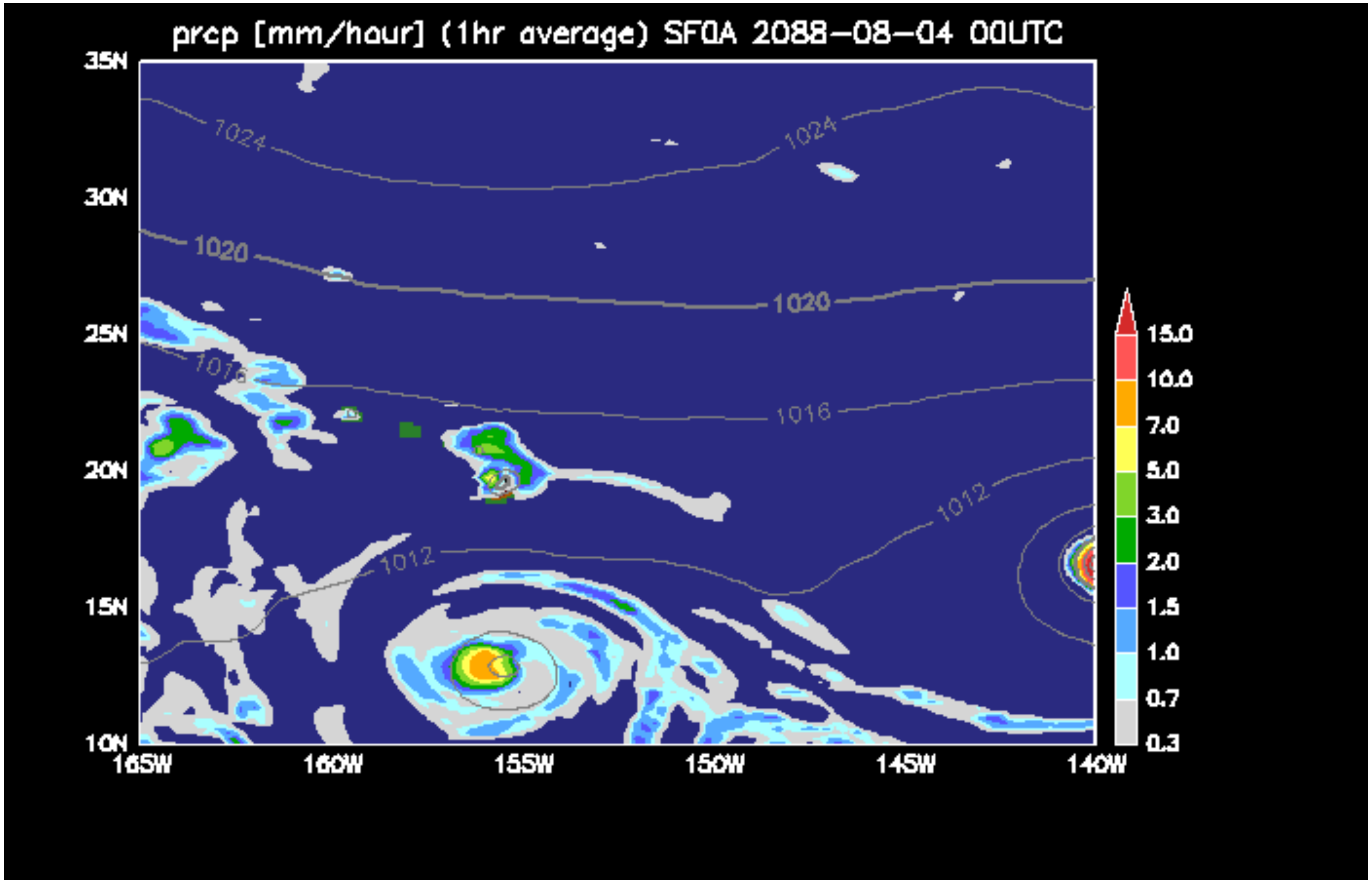
# Projected future increase of tropical cyclones near Hawaii

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# Review of effect of global warming on TC activity

nature geoscience

REVIEW ARTICLE

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Knutson et al. (2010, *Nat. Geosci.*)

**Tropical cyclones and climate change**

Thomas R. Knutson[1]*, John L. McBride[2], Johnny Chan[3], Kerry Emanuel[4], Greg Holland[5], Chris Landsea[6], Isaac Held[1], James P. Kossin[7], A. K. Srivastava[8] and Masato Sugi[9]

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1. **Consistent results** (consensus)
   - Reduction in frequency of global TCs
   - Increase in frequency of intense TCs
2. **Inconsistent results** (uncertainty)
   - Projected future changes in TC frequency in a specific ocean basin

     *Among 14 previous numerical studies, 5 indicated an increase in the North Atlantic, while 9 reported a decreasing frequency (Murakami and Wang, 2010)*

**Regional changes in TC activity remain uncertain!**

# IPCC Assessment Reports



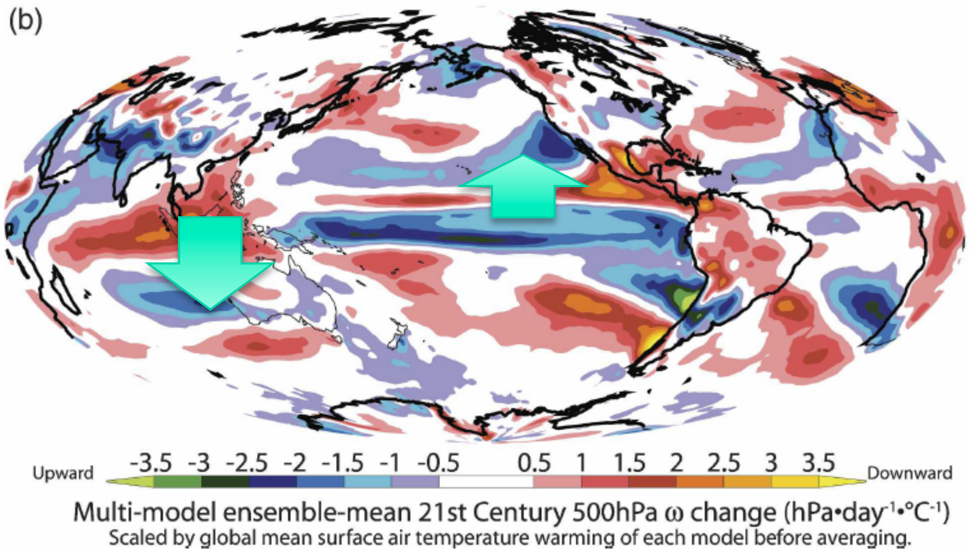


| | FAR 1990<br>**11 Chapters** | SAR 1995<br>**11 Chapters** | TAR 2001<br>**14 Chapters** | AR4 2007<br>**11 Chapters** | AR5 2013<br>**14 Chapters** |
|---|---|---|---|---|---|
| **observations** | ✓ | ✓ | ✓ | ✓✓✓ | ✓✓✓ |
| **paleoclimate** | | | | ✓ | ✓ |
| **sea level** | ✓ | ✓ | ✓ | | ✓ |
| **clouds** | | | | | ✓ |
| **carbon cycle** | | | ✓ | | ✓ |
| **regional change** | | | ✓ | ✓ | ✓✓✓ |

SREX 2011

(Extreme Events)

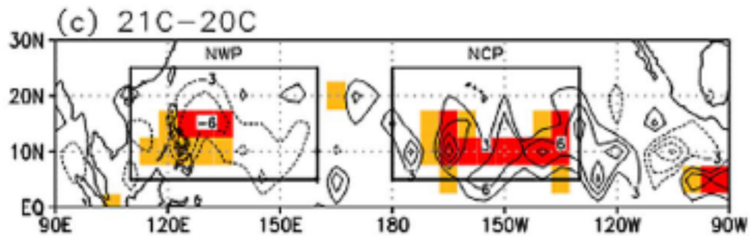
# Consistency in projected weakening of Walker Circulation



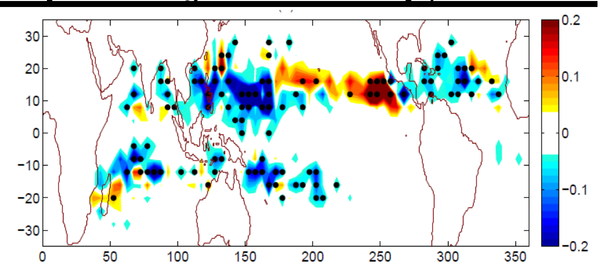

Vecchi and Soden (2007, *J. Climate*) documented that CMIP3 models consistently project weakening of Pacific Walker Circulation in the future.

A few studies also reported that frequency of TC genesis is projected to decrease in the tropical western North Pacific and increase in the tropical Central Pacific.

Projected future change in frequency of TC genesis

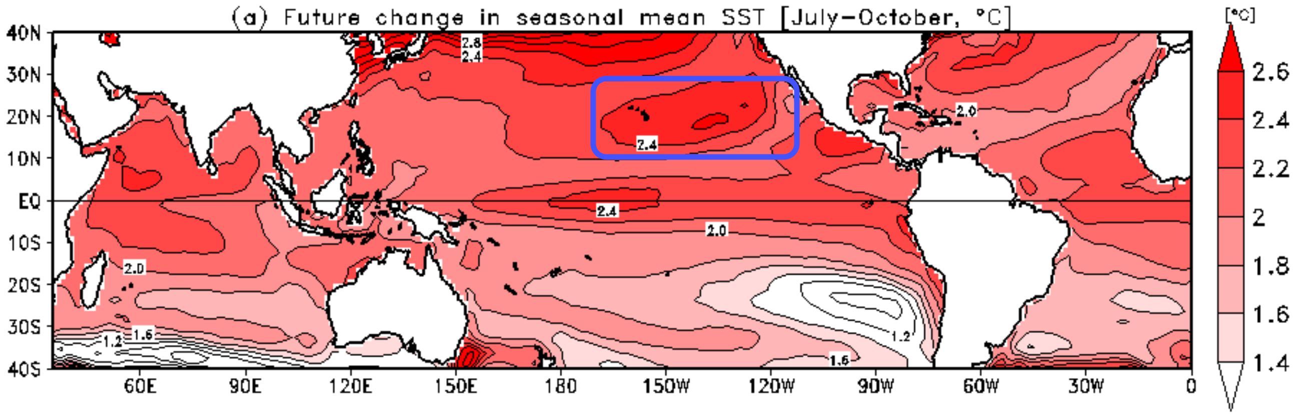



Li et al. (2010, *GRL*)



Zhao and Held (2012, *J. Climate*)

# Motivation




Annual mean of future changes (2075−2099) in SST by 18 CMIP3 models mean projected under A1B scenario.

・Effect of the surface warming on TC activity in the subtropical region has not been paid much attention so far.

・In order to investigate future changes in TC frequency around the Hawaiian Islands, we analyze results of ensemble future experiments using the high-resolution MRI-AGCM.

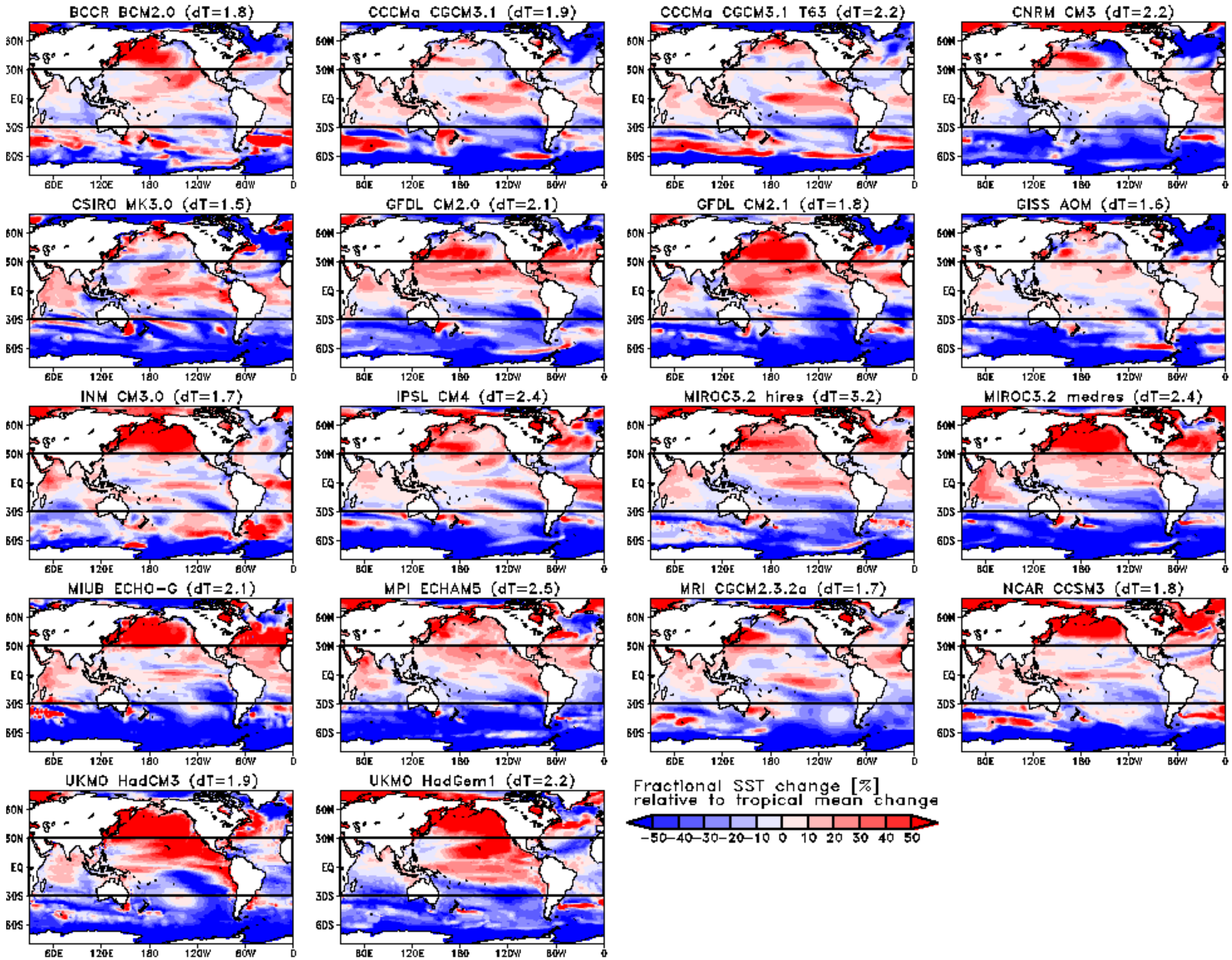
・The goal of this study is to investigate if we can derive robust future change in TC frequency of occurrence around the Hawaiian Islands across different experimental settings.

# Experiment Design

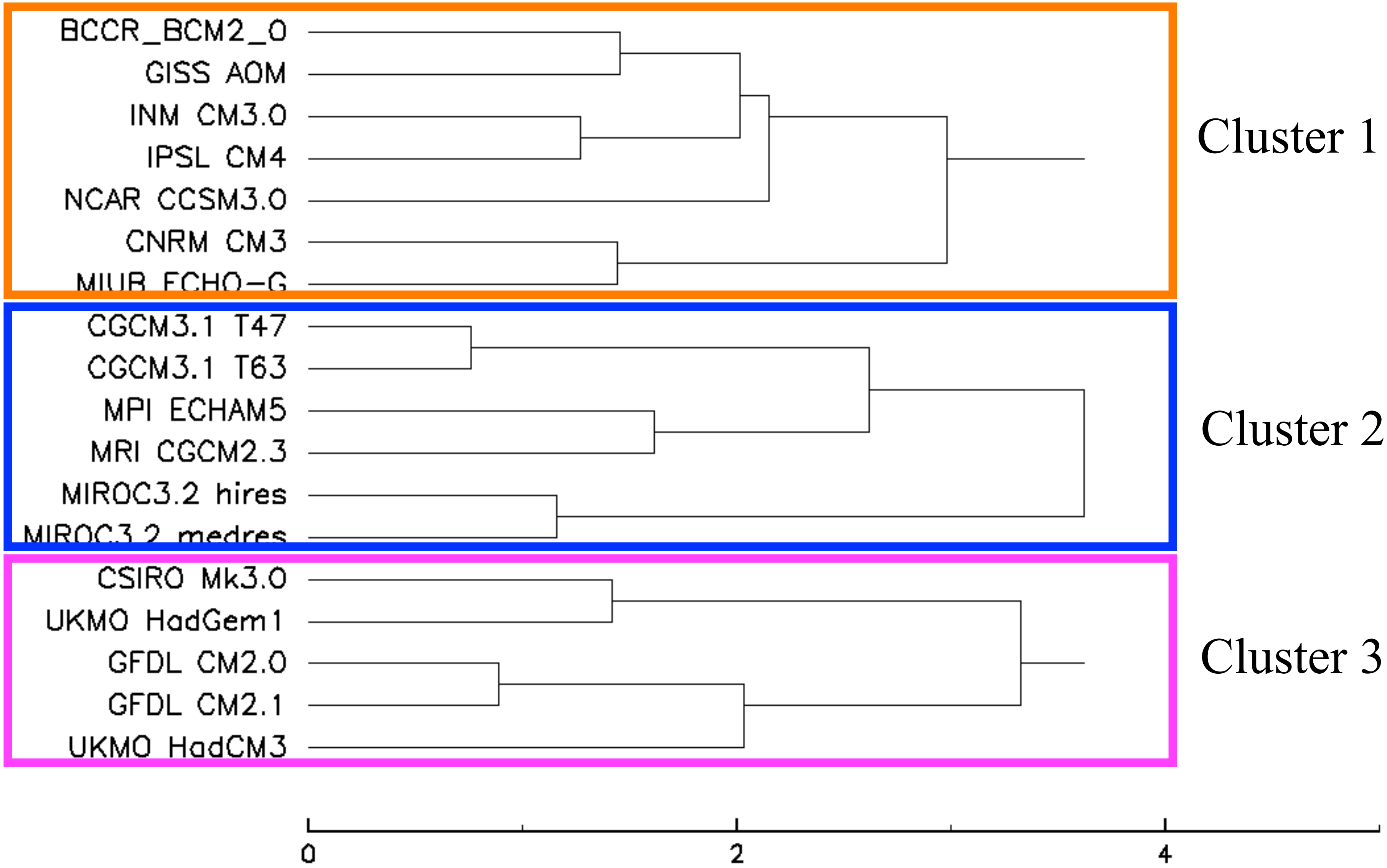
| No | Model Version | Cumulus Convection Scheme | Sea Surface Temperature | Grid Size (km) |
|---|---|---|---|---|
| | | *Present-day Simulations for 1979–2003 (25 years)* | | |
| 1 | v3.1 | Arakawa-Schubert (AS) | Observation HadISST | 20 |
| 2 | v3.1 | Arakawa-Schubert (AS) | Observation HadISST | 60 |
| 3 | v3.2 | Yoshimura (YS) | Observation HadISST | 20 |
| 4 | v3.2 | Yoshimura (YS) | Observation HadISST | 60 |
| 5 | v3.2 | Kain-Fritsch (KF) | Observation HadISST | 60 |
| | | *Future Projections for 2075–2099 (25 years)* | | |
| 1 | v3.1 | Arakawa-Schubert (AS) | CMIP3 MME (MME) | 20 |
| 2 | v3.1 | Arakawa-Schubert (AS) | CMIP3 MME (MME) | 60 |
| 3 | v3.2 | Yoshimura (YS) | CMIP3 MME (MME) | 20 |
| 4 | v3.2 | Yoshimura (YS) | CMIP3 MME (MME) | 60 |
| 5 | v3.2 | Yoshimura (YS) | Cluster 1 (C1) | 60 |
| 6 | v3.2 | Yoshimura (YS) | Cluster 2 (C2) | 60 |
| 7 | v3.2 | Yoshimura (YS) | Cluster 3 (C3) | 60 |
| 8 | v3.2 | Kain-Fritsch (KF) | CMIP3 MME (MME) | 60 |
| 9 | v3.2 | Kain-Fritsch (KF) | Cluster 1 (C1) | 60 |
| 10 | v3.2 | Kain-Fritsch (KF) | Cluster 2 (C2) | 60 |
| 11 | v3.2 | Kain-Fritsch (KF) | Cluster 3 (C3) | 60 |

We conducted **5** present-day (1979−2003) climate simulations and **11** future (2075−2099) climate projections under IPCC A1B scenario using the high-resolution MRI-AGCM that consider differences in model version (v3.1 and v3.2), cumulus convection scheme, tropical spatial pattern of SST changes, and model resolution.

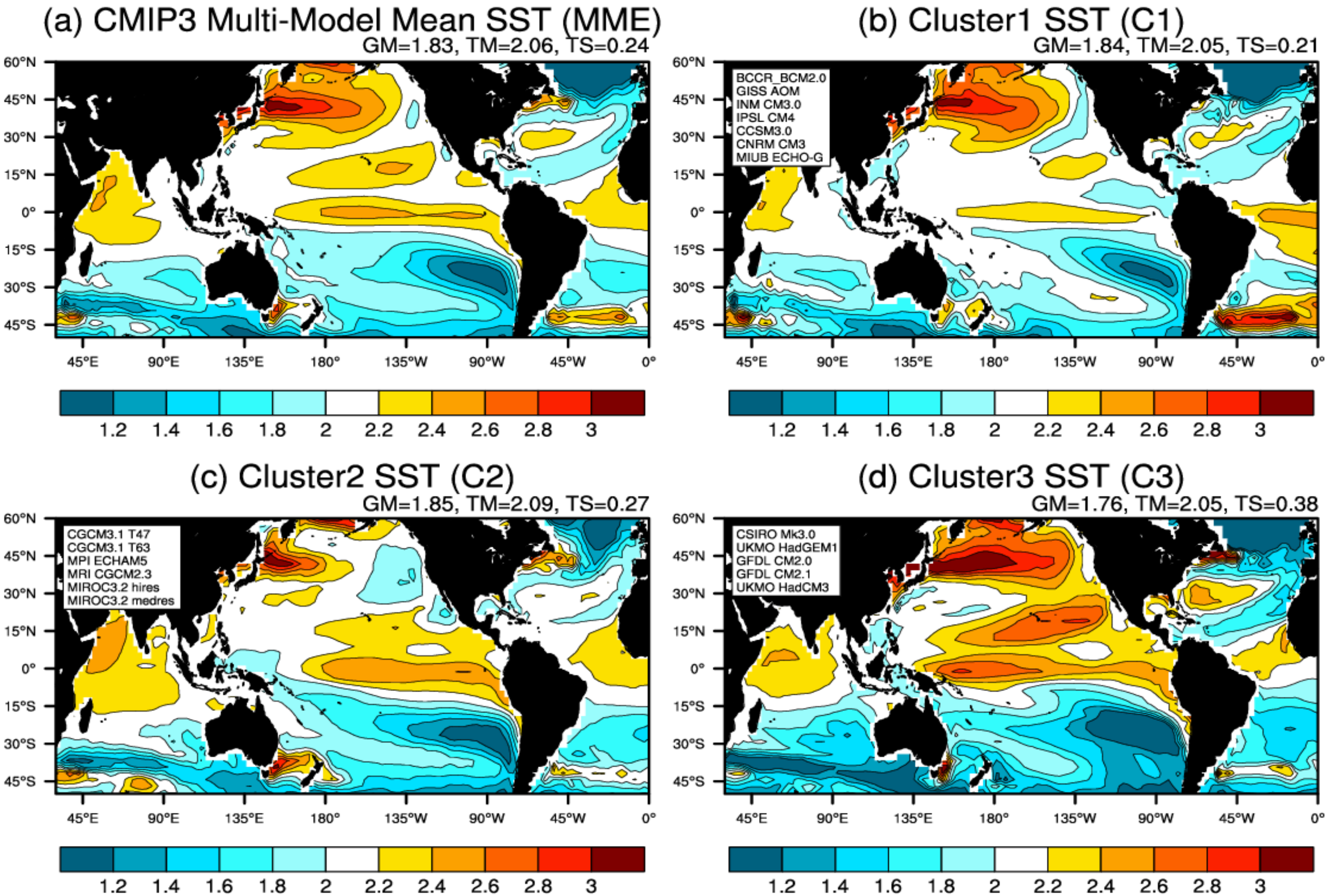
# Future changes in SST in CMIP3 models under A1B scenario



# Cluster Analysis based on changes in tropical SST distribution



# Prescribed Future Changes in SSTs

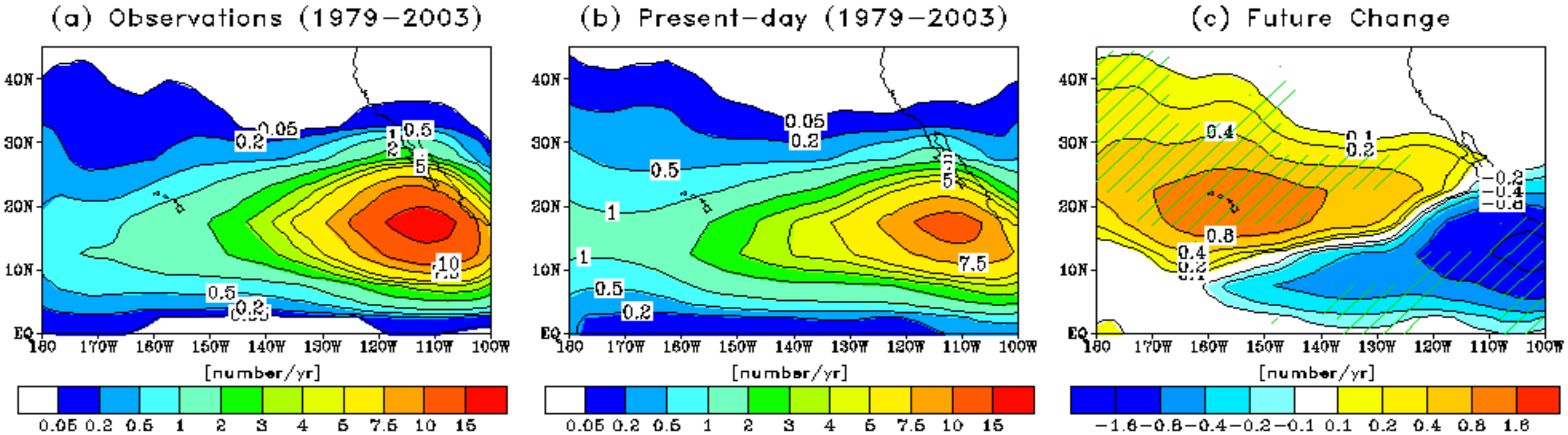


# TC Detection Criteria

Based on Murakami and Sugi (2010)

- Maximum relative vorticity at 850 hPa
- Temperature deviation at the 300, 500, and 700 hPa
- Duration (36 hours)
- Maximum wind speed at 850 hPa should be greater than the 300 hPa (to exclude extra-tropical cyclones).

# Tropical Cyclone Frequency of Occurrence (TCF)




Annual mean of tropical cyclone frequency of occurrence counted at every 5 x 5 degree grid box. Region with green hatching in (c) indicates significance (99% level) and robustness in the change among the experiments.

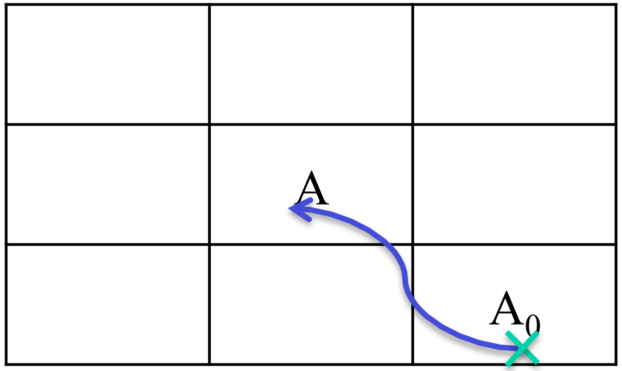
Fig. C reveals an east-west contrast in projected future changes in TCF: **increase in the subtropical central Pacific** and **reduction in the eastern tropical Pacific**.

# Empirical Statistical Analysis (Total Analysis)

To assess the relative importance of TC genesis and tracks in terms of future changes in local TCF, a simple empirical statistical analysis is applied.

TCF in a grid cell ($A$) can be written as follows.

$$f(A) = \iint_C g(A_0) \times t(A, A_0)\, dA_0$$




$g\ (A_0)$ : Frequency of TC genesis in a grid cell $A_0$

$t\ (A, A_0)$ : Probability that a TC generated in grid cell $A_0$ travels to the grid cell $A$.

$C$ : Entire eastern Pacific domain to be integrated

Future change in TCF in the grid cell $A$ is computed as follows.

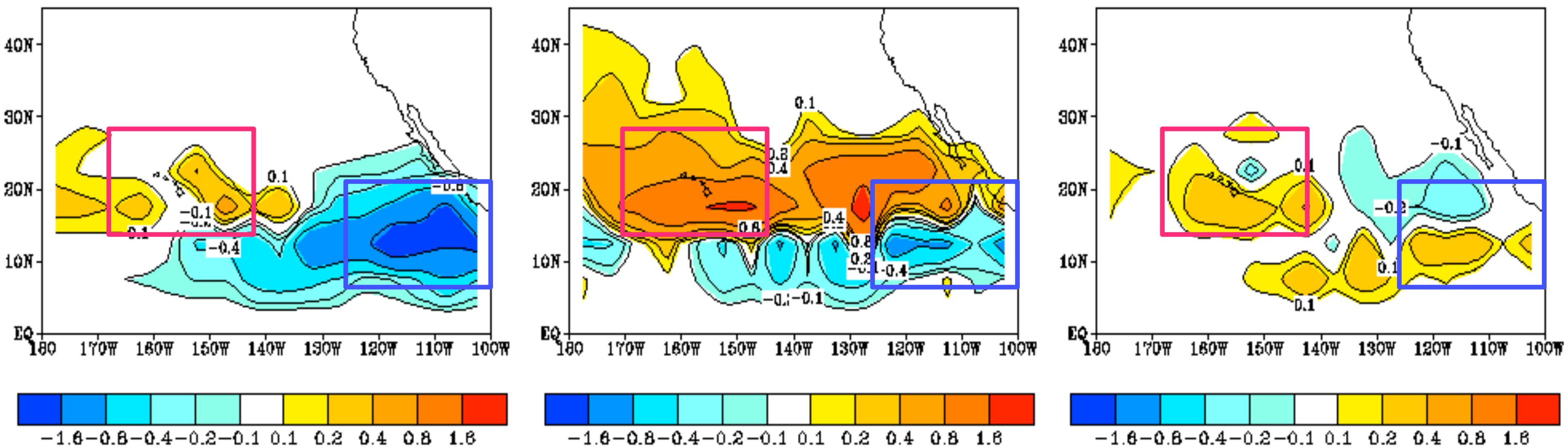
$$\delta f(A) = \underbrace{\iint_C \delta g(A_0) \times t(A, A_0)\, dA_0}_{\text{Genesis Effect}} + \underbrace{\iint_C g(A_0) \times \delta t(A, A_0)\, dA_0}_{\text{Track Effect}} + \underbrace{\iint_C \delta g(A_0) \times \delta t(A, A_0)\, dA_0}_{\text{Non-linear Effect}}$$

**Genesis Effect** **Track Effect** **Non-linear Effect**

# Empirical Statistical Analysis (Total Analysis)

**Genesis Effect** | **Track Effect** | **Non-linear Effect**

(a) $\iint \delta g(A_0)\,t(A,A_0)\,dA_0$ (b) $\iint g(A_0)\,\delta t(A,A_0)\,dA_0$ (c) $\iint \delta g(A_0)\,\delta t(A,A_0)\,dA_0$




- TC track effect has the largest contribution to the projected increase in TCF around the Hawaiian regions.

- TC genesis effect has the largest contribution to the projected decrease in TCF in the tropical eastern Pacific.

# Empirical Statistical Analysis (Origin Analysis)

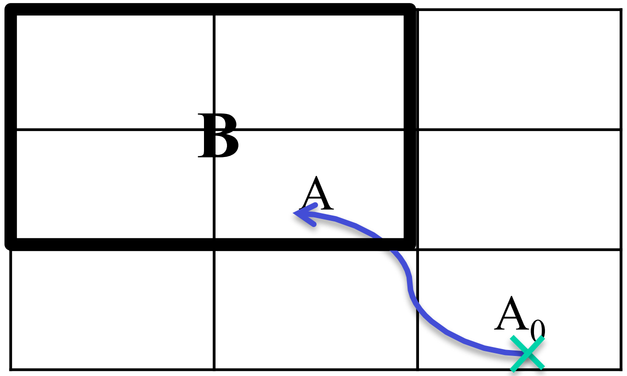
Here, we want to identify the locations associated with a large contribution to the increase in TCF in a specific region near Hawaii.
The effect of remote grid cell $A_0$ on TCF changes in a specific region $B$ (e.g., Hawaiian region) is described as follows.

$$\delta f(B,A_0) = \iint_B \delta g(A_0) \times t(A,A_0)dA + \iint_B g(A_0) \times \delta t(A,A_0)dA + \iint_B \delta g(A_0) \times \delta t(A,A_0)dA$$

**Effect of TC genesis change in A0 on TCF change in region B**

**Effect of TC track change**

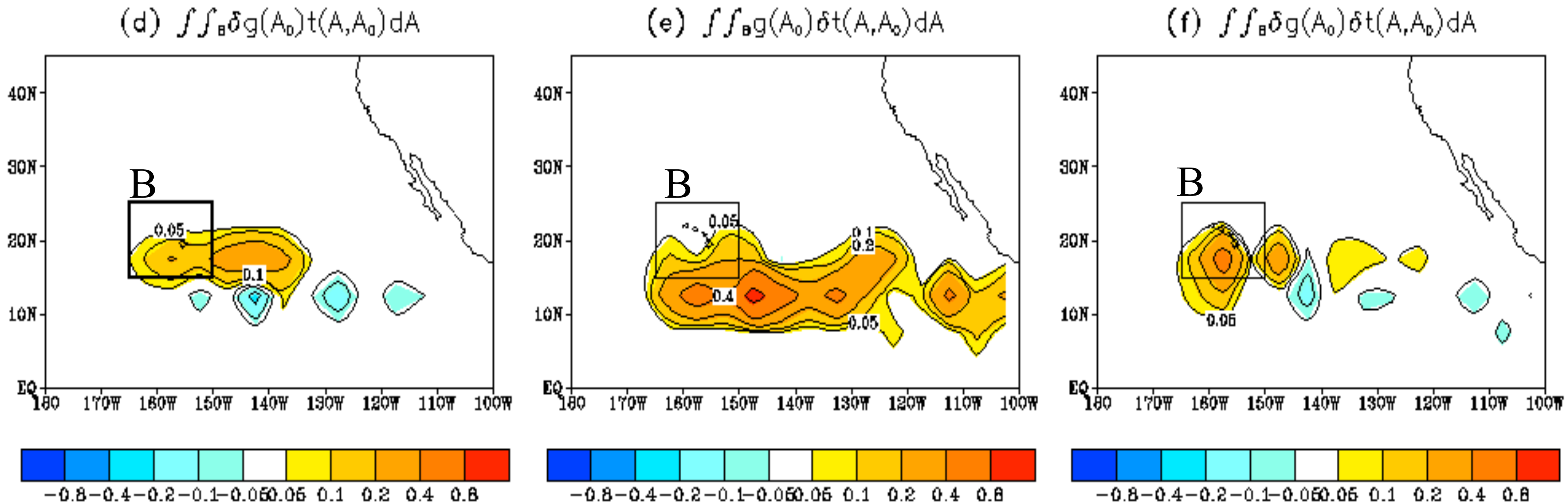
**Effect of Non-linearity**




B : Region including multiple grid cells
$g\ (A_0)$: Frequency of TC genesis in a grid cell $A_0$
$t\ (A, A_0)$: Probability that a TC generated in grid cell $A_0$ travels to the grid cell $A$.

# Empirical Statistical Analysis (Origin Analysis)

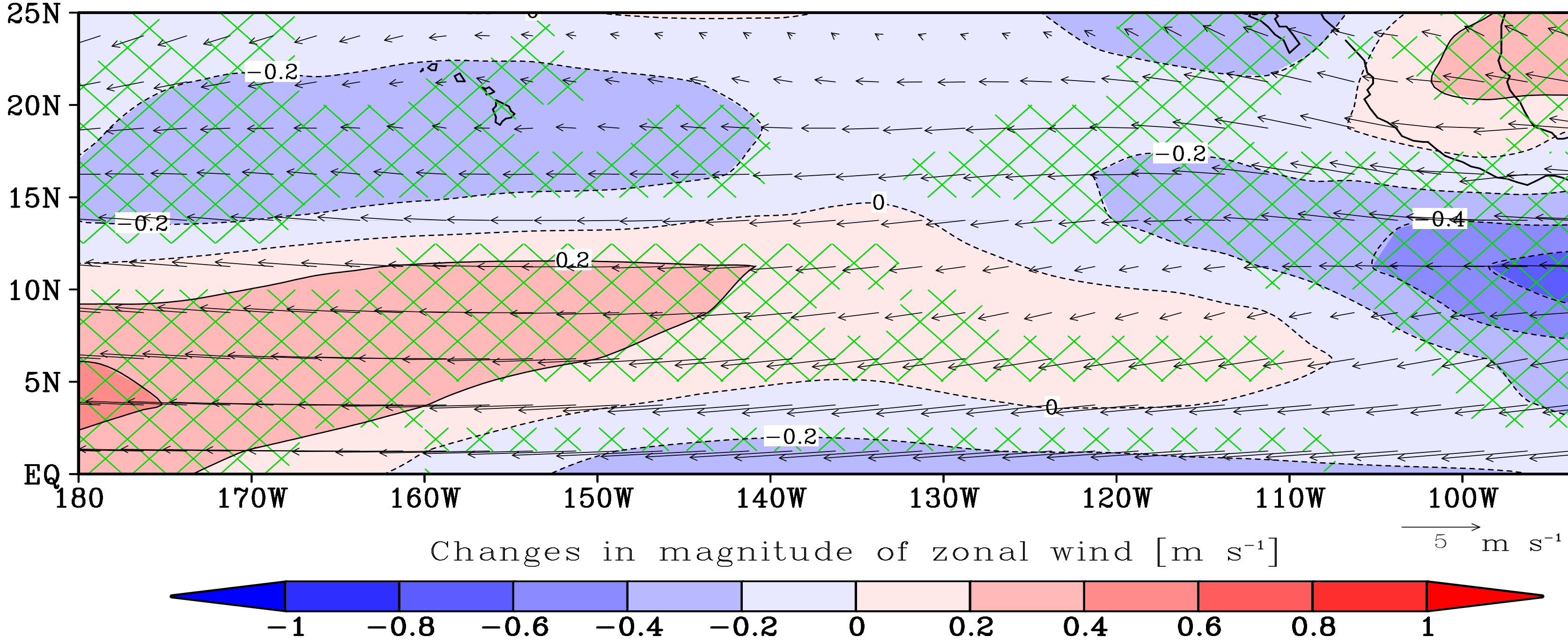
**Genesis Effect** **Track Effect** **Non-linear Effect**




・Contribution of TC track change (middle) is the largest southeast of the Hawaiian domain, indicating that TCs generated southeast of the domain tend to propagate to the Hawaiian domain regardless of projected changes in TC genesis frequency.

・TC genesis change and nonlinear change nearby the domain partly contributes TCF increase in the domain.

# Steering flow[1] changes (July–October)

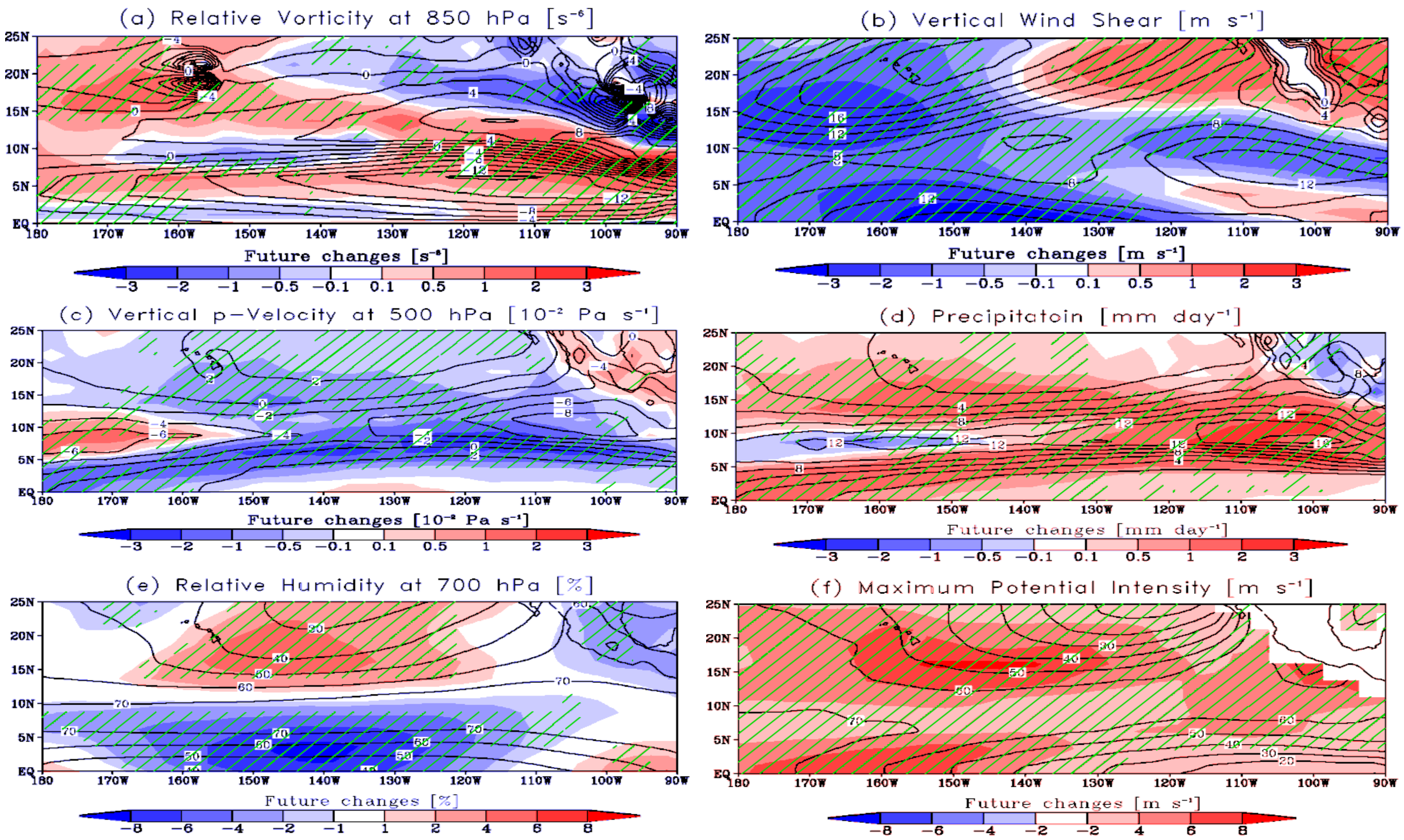



Vectors: present-day mean steering flows.
Shadings: projected future changes in zonal component of steering flows.

Increases in easterly steering flow lead to the westward propagation of TCs.

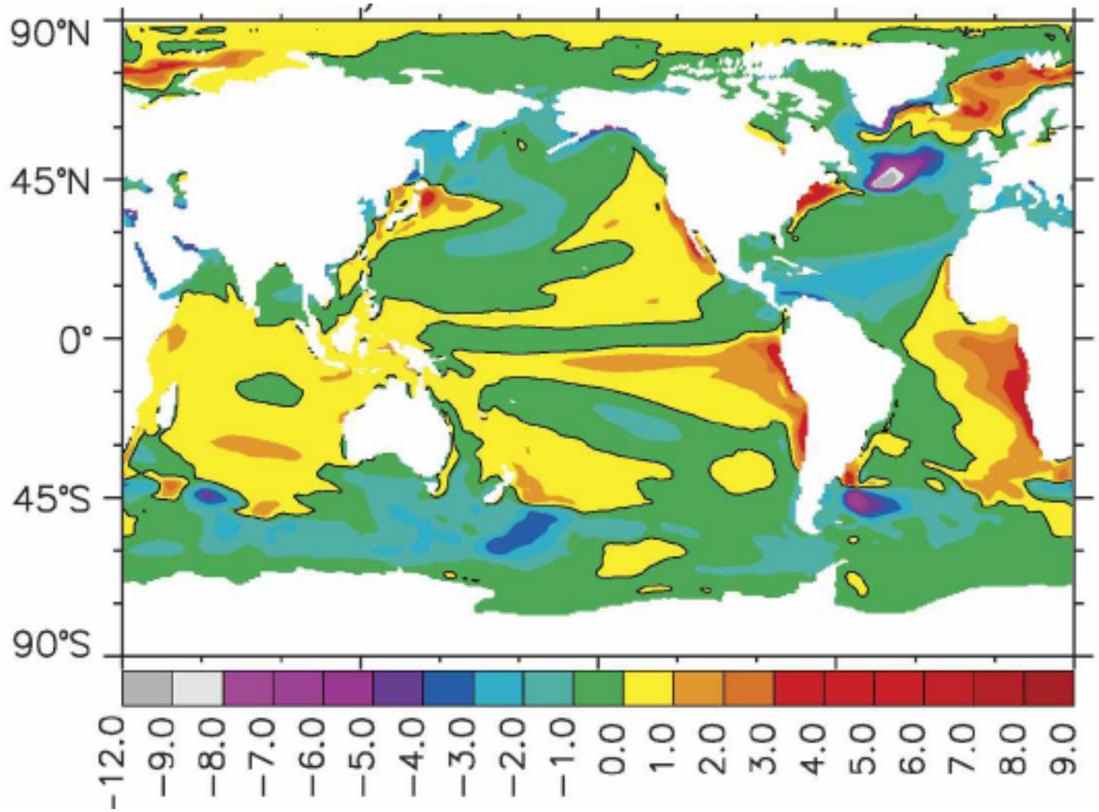
[1] Steering flows are defined as mass weighted vertically integrated flows between 850 and 300 hPa

# Projected Changes in Large-scale Variables (JJAS)




All variables show significant and robust future changes
that are more favorable for TC activity in the subtropical central Pacific.

# Caveat




SST difference from observations
in the historical experiment using CCSM3.

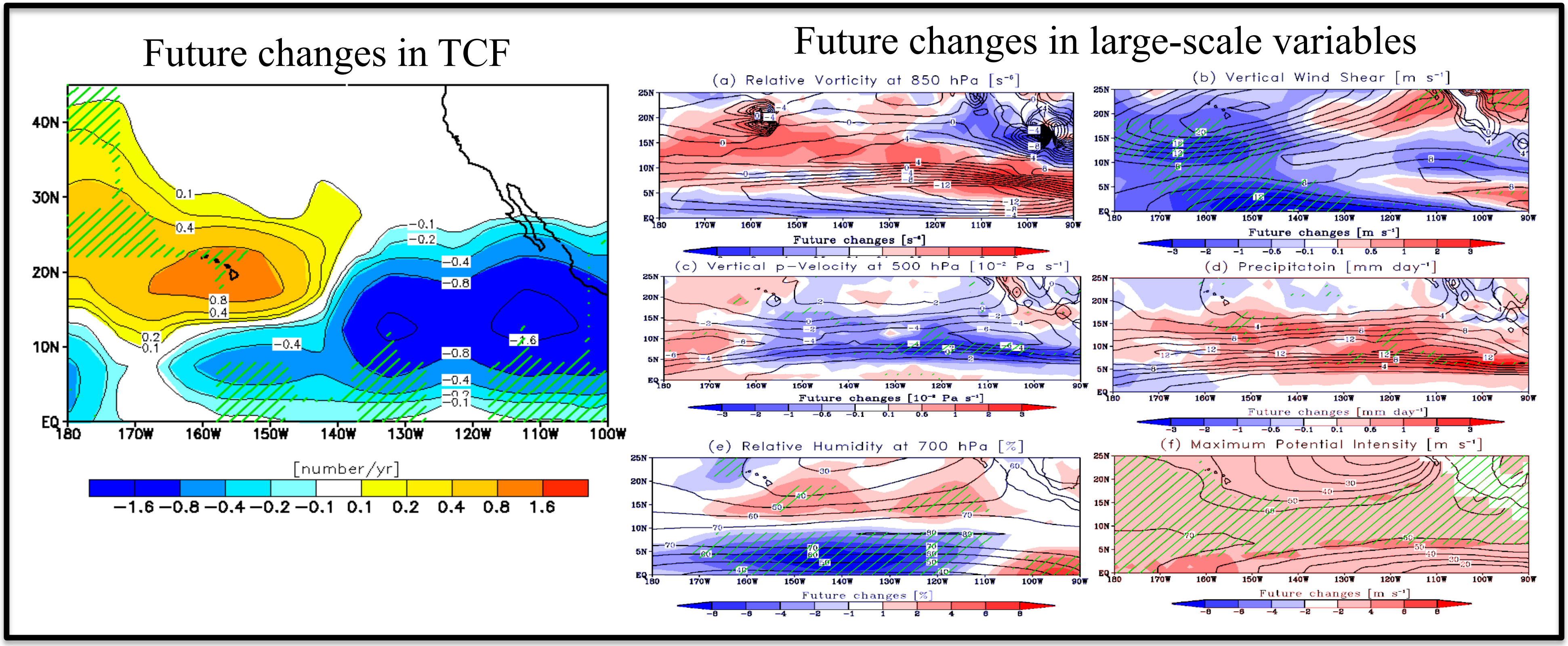
Large and Danabasoglu (2006, *J. Climate*)

Most of the CMIP3 models show warmer bias in surface temperature in the eastern Pacific in their present-day experiments.

⇒ Projected weakening of the Walker Circulation may be largely affected by the model's biases in CMIP3.

# Uniform Warming Experiment

To minimize the biases in CMIP3, we conducted an additional idealized experiment with uniform SST increase by about 2 °C globally from the present-day observed SST.




The ideal experiment also project increase in TCF around the Hawaiian Islands and similar changes in large-scale variables, suggesting that underlying global warming will induce these changes.

# Conclusion

(a) A suite of future warming experiments (2075−2099) robustly project increase in TC frequency of occurrence around the Hawaiian Islands relative to the present-day (1979−2003) simulations.

(b) A physically based empirical statistical analysis reveals that the substantial increase of the likelihood of TC frequency is primarily associated with a northwestward expansion of TC track in the open ocean southeast of the Hawaiian Islands.

(c) In addition, the significant and robust changes in large-scale environmental conditions also strengthen *in situ* TC activity in the subtropical Central Pacific, which also contribute to the increase of TC frequency of occurrence around the Hawaiian Islands.

(d) Idealized experiment prescribing uniform SST warming also project increases in TC frequency of occurrence around the Hawaiian regions as well as similar large-scale environmental parameters associated with weakening of Walker Circulation.

# Thank you

# Difference in model version

| Model version | MRI-AGCM3.1 (v3.1)[27] | MRI-AGCM3.2 (v3.2)[28] |
|---|---|---|
| Cumulus convection | Prognostic Arakawa-Schubert (AS) | Yoshimura (YS), Kain-Fritsch (KF) |
| Cloud | Smith (1990) | Tiedtke (1993) |
| Radiation | Shibata and Aoki (1989), Shibata and Uchiyama (1992) | JMA(2007) |
| Gravity wave drag | Iwasaki et al. (1989) | |
| Land surface | Hirai et al. (2007) | |
| Boundary layer | Mellor and Yamada (1974, level 2) | |
| Aerosol (direct) | Sulfate aerosol | Five species |

# How to prescribe SST for the future experiment

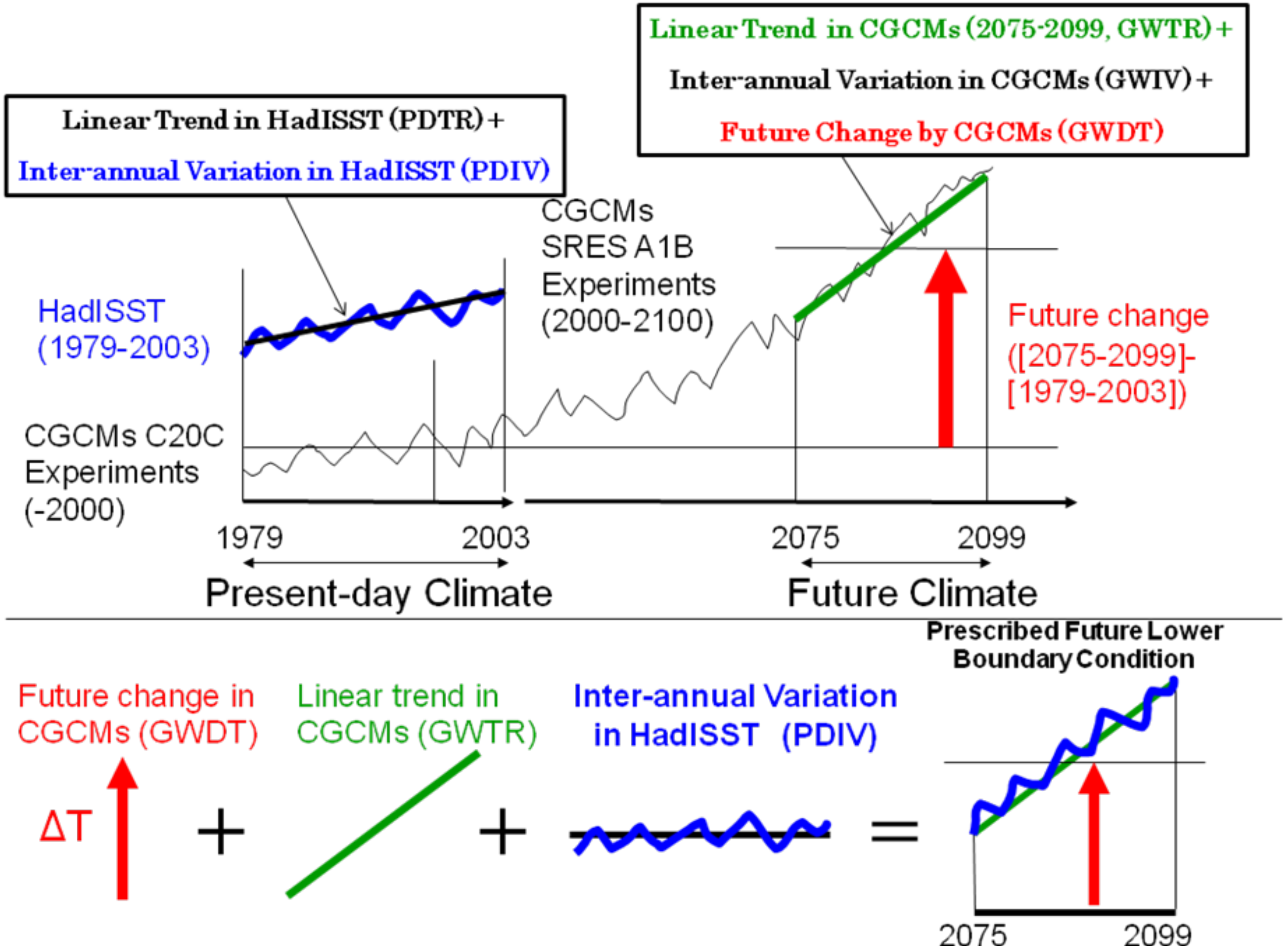
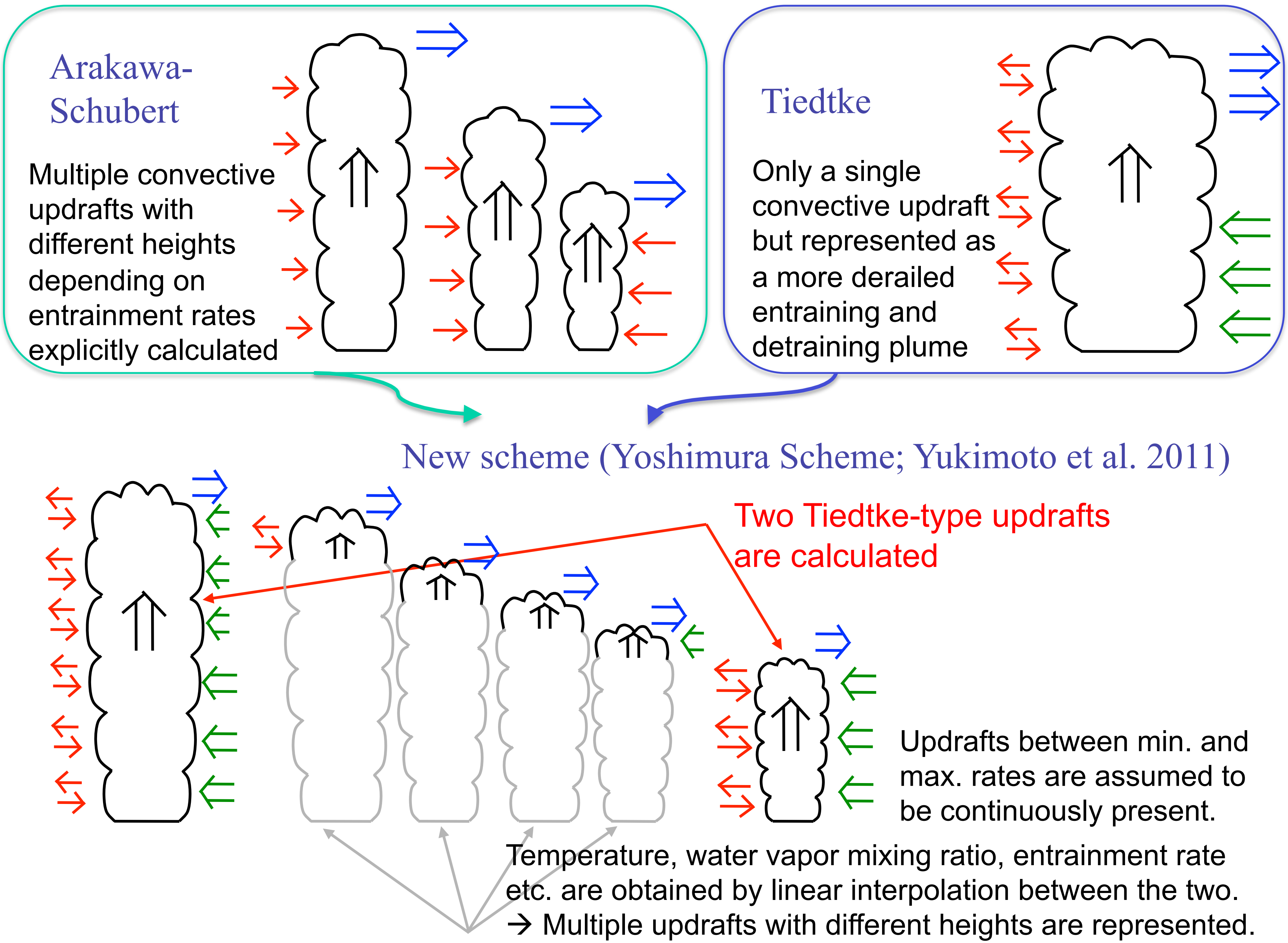
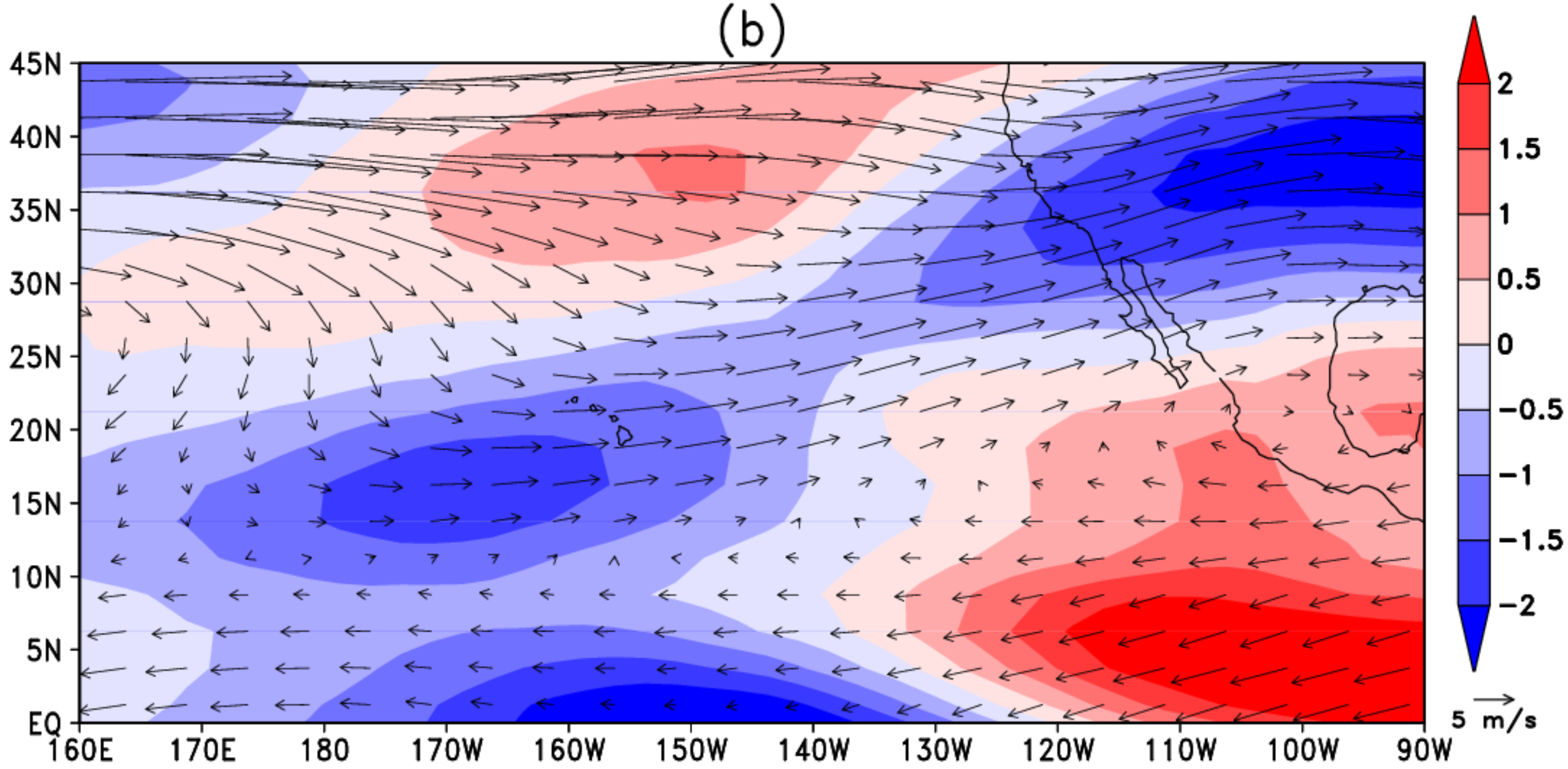



FIG. Schematic diagram of prescribed lower boundary conditions for the future simulation.


Arakawa-Schubert
Multiple convective updrafts with different heights depending on entrainment rates explicitly calculated
Tiedtke
Only a single convective updraft but represented as a more derailed entraining and detraining plume
New scheme (Yoshimura Scheme; Yukimoto et al. 2011)
Two Tiedtke-type updrafts are calculated
Updrafts between min. and max. rates are assumed to be continuously present.
Temperature, water vapor mixing ratio, entrainment rate etc. are obtained by linear interpolation between the two.
→ Multiple updrafts with different heights are represented.

# Change in large-scale flow at 300 hPa (Jul-Oct)




Vector　：Simulated present-day July–October mean wind at 300 hPa [m $s^{-1}$]

Shading: Projected future change in zonal wind

# Simulated TC tracks

Observations | Present-day | Future