COMMENTARY

Global warming-accelerated drying in the tropics

Rong Fu[1]

Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX 78712

Many regions of the subtropical and tropical continents such as southern Amazonia, Australia, and the southwestern and central United States, have repeatedly experienced extreme droughts over the past few decades, and accompanied by an increasing wetness over the equatorial regions. These phenomena seems to be consistent with an apparent intensified and poleward expansion of the tropical meridional circulation (1, 2), i.e., the Hadley Circulation (HC) observed in recent decades. However, most global climate models, including those that participated in the Intergovernmental Panel for Climate Change (IPCC) Fourth and Fifth Assessments (CMIP3 and CMIP5), have suggested that the HC will become weaker with a future warmer climate. Thus, it has not been known whether the intensified droughts and wet anomalies in the tropics have been a result of recurring natural climate variability on a decadal time scale or a trend forced by increasing atmospheric CO_2. Lau and Kim (3) find, in climate models for the first time, an intensification of the HC induced by CO_2 warming.

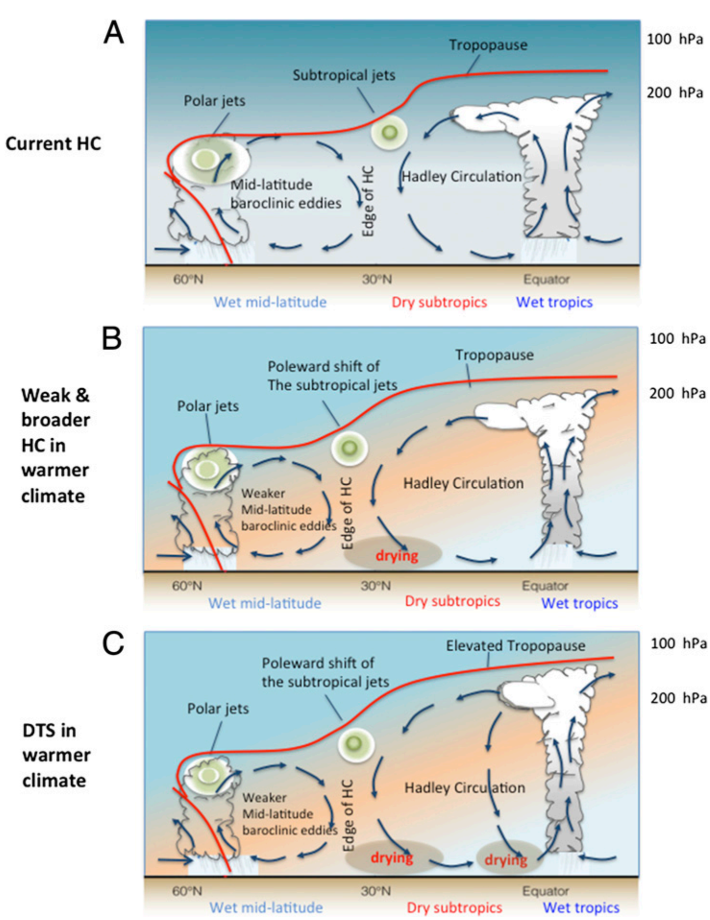

Fig. 1. Illustration of the HC and its relationship to the midlatitude baroclinic eddies: (*A*) climatology in current climate; (*B*) the weaker and broader HC projected by many CMIP3 and CMIP5 models; and (*C*) the stronger and broader HC due to DTS in Lau and Kim. The light orange color illustrates the warming due to greenhouse effect that increases the static stability of the atmosphere and weakens the equator-to-pole surface temperature gradient.

As the globally annually averaged latitudinal circulation over the tropics and subtropics, the HC features rising air centered a few degrees north of the equator and almost 25° in width and a large seasonal reversing component associated with monsoons (4). The subsidence of the air required by mass balance, occurs in the subtropics (15°–40° N/S), converging in the lower troposphere toward the rising branch of the HC and diverging away from it in the upper troposphere (Fig. 1*A*). The HC is named after George Hadley, an English lawyer and amateur meteorologist, who identified it as the atmospheric mechanism by which the Trade Winds are sustained, a key factor in the early 18th century in ensuring that European sailing vessels reached North American shores. The HC influences the latitudinal distributions of rainfall, clouds, and relative humidity over half of the earth's surface, and consequently, it controls the geographic distribution of the world's dry and wet regions. It can expand or contract in a warmer or colder global climate, leading to major floods and droughts that might have triggered the collapse of ancient civilizations in the past (5). Over the last decade or two, the HC has been expanding poleward at a rate faster than that predicted by the global climate models, contributing to increased droughts over many subtropical regions. Thus, understanding the mechanisms that control the HC's variability is not only fundamental, to climate change research, but also central in determining abrupt regional rainfall regime change in the tropics–subtropics and subtropics–midlatitude margins.

Variations of the intensity and width of the HC depend on a balance of different processes. The poleward boundary of the HC is determined by a balance between the extratropical baroclinic eddies (i.e., synoptic frontal systems) and the subsidence in the subtropics induced by radiative cooling. An earlier theoretical framework suggested that the HC would become stronger due to the increase of rainfall in its rising branch in a warmer climate (6). The width of the HC, as scaled by its height and strength (6), has

Author contributions: R.F. wrote the paper.

The author declares no conflict of interest.

See companion article on page 3630.

[1]Email: rongfu@jsg.utexas.edu.

thus been expected to increase. However, this "tropical-driven" theory could not explain the weaker HC projected for a future warmer climate by global climate models that participated in the CMIP3 and CMIP5 (Fig. 1*B*). The observed HC change, especially of its intensity, also appears to depend on the variables and datasets used to describe the changes (2, 7). In some models the intensification of the HC due to the increasing rainfall predicted by the earlier theory (6) was compensated by an increased stability, hence stronger dynamic cooling in the tropospheric column and stronger radiative cooling in the upper troposphere, leading to an overall weaker HC (8). In the extratropics, the increased thermodynamic stability and weaker latitudinal temperature gradient were expected to reduce extratropical baroclinic instability and eddies, leading to a poleward movement of the HC boundary (9–11). This "extratropical-driven" theory for the HC change has been further supported by the strong impact of the Antarctic ozone hole on the poleward expansion of the southern edge of the HC (12) and by a connection between northern hemispheric aerosols, especially black carbon, and the northward expansion of the HC northern edge (13).

Some studies have attributed the weakening of the HC in the models to their overestimation of the increase of atmospheric stability in the tropics with warming climate due to their tendency to adjust atmosphere temperature profiles to the moist adiabatic lapse rate (14), whereas most past literature has accepted the weakening of HC as a likely outcome in a future warmer climate (15, 16). Lau and Kim's study (3), with an ensemble of CMIP5 models, is the first to report an intensified HC in such climate models' projections forced by increasing atmospheric CO_2, i.e., a change supported by the earlier tropical-driven theory (6). These changes are primarily due to the equatorward contraction of the rising branch of the HC, referred to by Lau and Kim as the deep tropical squeeze (DTS; Fig. 1*C*). The broadening of the stronger HC appears to be positively related to the intensified and elevated tropopause, also consistent with the earlier tropical-driven theory (6), although an extratropical influence on the HC width has not been ruled out. The DTS elevates the outflow of the rising branch of the HC, which is consequently dehydrated by colder temperatures and thus becomes even drier when it subsides to the subtropical surface. Thus, DTS would cause stronger drying than that anticipated for a weaker HC in both the tropical–subtropical and the subtropical–extratropical transition zones. If this mechanism were to occur, the midtroposphere and surface drying in the subtropics would be more sensitive to the CO_2 forcing than previously anticipated, thus possibly detectable sooner than any changes of HC width, the latter previously taken as an indicator of the HC change in a warming climate.

Interestingly, the CMIP5 RCP8.5 climate projections for the period of 2081–2100 by largely the same group of climate models and under similar atmospheric CO_2 concentration as those in Lau and Kim did not report the HC intensification (16). What could have caused Lau and Kim's DTS in their analysis of the CMIP5 models forced by 1% increase of annual CO_2 experiments that was not seen in the other analyses of the CMIP5 RCP8.5 and CMIP3 climate projections? Until this question is better understood, the work of Lau and Kim may be somewhat controversial. This difference could be due to both different ways used to describe the HC intensity and the different climate forcings between these projections. Lau and Kim (3) focus on the vertical velocity in the upper troposphere (250 hPa, i.e., about 11 km above sea level) or mass outflow in the tropopause layer (200–150 hPa, i.e., about 12.5–14 km above sea level), and show that they are most sensitive to the HC intensity associated with DTS. By contrast, the conventional measure of the HC strength has been based on mass flow below or at 200 hPa and so will have missed the extension of the HC to above 200 hPa. In fact, the analysis of Lau and Kim (figure 5*C*) shows a rapid increase of upward motion at 200 hPa and mass flux between 200 and 150 hPa with increased CO_2, but a small decrease of mass flux below 250 hPa. Thus, the apparent discrepancy between Lau and Kim's study and others may be due to their use of a different measure than that used previously. On the other hand, the CMIP5 RCP8.5 projections include aerosols and land use in addition to increases of greenhouse gases. These forcings are absent in the 1% annual increase of CO_2 of the CMIP5 experiments that were analyzed by Lau and Kim. Could these different forcings, especially that of the aerosols, contribute to the weaker HC in the CMIP5 RCP8.5 climate projections?

The changes of HC intensity and width are sensitive to radiative cooling in the upper troposphere and stratosphere, sea surface temperature distributions, and land surface temperature changes, especially in the northern hemisphere (8, 12, 15). Different cloud and convective parameterizations appear to contribute to the intermodel discrepancies in modeled HC intensity and frequency (14). Lau and Kim's work casts doubt as to whether the future weaker HC previously inferred from CMIP3 and most of the CMIP5 climate change scenarios will occur for increasing anthropogenic forcing: how sensitive are such projections to the changes of clouds/rainfall, sea surface and land surface temperature, and aerosols in the climate models simulations? Why have climate models failed to reproduce the apparently observed intensification and broadening of the HC (14)? Could the DTS mechanism work with changes of the midlatitude baroclinic eddies to further enhance the poleward expansion of the HC? Could the observed intensification of the droughts over tropic–subtropical margins be a new norm due to the DTS mechanism in a higher CO_2 and warmer climate? The answers to these questions are not only important for clarifying the fundamental processes that drive the HC changes with global climate change, but also to provide a theoretical framework for determining the trends of climate change over the tropical–subtropical margins, e.g., the drying trends over southern Amazonia (17) and Congo (18), which are the regions that dominate carbon–climate feedbacks and future global atmospheric CO_2 concentration (19).

1 Nguyen H, Evans A, Lucas C, Smith I, Timbal B (2013) The Hadley circulation in reanalyses: Climatology, variability, and change. *J Clim* 26(10):3357–3376.

2 Wilcox LJ, Hoskins BJ, Shine KP (2012) A global blended tropopause based on ERA data. Part II: Trends and tropical broadening. *Q J Roy Meteor Soc* 138(664):576–584.

3 Lau WKM, Kim K-M (2015) Robust Hadley Circulation changes and increasing global dryness due to CO_2 warming from CMIP5 model projections. *Proc Natl Acad Sci USA* 112:3630–3635.

4 Dima IM, Wallace JM (2003) On the seasonality of the Hadley cell. *J Atmos Sci* 60(12):1522–1527.

5 Hodell DA, Curtis JH, Brenner M (1995) Possible role of climate in the collapse of classic Maya civilization. *Nature* 375(6530):391–394.

6 Held IM, Hou AY (1980) Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. *J Atmos Sci* 37(3):515–533.

7 Davis SM, Rosenlof KH (2012) A multidiagnostic intercomparison of tropical-width time series using reanalyses and satellite observations. *J Climate* 25(4):1061–1078.

8 Knutson TR, Manabe S (1995) Time-mean response over the tropical Pacific to increased CO2 in a coupled ocean-atmosphere model. *J Clim* 8(9):2181–2199.

9 Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. *J Clim* 19(21):5686–5699.

10 Lu J, Vecchi GA, Reichler T (2007) Expansion of the Hadley cell under global warming. *Geophys Res Lett* 34(6):L06805.

11 Walker CC, Schneider T (2006) Eddy influences on Hadley circulations: Simulations with an idealized GCM. *J Atmos Sci* 63(12):3333–3350.

12 Kang SM, Polvani LM, Fyfe JC, Sigmond M (2011) Impact of polar ozone depletion on subtropical precipitation. *Science* 332(6032):951–954.

13 Allen RJ, Sherwood SC, Norris JR, Zender CS (2012) Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. *Nature* 485(7398):350–354.

14 Mitas CM, Clement A (2006) Recent behavior of the Hadley cell and tropical thermodynamics in climate models and reanalyses. *Geophys Res Lett* 33(1):L01810.

15 Ma J, Xie SP, Kosaka Y (2012) Mechanisms for tropical tropospheric circulation change in response to global warming. *J Climate* 25(8):2979–2994.

16 Seo KH, Frierson DMW, Son JH (2014) A mechanism for future changes in Hadley circulation strength in CMIP5 climate change simulations. *Geophys Res Lett* 41(14):5251–5258.

17 Fu R, et al. (2013) Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *Proc Natl Acad Sci USA* 110(45):18110–18115.

18 Zhou L, et al. (2014) Widespread decline of Congo rainforest greenness in the past decade. *Nature* 509(7498):86–90.

19 Friedlingstein P, et al. (2006) Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *J Clim* 19(14):3337–3353.