Global warming-accelerated drying in the tropics

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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 CO2. Lau and Kim (3) find, in climate models for the first time, an intensification of the HC induced by CO2 warming.

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. 1A). 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 an intensification of the HC induced by CO2 warming.

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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.
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. 1B). 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 tropospheric (DTS; Fig. 1C). 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 subsurface tropical. 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 sub tropics would be more sensitive to the CO$_2$ forcing than previously anticipated.