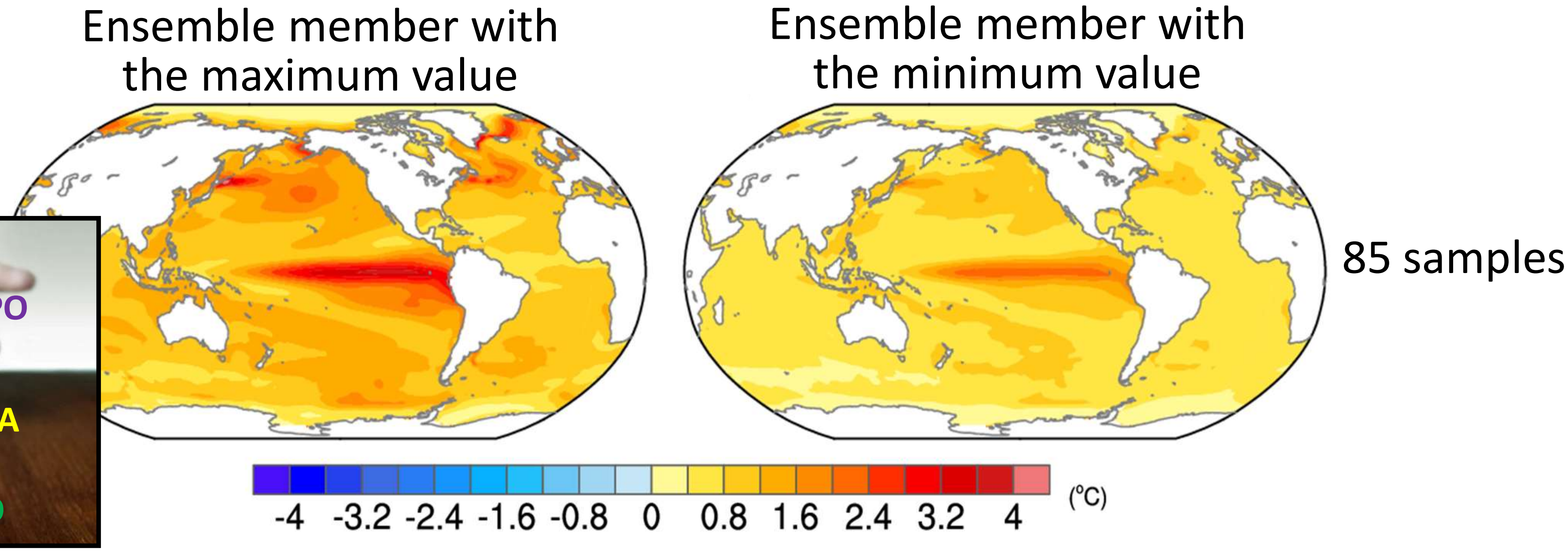


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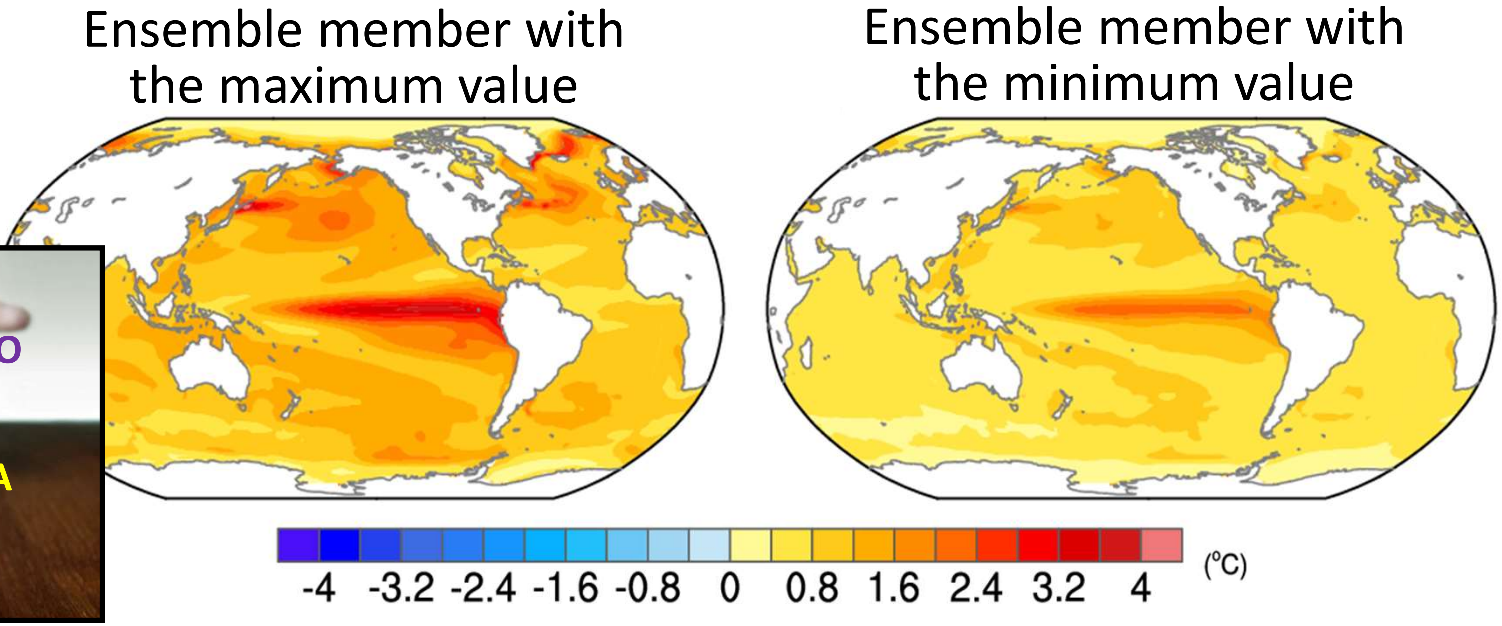


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**Spread is due to inadequate sampling of random internal variability!**

**How well do we know the observed average intensity?**

**How do we evaluate our models?**

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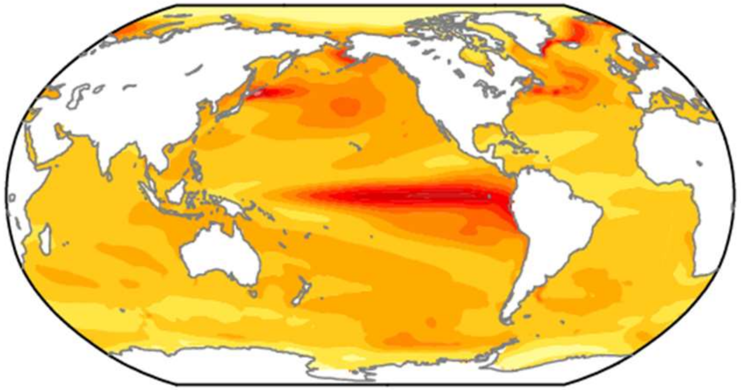
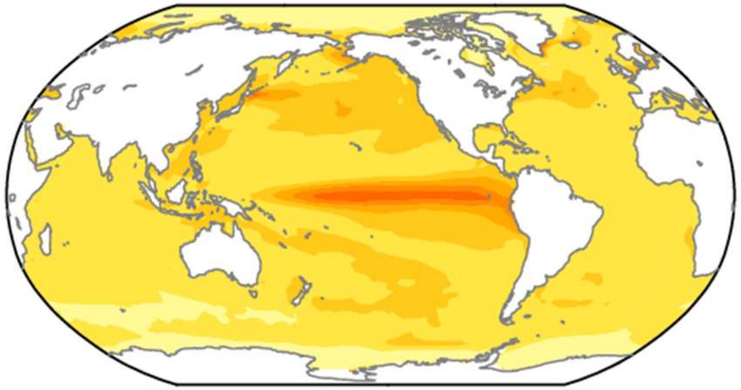
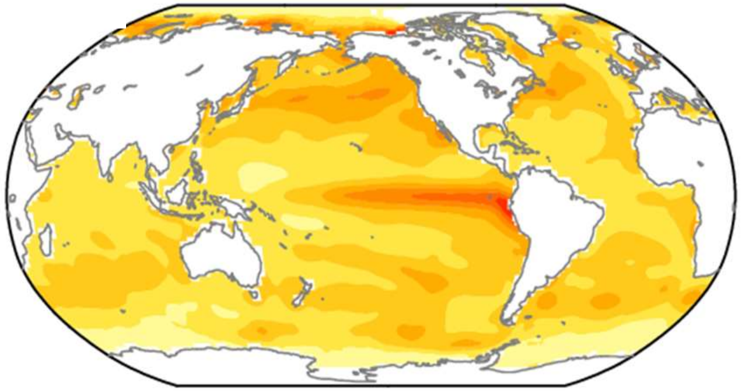


Ensemble member with the minimum value



85 samples

Observations (ERSSTv5)



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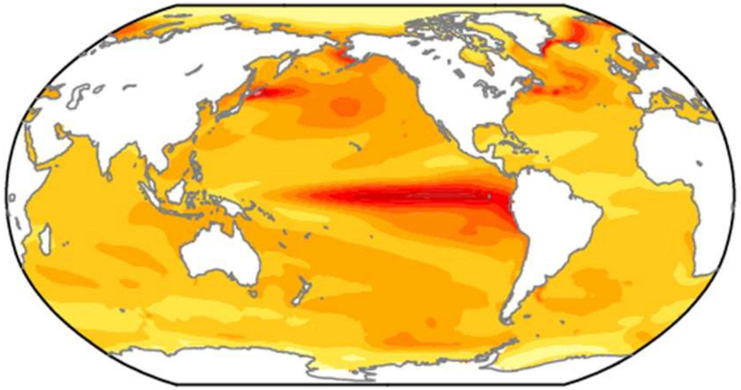

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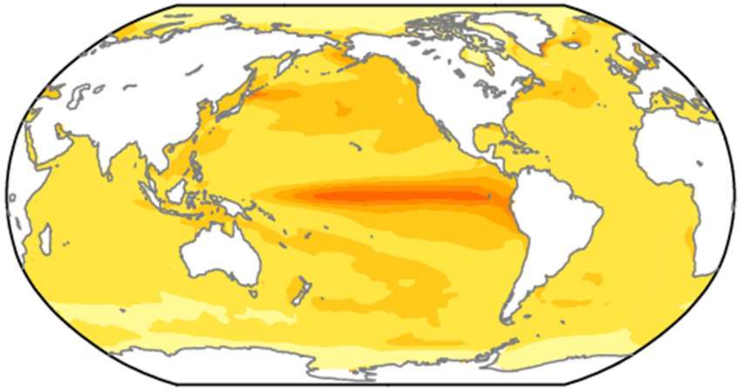

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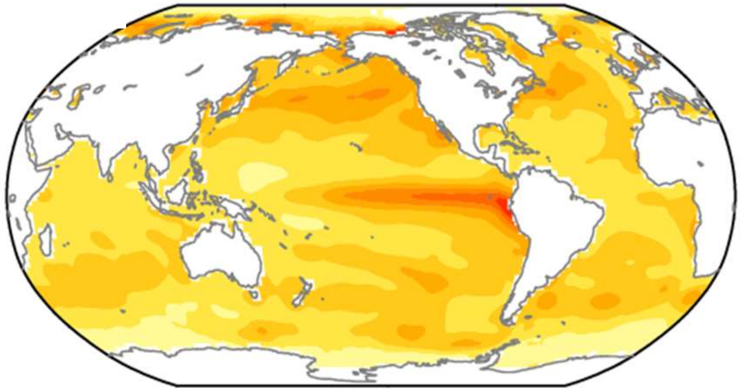

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Do the observations lie within the model's ensemble spread?

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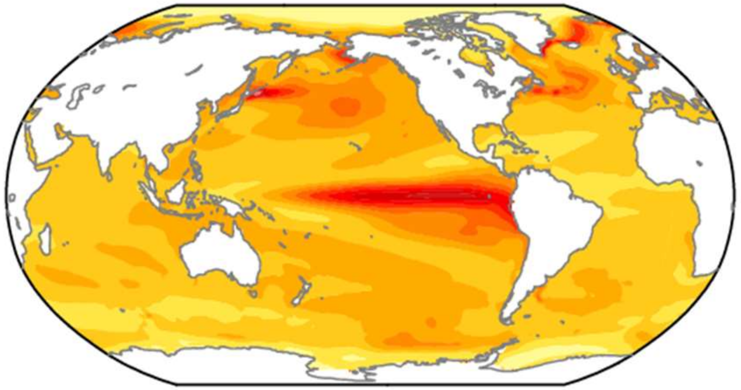

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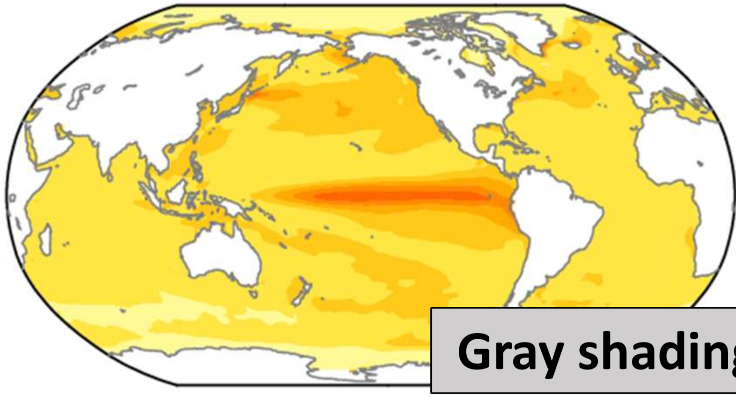
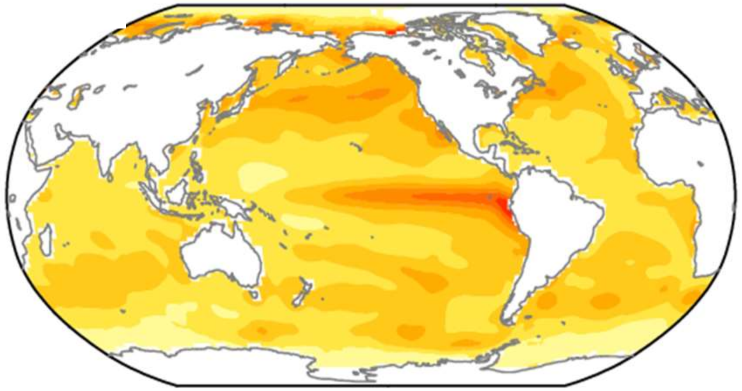


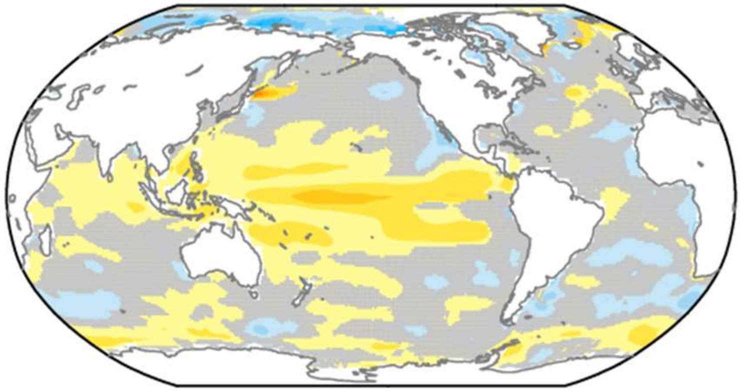
85 samples

**Gray shading = Yes**

Observations (ERSSTv5)



Model - Obs



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# CESM2 100-member Large Ensemble

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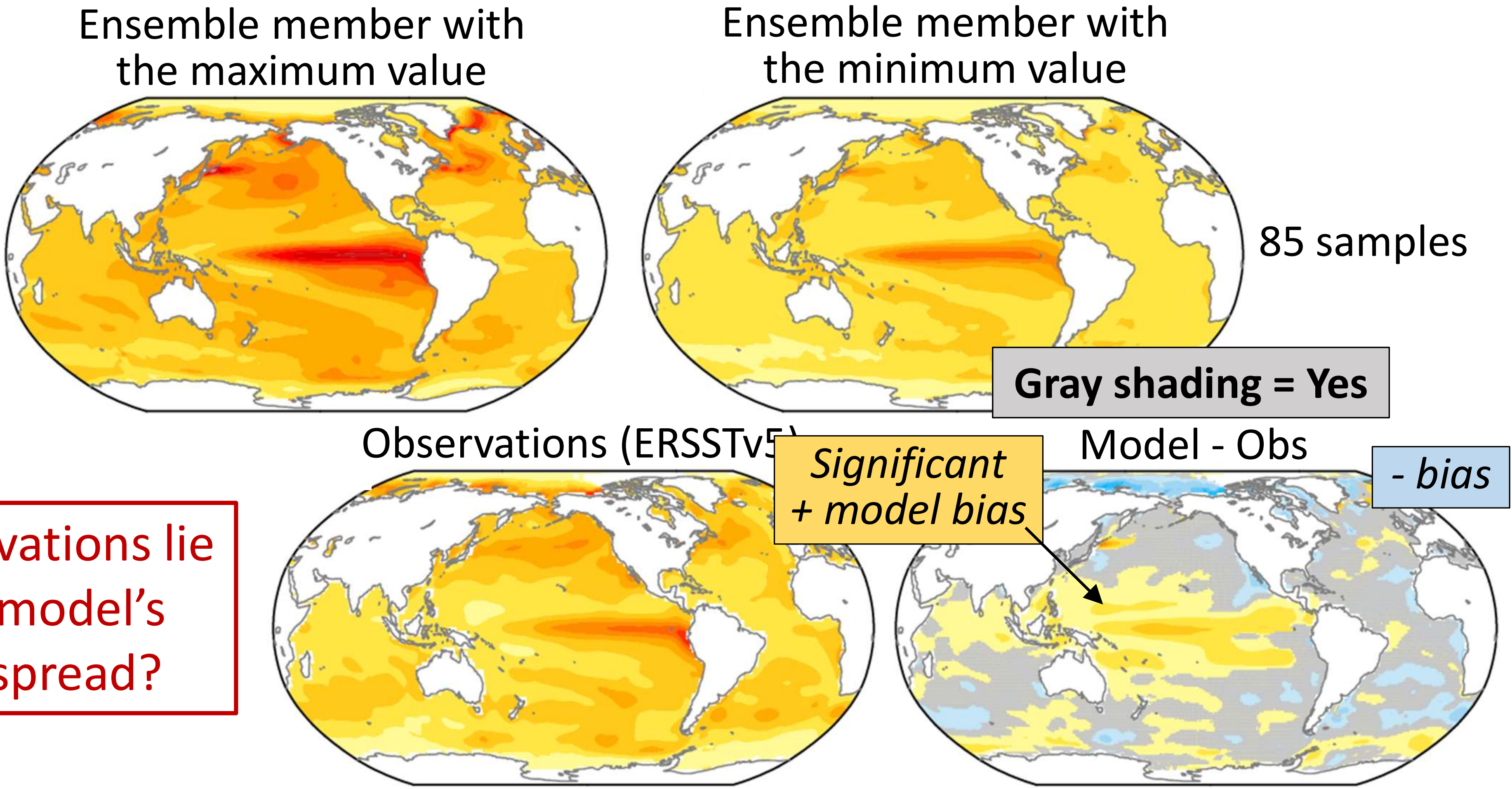


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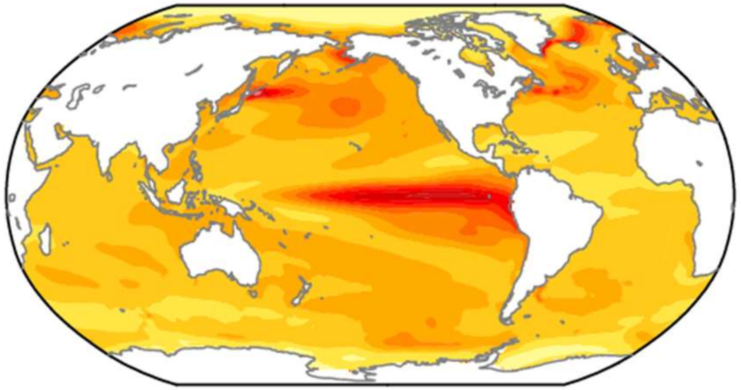

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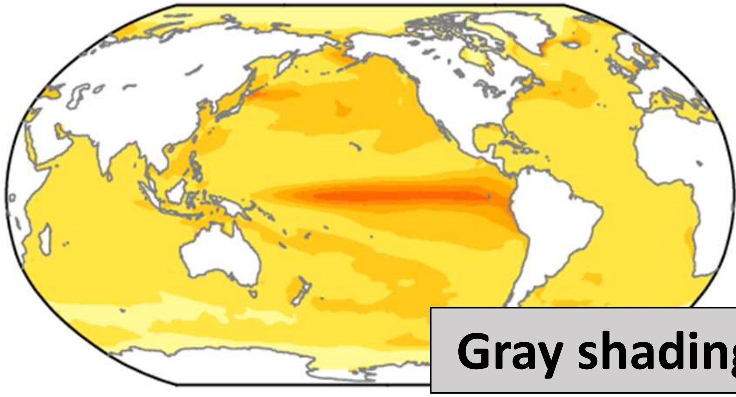

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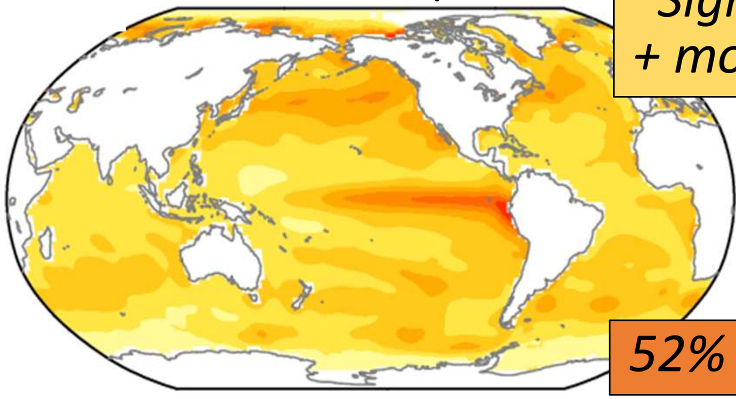

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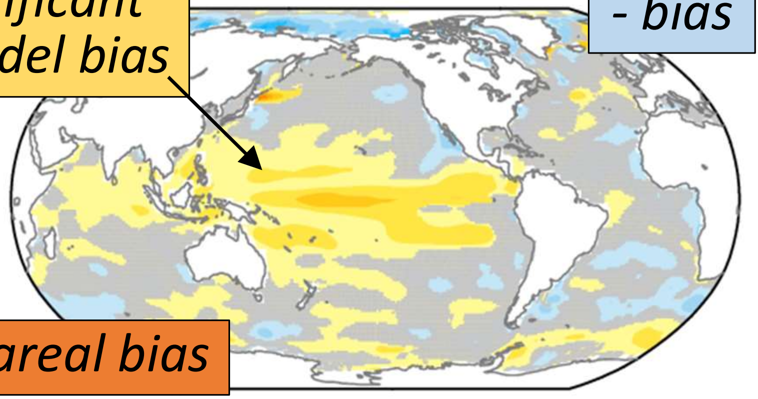


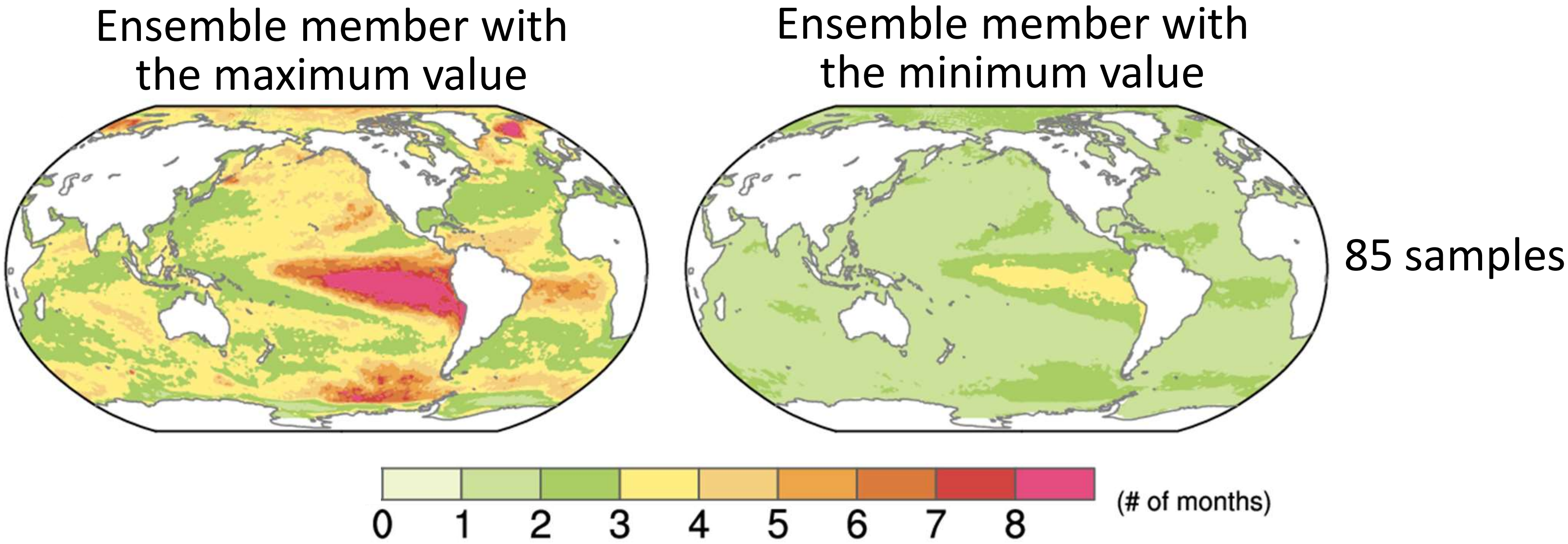

Do the observations lie within the model's ensemble spread?

# Marine Heatwave Duration

(# consecutive months above the 90$^{th}$ percentile threshold)

# CESM2 100-member Large Ensemble

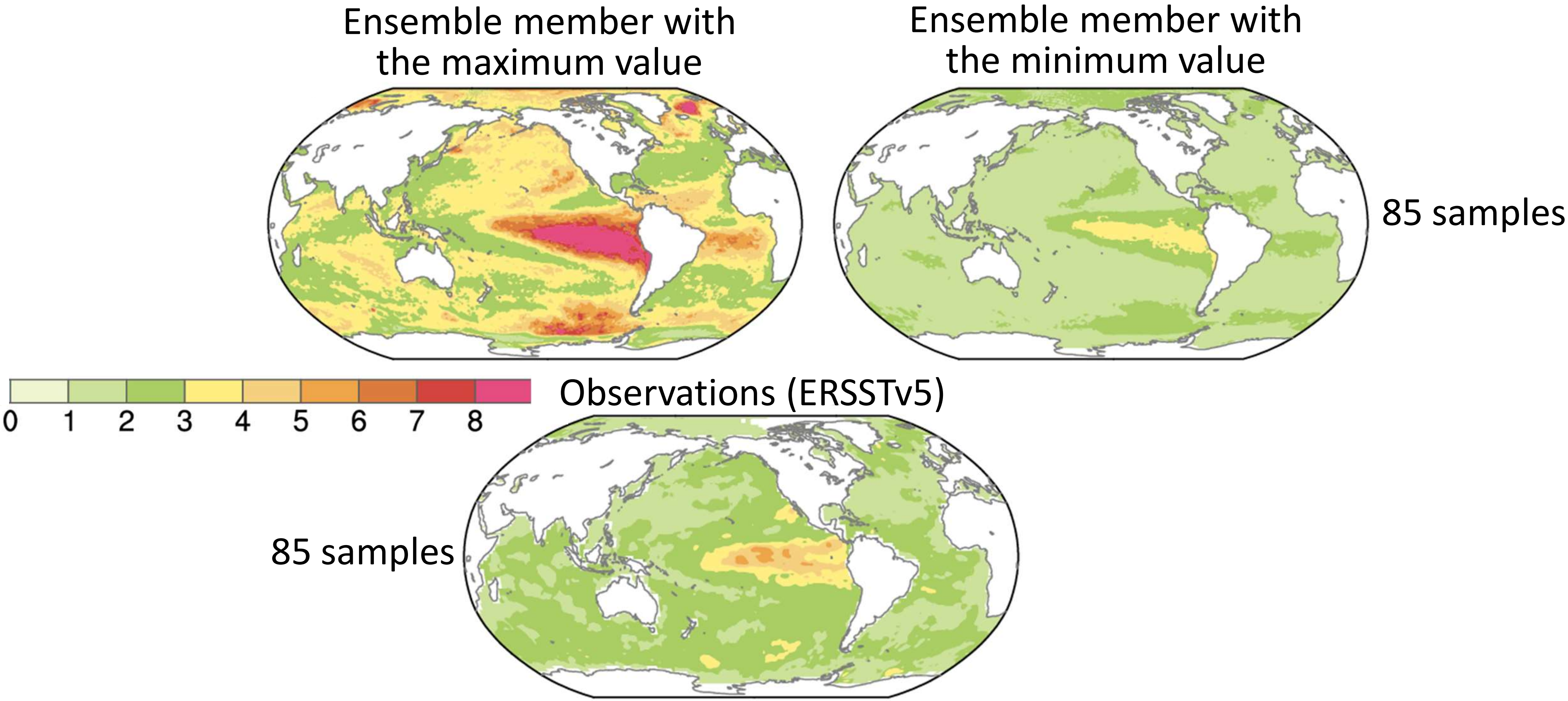
## Average **DURATION** of all Marine Heatwaves during 1950-2020




**Large spread due to inadequate sampling of random internal variability!**

# CESM2 100-member Large Ensemble

## Average **DURATION** of all Marine Heatwaves during 1950-2020



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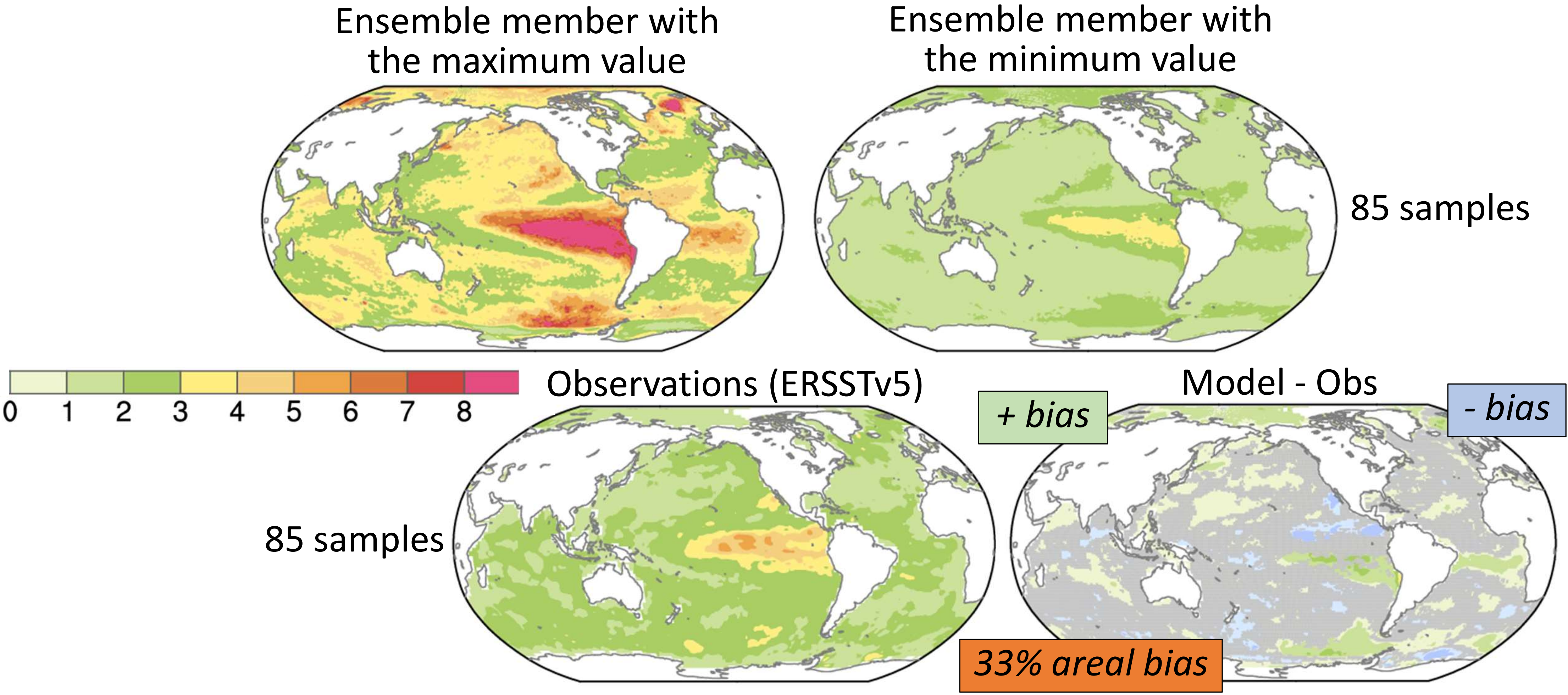


# How do models compare?

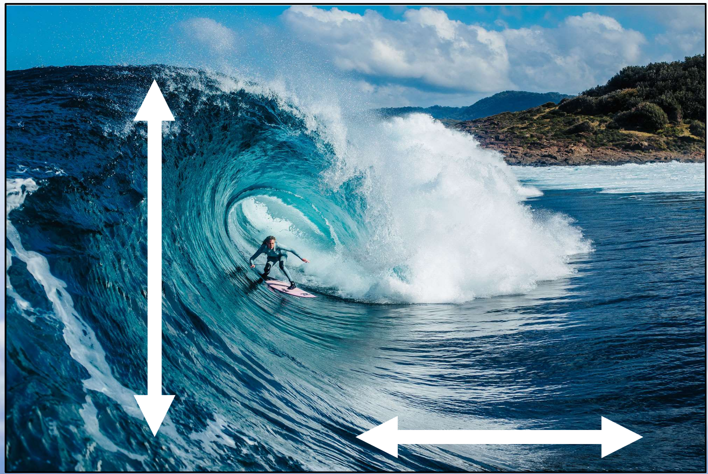
7 different model Large Ensembles,
30-100 members each.

Areal fraction of significant model bias (1950-2020)

- Intensity: 51-68%
- Duration: 33-53%

# Future Changes

1) Due to changes in variability.
2) Superimposed upon changes in the mean state.



## 2. How will marine heatwaves change in the future?

CESM2 100-member Large Ensemble

Compare 2020-2050 and 2070-2100 against the reference period 1970-2000.

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## CESM2 100-member Large Ensemble

Compare 2020-2050 and 2070-2100 against the reference period 1970-2000.

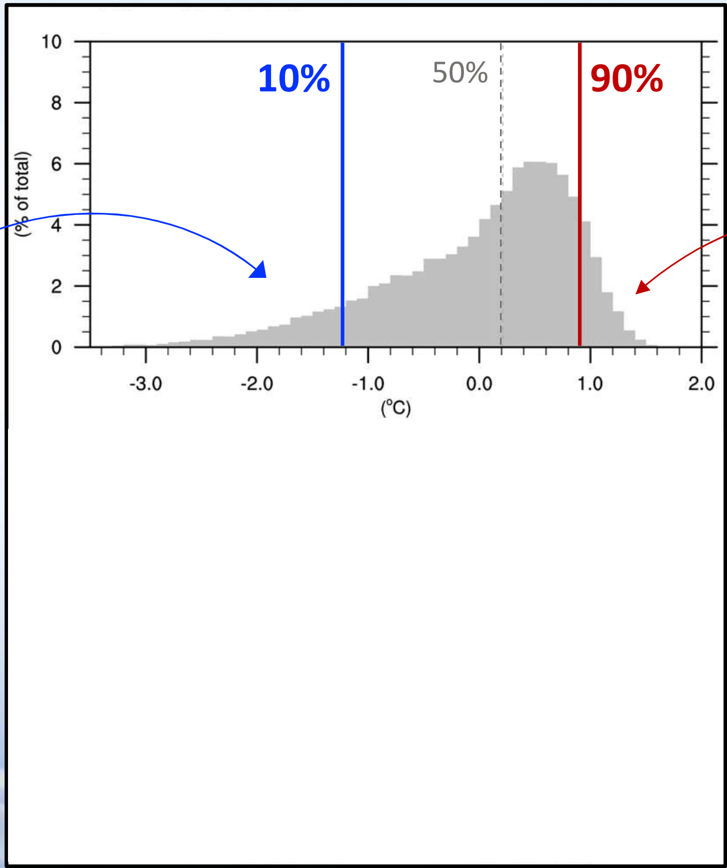
1. Remove the ensemble mean from each member at each time step to isolate the variability.
2. Compute $90^{th}$ percentile thresholds for each month using output from step 1 (all 100 members) for each 31-year period separately.
3. Compute average MHW intensity and duration for each period from the samples identified in step 2.

# MHW and MCW Thresholds

CESM2 100-member
Large Ensemble

Mean state
changes removed.

Monthly iSST (West Tropical Pacific)




3720 MCW samples

*1970-2000*

3720 MHW samples

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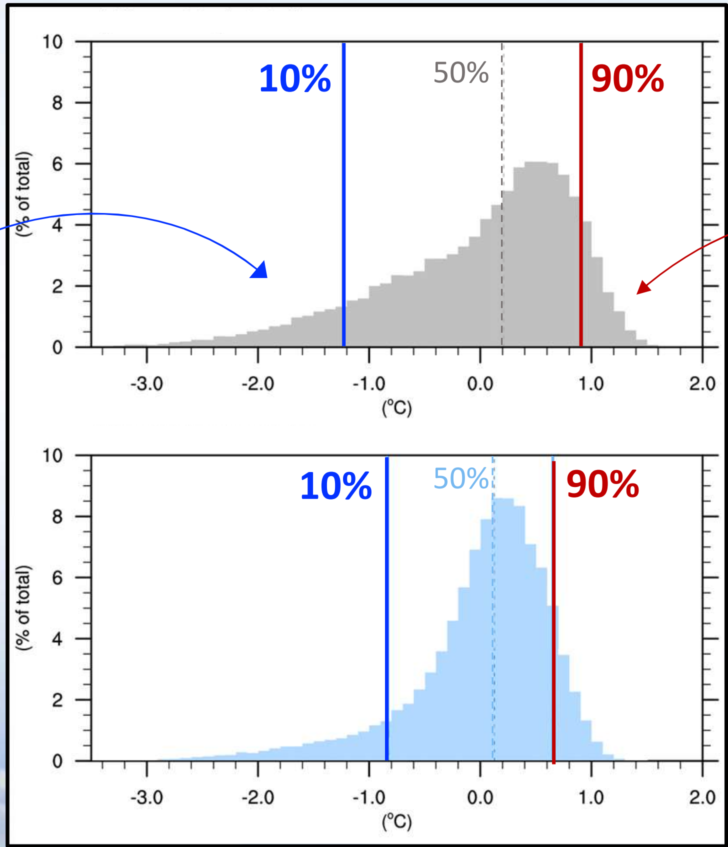



*1970-2000*

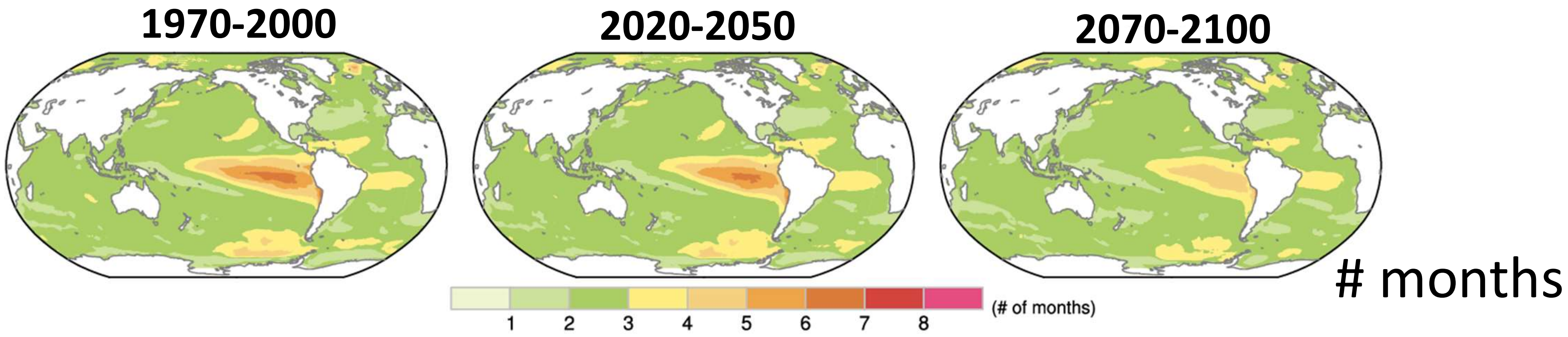
*2070-2100*

3720 MCW samples

3720 MHW samples

# Marine Heat Wave **Duration** (100-member CESM2 Large Ensemble)

Mean state changes removed.



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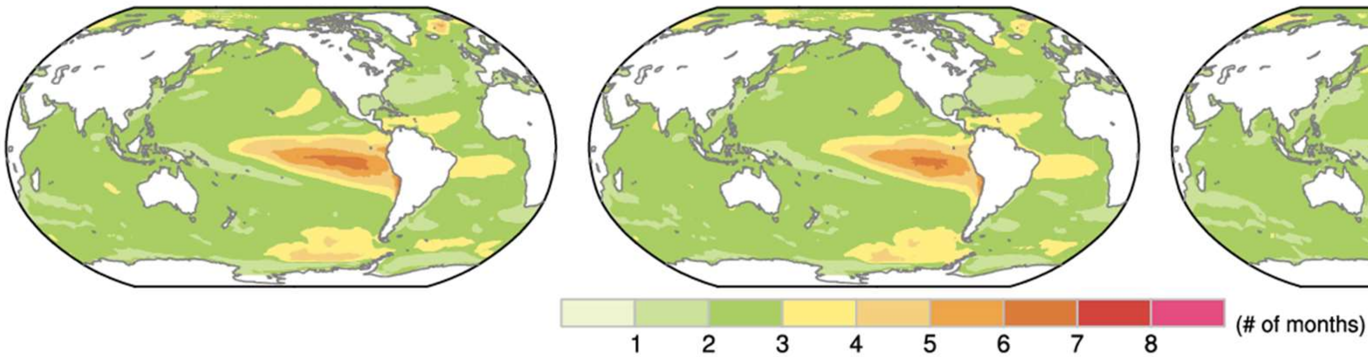
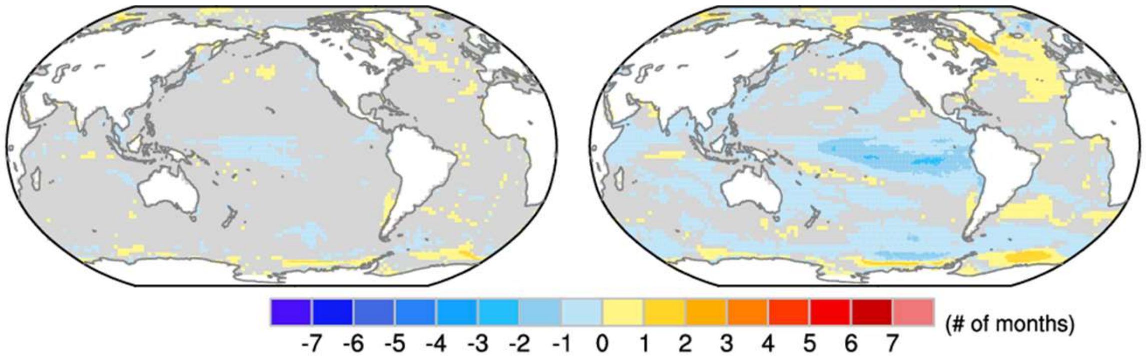
**1970-2000** **2020-2050** **2070-2100**




# months

**2020-2050** **2070-2100**

**Difference relative to 1970-2000**




**Longer**
**Shorter**

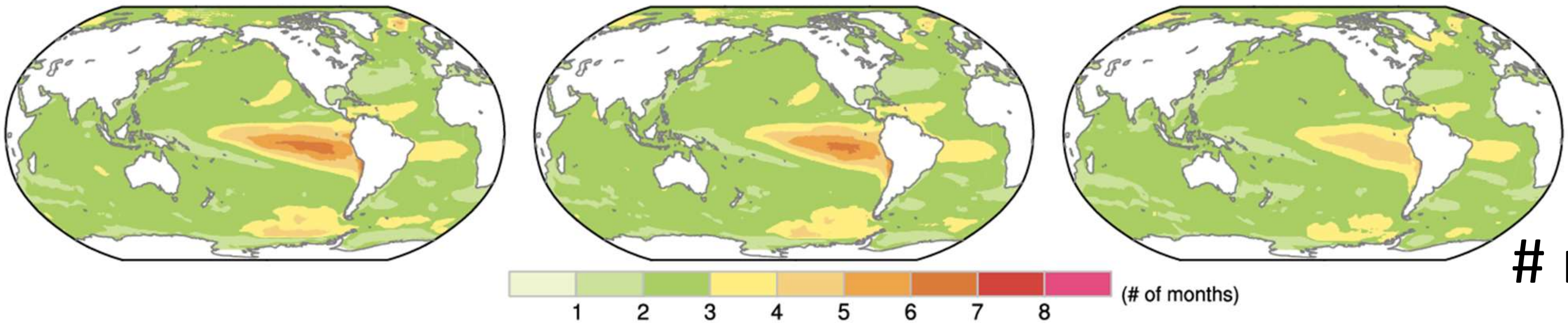
Gray shading: change is insignificant

(False Discovery Rate test applied to the t-test at the 5% confidence level)

# Marine Heat Wave **Duration** (100-member CESM2 Large Ensemble)

Mean state changes removed.

**1970-2000** **2020-2050** **2070-2100**




# months

**2020-2050** **2070-2100**

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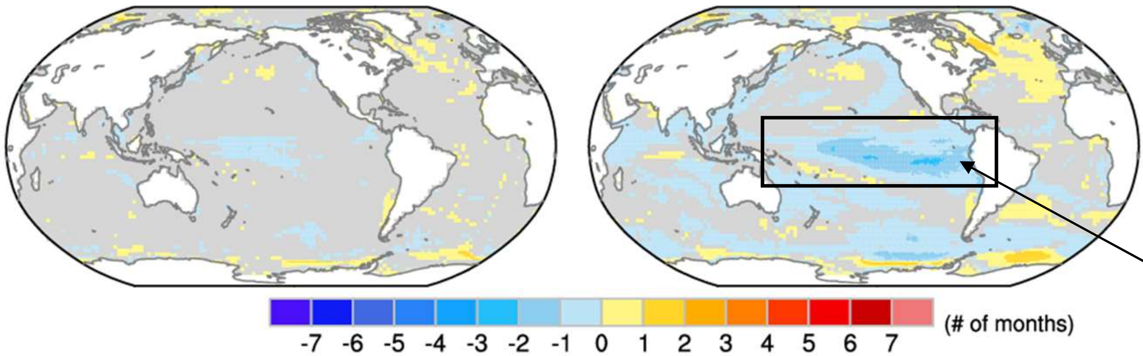


**Longer**

**Shorter**

*Shorter El Nino duration*

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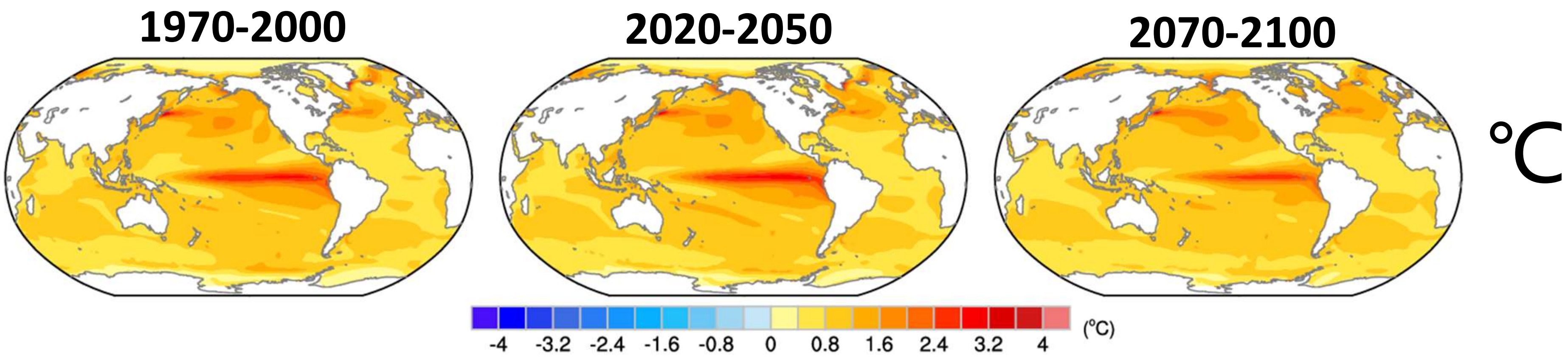
# Marine Heat Wave **Intensity** (100-member CESM2 Large Ensemble)

Mean state changes removed.



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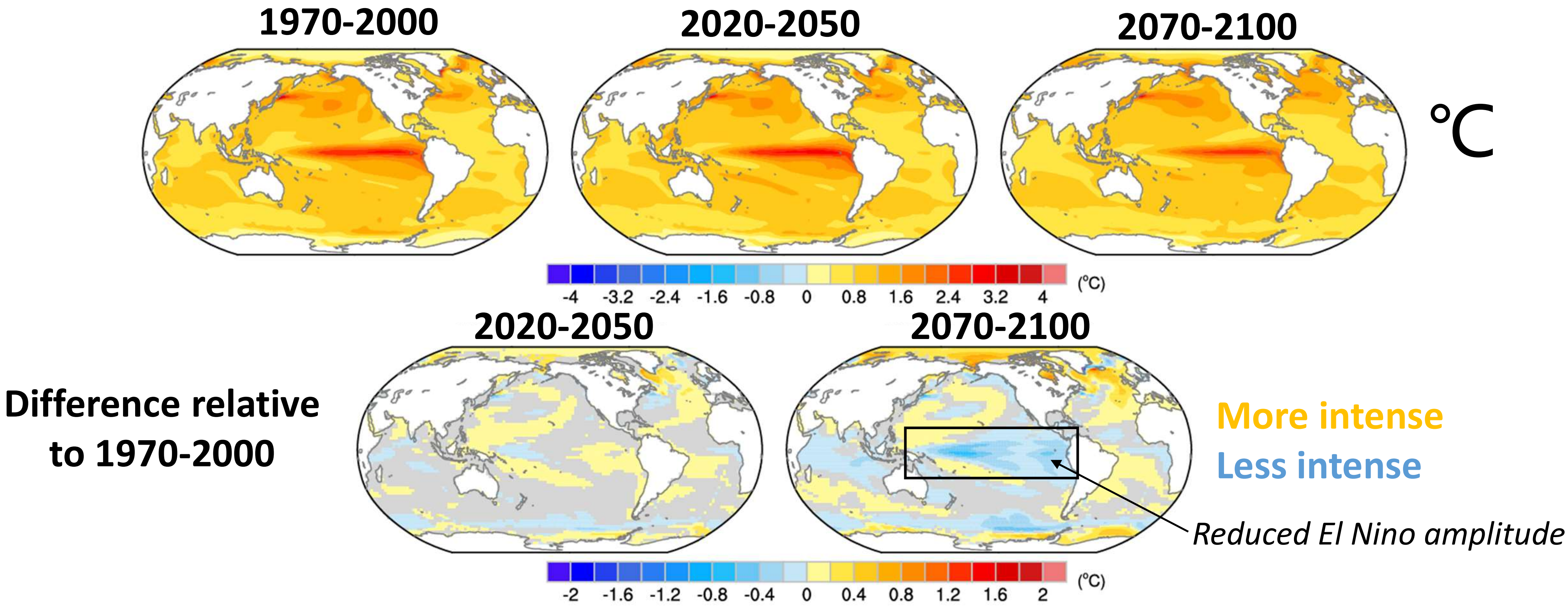


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# 3. What Role does ENSO play?

Select only those MHW samples that occur during ENSO-neutral conditions in the concurrent month and each of the preceding 5 months.

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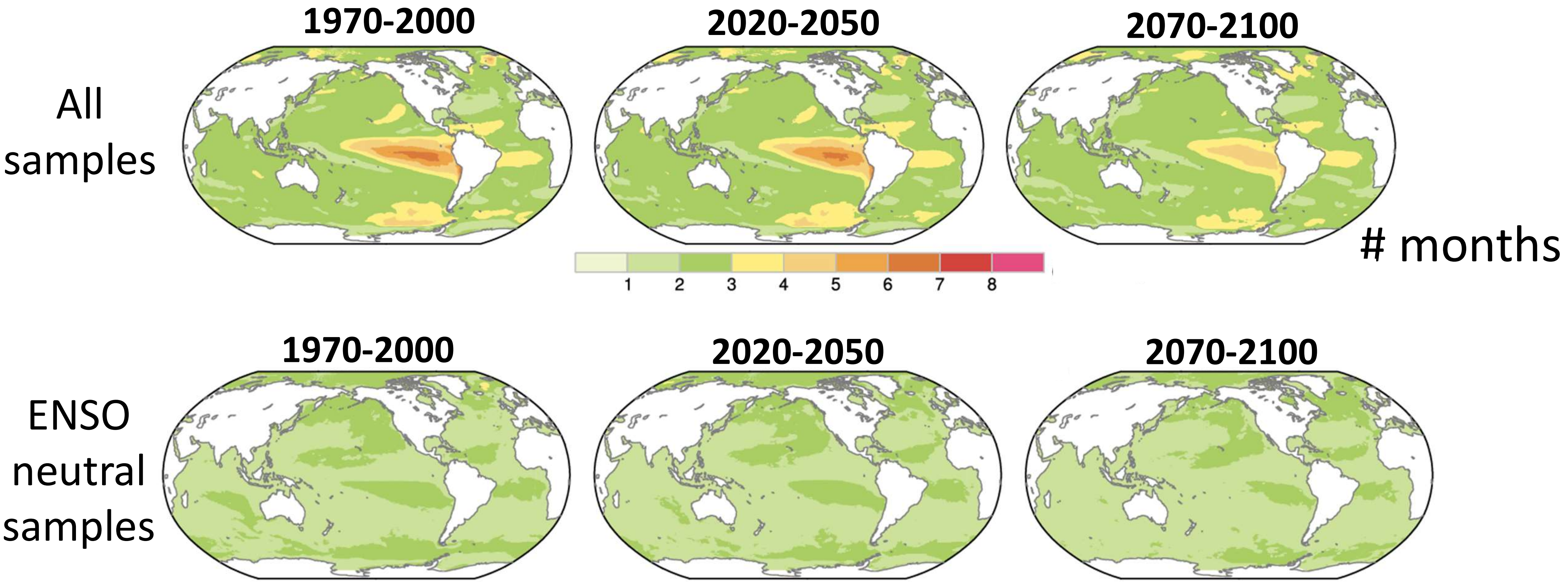
ENSO-neutral definition:

$$30^{\text{th}}\,\% < \text{PC1 Tropical Pacific iSST}(t) < 70^{\text{th}}\,\%$$

(seasonally-varying, all ensemble members, each time period separately).

# Marine Heat Wave **Duration** (100-member CESM2 Large Ensemble)

Mean state changes removed.



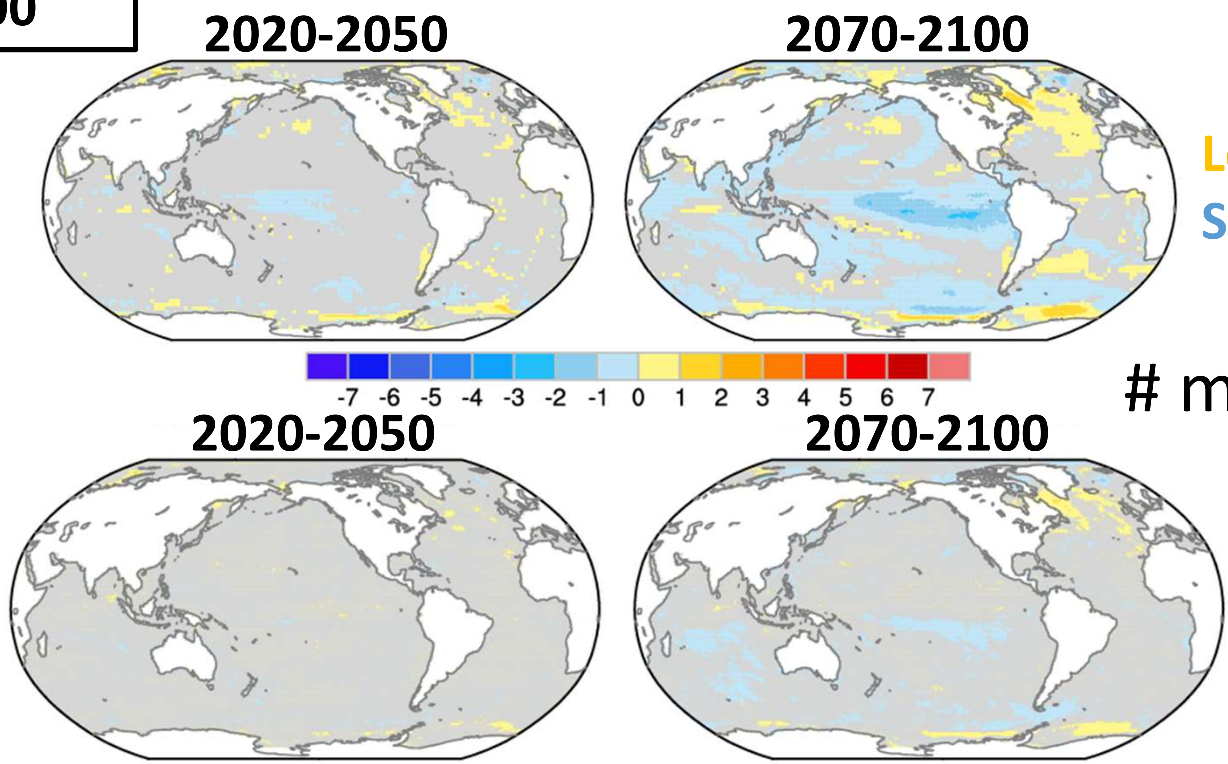
# Marine Heat Wave **Duration** (100-member CESM2 Large Ensemble)

**Differences relative to 1970-2000**

Mean state changes removed.

All samples

ENSO neutral samples

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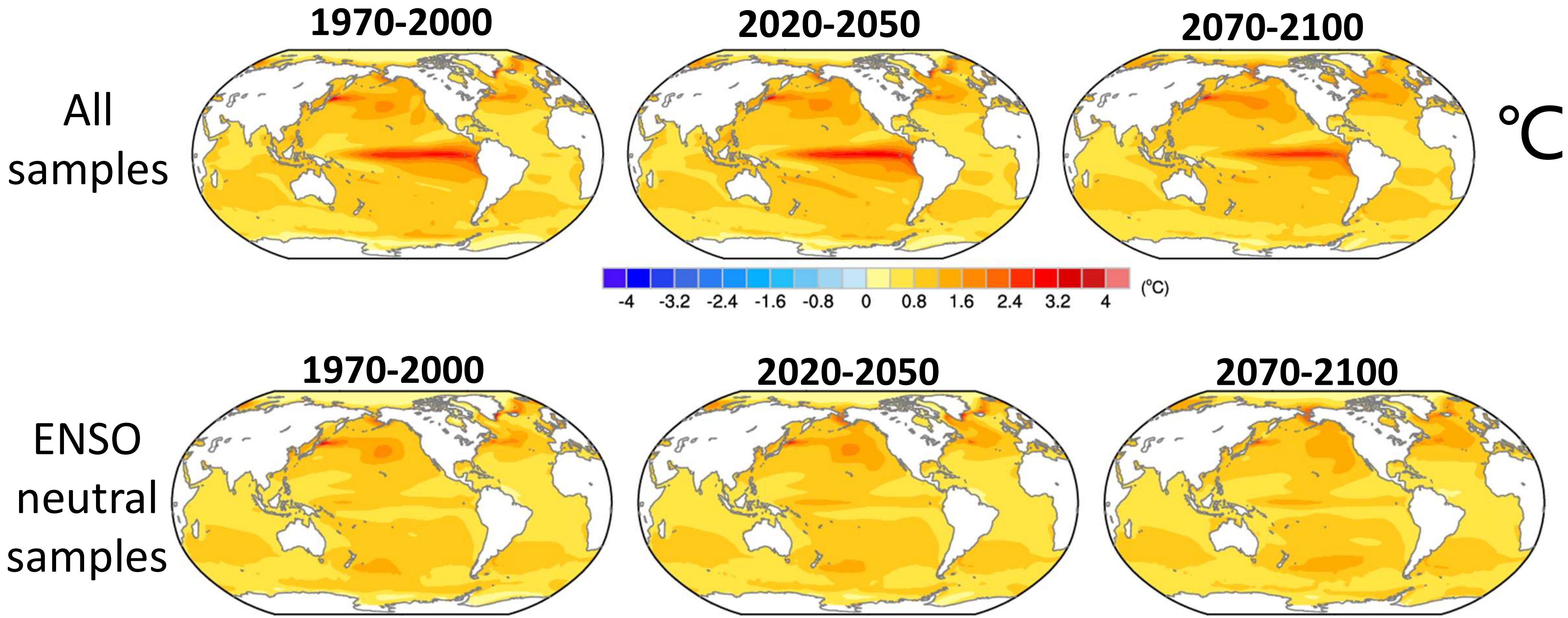


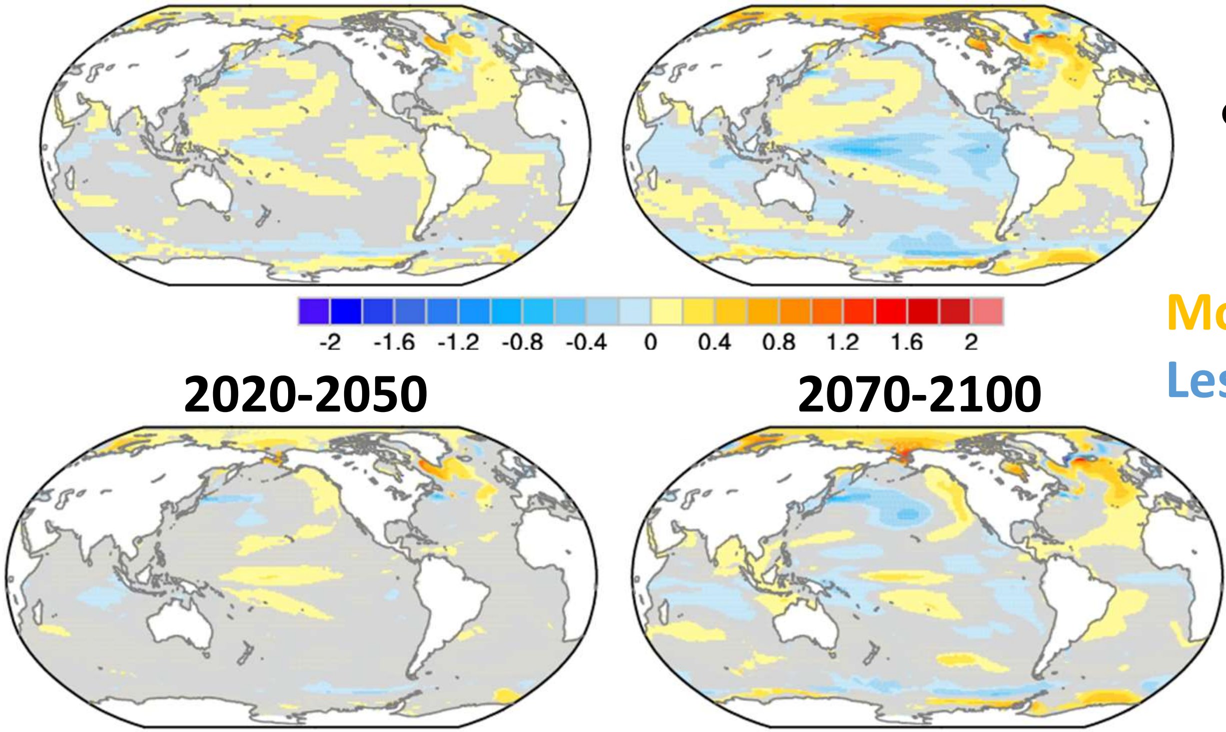
# Marine Heat Wave **Intensity** (100-member CESM2 Large Ensemble)

**Differences relative to 1970-2000**

Mean state changes removed.

All samples — **2020-2050** | **2070-2100**

ENSO neutral samples — **2020-2050** | **2070-2100**




°C

**More intense**

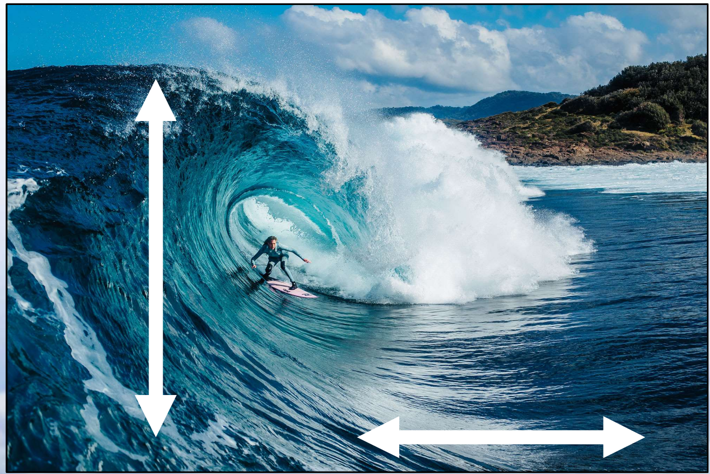
**Less intense**

Gray shading: change is insignificant

(False Discovery Rate test applied to the t-test at the 5% confidence level)

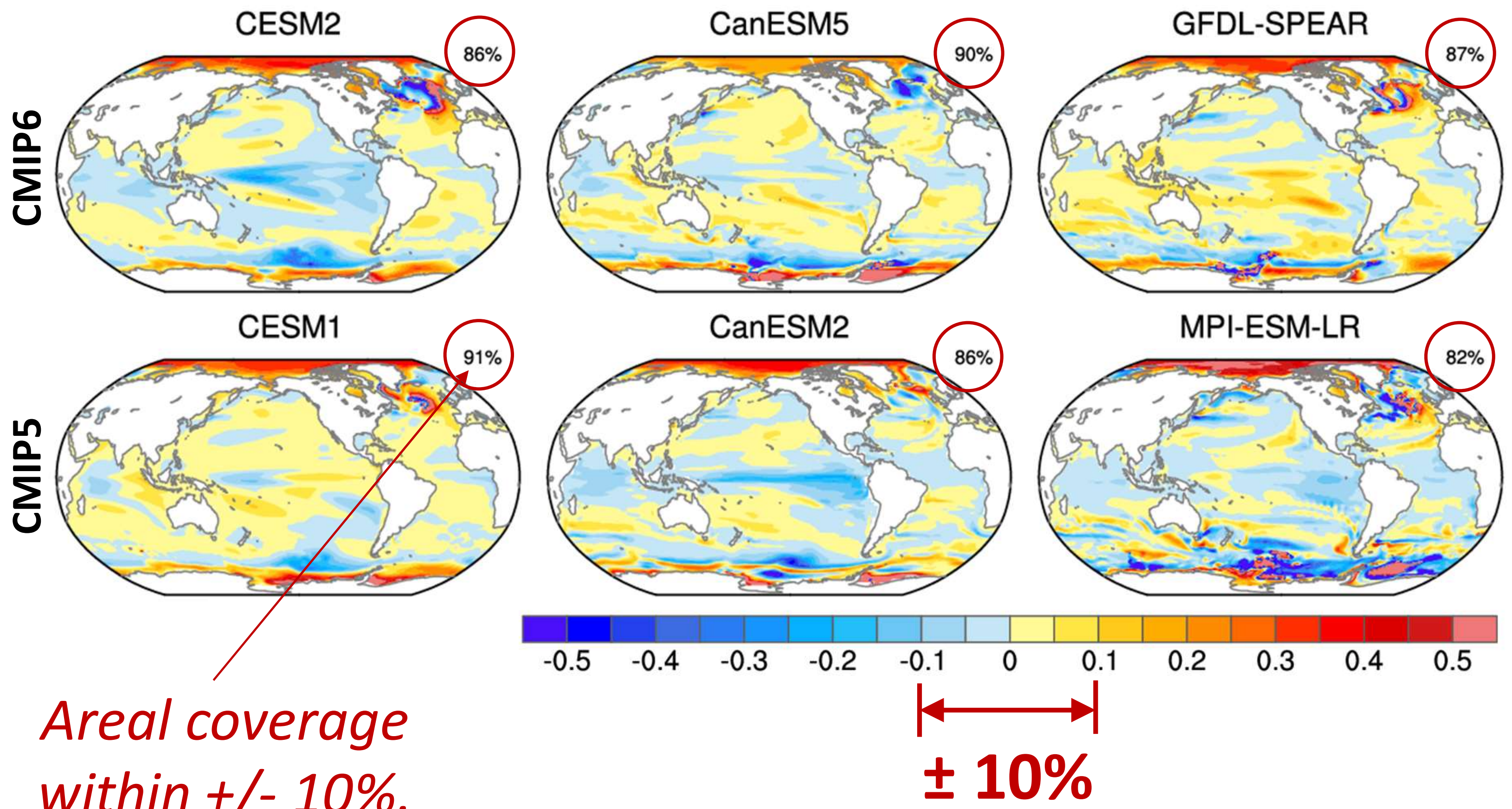
# Future Changes

## Δ Variability / Δ (Variability + Mean State)



# Marine **Heat** Wave **Intensity** Change (%)

## Δ Variability / Δ (Variability + Mean State)




*Areal coverage within +/- 10%.*

2070-2100
*minus*
1970-2000

# Summary and Outlook

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# Summary and Outlook

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- Large observational uncertainty due to limited number of samples, even with 71 years of (monthly) data.
- Area of significant model bias (observations lie outside the ensemble spread) ranges between 51-68% for intensity and 33-53% for duration across models.
- Large Ensembles are crucial for proper assessment.

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## 2. How will marine heatwaves change in the future?

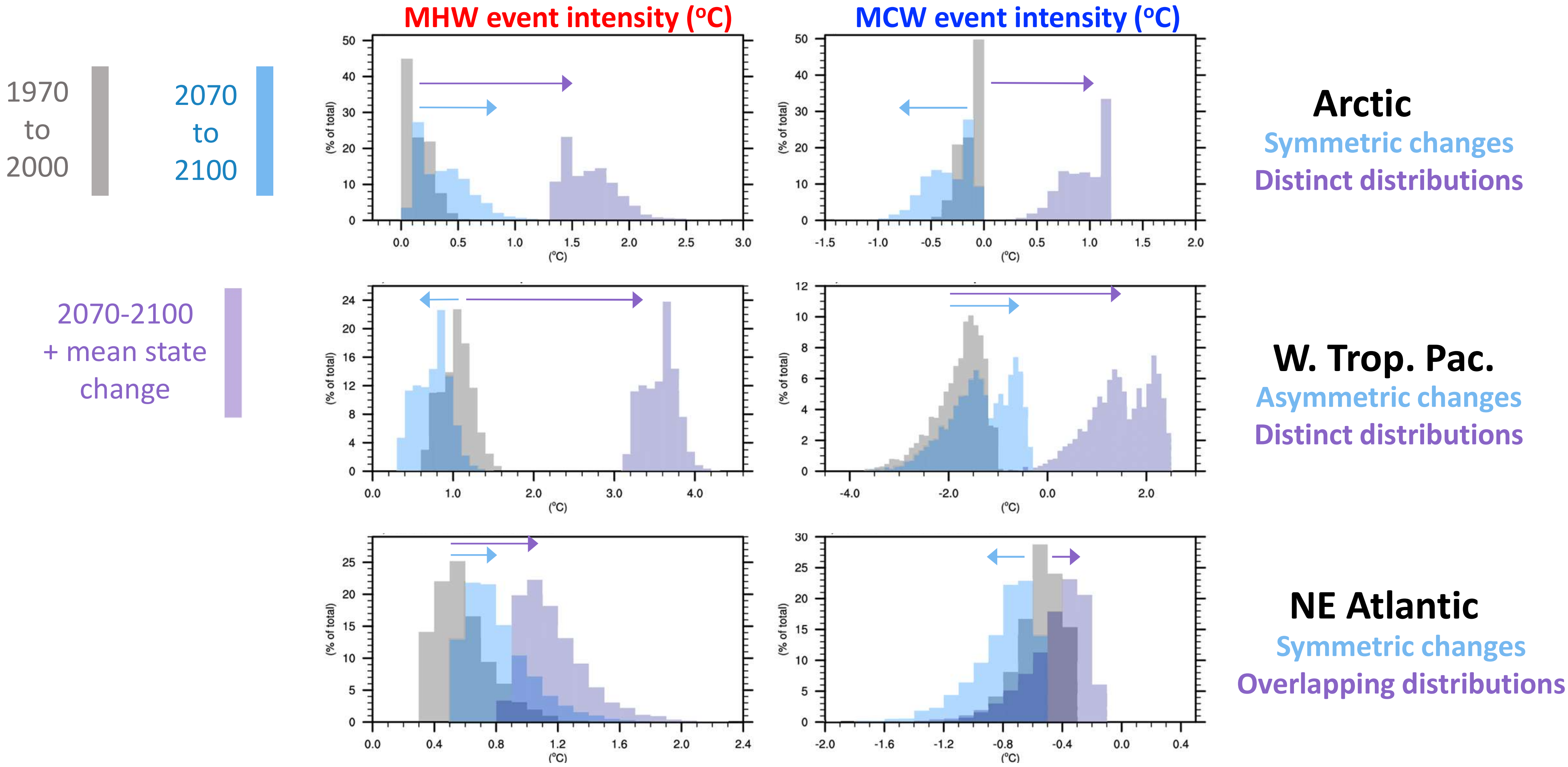
- Highly model dependent, largely because models project different future changes in ENSO variability.
- Changes in variability have a small (<10-20% except in polar regions) impact on MHW amplitude compared to changes in the mean state (e.g., "a rising tide lifts all ships" is still the dominant paradigm).

# Open questions and next steps

- Seasonal dependency and role of ENSO?
- Subsurface structure?
- Physical mechanisms?
- Role of changes in atmospheric circulation vs. mixed layer depth?
- Relationship with general SST anomaly variance and persistence?
- Impact of changes in MHWs and MCW on the atmosphere?
- Additional insights from daily data?
- Better ways of removing ENSO influences?

# Extra Slides

# Background warming + Changes in variability (CESM2)

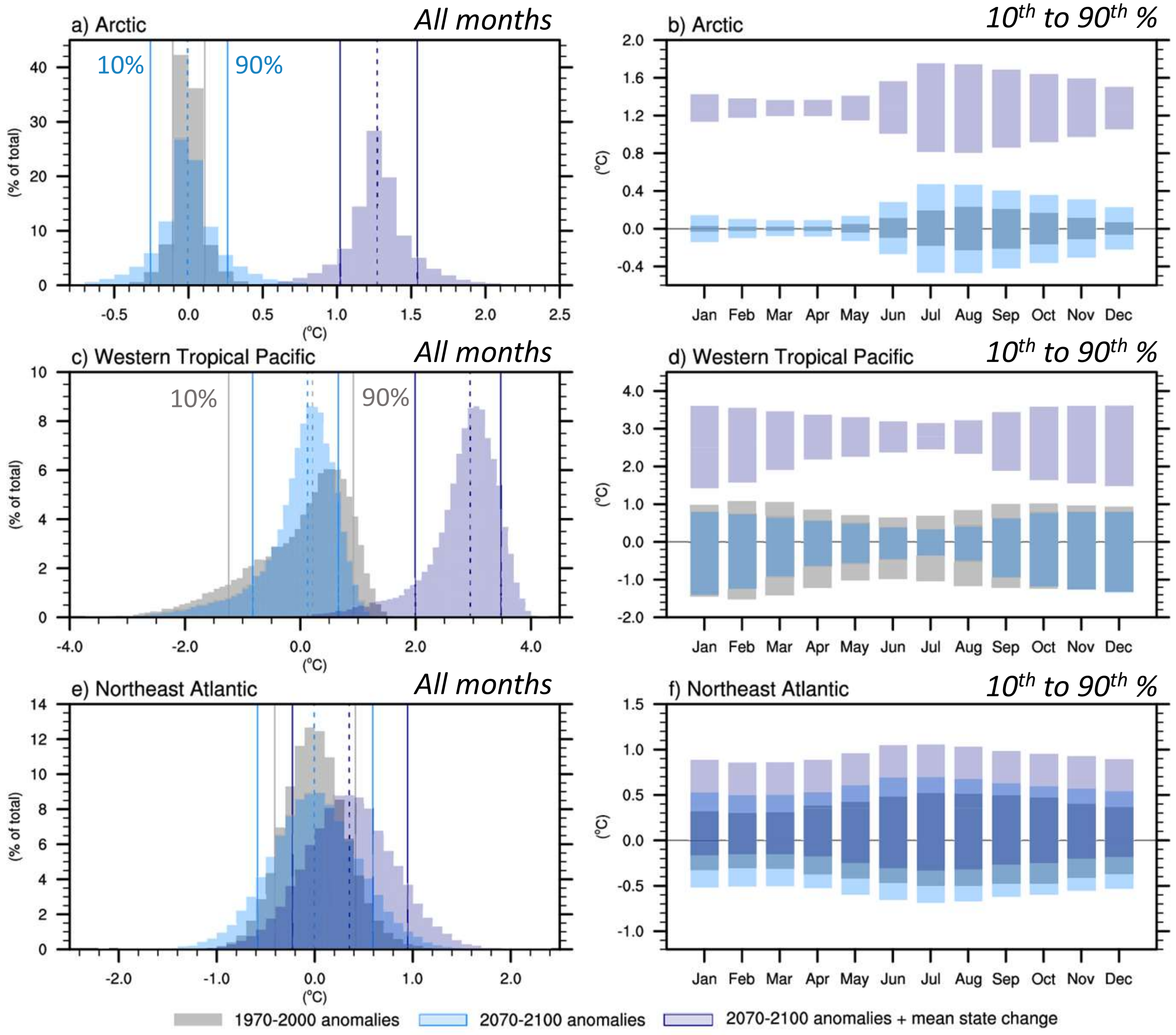


# Background warming + Changes in variability

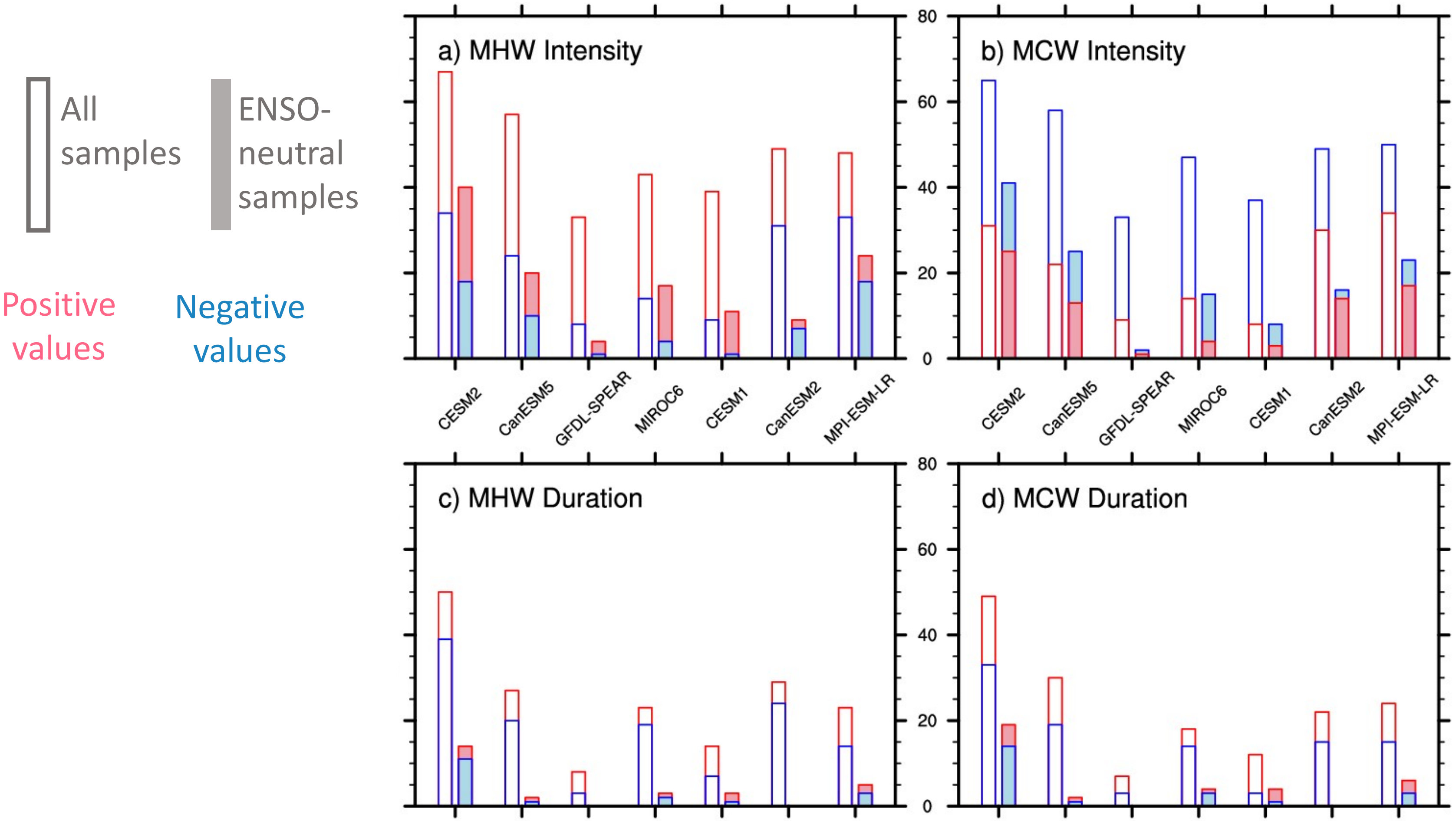
1970 to 2000

2070 to 2100

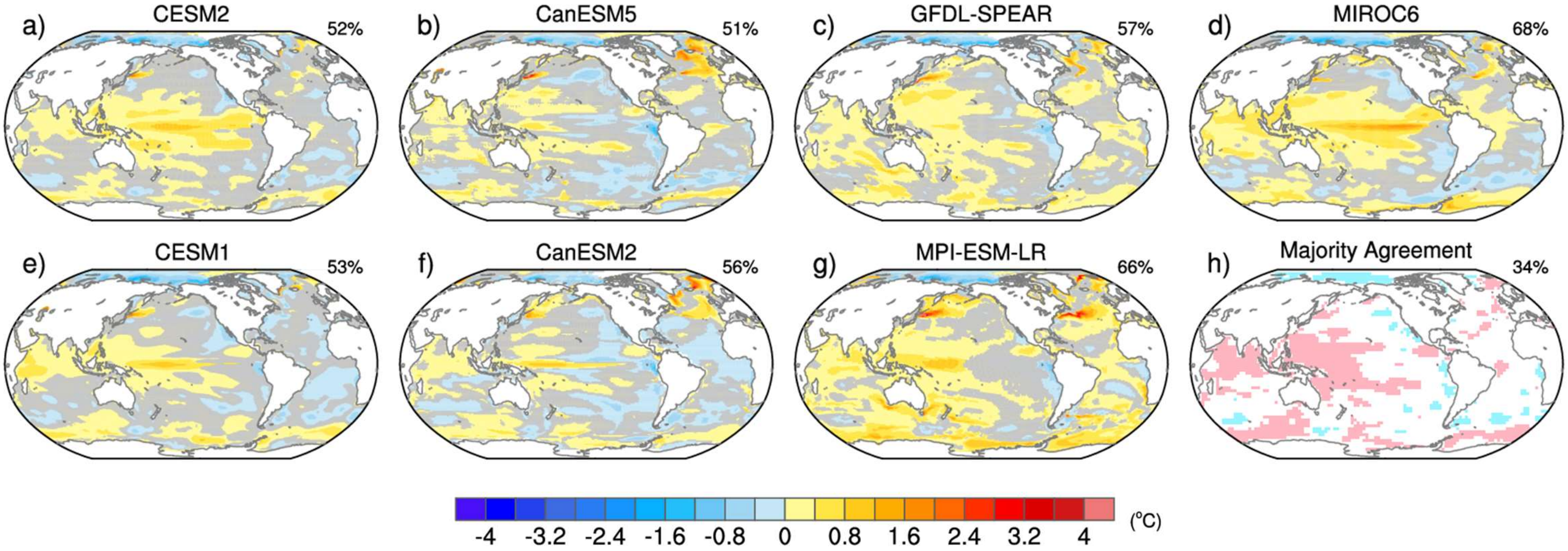
2070-2100 + mean state change



# % area with significant future change (2070-2100 minus 1970-2000)



# Model Bias in Average Intensity of all MHWs during 1950-2020




Significant positive bias

No significant bias
**(Obs within ensemble spread)**

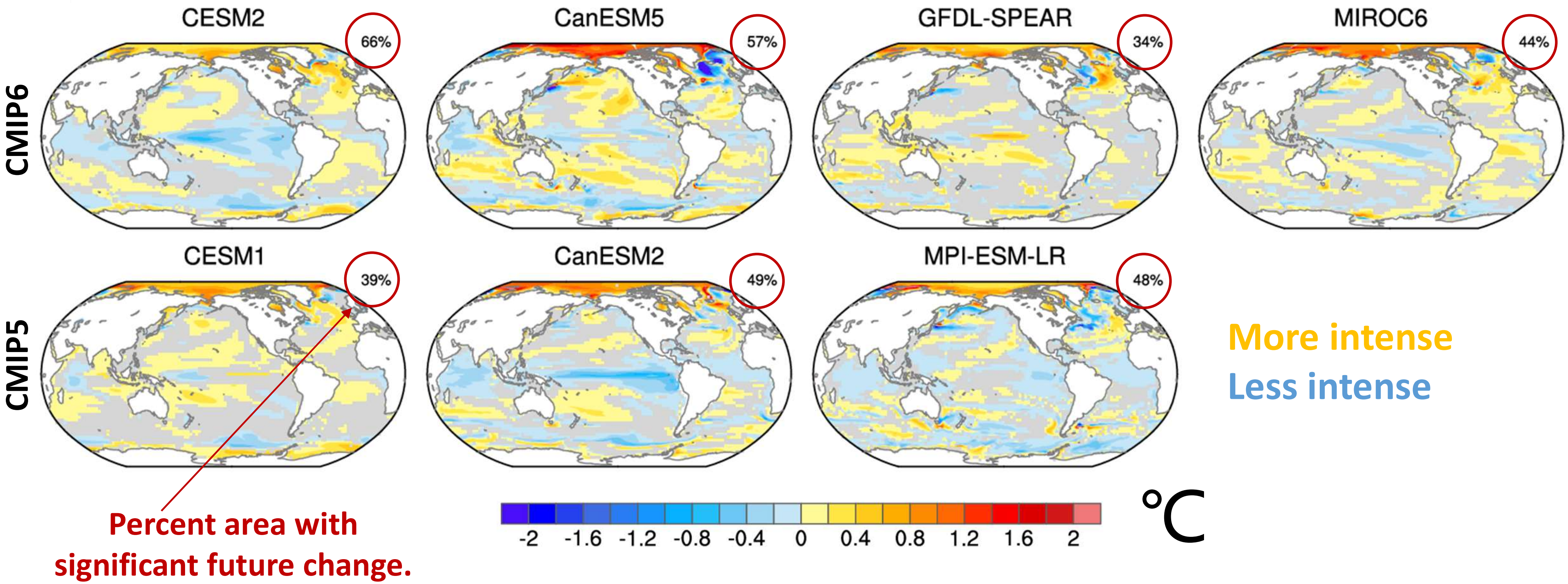
Significant negative bias

# Inter-model Comparison

## Future Changes

(2070-2100 minus 1970-2000)

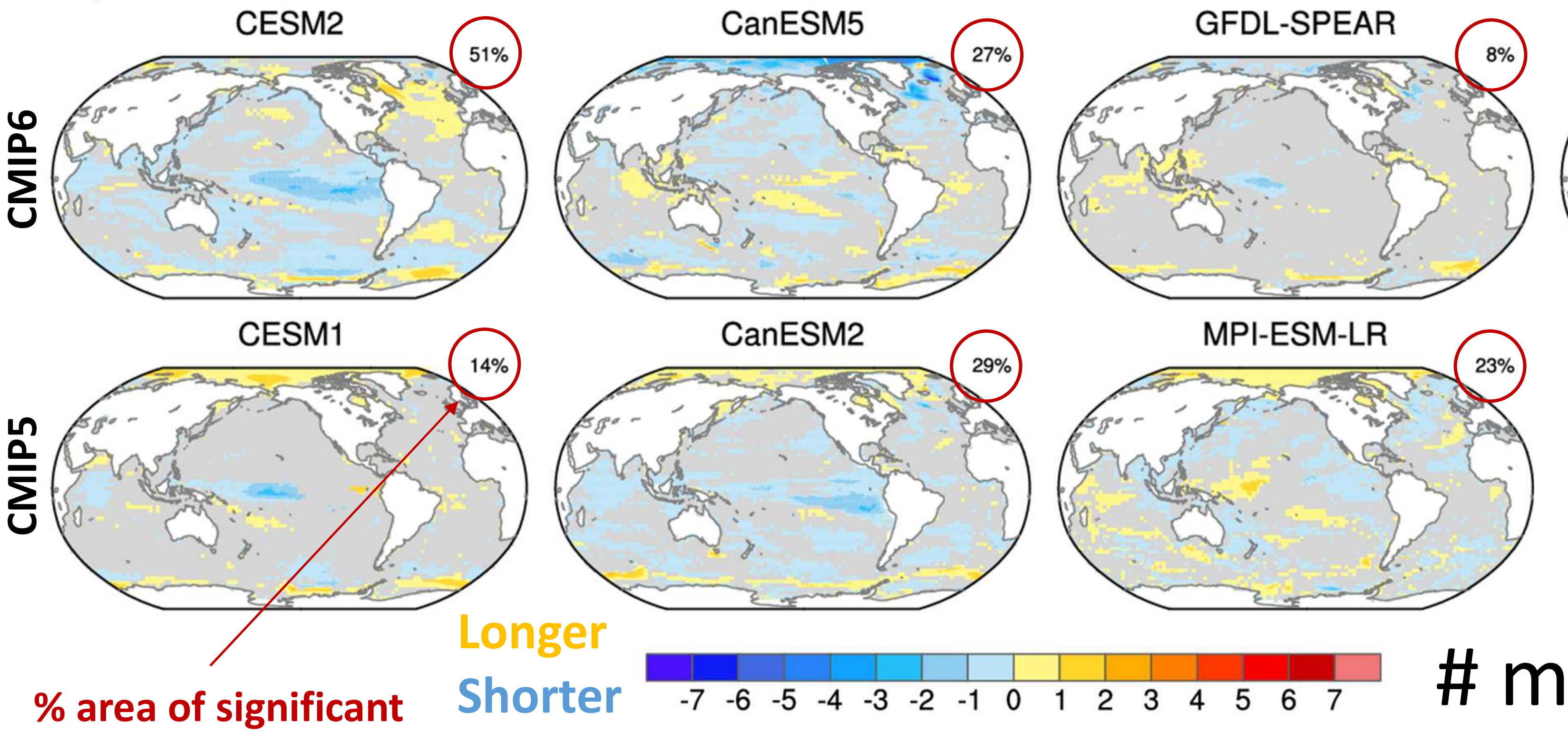
# Marine **Heat** Wave **Intensity** Changes: 2070-2100 minus 1970-2000




Gray shading: change is insignificant

(False Discovery Rate test applied to the t-test at the 5% confidence level)

# Marine **Heat** Wave **Duration** Changes: 2070-2100 minus 1970-2000




# months

**General decrease in duration, except in the Arctic where models disagree on the sign of the forced change.**

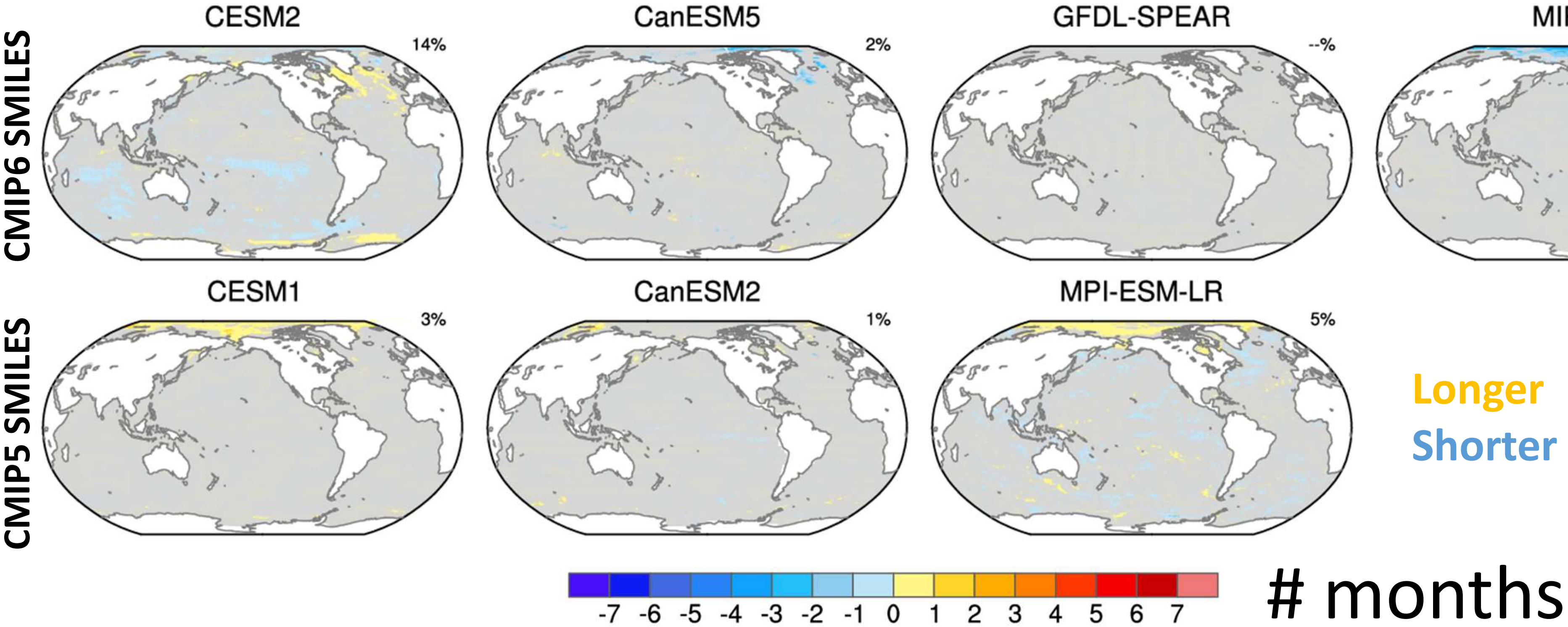
**% area of significant change is much smaller.**

Gray shading: change is insignificant

(False Discovery Rate test applied to the t-test at the 5% confidence level)

# Marine **Heat** Wave **Duration** Changes: 2070-2100 minus 1970-2000

## *ENSO-neutral samples*

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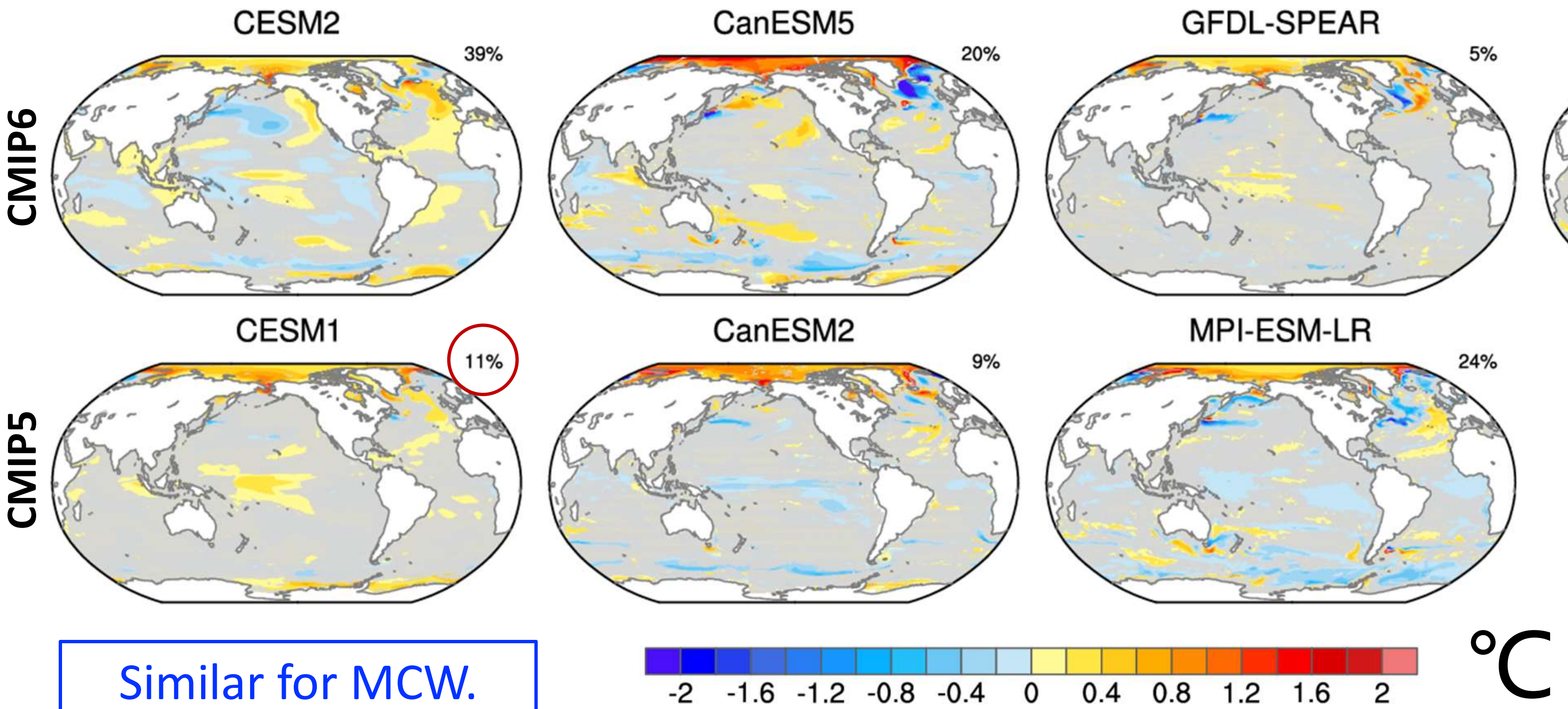
# Marine **Heat** Wave **Intensity** Changes: 2070-2100 minus 1970-2000

## ***ENSO-neutral samples***




More intense

Less intense

Similar for MCW.

Arctic is the only region with 100% model agreement.

Gray shading: change is insignificant

scovery Rate test applied to the t-test at the 5% confidence level)

# Mean State Change: 2070-2100 minus 1970-2000