nature portfolio

Peer Review File

Present-day warm pool constrains future tropical precipitation

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Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

16th May 22

Dear Professor Yeh,

Please allow us to apologise for the long delay with sending a decision on your manuscript titled "Present-day warm pool constrains future tropical precipitation". It has now been seen by 2 reviewers, and I include their comments at the end of this message. Reviewer 1 finds your work to be of overall interest, but reviewer 2 raises important concerns about the novelty and usefulness of the proposed emergent constraint. Therefore, while we are interested in the possibility of publishing your study in Communications Earth & Environment, we would like to first consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

In particular, for further consideration in Communications Earth & Environment to be appropriate, we will need you to:
* add more discussion addressing how the emergent constraint you propose stands in contrast to (or builds significantly upon) alternative possible emergent relationships, taking into account comments from reviewer 2.
* fully justify your use of linear regression to define the emergent constraint, taking into account the comments from reviewer 1.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and the completed checklist:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Clara Orbe, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-5344-3599

Heike Langenberg, PhD
Chief Editor
Communications Earth & Environment

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Editorial Policy: Policy requirements

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All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

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- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
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DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

In this paper, Park et al show that there is a relatively strong relationship across climate models between the size of the Indo-Pacific warm pool (IPWP) in the present-day climate and changes in future tropical precipitation over the central/eastern tropical Pacific (CETP). Models with larger present-day warm pools tend to exhibit stronger precipitation increases in the CETP. The authors suggest a physical mechanism to explain this relationship, and show that it can be used to reduce uncertainty in projections of precipitation changes in the CETP by ~25%, through the use of an emergent constraint.

Overall, the paper is well written (though it could use some minor editing), logically presented and the results are convincing. I do have some questions/comments, but recommend publication after the authors have addressed these.

Comments:
1. L45: What about CMIP6 models? These are actually the focus of the rest of the paper.

2. L51: "variabilities" -> "variability". And variability in what sense? Across models? In time?

3. L59-62: Suggest citing Caldwell et al (2014) in this discussion of emergent constraints
Caldwell, P. M., C. S. Bretherton, M. D. Zelinka, S. A. Klein, B. D. Santer, and B. M. Sanderson (2014), Statistical significance of climate sensitivity predictors obtained by data mining, Geophys. Res. Lett., 41, 1803–1808, doi:10.1002/2014GL059205
also:
Caldwell, P. M., Zelinka, M. D., and Klein, S. A.: Evaluating Emergent Constraints on Equilibrium Climate Sensitivity, J. Climate, 31, 3921–3942, 2018.

4. L79: The weakening is only really evident in the east Pacific. In discussing the low level winds over the CETP, it might also be helpful to reference Seager et al (2019), which discusses mean-state biases in climate models and how these relate to projected changes in the tropical Pacific.
Seager, R, M.A. Cane, N. Henderson, D.-E. Lee, R. Abernathy and H. Zhang, 2019: Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases, Nature Climate Change, p.517-522

5. Figure 1a: It might be helpful to also show (or discuss) the robustness of the sign of the precip changes across models. Showing intermodel standard deviations > 0.3mm/day/C highlights regions with strong precip in the present climate, but these might not have the highest (relative) uncertainty. Evaluating robustness in terms of sign is more similar to how e.g., the IPCC does things.

6.Figure 1c: I'm not sure what the authors mean by "Tropical SST". Could they define this?

7.Figure 1d: Is precipitation change evaluated /C of warming?

8. Figure 2. In all of the colorbars, suggest flipping the order of the units so %-1 is last. E.g. C C-1 %-1, since the regressions are of changes (/C) onto size (in %). Also, how is the "Indo-Pacific Ocean" defined when calculating the IPWP size? Finally, shouldn't the arrows ub panels a and b have units m/s /C / %? It's a bit confusing which variables are responses and which are present day values in this figure.

9. Figure 3: it would be nice to state the slope in each panel.

10. The emergent constraint. While the authors have been careful in how they calculate the emergent constraint, I am increasingly against using linear regressions for ECs. As discussed by Brient & Schneider (2016), linear regression emphasizes outlier models, which we believe are "bad" in some sense. For example, in Figure 4a, the FGOALS model is a clear outlier, and so exerts the most leverage on the slope of the regression. I suggest using the information theoretic approach developed by Brient & Schneider instead (see also Lutsko et al (2021) for a slightly different version).
Brient, F., & Schneider, T. (2016). Constraints on climate sensitivity from space-based measurements of low-cloud reflection. Journal of Climate, 29(16), 5821– 5835. https://doi.org/10.1175/jcli-d-15-0897.1

Lutsko, N. J., Popp, M., Nazarian, R. H., & Albright, A. L. (2021). Emergent constraints on regional cloud feedbacks. Geophysical Research Letters, 48, e2021GL092934. https://doi.org/10.1029/2021GL092934

Reviewer #2 (Remarks to the Author):

The authors demonstrate that the present-day Indo-Pacific Warm Pool (IPWP) size is closely tied to projected precipitation changes over the central-to-eastern tropical Pacific (CETP) in both CMIP6 and CMIP5 ensemble. Based on this emergent constraint, it is shown that the projected uncertainty of the CETP precipitation change can be reduced by 25% when constrained by the present-day IPWP size. For the reasons stated below, I do not find this emergent constraint useful nor interesting. Thus, I cannot recommend publication of this manuscript.

Major comments

The relationship between the present-day IPWP size and CETP precipitation changes arises simply because the IPWP size is closely tied to the location of the Walker circulation ascending branch (Supplementary Fig. 3) and the mixed layer temperature in the eastern tropical Pacific (Supplementary Fig. 5). That is, the models with warmer eastern tropical Pacific mixed layer in the present day would be associated with a larger SST increase in the eastern basin, giving rise to a larger weakening of the Walker circulation, thereby enhancing the CETP precipitation increase. It is because the IPWP size is larger with warmer eastern tropical Pacific mixed layer that makes the CETP precipitation changes to be proportional to the present-day IPWP size. Hence, I find this emergent constrain to be not surprising.

Moreover, the IPWP size index doesn't sound physical but sound rather numeric. One could have constructed an emergent constraint with the present-day Walker circulation edge or mean tropical SST. It is suggested that more realistic simulations of the IPWP size would improve the credibility of future projections of tropical hydrological cycle. However, the IPWP size is not a meteorological variable that modelers target to simulate. Rather, it is the outcome of the simulated tropical SST distributions. It would be more informative to suggest an emergent constraint with the mean tropical SST bias, for example.

Minor comments

I was wondering the definition of the IPWP size while reading the manuscript. The method section (Line 277-280) should be referred to when first introducing the IPWP size.

Fig. 1c: Please be more specific about the tropical basin SST. Is it the average over the Indo-Pacific basin between 30S-30N, not including the Atlantic?

Reviewer #1 (Remarks to the Author):

In this paper, Park et al show that there is a relatively strong relationship across climate models between the size of the Indo-Pacific warm pool (IPWP) in the present-day climate and changes in future tropical precipitation over the central/eastern tropical Pacific (CETP). Models with larger present-day warm pools tend to exhibit stronger precipitation increases in the CETP. The authors suggest a physical mechanism to explain this relationship, and show that it can be used to reduce uncertainty in projections of precipitation changes in the CETP by ~25%, through the use of an emergent constraint.

Overall, the paper is well written (though it could use some minor editing), logically presented and the results are convincing. I do have some questions/comments, but recommend publication after the authors have addressed these.

→ Thank you for the reviewer's constructive and helpful comments. We addressed all issues raised by the reviewer and incorporated these comments in the revised manuscript with "Tracked Changes". Our point-by-point replies are as follows:

1. L45: What about CMIP6 models? These are actually the focus of the rest of the paper.

→ Thank you for the reviewer's careful comment. Most CMIP6 climate models also tend to project a weakening of the Walker circulation under global warming. Responding to the reviewer's comment, we add the following sentences in the revised manuscript.

Line45: "While most Climate Model Intercomparison Project phase 5 and phase 6 (CMIP5/CMIP6) climate models project a weakening of the Walker circulation under global warming (Bayr et al . 2014, Parsons, 2020; Beobide-Arsuaga et al. 2021; Heede and Fedorov 2021), the robustness of this projection remains unclear because CMIP5/CMIP6 models fail to reproduce observed trends in recent decades and exhibit a large inter-model spread (Plesca et al. 2018)."

Parsons LA. Implications of CMIP6 Projected Drying Trends for 21st Century Amazonian Drought Risk. *Earths Future* 2020, 8(10). https://doi.org/10.1029/2020EF001608

Beobide-Arsuaga, G., Bayr, T., Reintges, A. & Latif, M. Uncertainty of ENSO-amplitude projections in CMIP5 and CMIP6 models. *Clim Dynam* 56(11), 3875-3888 (2021).

https://doi.org/10.1007/s00382-021-05673-4

Heede, U. K. & Fedorov, A. V. Eastern equatorial Pacific warming delayed by aerosols and thermostat response to CO2 increase. *Nat Clim Change* 11(8), 696-703 (2021). https://doi.org/10.1038/s41558-021-01101-x

2. L51: "variabilities" -> "variability". And variability in what sense? Across models? In time?

→ Thank you for the reviewer's careful comments. "Variability" means the relationship between the IPWP size and the precipitation in the CETP on inter-annual time scales. Following the reviewer's comment, we clarify the above sentence as follows: "As the edge of the IPWP is in contact with the CETP, a strong relationship exists between the variability in the IPWP size and the precipitation in the CETP on inter-annual time scale (Chen and Majda 2016)"

3. L59-62: Suggest citing Caldwell et al (2014) in this discussion of emergent constraints
Caldwell, P. M., C. S. Bretherton, M. D. Zelinka, S. A. Klein, B. D. Santer, and B. M. Sanderson (2014), Statistical significance of climate sensitivity predictors obtained by data mining, Geophys. Res. Lett., 41, 1803–1808, doi:10.1002/2014GL059205
also:
Caldwell, P. M., Zelinka, M. D., and Klein, S. A.: Evaluating Emergent Constraints on Equilibrium Climate Sensitivity, J. Climate, 31, 3921–3942, 2018.

→ Thank you for the reviewer's suggestion. Following the reviewer's comment, we referred the above references in the revised manuscript.

4. L79: The weakening is only really evident in the east Pacific. In discussing the low level winds over the CETP, it might also be helpful to reference Seager et al (2019), which discusses mean-state biases in climate models and how these relate to projected changes in the tropical Pacific.

Seager, R, M.A. Cane, N. Henderson, D.-E. Lee, R. Abernathy and H. Zhang, 2019: Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases, Nature Climate Change, p.517-522

→ Thank you for the reviewer's constructive comments and relevant literature. Following the reviewer's comment, we add the following sentences in the revised manuscript: "While the strengthening of easterly winds at low levels is dominant over the central Indian Ocean, a weakening of the low-level winds in the eastern tropical Pacific is consistent with the result in

CMIP5 climate model (Li et al. 2017). Uncertainty of changes in the low-level winds over the CETP under increased anthropogenic CO_2 is associated with the climatological mean-state bias across the tropical Pacific basin in CMIP6 climate models (Seager et al. 2019)"

5. Figure 1a: It might be helpful to also show (or discuss) the robustness of the sign of the precip changes across models. Showing intermodel standard deviations > 0.3mm/day/C highlights regions with strong precip in the present climate, but these might not have the highest (relative) uncertainty. Evaluating robustness in terms of sign is more similar to how e.g., the IPCC does things.

→ Thank you for the reviewer's helpful suggestion. As the reviewer suggested, we displayed the robustness of the sign following the IPCC assessment report (please see the below Fig. 1). We found that there is strong inter-model consistency in the sign of CETP precipitation changes. Following the reviewer's comment, we revised Fig. 1 and add the following sentences in the revised manuscript: "The CETP exhibited strong positive trends of precipitation change in future climate with a high inter-model consistency in terms of their sign, while there is a low consistency over the Indian Ocean and western tropical Pacific (Fig. 1a)."

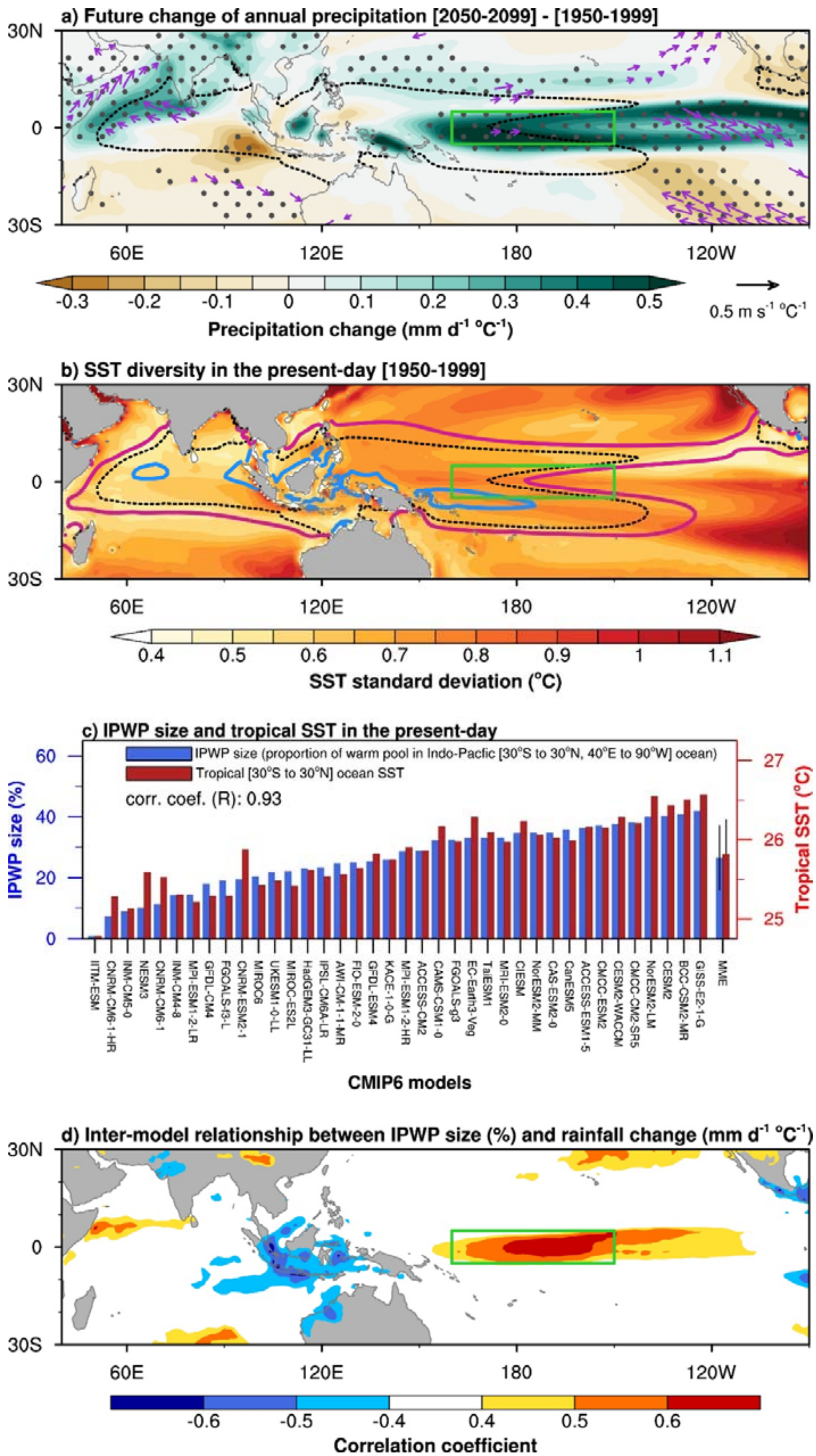

a) Future change of annual precipitation [2050-2099] - [1950-1999]
30N
0
30S
60E
120E
180
120W
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Precipitation change (mm d-1 °C-1)
0.5 m s-1 °C-1
b) SST diversity in the present-day [1950-1999]
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
SST standard deviation (°C)
c) IPWP size and tropical SST in the present-day
IPWP size (proportion of warm pool in Indo-Pacific [30°S to 30°N, 40°E to 90°W] ocean)
Tropical [30°S to 30°N] ocean SST
corr. coef. (R): 0.93
IPWP size (%)
Tropical SST (°C)
IITM-ESM
CNRM-CM6-1-HR
INM-CM5-0
NESM3
CNRM-CM6-1
INM-CM4-8
MPI-ESM1-2-LR
GFDL-CM4
FGOALS-f3-L
CNRM-ESM2-1
MIROC6
UKESM1-0-LL
MIROC-ES2L
HadGEM3-GC31-LL
IPSL-CM6A-LR
AWI-CM-1-1-MR
FIO-ESM-2-0
GFDL-ESM4
KACE-1-0-G
MPI-ESM1-2-HR
ACCESS-CM2
CAMS-CSM1-0
FGOALS-g3
EC-Earth3-Veg
TaiESM1
MRI-ESM2-0
CIESM
NorESM2-MM
CAS-ESM2-0
CanESM5
ACCESS-ESM1-5
CMCC-ESM2
CESM2-WACCM
CMCC-CM2-SR5
NorESM2-LM
CESM2
BCC-CSM2-MR
GISS-E2-1-G
MME
CMIP6 models
d) Inter-model relationship between IPWP size (%) and rainfall change (mm d-1 °C-1)
-0.6
-0.5
-0.4
0.4
0.5
0.6
Correlation coefficient

Figure 1. Future climate changes, present-day diversity, and the relationship between future tropical precipitation changes and the present-day Indo-Pacific warm pool (IPWP) size. a) Multi-model ensemble mean (MMEM) changes of annual precipitation (shading, mm d^{-1} $°C^{-1}$) and 850hPa wind (vector scale is shown in the bottom right, m s^{-1} $°C^{-1}$) in future climate by 38 CMIP6 models under SSP5-8.5 scenario. Stipples represent the area with a high consistency of the sign in future precipitation changes (> 80% , 31 of total 38 models have the same sign). Black dashed lines indicate MMEM of IPWP boundary (28°C isotherms) in the present-day climate. **b)** Inter-model standard deviations of SST (shading) in the present-day. Black dashed lines are same as in a) and solid pink lines are the averaged IPWP boundary of the five models with the largest IPWP size, while solid blue lines indicate the same for the smallest IPWP boundary of the five models for the present-day. **c)** The IPWP size (blue bars) and tropical basin SST (red bars) among climate models in the present-day. Black lines in MMEM illustrate one standard deviation of inter-model values. **d)** Inter-model correlations between the projected precipitation changes and the present-day IPWP size among CMIP6 models. In all panels, boxes denote the central-to-eastern tropical Pacific (5°S–5°N, 160°E–150°W, same as Niño 4). Unless otherwise specified, all projected changes are derived from future (2050–2099) minus present-day (1950–1999) values and are normalized though dividing by the global mean surface temperature anomalies of each model.

6.Figure 1c: I'm not sure what the authors mean by "Tropical SST". Could they define this?

→ We are sorry for this confusion. Tropical SST is defined as the SST averaged in the tropical domain (30°S to 30°N, 0 to 360°E) in each climate model. The manuscript has been revised as follows: “The IPWP size is defined as that the ocean proportion with enclosed by the 28°C isotherm in the Indo-Pacific Ocean (30°S–30°N, 40°E–90°W) with a percentage (%) unit. The simulated present-day IPWP size and tropical SST (defined as area-weighted SST mean over 30°S to 30°N, 0 to 360°E) in 38 CMIP6 climate models exhibits a large inter-model spread and one-standard deviations of approximately 10% and 0.5°C, respectively”

7.Figure 1d: Is precipitation change evaluated /C of warming?

→ All changes in CMIP6 climate models are normalized by diving global mean surface temperature (GMST) changes. Therefore, a unit of precipitation change is mm/d/°C in Fig. 1d as the reviewer pointed out. We corrected Fig. 1d's caption as follows: "d) Inter-model relationship between IPWP size (%) and rainfall change (mm d^{-1} $°C^{-1}$)" Note that the correlation coefficient between the present-day IPWP size (%) and future precipitation change over the CETP is almost identical with that using precipitation changes per GMST (see the below Fig. A1).

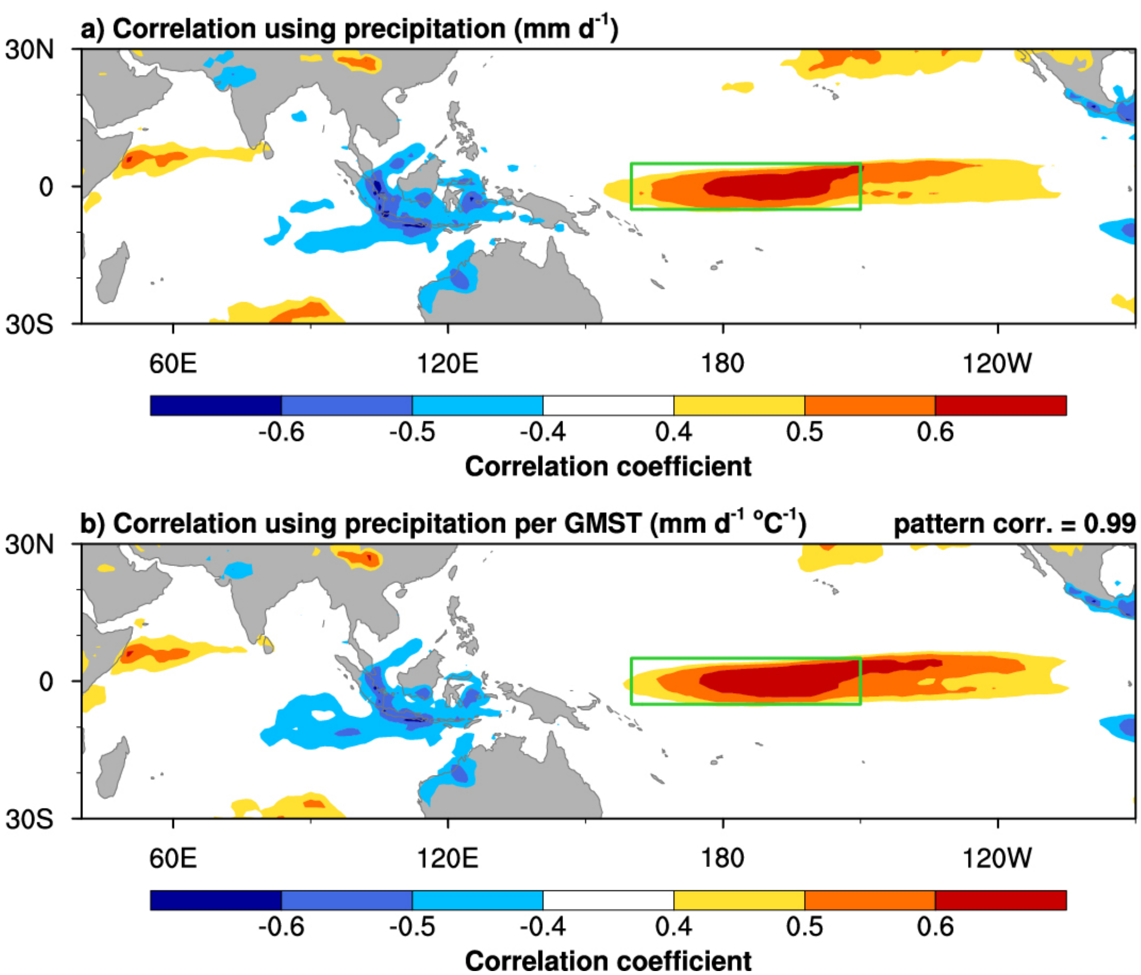


Figure A1. Inter-model correlations between the projected precipitation changes under SSP5-8.5 and the present-day IPWP size among 38 models of CMIP6. In all panels, boxes denote the central-to-eastern tropical Pacific (5°S–5°N, 160°E–150°W, same as Niño 4). **a)** precipitation changes (mm/d) and **b)** precipitation changes per global mean surface temperature changes (mm/d/°C).

8. Figure 2. In all of the colorbars, suggest flipping the order of the units so %-1 is last. E.g. C C-1 %-1, since the regressions are of changes (/C) onto size (in %). Also, how is the "Indo-Pacific Ocean" defined when calculating the IPWP size? Finally, shouldn't the arrows ub panels a and b have units m/s /C / %? It's a bit confusing which variables are responses and which are present day values in this figure.

→ Thank you for the reviewer's careful comments. Responding to the reviewer's suggestion, we revised the units in the Fig. 2 by flipping the order of the units. Also, $\%^{-1}$ units are illustrated in the arrow reference (see the below Fig. 2).

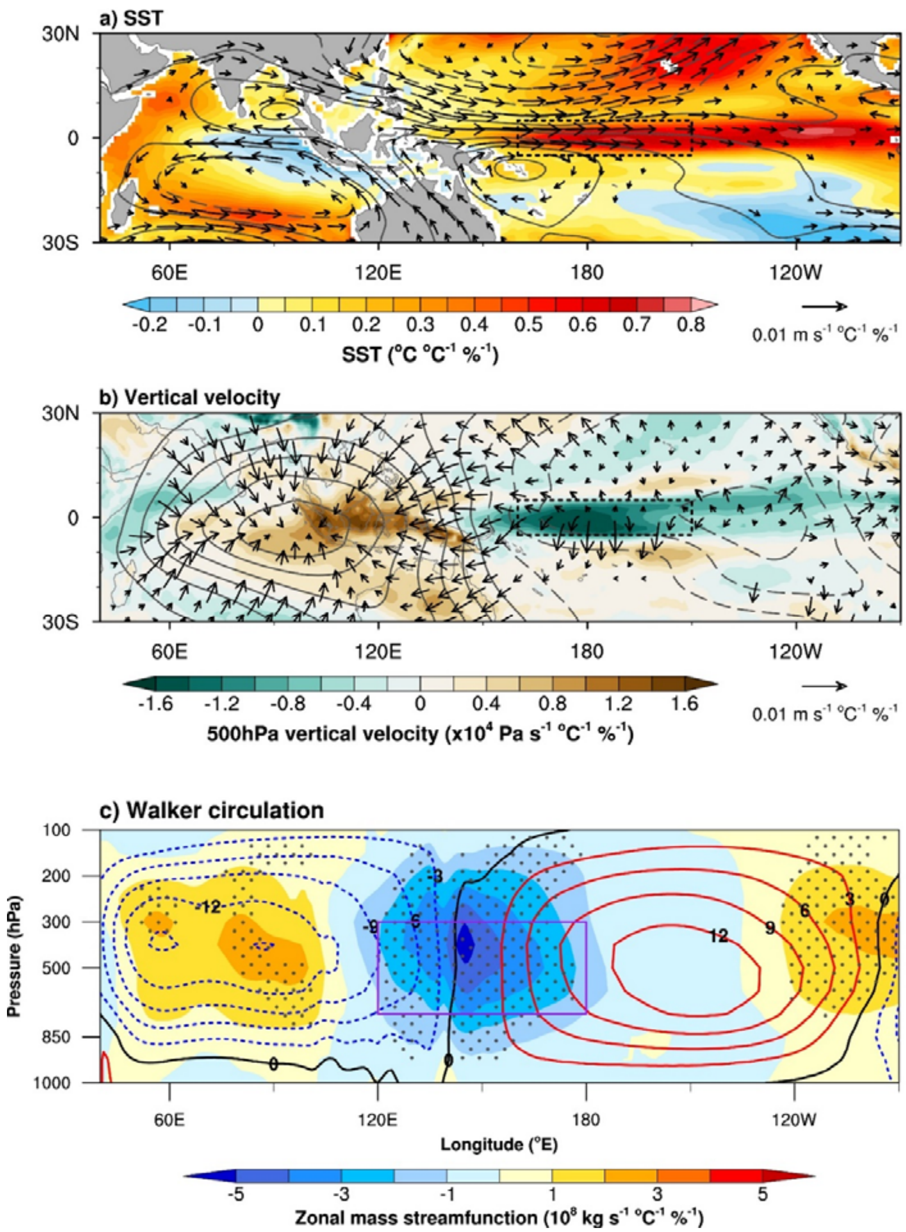


Figure 2. Inter-model regression patterns of future changes under SSP5-8.5 scenario onto the present-day IPWP size. a) Regressed future changes in SST (shading, °C), 850hPa stream function (contour interval: 0.3×10^3 s^{-1}) and rotational wind (vectors, m s^{-1}). **b)** Regressed future changes in 500hPa vertical velocity ($\times 10^4$ Pa s^{-1}; the upward motion is negative), 200hPa velocity potential (contour interval: 0.3×10^3 s^{-1}) and divergent wind (vectors, m s^{-1}). **c)** Regressed future changes in zonal stream function (shading, 10^8 kg s^{-1}) along the equator (meridional mean between 5°S and 5°N). Contours indicate MMEM of zonal stream function

(10^{10} kg s^{-1}) in the present-day (1950–1999). Stipples indicate regions of significance at the 99% confidence level in a student t-test. Positive values indicate a clockwise movement and negative values indicate the reverse; the resulting zero line is the center of strongest upward motion. The purple box is the region used to define the strength of Walker circulation.

9. Figure 3: it would be nice to state the slope in each panel.

→ Corrected as follows:

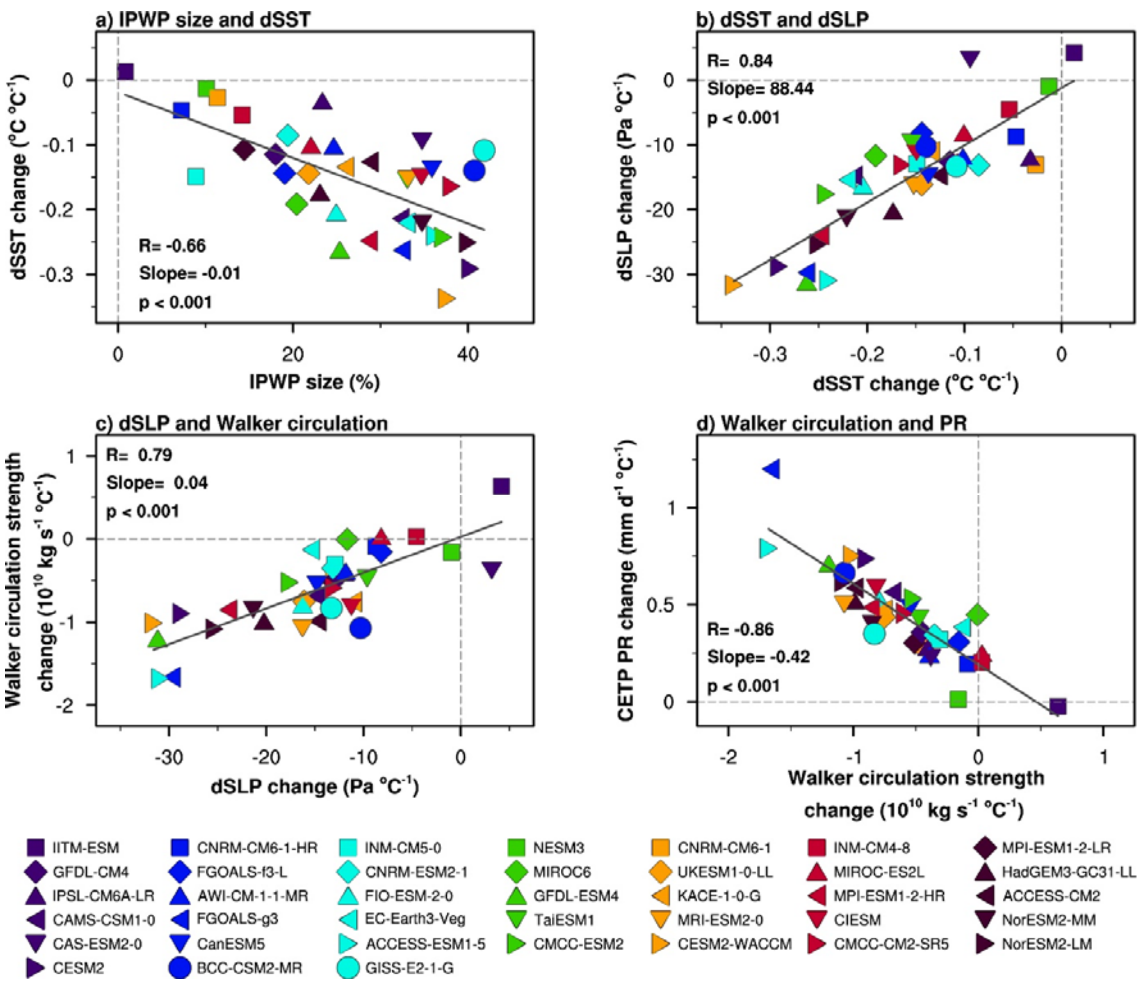


Figure 3. Inter-model correlation of future projected changes against present-day IPWP size in SSP5-8.5 scenarios of CMIP6 models. a) Simulated present-day IPWP size (%) versus future changes in the Pacific zonal SST gradient (west-minus-east, negative values indicate

reducing of zonal SST gradient). **b)** Future changes in the Pacific zonal SST gradient versus future changes in the Pacific zonal sea level pressure gradient (Pa). **c)** Future changes in the Pacific zonal sea level pressure gradient versus that of Walker circulation strength (10^{10} kg s^{-1}). **d)** Future changes of Walker circulation strength (averaging 120°E–180, 700–300hPa) versus that of CETP precipitation (mm day^{-1}, 5°S–5°N, 160°E–150°W). The inter-model correlation coefficients (r), slope and p-value are displayed in each panel are statistically significant at the 99% confidence level.

10. The emergent constraint. While the authors have been careful in how they calculate the emergent constraint, I am increasingly against using linear regressions for ECs. As discussed by Brient & Schneider (2016), linear regression emphasizes outlier models, which we believe are "bad" in some sense. For example, in Figure 4a, the FGOALS model is a clear outlier, and so exerts the most leverage on the slope of the regression. I suggest using the information theoretic approach developed by Brient & Schneider instead (see also Lutsko et al (2021) for a slightly different version).

Brient, F., & Schneider, T. (2016). Constraints on climate sensitivity from space-based measurements of low-cloud reflection. Journal of Climate, 29(16), 5821– 5835. https://doi.org/10.1175/jcli-d-15-0897.1

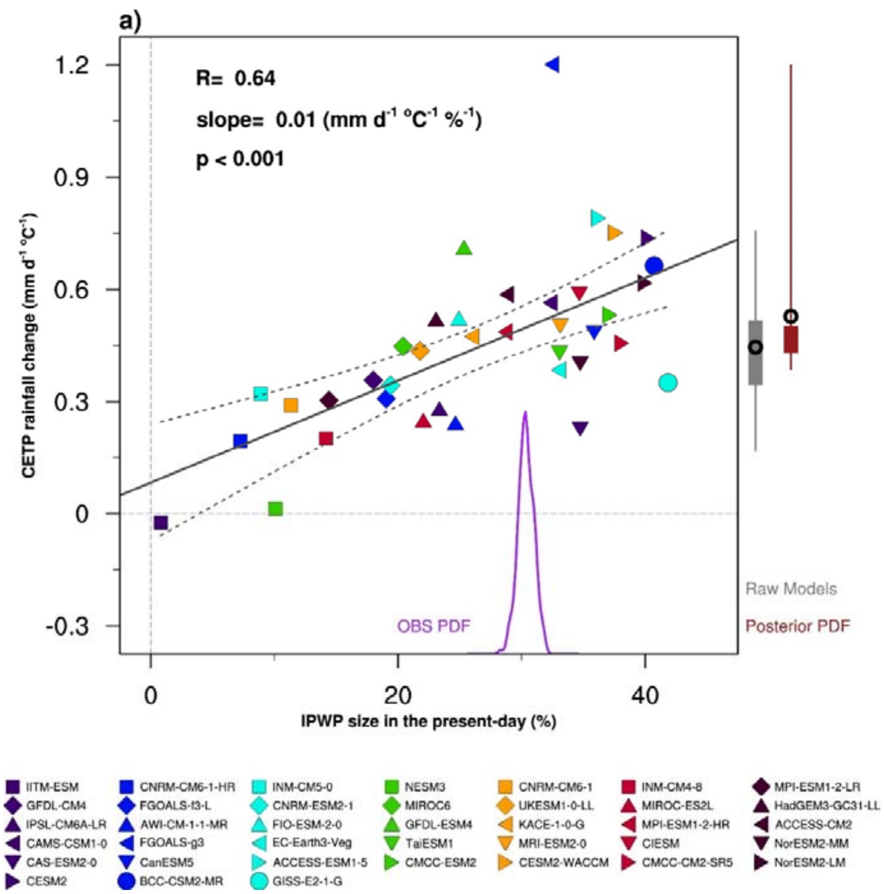
Lutsko, N. J., Popp, M., Nazarian, R. H., & Albright, A. L. (2021). Emergent constraints on regional cloud feedbacks. Geophysical Research Letters, 48, e2021GL092934. https://doi.org/10.1029/2021GL092934

→ Thank you for the reviewer’s constructive and critical comments. As the reviewer pointed out, linear regression analysis may tend to emphasizes outlier models like FGOAL-g3 to calculate the emergent constraint. Responding to the reviewer’s suggestion, we constrained the future CETP changes based on the methodology following Brient and Schneider (2016) (see also Supplementary Fig. 11 and the below figure). To compare the distribution of the present-day IPWP area between climate model simulation and the observation, we fit the probability density functions (PDFs) to the bootstrap samples (200 in this study) using a Gaussian kernel density estimator with a bandwidth to minimize the mean integrated squared error. Then, we obtain the model weightings using an information theoretic distance measure between the PDFs of the observed and modeled IPWP area in the present-day as follows.

$$\Delta_i = \int p(x) log \frac{p(x)}{q_i(x)} dx$$

Here, the Kullback–Leibler divergence Δ_i denotes the relative entropy between the observation PDF $p(x)$ and the model PDF $q(x)$ and i indicates each climate model. The smaller the value is, the higher the PDF's agreement between the model and the observation is. Therefore, the exponential of this divergence ($l_i = \exp(-\Delta_i)$) could be used as a weighting of model simulation. To obtain the model weighting (w_i), we use the following normalization:

$$w_i = \frac{l_i}{\sum_i l_i}$$



Supplementary Figure 11. Emergent constraints on the central-to-eastern tropical Pacific (CETP) precipitation changes in CMIP6 climate models using the information theoretic approach. Projected precipitation changes in the CETP under SSP5-8.5 across the CMIP6 climate models versus the Indo-Pacific warm pool (IPWP) size in the present-day (1950–1999). The solid black line follows the linear regression of 38 CMIP6 climate models, while the dashed black lines indicate prediction errors with one-standard deviation (68% confidence intervals). A solid purple line indicates the PDF of the observed IPWP size in HadISST using 200-ramdom bootstrap. The raw model spread of the future CETP changes is compared with posterior PDF using its weighted average, given the observed IPWP area in the present-day. The bars and error bars in the right y-axis indicate 66% and 90% confidence interval (one- and two- standard deviation among CMIP6 climate models with/without constraint). Circles indicate multi-model means of future precipitation changes over the CETP.

Unfortunately, only 6-models of total 38-models in CMIP6 climate models is able to meet the Kullback–Leibler divergence, indicating only these models can reproduce the observed IPWP area in the present-day, reasonably. The weighting values are 19 (MPI-ESM1-2-HR), 15(ACCESS-CM2), 2(CAMS-CSM1-0), 8(FGOALS-g3), 21(EC-Earth3-Veg), 22(TaiESM1) and 13(MRI-ESM2-0), respectively. Indeed, the information theoretic approach may allow to reduce the uncertainty of future CETP changes substantially, however, it also contains the outliner model like FGOALS-g3 obtained from the linear regression approach. Responding to the reviewer's comment, the following sentences are added in the revised manuscript:

"**Information theoretic approach on constraint.** To compare the distribution of the present-day IPWP size between climate model simulations and the observation following a previously established methodology (Brient and Schneider 2016), a Gaussian kernel density estimator based on 200 bootstrapped samples makes a Probability density functions (PDFs) with the best bandwidth, which minimizes the mean integrated squared error for normal data. Then, the model weightings are calculated using an information theoretic distance measure between the Probability density functions (PDFs) of the observed and modeled IPWP area in the present-day.

$$\Delta_i = \int p(x) log \frac{p(x)}{q_i(x)} dx$$

Here, the Kullback–Leibler divergence Δ_i denotes the relative entropy between the observation PDF *p(x)* and the model PDF *q(x)* and *i* indicates each climate model. The smaller the value is, the higher the PDF's agreement between the model and the observation is. Therefore, the exponential of this divergence ($l_i = \exp(-\Delta_i)$) could be used as a weighting of model simulation. To obtain the model weighting (w_i), we use the following normalization:

$$w_i = \frac{l_i}{\sum_i l_i}$$

Future precipitation changes of the CETP are constrained by model weighting from the performance of the present-day IPWP sizes."

"To exclude the influence of outlier models on the emergent relationship obtained from the linear regression analysis, we further examine the information theoretic approach to constrain the future CETP precipitation changes (Methods, Brient and Schneider 2016). This may lead to a reasonable constraint based on the observations by more weighting on good climate models for simulating the observed IPWP in the present-day. It is found that the main results are similar to that from the linear regression analysis. (Supplementary Fig. 11)."

Reviewer #2 (Remarks to the Author):

The authors demonstrate that the present-day Indo-Pacific Warm Pool (IPWP) size is closely tied to projected precipitation changes over the central-to-eastern tropical Pacific (CETP) in both CMIP6 and CMIP5 ensemble. Based on this emergent constraint, it is shown that the projected uncertainty of the CETP precipitation change can be reduced by 25% when constrained by the present-day IPWP size. For the reasons stated below, I do not find this emergent constraint useful nor interesting. Thus, I cannot recommend publication of this manuscript.

→ Thank you for the reviewer's constructive and important comments. We addressed all issues raised by the reviewer and incorporated these comments in the revised manuscript with "Tracked Changes". Our point-by-point replies are as follows:

Major comments

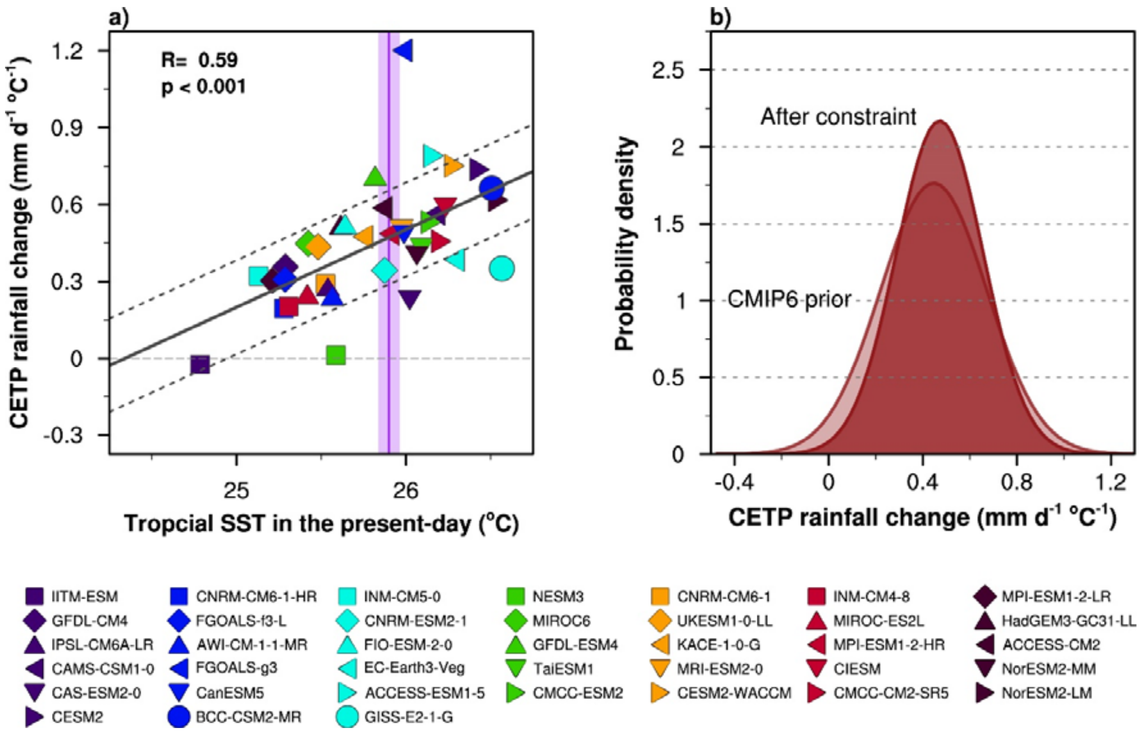
The relationship between the present-day IPWP size and CETP precipitation changes arises simply because the IPWP size is closely tied to the location of the Walker circulation ascending branch (Supplementary Fig. 3) and the mixed layer temperature in the eastern tropical Pacific (Supplementary Fig. 5). That is, the models with warmer eastern tropical Pacific mixed layer in the present day would be associated with a larger SST increase in the eastern basin, giving rise to a larger weakening of the Walker circulation, thereby enhancing the CETP precipitation increase. It is because the IPWP size is larger with warmer eastern tropical Pacific mixed layer that makes the CETP precipitation changes to be proportional to the present-day IPWP size. Hence, I find this emergent constrain to be not surprising.

→ Thank you for the reviewer's careful comments. As the reviewer pointed out, we suggested that the present-day IPWP size is a key ingredient to determine the precipitation change over the CETP in future climate through the Walker circulation change. We found that climate models with a larger IPWP size in the present-day tend to simulate warmer mixed layer temperature in the eastern tropical Pacific Ocean than those with a small IPWP size. And then, we further examined the physical processes of how climate models with a larger IPWP size during the present-day simulate a larger SST increases in the eastern tropical Pacific basin in future climate, resulting in a larger increase of precipitation amount over the CETP with a weakening of Walker circulation compared to those with a small IPWP during the present-day. Based on this finding, we found the emergent relationship between the present-day IPWP size and future precipitation change over the CETP. To our knowledge, there is no systematic study to examine these processes using both CMIP5/6 climate models. The originality of this study is that we obtained statistically significant relationship between the present-day IPWP size and future precipitation change over the CETP with a plausible mechanism using all the available models (38-models) from CMIP6 climate models (Fig. 3).

Moreover, the IPWP size index doesn't sound physical but sound rather numeric. One could have constructed an emergent constraint with the present-day Walker circulation edge or mean tropical SST. It is suggested that more realistic simulations of the IPWP size would improve the credibility of future projections of tropical hydrological cycle. However, the IPWP size is not a meteorological variable that modelers target to simulate. Rather, it is the outcome of the simulated tropical SST distributions. It would be more informative to suggest an emergent constraint with the mean tropical SST bias, for example.

→ The reviewer's comments are critical. Indeed, the IPWP size is closely tied to the tropical mean SST and we found a strong correlation between the IPWP size and the tropical mean SST in CMIP6 climate models (Fig. 1c, correlation coefficient is 0.93). This indicates that the IPWP size can represent the state of tropical mean SST.

Responding to the reviewer's suggestion, we further analyze the emergent relationship using the present-day tropical mean SST. Supplementary Fig. 8 shows that the tropical mean SST in the present-day among CMIP6 climate models has a significant correlation with the future CETP precipitation changes (r=0.59, here r is correlation coefficient with a statistically significant above the 99% confidence level). This result is similar to that of using the IPWP size due to strong correlation between both variables in the present-day (Fig. 1c), but correlation coefficient is slightly lower than that of using the IPWP size (r=0.63). The uncertainty range of CETP precipitation changes using the tropical mean SST is 0.18 mm/day (±1 standard deviation after constraint), which is a bit larger than that of using the IPWP size (0.17 mm/day). When the tropical mean SST is used, the reduction rate of future uncertainty is 22% compared to a raw uncertainty (0.23 mm/day). This rate is slightly lower than that using the IPWP size (25%).



Supplementary Fig. 8. Emergent constraints on the central-to-eastern tropical Pacific (CETP) precipitation changes in CMIP6. a) Projected precipitation changes in the CETP under SSP5-8.5 across the CMIP6 models versus the Tropical mean SST in the present-day (1950–1999). The solid black line follows the linear regression of 38 CMIP6 models, while the dashed black lines indicate prediction errors with one-standard deviation (68% confidence intervals). A solid purple line (shading) indicates the average (one-standard deviation) of the observed IPWP size among three datasets: HadISST, ERSSTv5, and COBE-SST2. b) Probability density functions for the projected precipitation changes in the CETP under SSP5-8.5, before ("CMIP6 prior", transparent) and after ("after constraint", opaque) the emergent constraint is applied.

In addition, the reason of why future CETP precipitation changes are more correlated with the present-day IPWP size than the present-day tropical mean SST is because of a close relationship between the Indo-Pacific Ocean SST and future CETP precipitation changes (see the below Fig. A2). Inter-model correlations between the future CETP changes and SST in the present-day are higher over the Indo-Pacific regions including the IPWP than any other oceans.

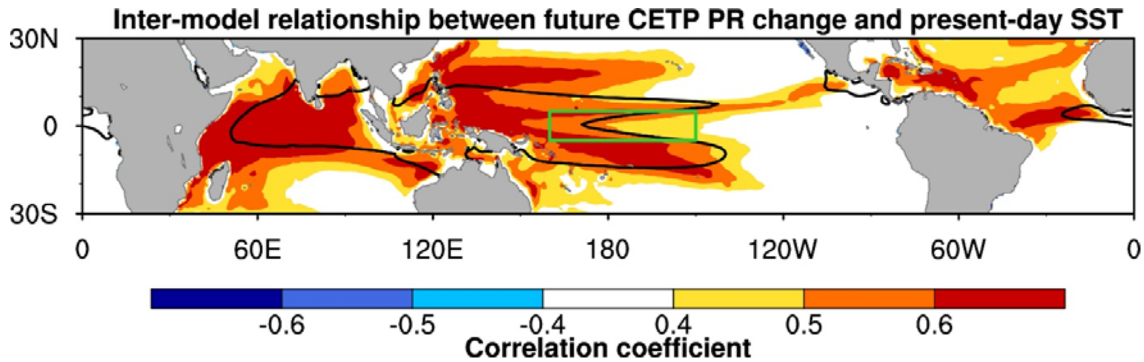


Figure A2. Inter-model correlations between the projected precipitation changes over the CETP and the SST in the present-day among CMIP6 climate models. Black contour indicates the warm pool threshold (28°C) isotherms.

Accordingly, the emergent relationship using the IPWP size in the present-day not only represents the tropical mean SST (Fig. 1c), but also includes physical processes such as a weakening of zonal SST gradient in tropical Pacific and a large warming in the eastern Pacific. These features are not found clearly when we used the tropical mean SST only. Meanwhile, we also analyze an emergent relationship using the Walker circulation variables (longitude of western Pacific edge and strength in the present-day). Figure A3 shows the relationship of future precipitation changes over the CETP with Walker circulation variables in the present-day. Unfortunately, there is no significant relationship between the present-day Walker circulation and future CETP precipitation changes.

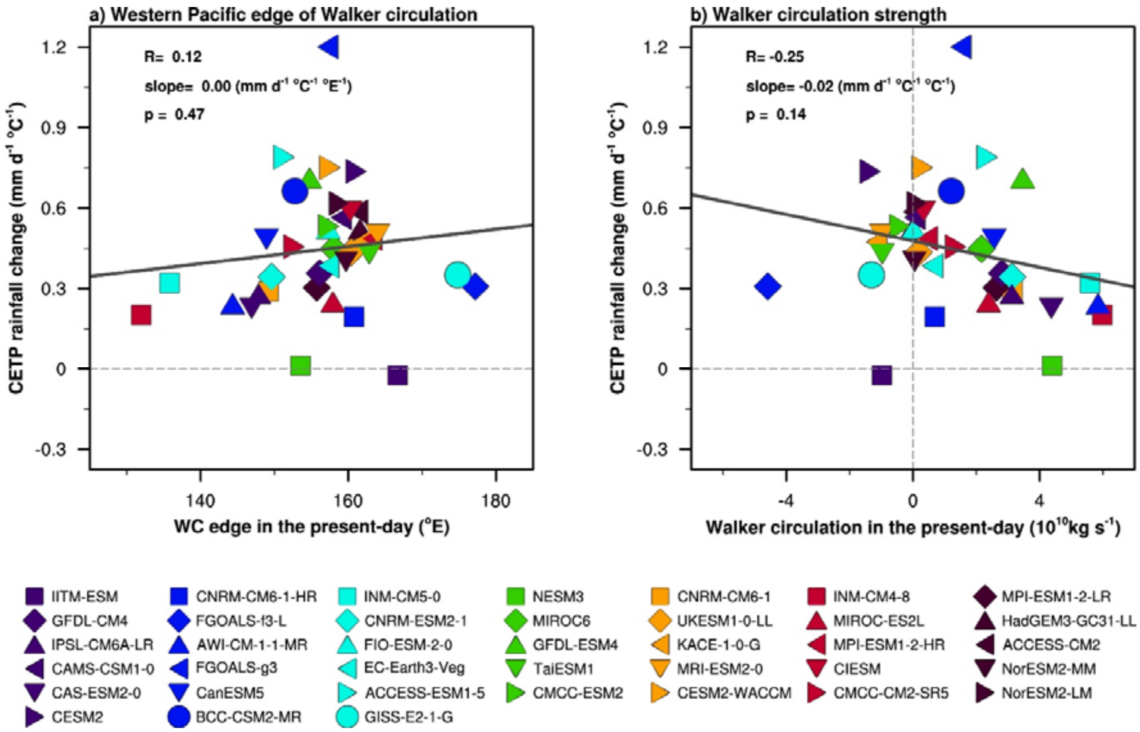


Figure A3. Emergent relationship on the central-to-eastern tropical Pacific (CETP) precipitation changes in CMIP6. Projected precipitation changes in the CETP under SSP5-8.5 across the CMIP6 models versus a) the western Pacific edge longitude and b) strength of Walker circulation in the present-day (1950–1999).

Following the reviewer's comments, we add the following discussion in the revised manuscript.

"Emergent constraint based on the tropical mean SST in the present-day has a similar result with 0.47 ± 0.18 mm/day (the range of ±1 standard deviation) compared to that of the IPWP size. This is due to a close relationship between the IPWP size and tropical mean SST (Fig 1c). However, the emergent relationship using the present-day tropical mean SST is a bit lower with the precipitation changes in the CETP in future climate (r=0.59) than that using the IPWP size (r=0.64), resulting in a slightly reduced uncertainty range compared to that of the IPWP size (Supplementary Fig. 8)"

“The present-day IPWP size does not only represents the tropical mean SST (Fig. 1c), but also includes physical processes such as a weakening of zonal SST gradient in tropical Pacific and a large warming in the eastern Pacific due to a strong relationship with the Walker Circulation branches (Supplementary Fig. 5). Therefore, our result suggests that more realistic simulations of the IPWP size during the present-day climate would be helpful to improve the credibility of climate mitigation and adaptation policy.”

Minor comments

3. I was wondering the definition of the IPWP size while reading the manuscript. The method section (Line 277-280) should be referred to when first introducing the IPWP size.

→ Following the reviewer’s suggestion, we add the description on the definition of Indo-Pacific warm pool size in the revised manuscript. “The IPWP size is defined as that the ocean proportion with enclosed by the 28°C isotherm for the Indo-Pacific Ocean (30°S–30°N, 40°E–90°W) with a percentage (%) unit.”

4. Fig. 1c: Please be more specific about the tropical basin SST. Is it the average over the Indo-Pacific basin between 30S-30N, not including the Atlantic?

→ Following the reviewer’s comment, to avoid ambiguity about Tropical SST, defined as the SST averaged in the tropical domain (30°S to 30°N, 0 to 360°E) in each climate model, the manuscript has been revised as follows: “The IPWP size is defined as that the ocean proportion with enclosed by the 28°C isotherm for the Indo-Pacific Ocean (30°S–30°N, 40°E–90°W) with a percentage (%) unit. The simulated present-day IPWP size and tropical SST (defined as area-weighted mean over 30°S to 30°N, 0 to 360°E) in the 38 CMIP6 climate models exhibit a large inter-model spread and one-standard deviations of approximately 10% and 0.5°C, respectively”

27th Sep 22

Dear Professor Yeh,

Please allow me to sincerely apologise for the long delay in sending a decision on your revised manuscript titled "Present-day warm pool constrains future tropical precipitation" has now been seen again by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Deep apologies for the very slow review. Park et al have done a good job responding to the initial review round, and I suggest publication after a few small comments are cleaned up. I would also like to agree with the authors that Reviewer #2's statement that they find the emergent constraint "to be not surprising" actually supports the EC. The most robust ECs have an underlying physical mechanism, which is actually what the reviewer outlines in their review, and the authors discuss at the end of their paper. This gives me confidence in this result.

Minor comments:
1. As far as I can tell, the only place the authors define the CETP is in the supplement. Suggest defining the domain early in the main text.

2. In Figure 1c a correlation coefficient is given, but it's not stated what this is for. I think it's the correlation between tropical SST and IPWP size, but this should be stated somewhere.

3. L162: Suggest the authors expand on what they mean by "accelerate ocean stratification under global warming" and how this relates to the rapid warming trends. This also affects the schematic in Figure 5.

4. L156 and elsewhere: it's conventional to just say "east-west" gradient, rather than "east-minus-west" gradient.

5. The most major comment I have is agreeing with Reviewer #2 that the emergent constraint should also work for SSTs, which the authors have now shown. They justify focusing on IPWP size rather than SSTs because the correlation is slightly stronger, but it would be nice if they could provide a

better justification. I've been going back and forth myself over which I would emphasize. This emergent constraint should help modelers improve their simulations of the tropical Pacific and its precipitation changes, but both IPWP size and SSTs are emergent properties, and not easily tuned for. Suggest the authors either put the two constraints on a more equal footing, or else do more to justify the focus on size over SSTs.

Reviewer #2 (Remarks to the Author):

I thank the authors for addressing my comments. However, I am still not convinced that IPWP size is a physically sound metric to be focused on. The IPWP size sounds like it is the SST spatial pattern that matters but it is in fact the SST amplitude that matters. Also, please elaborate more on the mechanism by which the IPWP size is linked to the larger eastern Pacific warming, thereby a larger reduction in the zonal SST gradient. That is, I do not understand L157-160, which I suppose is the key in this study. I suggest substituting Fig. 3 to the figure that shows the physical mechanism that connects the present-day IPWP size and the projected reduced SST gradient. Figure 3 is rather redundant and self-evident.

Reviewer #1 (Remarks to the Author):

Deep apologies for the very slow review. Park et al have done a good job responding to the initial review round, and I suggest publication after a few small comments are cleaned up. I would also like to agree with the authors that Reviewer #2's statement that they find the emergent constraint "to be not surprising" actually supports the EC. The most robust ECs have an underlying physical mechanism, which is actually what the reviewer outlines in their review, and the authors discuss at the end of their paper. This gives me confidence in this result.

→ Thank you for the reviewer's constructive and helpful comments. We addressed all issues raised by the reviewer and incorporated these comments in the revised manuscript with "Tracked Changes". Our point-by-point replies are as follows:

1. As far as I can tell, the only place the authors define the CETP is in the supplement. Suggest defining the domain early in the main text.

→ Added as follows: "(CETP), defined as the Niño 4 (5°S–5°N, 160°E–150°W) region,"

2. In Figure 1c a correlation coefficient is given, but it's not stated what this is for. I think it's the correlation between tropical SST and IPWP size, but this should be stated somewhere.

→ Added as follows: "in spite of a strong relationship between both variables (correlation coefficient is 0.93, Fig. 1c)."

3. L162: Suggest the authors expand on what they mean by "accelerate ocean stratification under global warming" and how this relates to the rapid warming trends. This also affects the schematic in Figure 5.

→ Thank you for the reviewer's careful comments. Climate models with a high mixed layer temperature in the eastern tropical Pacific in the present-day tend to simulate a shallow thermocline depth, implying that the upwelling's influence on the surface layer is limited. Therefore, these models simulate stronger ocean warming in the near surface layer under greenhouse-gas induced warming than models with a low mixed layer temperature, resulting in the enhanced ocean stratification in the eastern tropical Pacific. Subsequently, the enhanced ocean stratification in the eastern Pacific is associated with increasing of the dynamical coupling between the ocean and the atmosphere (Cai et al. 2018), resulting in the weakening of the trade wind and the rapid warming trend of upper ocean in the eastern Pacific. The following sentences are added in the revised manuscript.

"Climate models with a higher mixed-layer temperature in the eastern tropical Pacific in the present-day tend to simulate a shallow thermocline depth than those with relatively lower mixed-layer temperatures in the eastern tropical Pacific in the present-day climate (i.e., climate models with a small IPWP size), implying that the upwelling's influence on the surface layer is limited. This feature leads to strong ocean warming in the near surface layer under greenhouse-gas induced warming accelerate ocean stratification under global warming, resulting in the enhanced ocean stratification in the eastern tropical Pacific (Supplementary Fig. 5b). Subsequently, the enhanced ocean stratification in the eastern Pacific is associated with increasing of the dynamical coupling between the ocean and the atmosphere [42] resulting in the weakening of the trade wind and the rapid warming trend of upper ocean in the eastern Pacific (Supplementary Fig. 5c)."

4. L156 and elsewhere: it's conventional to just say "east-west" gradient, rather than "east-minus-west" gradient.

→ Corrected.

5. The most major comment I have is agreeing with Reviewer #2 that the emergent constraint should also work for SSTs, which the authors have now shown. They justify focusing on IPWP size rather than SSTs because the correlation is slightly stronger, but it would be nice if they could provide a better justification. I've been going back and forth myself over which I would emphasize. This emergent constraint should help modelers improve their simulations of the tropical Pacific and its precipitation changes, but both IPWP size and SSTs are emergent properties, and not easily tuned for. Suggest the authors either put the two constraints on a more equal footing, or else do more to justify the focus on size over SSTs.

→ Thank you for the reviewer's helpful suggestion. Indeed, we found that the IPWP size can represent the state of the tropical mean SST CMIP6 climate models (Fig. 1c, correlation coefficient is 0.93). As the reviewer pointed out, the emergent constraint on the future CETP precipitation is slightly better than the tropical mean SST when the IPWP size is used (Fig. 4

and Supplementary Fig. 8). In our understanding, however, the IPWP size is not considered by the emergent constraint in previous literature. In addition, the advantage using the IPWP size comes from the notion that the change of IPWP size is closely associated with the dynamical variables including the Walker circulation intensity, zonal SST gradient and the ocean stratification in the eastern tropical Pacific. Therefore, we are able to provide the physical processes of how the IPWP size can serve as the emergent constraint of the future CETP precipitation changes (Supplementary Fig. 3 and Fig. 5). Responding to the reviewer’s comments, the earlier version has been revised as follows: “The present-day IPWP size does not only represent the tropical mean SST (Fig. 1c), but also the change of IPWP size is closely associated with the dynamical variables including the Walker circulation intensity, zonal SST gradient and the ocean stratification in the eastern tropical Pacific. Therefore, we are able to provide the physical processes of how the IPWP size can serve as the emergent constraint of the future CETP precipitation changes (Supplementary Fig. 3 and Fig. 5).”

Reviewer #2 (Remarks to the Author):

I thank the authors for addressing my comments. However, I am still not convinced that IPWP size is a physically sound metric to be focused on. The IPWP size sounds like it is the SST spatial pattern that matters but it is in fact the SST amplitude that matters. Also, please elaborate more on the mechanism by which the IPWP size is linked to the larger eastern Pacific warming, thereby a larger reduction in the zonal SST gradient. That is, I do not understand L157-160, which I suppose is the key in this study. I suggest substituting Fig. 3 to the figure that shows the physical mechanism that connects the present-day IPWP size and the projected reduced SST gradient. Figure 3 is rather redundant and self-evident.

→ Thank you for the reviewer's constructive and important comments. As the reviewer pointed out, the IPWP size may indicate the SST spatial pattern rather than the SST amplitude in the tropical basin. However, the eastern edge of IPWP is consistent with the western Pacific branch of the Walker circulation in the present and future climate among CMIP6 ESMs, therefore, the change in IPWP size is closely associated with the dynamical variables including the Walker circulation intensity, zonal SST gradient and the ocean stratification in the eastern tropical Pacific. We argued that climate models with a high mixed layer temperature in the eastern tropical Pacific in the present-day tend to simulate a shallow thermocline depth, implying that the upwelling's influence on the surface layer is limited. Therefore, these models simulate stronger ocean warming in the near surface layer under greenhouse-gas induced warming than models with a low mixed layer temperature, resulting in the enhanced ocean stratification in the eastern tropical Pacific. Subsequently, the enhanced ocean stratification in the eastern Pacific is associated with increasing of the dynamical coupling between the ocean and the atmosphere (Cai et al. 2018), resulting in the weakening of the trade wind and the rapid warming trend of upper ocean in the eastern Pacific. Responding to the reviewer's comment, we add the following sentences in the revised manuscript:

"Climate models with a higher mixed-layer temperature in the eastern tropical Pacific in the present-day tend to simulate a shallow thermocline depth than those with relatively lower mixed-layer temperatures in the eastern tropical Pacific in the present-day climate (i.e., climate models with a small IPWP size), implying that the upwelling's influence on the surface layer is limited. This feature leads to strong ocean warming in the near surface layer under greenhouse-gas induced warming accelerate ocean stratification under global warming, resulting in the enhanced ocean stratification in the eastern tropical Pacific (Supplementary Fig. 5b). Subsequently, the enhanced ocean stratification in the eastern Pacific is associated with increasing of the dynamical coupling between the ocean and the atmosphere [42] resulting in the weakening of the trade wind and the rapid warming trend of upper ocean in the eastern Pacific (Supplementary Fig. 5c)."

"The present-day IPWP size does not only represent the tropical mean SST (Fig. 1c), but also the change of IPWP size is closely associated with the dynamical variables including the Walker circulation intensity, zonal SST gradient and the ocean stratification in the eastern tropical Pacific. Therefore, we are able to provide the physical processes of how the IPWP size can serve as the emergent constraint of the future CETP precipitation changes (Supplementary Fig. 3 and Fig. 5)."