tested the reconstructed storminess series for inhomogeneities. We found no statistically significant (0.05 level) change point using the RA-20CR-EM series and weak evidence for a change point across RA-20CR-CMs in 1909. Even if all pre-1909 reconstructed storminess indices are revised upward by an amount equal to the maximum difference in means between all ensemble members (pre- and post-1909), W2013–14 remains the stormiest on record (see Supplementary Information). Furthermore, using the long-running England and Wales Precipitation series (for the winters 1872–2014), we find no evidence that correspondence with reconstructed RA-20CR-EM storminess is weaker in the early years of the 20CR dataset (Fig. 2c), thus bolstering confidence in a part of the 20CR record where data quality has been questioned[9].

We conclude that W2013–14 experienced the most severe storminess for at least 143 years when cyclone frequency and intensity are considered together. This finding is supported by independent measures of precipitation, atmospheric circulation and gales (see Supplementary Information on gales). Given the severe impacts of storminess experienced in the Ireland–UK domain during W2013–14, as well as climate model projections showing enhanced cyclone activity for this part of the North Atlantic[15], further research is needed into the key processes driving extreme storminess over the region. ❐

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Additional information

Supplementary information is available in the online version of the paper.

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CORRESPONDENCE:

Ever-wet tropical forests as biodiversity refuges

To the Editor — Species assemblages are exceptionally rich in ever-wet tropical forests[1], here broadly defined as tropical forests that experience high annual rainfall (≥2,000 mm yr^{-1}) and are aseasonal (that is, zero months with ≤60 mm precipitation). Protecting as many of the remaining ever-wet tropical forests as we can stands to yield a double dividend through providing refugia for large numbers of tropical forest species that may be particularly vulnerable to the drier conditions presently occurring[2] and predicted to occur over coming decades[3,4], and helping to mitigate climate change impacts overall[5]. We estimate that ever-wet zones currently cover 30% of the tropical forest biome[6,7], with 50% of this area remaining as intact natural forest[8], of which only 6% is formally protected[9] (Supplementary Information). A standard set of global climate models[3,7] generally agree that tropical ever-wet zones will contract by at least 20% (Supplementary Fig. S1), potentially drying out one-fifth of extant intact ever-wet tropical forest and one-quarter of the protected ever-wet tropical forests by 2050 (Fig. 1 and Supplementary Tables S1–S3).

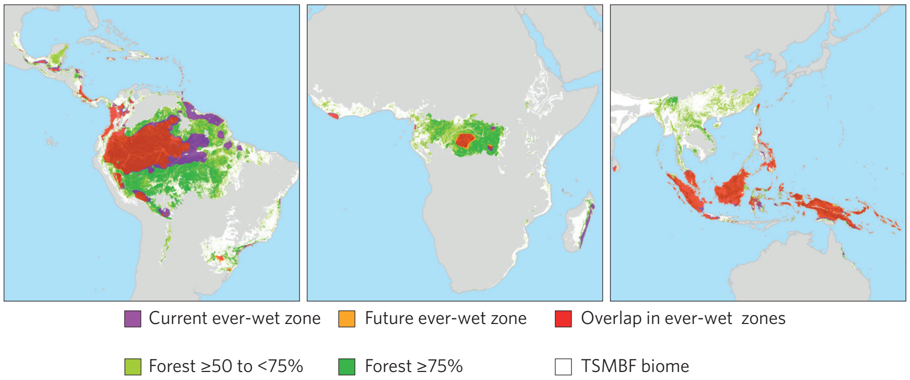

Figure 1 | Ever-wet zones within the tropical and subtropical moist broadleaf forest (TSMBF) biome[6] defined using current climate and future climates[3,7] in 2050 under representative concentration pathway 8.5 (where ≥75% of 17 global climate models agree). Ever-wet zones are underlain with remaining forest data[8] consisting of two classes of tree cover (also see Supplementary Fig. S2).

The footprint of ever-wet zones is projected to largely contract throughout the tropics rather than expand or shift to new areas, attributable in our analysis to increasing seasonal variability in rainfall rather than pronounced decreases in areas that receive high (≥2,000 mm) annual precipitation. Extensive areas of the central Amazon Basin and the Guianas, however, will no longer qualify as ever-wet zones due to both longer dry spells and less annual rainfall (Supplementary Fig. S2). The projected loss of ever-wet zones in these two regions dominate global losses, with a marked trend of contraction westward, resulting in an estimated loss of one-third of the Neotropical ever-wet zone (Supplementary Table S1).

Substantial contraction also occurs in northern Central America, the southwest Amazon Basin, eastern Sulawesi, and eastern Madagascar. The few ever-wet zones in the rest of the Afrotropics remain largely unaltered in extent under future climates, a pattern shared with the extensive ever-wet zones of the archipelagic Indo-Malay and Australasia realms (Supplementary Fig. S2). Overall drying in these three realms is expected to be less pronounced than in the Neotropics[4]. Although climate change models project that certain tropical regions may receive more annual precipitation[3], our analysis suggests that a shift towards increasing dry months may preclude ever-wet zones of any substantial size beyond their current footprint.

Within current ever-wet zones, the most extensive remaining forests[8] occur in the central and western Amazon Basin, the coastal forests of the Guianas, New Guinea, the central Congo Basin, and the highlands of northern Borneo. Nearly one-quarter of the remaining ever-wet forests in the Neotropics are projected to dry out to such an extent that they will no longer qualify as ever-wet (Supplementary Table S2). Some distinctive ever-wet forests, such as those in eastern Madagascar, southern Mexico, southern Sulawesi, and northeast Australia, are projected to lose their ever-wet conditions almost entirely.

The Neotropics, particularly the Amazon Basin and Guianas, at present formally protect[9] the largest area of ever-wet forests, estimated at 8% of the remaining ever-wet forests of the realm (Supplementary Table S3). Protection of forests with ever-wet conditions in this region is projected to decrease by one-third by 2050 due to contraction of ever-wet zones. Sizeable protected areas also occur in western New Guinea and the northern Salonga region of the Congo Basin, but overall, protection of ever-wet forests is limited for the tropical forest biome outside of the Neotropics.

Less likely to be captured in global-scale projections are numerous sites where extant ever-wet forests occur where climate conditions will likely remain decoupled from regional trends and conditions due to organized convection zones, being on windward slopes facing tradewinds, or other orographic precipitation[10,11]. Ever-wet forests whose species assemblages suggest long-term palaeoclimatic stability conferred by physiognomic situations include the Eastern Arc Mountains of coastal East Africa[12] and the Atlantic Forests of Brazil.

Global-scale projections also cannot resolve the increasing day-to-day variability in precipitation that is being documented and attributed to climate change[3,13]. Monthly precipitation of >60 mm may qualify a forest as ever-wet, but if concentrated into a few days rather than evenly distributed throughout the month, the lengthening dry spells may compromise its effectiveness as a refuge for wet-forest specialist species. Even in physiognomic situations that confer wet conditions, diminishing mist and fog precipitation, such as that being documented in tropical montane forests[14], may stress and eliminate many species dependent on ever-wet conditions over time.

While it may get hotter and drier throughout much of the tropics, with complex and novel climates emerging[15] and increasingly variable precipitation patterns, those sites where forests are currently ever-wet and, especially, that subset projected to maintain ever-wet environments in future climates, are likely to offer the best chance for thousands of tropical, wet-forest species to persist in the face of drying conditions. Protecting as many ever-wet tropical forests as we can, as quickly as we can, provides an effective bet-hedging tactic that will contribute well to a global strategy to retain biodiversity in the face of climate change. ❐

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Author contributions

E.C.U and D.O. conceived and designed the study and wrote the Correspondence. A.D.H. and E.C.U. analysed the data and J.F.Q. contributed materials and conceptual advice.

Additional information

Supplementary Information is available in the online version of the paper and also at http://tropicalforests.ice.ucdavis.edu. Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to E.C.U.

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Questions of bias in climate models

To the Editor — Shindell[1] has contributed to the debate on estimating the equilibrium climate sensitivity (ECS) by noting that the transient response to external forcing depends on the spatial distribution of the forcing; forcings over land lead to more rapid warming than similar forcings over the oceans. He suggests that the omission of spatial forcing details will lead simple models to give biased results for the transient climate response. Shindell chooses to reference only two previous studies[2,3] as examples of analyses affected by such a bias, stating for the latter[3] that "such biases lead to underestimates of aerosol impacts in [the] calculations". Shindell's criticism of these particular results is incorrect. Both of these papers use the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC)[4], which has always[5] accounted for the effect highlighted by Shindell.