nature climate change

LETTERS

| DOI: 10.1038/NCLIMATE1890

Projected increase in tropical cyclones near Hawaii

Hiroyuki Murakami[1,2,3]*, Bin Wang[2], Tim Li[2,4] and Akio Kitoh[1]

Projections of the potential impacts of global warming on regional tropical cyclone activity are challenging owing to multiple sources of uncertainty in model physical schemes and different assumptions for future sea surface temperatures[1]. A key factor in projecting climate change is to derive robust signals of future changes in tropical cyclone activity across different model physical schemes and different future patterns in sea surface temperature. A suite of future warming experiments (2075–2099), using a state-of-the-art high-resolution global climate model[1–3], robustly predicts an increase in tropical cyclone frequency of occurrence around the Hawaiian Islands. A physically based empirical model analysis[3,4] reveals that the substantial increase in the likelihood of tropical cyclone frequency is primarily associated with a northwestward shifting of the tropical cyclone track in the open ocean southeast of the islands. Moreover, significant and robust changes in large-scale environmental conditions strengthen *in situ* tropical cyclone activity in the subtropical central Pacific. These results highlight possible future increases in storm-related socio-economic and ecosystem damage for the Hawaiian Islands.

The effect of global warming on tropical cyclone activity is a major concern for both the public and scientists[5–7]. Although a number of previous studies using state-of-the-art climate models have suggested that the frequency of tropical cyclone genesis would decrease globally and maximum tropical cyclone intensity would increase with global warming in the future[2,8–11], projected future changes in tropical cyclone activity are highly variable at a regional scale[1,8,11–13], suggesting little confidence in the projected future changes in regional tropical cyclone activity[8,14].

Previous studies using atmosphere–ocean coupled models have robustly shown marked weakening of the Pacific zonal asymmetric circulation[15] (that is, weakening of the Walker circulation), accompanying a stronger sea surface temperature (SST) rise in the tropical and subtropical central Pacific relative to other parts of the tropics[16]. Given the stronger surface warming in the tropical central Pacific, numerical studies have projected a corresponding increase in the frequency of tropical cyclone genesis over the basin in a warmer environment[1,17]; however, the effect of the surface warming on tropical cyclone activity in the subtropical region has yet to be addressed in detail.

Observations based on the National Hurricane Center Best Track Database[18] show that the frequency of tropical cyclones reaching the Hawaiian Islands is very low: only eight named storms have impacted the Hawaiian Islands over the period 1979–2010 (Supplementary Fig. S1). Most of the tropical cyclones approaching the Hawaiian Islands originate in the eastern Pacific. Therefore, future changes in tropical cyclone activity or large-scale conditions in the eastern Pacific may be a key factor for projecting future changes in tropical cyclone activity around the Hawaiian Islands.

To investigate possible future changes in tropical cyclone frequency around the Hawaiian Islands, we analyse the results of an ensemble simulation of the future using the state-of-the-art high-resolution Meteorological Research Institute Atmospheric General Circulation Model (see Supplementary Methods for details)[1–3,9,19–21]. The goal of this study is to investigate whether we can derive robust predictions of change in tropical cyclone frequency of occurrence (TCF) around the Hawaiian Islands across different experimental settings.

The targeted projection for the future climate is the last quarter of the twenty-first century (2075–2099) under the Special Report on Emission Scenarios A1B scenario[14]. To evaluate uncertainty in future projections, we conducted 11 ensemble future experiments with different model versions, resolutions, cumulus convection schemes and different assumptions of future spatial distribution of SST as the lower boundary conditions. The experiment design was identical to that reported by ref. 1 (details are available in Supplementary Methods). For the future SST, predicted mean changes and future trends in SST were estimated from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) models[22]; these anomalies were then superposed on the detrended mean observed SST for the period 1979–2003. These future projections were compared with five ensemble present-day simulations in which the observed monthly mean SST is prescribed during 1979–2003. On the basis of ref. 19, model-generated tropical cyclones are detected using several criteria based on maximum low-level vorticity, temperature anomaly and other parameters (Supplementary Methods). Tropical cyclone positions are counted for each 5° × 5° grid cell within an eastern Pacific domain (0°–45° N, 100° W–180°) at 6-hourly intervals. The total count for each grid cell is defined as the TCF.

Figure 1 shows the observed[23] annual mean TCF (Fig. 1a) and the ensemble mean of five present-day simulations (Fig. 1b). The model reproduces the present-day TCF both around the Hawaiian Islands and in the eastern Pacific reasonably well; however, the model tends to slightly overestimate TCF west of 135° W, and underestimate it east of 125° W relative to observations. Figure 1c shows projected TCF in the future, and Fig. 1d reveals an east–west contrast in projected future changes in TCF: reduction in the

---

[1]Meteorological Research Institute, Tsukuba, Ibaraki 305-0052, Japan, [2]Department of Meteorology and International Pacific Research Center, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA, [3]International Pacific Research Center (IPRC), University of Hawaii, 1680 East-West Road, Honolulu, Hawaii 96822, USA, [4]Key Laboratory of Meteorological Disaster, College of Atmospheric Science, Nanjing University of Information Science and Technology, Nanjing 210044, China. *e-mail: hir.murakami@gmail.com.

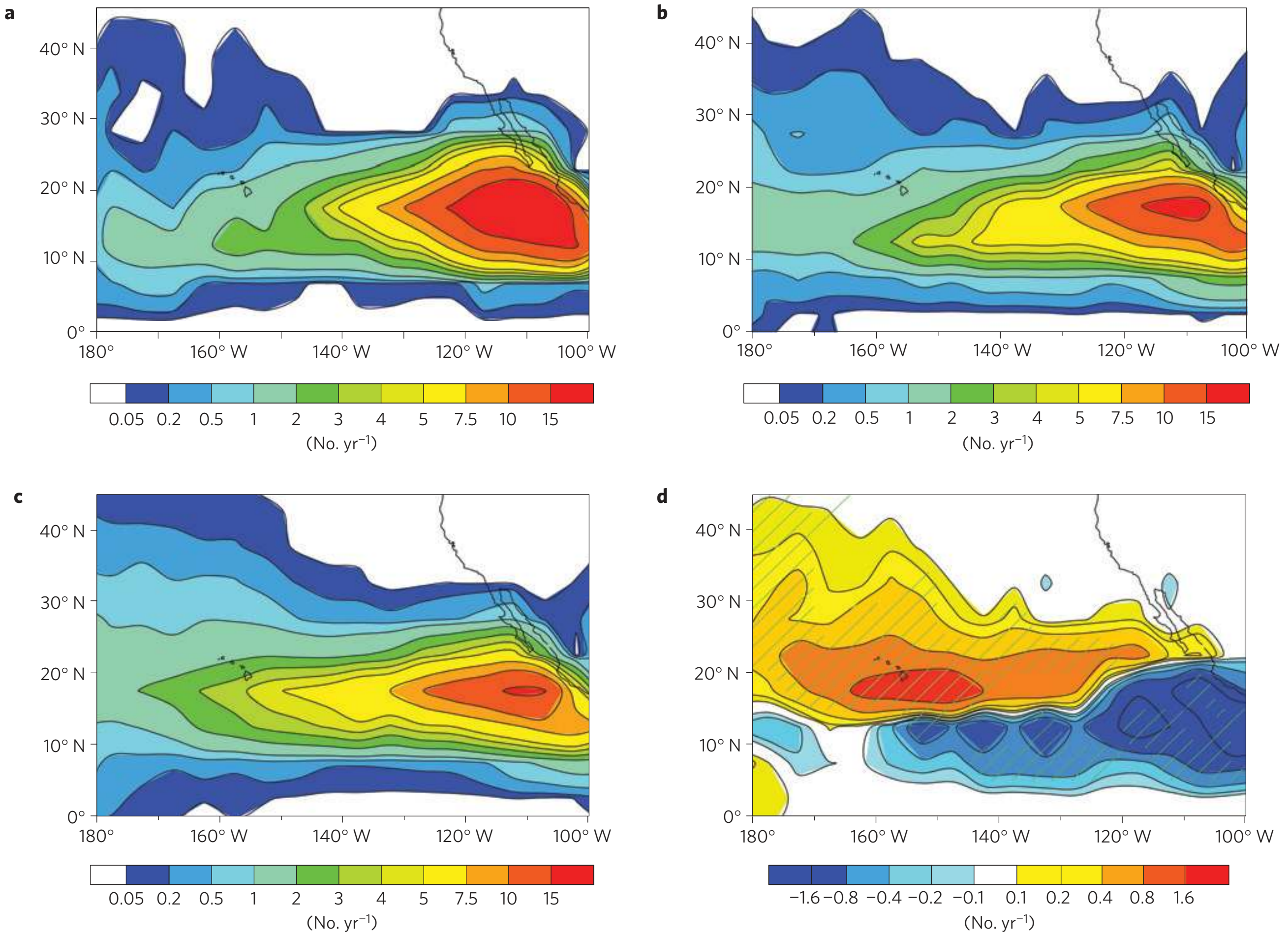

Figure 1 | Annual mean of TCF (number per year, colour scale) counted at every 5° × 5° grid cell. a, Observations (1979–2003). **b**, Ensemble mean of present-day experiments (1979–2003). **c**, Ensemble mean of future experiments (2075–2099). **d**, The projected future change. The green hatching indicate statistical significance at the 99% confidence level or above (by the bootstrap method) and give an indication of the robustness, with 8 of the 11 future experiments predicting mean changes of the same sign.

eastern tropical Pacific and increase in the subtropical central Pacific including the Hawaiian Islands. Note that the changes in TCF are statistically significant (at the 99% level or above by the bootstrap method; see Methods) and consistent among the individual future experiments, indicating that the changes are robust and independent of experimental settings.

To identify the factors responsible for the future changes in TCF, a simple empirical statistical analysis for TCF (refs 3,4) is applied (see Methods). The analysis reveals which of three factors (tropical cyclone genesis, tropical cyclone tracks, and nonlinearity) affects local changes in TCF. We conducted two types of analysis, referred to as total and origin below, to investigate domain-wide and location-specific effects. Local TCF is influenced by both remote (and local) tropical cyclone genesis and propagation properties (equation (1)); therefore, future change in local TCF results from the changes in these properties integrated over the entire eastern Pacific domain. The total analysis (equation (2), Fig. 2a–c) reveals the contribution of each of the three factors integrated over the entire domain to the change in TCF in a given grid cell. Overall, the effect of changes in tropical cyclone track (Fig. 2b) makes the largest contribution around the Hawaiian Islands, indicating that the TCF increases were mainly attributed to projected future changes in tropical cyclone tracks over the entire domain. Although the effect of tropical cyclone genesis change (Fig. 2a) contributes substantially to the local decreases in TCF in the eastern Pacific, this effect is smaller than the tropical cyclone track effect around the Hawaiian Islands. The nonlinear effect (Fig. 2c), which is the combined effect of both tropical cyclone genesis and track changes, is relatively small compared with either the tropical cyclone genesis or track effect on the same grid cell.

The total analysis is unable to identify the location of the changes that are important for the change in local TCF. The origin analysis (equation (3), Fig. 2d–f) identifies the locations of the contribution of each term to the projected increase in TCF in the Hawaiian domain (shown in rectangles). The contribution of the tropical cyclone track effect (Fig. 2e) southeast of the Hawaiian domain (that is, at 10°–20° N, 130°–165° W) is larger than the other effects, indicating that tropical cyclones generated southeast of the Hawaiian domain tend to propagate to the Hawaiian domain regardless of projected changes in frequency of tropical cyclone genesis in the southeast domain. The changes in tropical cyclone-track property may be dynamically linked to changes in large-scale steering flow. Projected future changes in the steering flow (defined here as mass-weighted vertically integrated flow between 850 and 300 hPa) during the summer (July–October) are shown in Fig. 3. The gross spatial pattern of the projected increase in mean easterly steering flow (between 12.5° and 20° N, shaded in blue) matches that of the increase in tropical cyclone track effect as shown in Fig. 2e, indicating that the increases in easterly

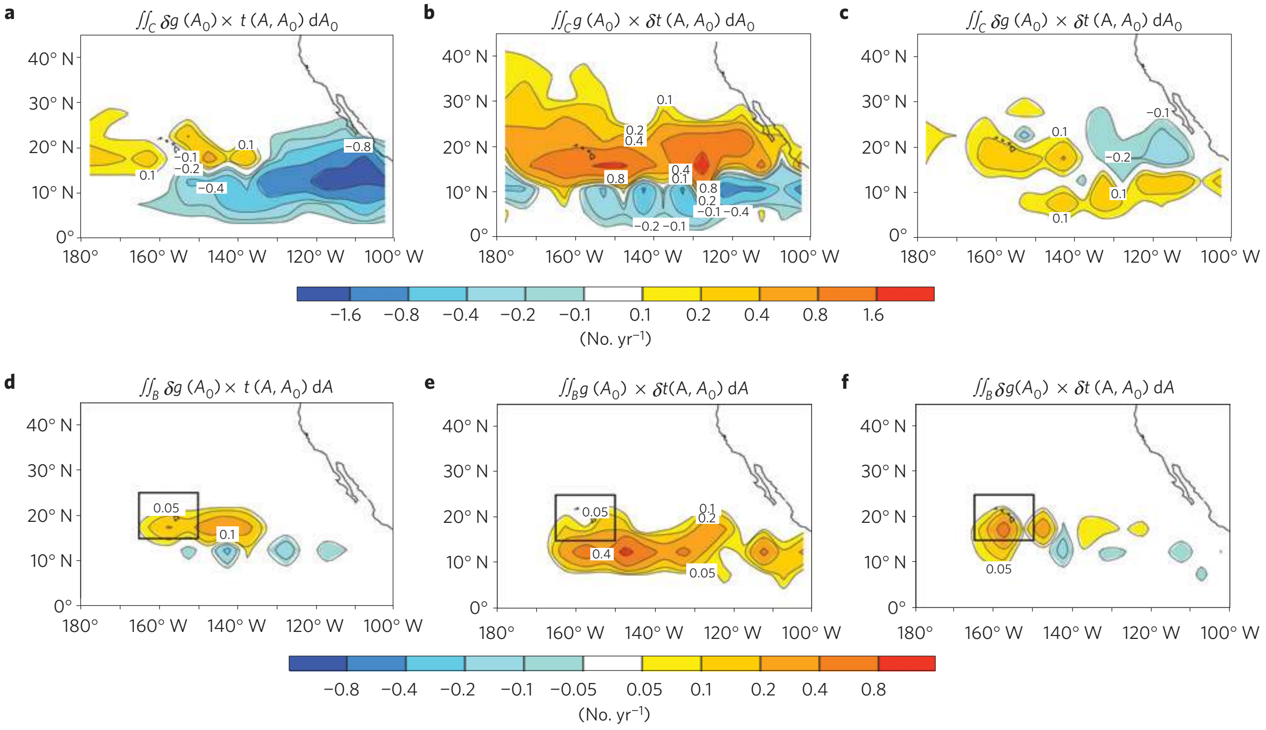

Figure 2 | Ensemble mean contribution of each term to changes in TCF (colour scale) calculated by the empirical statistical analysis. a–c, Factors that influence local TCF are tropical cyclone genesis (**a**), tropical cyclone track (**b**) and the nonlinear effect (**c**), as calculated for the total analysis in equation (2). **d–f**, The same as in **a–c**, but calculated for the origin analysis in equation (3), showing the remote contribution of each term to TCF changes in the Hawaiian domain (15°–25° N, 150°–165° W, shown as the rectangle).

steering flow lead to the westward propagation of tropical cyclones. However, the magnitude of the projected changes is very small (about 0.2–1.0 m s^{-1} as shown by shading) compared with the zonal component of climatological mean steering flow from the present-day simulations (about 2–3 m s^{-1} as indicated by vectors), implying that the steering flow changes alone may be insufficient to fully account for the projected change in tropical cyclone propagation. Another possibility is that the changes in tropical cyclone tracks may be due to the changes in the magnitude of the beta drift. The beta drift refers to the northwestward motion in the Northern Hemisphere of a tropical cyclone caused by the variation in the Coriolis parameter across the cyclone[24,25]. Previous studies have reported that the northward component of beta drift increases with increasing maximum wind speed and cyclone size[26]. The mean maximum wind velocity for the tropical cyclones generated in the southwest of the Hawaiian domain is projected to increase significantly as climate warms (not shown)[2], suggesting a potential increase in the northward component of beta drift in the future.

Although it seems to be of secondary importance, the effect of tropical cyclone genesis change in the open ocean east of the Hawaiian domain (Fig. 2d; 15°–20° N, 135°–150° W) is also positive, indicating that increases in tropical cyclone genesis frequency east of the Hawaiian domain directly contribute to the increase in TCF in this domain. A projected change-in-track effect off the coast of Mexico (Fig. 2e; 10°–20° N, 100°–115° W), in which tropical cyclone genesis frequency decreases as indicated in Fig. 2a, also contributes to the increase in TCF in the Hawaiian domain. This indicates that in a warmer climate, despite the decrease in tropical cyclone genesis frequency off the coast of Mexico, tropical cyclones that do form there are more likely to propagate into the Hawaiian domain. The nonlinear effect (Fig. 2f) is relatively large around the Hawaiian domain. In general, the nonlinear effect becomes larger where the climatological mean TCF is small, and both tropical cyclone genesis and tropical cyclone track properties are substantially changed simultaneously in the future. The large nonlinear effect near Hawaii indicates that tropical cyclone track and genesis changes are both related to the increase in TCF in the Hawaiian domain.

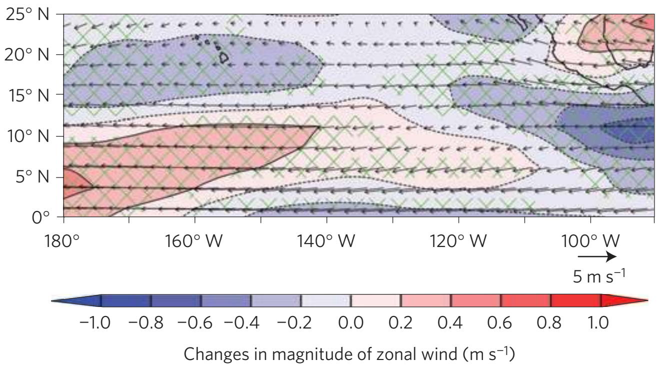

Figure 3 | Simulated mean steering flow during July–October. Superimposed are simulated mean steering flow for the 5 present-day experiments (vectors) and projected future changes in zonal component of steering flow for the 11 future experiments (colour shading; m s^{-1}). The green crossed lines indicate statistical significance and robustness as in Fig. 1.

The above results indicate increased tropical cyclone activity in the subtropical central Pacific in a warmer climate. Figure 4 shows projected future changes in large-scale variables associated with tropical cyclone activity, revealing that in the future the

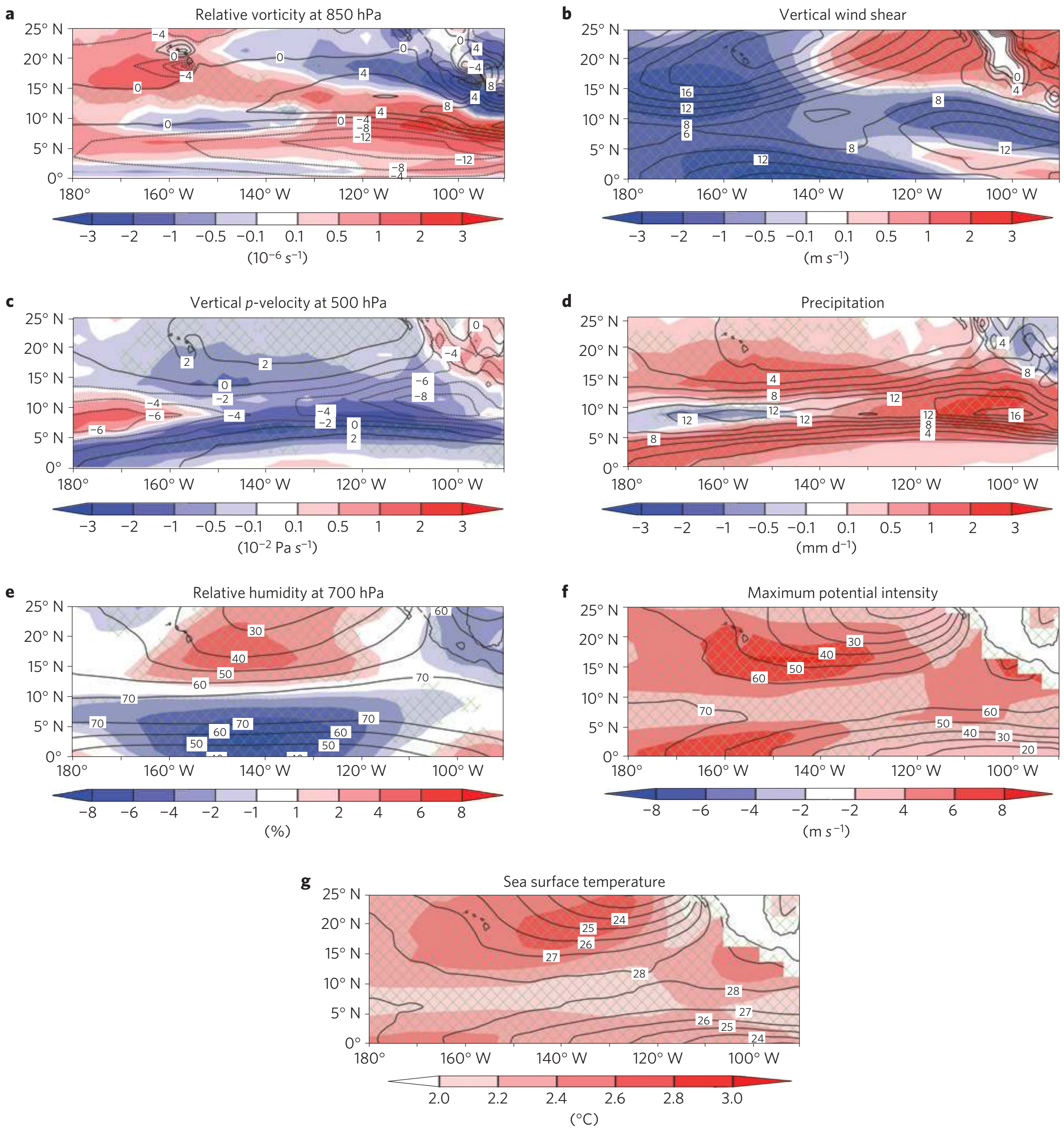

Figure 4 | July–October mean large-scale variables. a–g, Superimposed are projected future changes for the 11 future experiments (colour shading) and simulated present-day mean for the 5 present-day experiments (contours) for relative vorticity at 850 hPa (**a**), vertical wind shear between 200 and 850 hPa (**b**), vertical *p*-velocity at 500 hPa (**c**), precipitation (**d**), relative humidity at 700 hPa (**e**), maximum potential intensity (**f**) and prescribed SST (**g**). The green crossed lines indicate statistical significance and robustness as in Fig. 1.

large-scale variables are robustly projected to be more favourable for tropical cyclone activity in the subtropical central Pacific (12.5°–20° N, 120°–165° W), including increased low-level relative vorticity (Fig. 4a), reduced vertical wind shear (Fig. 4b), increased background ascending motion (Fig. 4c), increased precipitation (Fig. 4d), increased mid-level relative humidity (Fig. 4e), increased maximum potential intensity[27] (Fig. 4f) and increased prescribed SST (Fig. 4g). Previous numerical studies have also suggested that locations of marked SST increase show large increases in tropical cyclone genesis frequency[1–3,12,13,17], which is consistent with the present results.

As mentioned above, the projected large-scale changes seem to be closely related to the weakening of the Walker circulation: weakening of descending motion over the central Pacific and ascending motion over the western Pacific. The future projections used in this study also showed weakening of the Walker circulation[2,21]. However, model biases in the prescribed SSTs may have an effect here. Most of the CMIP3 models have significantly warmer biases in surface temperature in the eastern Pacific in present-day experiments[28], so that the projected weakening of the Walker circulation may be largely affected by the model biases. As our prescribed future changes in SST are derived from the

CMIP3 models, the model biases may be transmitted to the future projections to some degree in this study. To minimize the biases, we conducted an idealized experiment with uniform SST increase of about 1.83 °C globally from the present-day observed SST (the global mean SST increase between 1979–2003 and 2075–2099 based on the CMIP3 models) with other future settings being identical to those of the other future experiments. This idealized experiment also projects increases in TCF around the Hawaiian Islands (Supplementary Fig. S2) as well as similar changes in the large-scale fields (Supplementary Fig. S3), suggesting that the underlying global warming will induce these changes regardless of projected changes in the spatial pattern of SST.

Overall, the increase in TCF around the Hawaiian Islands is robust regardless of experimental design in this study. However, TCF around the Hawaiian Islands is still very low in a warmed climate, as in the present-day climate, so that a quantitative evaluation of the future change may involve significant uncertainties. Further effort is needed to address concerns about possible model dependency of the changes.

Methods

Empirical statistical analysis for TCF. To assess the relative importance of tropical cyclone genesis and tracks in terms of future changes in local TCF, we analysed TCF changes using an empirical statistical analysis[3,4] as follows. The analysis comprises two parts: the total equation (2) and origin equation (3) analyses. Although the two analyses are similar, the implications of their results are slightly different.

The climatological mean of TCF in a grid cell can be written as follows:

$$f_{\mathrm{p}}(A) = \int\int_C g_{\mathrm{p}}(A_0) t_{\mathrm{p}}(A, A_0)\, \mathrm{d}A_0 \qquad (1)$$

where $f(A)$ is the TCF in a specific grid cell A, the subscript p indicates present-day climatological mean, $g(A_0)$ is the frequency of tropical cyclone genesis in a grid cell A_0, $t(A, A_0)$ is the probability that a tropical cyclone generated in the grid cell A_0 travels to the grid cell A, and C is the entire domain of the eastern Pacific over which the integration is performed.

The future change in TCF in a grid cell A is computed as follows and this equation is referred to as the total analysis in this study:

$$\delta f(A) = \int\int_C \delta g(A_0) t_{\mathrm{p}}(A, A_0)\, \mathrm{d}A_0 + \int\int_C g_{\mathrm{p}}(A_0) \delta t(A, A_0)\, \mathrm{d}A_0 + \int\int_C \delta g(A_0) \delta t(A, A_0)\, \mathrm{d}A_0 \qquad (2)$$

where δ is the projected future change (relative to the present-day mean). The projected future change in TCF is decomposed into three factors: future change due to tropical cyclone genesis distribution (first term), tropical cyclone track (second term) and the nonlinear effect (third term). Equation (2) reveals the contribution of each term integrated over the entire domain of the eastern Pacific to the local change in TCF. For example, the contribution from the tropical cyclone genesis (track) term implies local TCF change under the condition that the tropical cyclone track (genesis) is not changed over the entire eastern Pacific in the future. The contribution of each term is calculated and shown in Fig. 2a–c for every grid cell A (5° × 5°).

This total analysis is unable to identify the location of the changes that are important for the local changes in TCF. Here, we want to identify the locations associated with a large contribution to the increase in TCF in a specific region near Hawaii. To identify the origin of changes, we conducted another analysis referred to as the origin analysis in this study. The effect of a remote grid cell A_0 on TCF changes in a specific region B (including multiple grid cells) is described as follows:

$$\delta f(B, A_0) = \int\int_B \delta g(A_0) t(A, A_0)\, \mathrm{d}A + \int\int_B g(A_0) \delta t(A, A_0)\, \mathrm{d}A + \int\int_B \delta g(A_0) \delta t(A, A_0)\, \mathrm{d}A \qquad (3)$$

The first (second) term is the contribution of future changes in tropical cyclone genesis frequency (tropical cyclone track) in the grid cell A_0 to the TCF changes in region B. Likewise, the third term is the contribution of the combined effect of tropical cyclone genesis and track changes to the TCF changes in region B. In Fig. 2d–f, B is set as the Hawaiian region (rectangle), and each term's contribution to the future change in TCF on B for each remote grid cell A_0 (5° × 5°) is shown.

The nonlinear effect of the third term in equations (2) and (3) arises mathematically because TCF is the product of tropical cyclone genesis frequency (g) and the probability function of tropical cyclone translation (t). This term implies a combined effect of tropical cyclone genesis and track, and is normally small enough to be neglected. However, the nonlinear term becomes larger when the magnitudes of projected future changes in both g and t are much larger than their climatological present-day means. In other words, a larger contribution of the nonlinear term to the TCF change is expected where the mean TCF is small in the present-day climate and where tropical cyclone genesis frequency and tracks both change substantially in a future climate.

Statistical significance tests. Statistical significance tests to evaluate the difference between present-day and future mean values were conducted using the bootstrap method. For the TCF changes, we performed 1,000 resamplings of tropical cyclone tracks, in which tropical cyclone tracks were randomly picked from the combined present-day and future data with replacement. The resampled tracks were assigned arbitrarily to the present or future group with the same sample size as the original data. The sampling distribution was based on the future changes from the resampling data; consequently, the P value was computed from the future change of the original data. Likewise, to assess the statistical significance of future changes in large-scale parameters, we performed 1,000 resamplings of 25-yr data with replacement.

Received 28 August 2012; accepted 2 April 2013; published online 5 May 2013

References

1. Murakami, H., Mizuta, R. & Shindo, E. Future changes in tropical cyclone activity projected by multi-physics and multi-SST ensemble experiments using the 60-km-mesh MRI-AGCM. *Clim. Dynam.* **39,** 2569–2584 (2012).
2. Murakami, H. *et al.* Future changes in tropical cyclone activity projected by the new high-resolution MRI-AGCM. *J. Clim.* **25,** 3237–3260 (2012).
3. Murakami, H., Sugi, M. & Kitoh, A. Future changes in tropical cyclone activity in the North Indian Ocean projected by high-resolution MRI-AGCMs. *Clim. Dynam.* **40,** 1949–1968 (2013).
4. Yokoi, S. & Takayabu, Y. N. Attribution of decadal variability in tropical cyclone passage frequency over the Western North Pacific: A new approach emphasizing the genesis location of cyclones. *J. Clim.* **26,** 973–987 (2013).
5. Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436,** 686–688 (2005).
6. Webster, P. J., Holland, G. J., Curry, J. A. & Chang, H-R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309,** 1844–1846 (2005).
7. Landsea, C. W., Harper, B. A., Hoarau, K. & Knaff, J. A. Can we detect trends in extreme tropical cyclones? *Science* **313,** 452–454 (2006).
8. Knutson, T. *et al.* Tropical cyclones and climate change. *Nature Geosci.* **3,** 157–163 (2010).
9. Oouchi, K. *et al.* Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: Frequency and wind intensity analysis. *J. Meteorol. Soc. Jpn* **84,** 259–276 (2006).
10. Bengtsson, L. *et al.* How may tropical cyclones change in a warmer climate? *Tellus* **59A,** 539–561 (2007).
11. Emanuel, K., Sundararajan, R. & Williams, J. Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. *Bull. Am. Meteorol. Soc.* **89,** 347–367 (2008).
12. Zhao, M., Held, I., Lin, S-J. & Vecchi, G. A. Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50 km resolution GCM. *J. Clim.* **22,** 6653–6678 (2009).
13. Zhao, M. & Held, I. M. Tropical cyclone-permitting GCM simulations of hurricane frequency response to sea surface temperature anomalies projected for the late-twenty-first century. *J. Clim.* **25,** 2995–3009 (2012).
14. Solomon, S. *et al.* (eds) *IPCC Climate Change 2007: The Physical Science Basis* (Cambridge Univ. Press, 2007).
15. Vecchi, G. A. & Soden, B. J. Global warming and the weakening of the tropical circulation. *J. Clim.* **20,** 4316–4340 (2007).
16. Xie, S-P. *et al.* Global warming pattern formation: Sea surface temperature and rainfall. *J. Clim.* **23,** 966–986 (2010).
17. Li, T. *et al.* Global warming shifts Pacific tropical cyclone location. *Geophys. Res. Lett.* **37,** L21804 (2010).
18. Landsea, C. W. *et al.* in *Hurricanes and Typhoons: Past, Present and Future* (eds Murname, R. J. & Liu, K-B.) 177–221 (Columbia Univ. Press, 2004).
19. Murakami, H. & Sugi, M. Effect of model resolution on tropical cyclone climate projections. *SOLA* **6,** 73–76 (2010).
20. Murakami, H. & Wang, B. Future change of North Atlantic tropical cyclone tracks: Projection by a 20-km-mesh global atmospheric model. *J. Clim.* **23,** 2699–2721 (2010).

21. Murakami, H., Wang, B. & Kitoh, A. Future change of western North Pacific typhoons: Projections by a 20-km-mesh global atmospheric model. *J. Clim.* **24,** 1154–1169 (2011).
22. Meehl, G. *et al.* The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Am. Meteorol. Soc.* **88,** 1383–1394 (2007).
23. Unisys weather hurricane/tropical data (Unisys); available at http://weather.unisys.com/hurricane/
24. Rossby, C. G. On displacement and intensity changes of atmospheric vortices. *J. Mar. Res.* **7,** 175–196 (1948).
25. Holland, G. J. Tropical cyclone motion: Environmental interaction plus a beta effect. *J. Atmos. Sci.* **40,** 328–342 (1983).
26. Wang, B. & Li, X. The beta drift of three-dimensional vortices: A numerical study. *Mon. Weath. Rev.* **120,** 579–593 (1992).
27. Bister, M. & Emanuel, K. A. Dissipative heating and hurricane intensity. *Meteorol. Atmos. Phys.* **65,** 233–240 (1998).
28. Large, W. G. & Danabasoglu, G. Attribution and impacts of upper-ocean biases in CCSM3. *J. Clim.* **19,** 2325–2346 (2006).

Acknowledgements

This work was conducted under the framework of the 'Projection of the Change in Future Weather Extremes Using Super-High-Resolution Atmospheric Models' supported by the KAKUSHIN and SOUSEI programmes of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. H.M. was supported by the 'Research on Prediction of Climate and Environmental Change to Contribute to Mitigation Plan Decision Against Climate Change' of the MRI of Japan. B.W. acknowledges the support from the Global Research Laboratory (GRL) Program of the Korean Ministry of Education, Science and Technology (MEST, 2011-0021927). Calculations were performed on the Earth Simulator. This contribution is School of Ocean and Earth Science and Technology publication No. 8917 and International Pacific Research Center publication No. 975.

Author contributions

H.M. designed this study, carried out the experiments and analysed the results. B.W. initiated this study and H.M. was the lead writer of the manuscript. Other authors made comments on and revised the initial manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to H.M.

Competing financial interests

The authors declare no competing financial interests.