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On the dynamics of the Hadley circulation and subtropical drying

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Abstract Changes in subtropical precipitation and the Hadley circulation (HC) are inextricably linked. The original Halley–Hadley model cannot explain certain aspects of the Earth's meridional circulation in the tropics and is of limited use in understanding regional changes in precipitation. Here, we expand on previous work on the regional and seasonal aspects of the HC, in particular how land–sea temperature contrasts contribute to the strength and width of the HC. We show that the Earth's HC is well described by three regionally distinct cells along the eastern edges of the major ocean basins with opposite circulations elsewhere. Moreover, comparable summertime hemisphere cells emerge in each region. While it has been recognized that continents modify the meridional pressure gradient, we demonstrate that a substantial part of the Earth's HC is driven by zonal pressure gradients (ZPGs) that only exist due to continental heating and air–sea interaction. Projected changes in land–sea temperature contrasts in a warming climate due to the relatively low thermal capacity of land will also affect ZPGs and thus HC strength and width, with implications for extremes in hydroclimate and freshwater resources across the increasingly vulnerable subtropics.

Keywords Hadley circulation · Precipitation · Hydrological cycle · Climate change

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1 Introduction

The Hadley circulation represents the Earth's major atmospheric overturning and is responsible for most of the heat exchange between the tropics and extratropics. The dynamics of the Hadley circulation have engaged generations of atmospheric scientists, and questions as to the mechanisms governing its mean state, variability, and trends remain (Webster 2005). Our theoretical understanding of the atmosphere's mean meridional overturning circulation began in the seventeenth and eighteenth centuries with Edmond Halley (Halley 1686) and George Hadley (Hadley 1735), who described two equator–to–pole thermally driven cells symmetric on either side of the equator: rising motion caused by thermal heating in the tropics results in poleward flow aloft, subsidence in the subtropics, and equatorward flow at the surface (see Fig. 6a). The term 'Hadley cell' traditionally refers to the zonal mean, thermally driven meridional overturning circulation (AMS). Throughout this paper, we use the term Hadley circulation (HC) to refer to the observed meridional overturning in the tropical and subtropical atmosphere without a priori assumptions of its structure, symmetry, or mechanism.

The original Halley–Hadley model, however, cannot explain certain aspects of the Earth's meridional circulation in the tropics. Lorenz (1967) argued that balancing observed angular momentum and poleward heat exchanges requires stronger overturning than predicted by Hadley's theory alone. As summarized by Webster (2005), a series of modifications to the Halley–Hadley model have been suggested over time to explain HC characteristics, such as the latitudinal constraint to the tropics and subtropics, rather than extending to the poles; the asymmetry between the structure of the HC in the summer and winter hemispheres; and the asymmetry of HC strength between solstitial and equinoctial seasons. These modifications address processes neglected in the Hadley–Halley model, including asymmetric heating (Dunkerton 1989; Hou and Lindzen 1992; Numaguti 1995), eddies and baroclinic instabilities (Kim and Lee 2001; Schneider 1987), radiative–convective processes (Raymond 2000; Satoh 1994), presence of continents (Cook 2003), and ocean heat transport (Clement 2006).

As summarized by Stachnik and Schumacher (2011), dynamic theories explaining the HC width and strength focus either on (1) 'interior' diabatic constraints based on the conservation of upper–tropospheric angular momentum (e.g., Held and Hou (1980)) or (2) 'exterior' constraints, such as subtropical static stability (Frierson et al. 2007; Lu et al. 2007) and midlatitude baroclinic eddies (e.g., Ceppi and Hartmann (2013) and references therein). It is possible that both of these types of constraints explain particular aspects of HC characteristics.

While to first order, the atmosphere is forced by the ocean surface, Held and Hou (1980) noted that the resultant meridional circulation with two equal cells symmetric about the equator, the so–called equinoctial pattern, was weaker than observed, echoing Lorenz (1967). Lindzen and Hou (1988) could attribute this weaker circulation to heating being concentrated symmetrically about the equator: once heating was moved off the equator, the separation between the two cells, the summer and the winter cell, becomes asymmetric, with the summer cell diminishing, while the winter cell strengthens considerably (Lindzen and Hou 1988). This is more in line with the observed meridional circulation, in which this solstitial pattern of a dominant cell with ascent in the summer hemisphere and subsidence on the other side of the equator takes precedence (Lindzen and Hou 1988; Oort and Rasmussen 1970). Furthermore, the strength of the mean meridional circulation increases dramatically in the presence of off–equatorial heating (Lindzen and Hou 1988; Plumb and Hou 1992). More recently, using idealized climate model experiments, Clement (2006) emphasized the role of ocean heat transport in influencing the structure and intensity of the seasonal HC characteristics by generating sea surface temperature (SST) maxima off the equator. She highlighted the importance of both oceanic and atmospheric processes, as well as their interactions, in determining the overall structure of the HC, its mean state and seasonal cycle. Not only is the mean SST structure important; on interannual timescales, variations in the meridional SST structure associated with different types of El Niño events have been shown to modulate HC characteristics on these timescales (Feng and Li 2013).

In contrast to Lindzen and Hou (1988), Dima and Wallace (2003), who decompose the seasonality of the HC in reanalysis data into the seasonally invariant pair of cells (i.e. equinoctial pattern) and the seasonally reversing solstitial pattern, associate the latter with the monsoons, rather than SST structure. As such, they point to the close temporal correspondence between the solstitial cells and the monsoon peaks, which both occur 6 weeks after the solstices, as well as spatial correspondence: using 200–hPa meridional wind as proxy for the longitudinal contribution to the solstitial cells, Dima and Wallace (2003) highlight that the regions with continental land masses and strong monsoon circulation contribute disproportionately to the solstitial cells, compared to the oceanic regions far from land. Cook (2003) also focused on the role of continents for modulating the seasonality of the HC and found that the presence of continents strengthens the winter cell due to increases in surface friction over land enhancing angular momentum flux. The summer cells are weakened by the monsoon circulation in the northern summer and convergence zones in the Southern Hemisphere, which weaken the subtropical highs, as mass is shifted out of the subtropics (Cook 2003). Related to this, Xie and Saito (2001) showed in model experiments that continental geometry in the east of an ocean basin is responsible for determining the meridional structure of the oceanic Intertropical Convergence Zone (ITCZ) in the west, based on linear wave dynamics, which could have implications for the HC.

Investigations of trends in the strength and extent of the HC over recent decades have yielded mixed results (Collins et al. 2013). Using a range of reanalysis products for the period 1979–2009, Nguyen et al. (2013) reported a consistent expansion of the HC at a rate of 0.55°/decade in both hemispheres, especially for summer and autumn. Trends in intensification, most pronounced in winter and spring, were less consistent amongst data sets (Nguyen et al. 2013), confirming earlier work by Mitas and Clement (2005) and Stachnik and Schumacher (2011). In an ensemble of eight different reanalyses, Stachnik and Schumacher (2011) reported an intensification of the northern cell and a widening of the HC by 1.1° latitude per decade over the past 30 years. In contrast, the expansion—while still occurring—was less pronounced when considering a longer time period since the 1950s (Stachnik and Schumacher 2011). Using the Twentieth Century reanalysis data set, Liu et al. (2012) found a widening HC only for recent decades, while on centennial timescales a tendency was seen towards an increasingly more intense and narrow state, suggesting substantial natural variability in HC strength and width.

The future behavior of the HC bears obvious societal importance as the descending branch of the HC is associated with the world's desert regions in the subtropics, and links have been made to regional precipitation changes (Cai et al. 2012; Previdi and Liepert 2007) and extreme events (Black et al. 2004; Trenberth et al. 2007). A weakening of the overturning circulation in the twenty-first century has been projected due to reduced low–level mass flux in the ascending regions in the tropics due to changes in the hydrological cycle (Held and Soden 2006; Vecchi and Soden 2007). Conversely, uncertainty in future changes in the hydrological cycle have been largely attributed to uncertainty in the trends of the meridional circulation (Kang et al. 2013). Projections from state–of–the–art climate models indicate a robust poleward expansion of the HC (Kang and Lu 2012; Lu et al. 2007, 2009; Meehl et al. 2007; Previdi and Liepert 2007; Tanaka et al. 2004), and associated subtropical dry zones (Scheff and Frierson 2012; Seager et al. 2010). In a 40–member ensemble of the National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3), Kang et al. (2013) further documented robust weakening of the HC in the Northern Hemisphere, mostly in winter, as well as a widening of the HC in both hemispheres in winter, and an increase in tropical tropopause height in both hemispheres and seasons. In projections for the twenty-first century, using Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models, Lu et al. (2007) found a consistent poleward expansion and weakening of the HC, as well as an expansion of the subtropical dry zone (Previdi and Liepert 2007). Using a hierarchy of models, this expansion has been attributed to increased global mean temperature and subtropical static stability suppressing the development of baroclinic instabilities necessary to break down the thermally–driven tropical cell, whereas only a small widening of the HC was seen for an increase in the meridional temperature gradient (Frierson et al. 2007; Lu et al. 2007). HC trends in a warming world have also been associated with changes in the eddy–driven westerly jet in the mid–latitudes (Ceppi and Hartmann 2013). These studies highlight how both tropical and extratropical features determine HC characteristics.

2 Rationale

The descending branch of the HC is associated with the world's desert regions in the subtropics. The strength and latitudinal extent of the HC are thus intricately linked to the hydroclimate of subtropical regions (e.g., Seidel et al. 2008), including its variability and long–term trends, past and future. In line with an expected wet–get–wetter and dry–get–drier type of response in the hydrological cycle in a warmer world (Collins et al. 2013 and references therein), precipitation in the subtropical regions is expected to decrease in the twenty-first century. This is due to thermodynamic changes associated with a rise in water vapor content in the lower troposphere at higher temperatures, leading to increased moisture convergence in the convergence zones and increased moisture divergence in the subtropical descending regions. These thermodynamic changes are expected to be particularly prevalent over the ocean (Collins et al. 2013). However, dynamic responses due to changing atmospheric circulation also play a large role on regional scales (Chou et al. 2009; Muller and O'Gorman 2010; Seager et al. 2010), and a weakening tropical circulation (Held and Soden 2006; Vecchi and Soden 2007) can oppose thermodynamically–driven changes. Ocean salinity observations, measuring the difference between precipitation and evaporation (P–E), for the second half of the twentieth century revealed an amplification of the water cycle (Durack and Wijffels 2010; Durack et al. 2012), consistent with increasing drying in subtropical latitudes, more pronounced over ocean than land (Liu and Allan 2013). Similarly, changes in the intensity of the subtropical high pressure zones are enhanced over the oceans, especially during summer for the Northern Hemisphere, as reported by Li et al. (2012). Using reanalyses, Coupled Model Intercomparison Project, phase 3 (CMIP3) climate model simulation and idealized general circulation models (GCMs), Li et al. (2012) show increasing intensity of the subtropical highs over the oceans in the twenty-first century, driven by an enhanced land–sea temperature contrast in a warmer world, with implications for circulation and hydroclimate in the subtropics.

We first illustrate the link between HC changes and precipitation trends to underscore the need to move beyond the zonal mean to fully understand the HC dynamics. To do this, we use monthly mean output for precipitation, vertical velocity, meridional velocity, and meridional wind stress from an ensemble of six CCSM4 simulations (Gent et al. 2011), provided as part of CMIP5. We use ensemble mean changes in response to 8.5 W m^{-2} radiative forcing (i.e., following the representative concentration pathway (RCP) 8.5 (Moss et al. 2010; Riahi et al. 2011)) in climatic fields in the last decade of the twenty-first century, relative to the first. With the exception of vertical velocity, all variables shown in Fig. 1 represent an ensemble average of six members.

Figure 1a depicts the climatological austral wintertime HC in terms of mean meridional overturning streamfunction (ψ) along with its projected change. While the descending branch of the cell expands poleward (red shading along the outermost mean contours), it also spreads inward (blue shading along the innermost mean contours). Since vertical velocity (ω) is proportional to the meridional gradient of streamfunction ($\partial\psi/\partial y$), the broadening of the descending branch implies weaker $\partial\psi/\partial y$ and thus dictates weaker descent by continuity (Fig. 1b). North of $\sim$15°S, the changes in vertical velocity ($\Delta\omega$) and precipitation (ΔP):

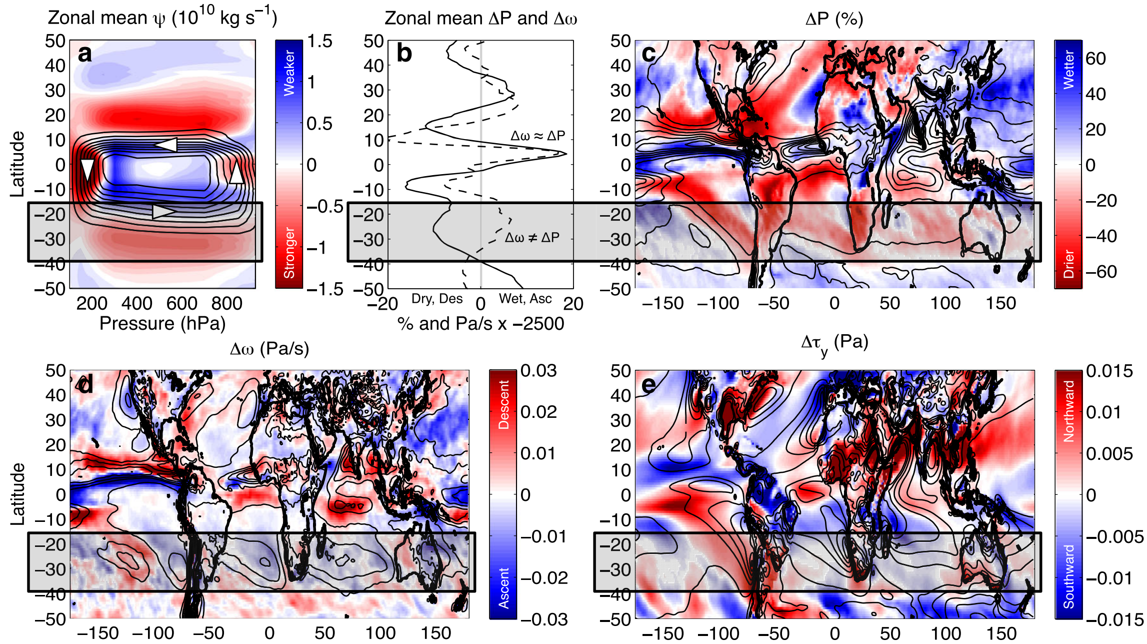

Fig. 1 Projected changes in circulation and precipitation. **a** Zonal mean meridional overturning streamfunction (*contours*) and its change (*colors*). **b** Zonal mean changes in precipitation (*solid line*) and vertical motion (ω [dP/dt]; *dashed line*, scaled by -2.5×10^3 to facilitate comparison). **c** Mean precipitation (*contours*) and its change (*colors*). **d** Mean vertical motion (ω [dP/dt]; contours) and its change (*colors*). **e** Mean meridional surface wind stress (*contours*) and its change (*colors*). All fields are shown for the JJA season. The model and experiment are NCAR CCSM4 and RCP8.5, respectively. All results for mean and change are the ensemble mean of six runs (with the exception of **d**). The first and last decades of the RCP8.5 experiment are compared (2006–2015 vs. 2091–2100)

i.e., where ω is trending toward ascent (descent), precipitation trends toward wetter (drier) conditions. However, in the latitude band surrounding the poleward limit of the descending branch of the HC (15–40°S), substantial drying ensues despite a weakening of the large–scale descent (Fig. 1b). The drying in this latitude band is far from zonally uniform; much of the drying extends in a northwestward band from 35°S at the eastern coastline of the ocean basins towards the equator and includes the oceanic dry zones typically characterized by large–scale descent (Fig. 1e), despite ω trends that would support the opposite (Fig. 1d). Alternatively, changes in midlatitude transient flow may contribute to the aforementioned drying, which is unlikely to be resolved in monthly circulation fields (Seager and Henderson 2013).

The HC is most commonly depicted in terms of ψ, which is simply the vertical integral of zonal mean meridional velocity (v). Given the robust spatial structure to the predicted changes in precipitation, it is illuminating to examine the spatial structure of meridional flow and its predicted change (Fig. 1e). Consistent with the pattern of drying across the subtropics, the equatorward surface flow associated with the HC is likewise predicted to translate poleward, particularly off the western coasts of the continents within this latitude band (South America, southern Africa, and Australia). The poleward expansion of the descending branch of the HC previously noted from a ψ perspective (Fig. 1a and by other investigators) indeed appears to be manifest regionally as a poleward translation of the equatorward surface flow along the major subtropical continental coastlines. The essence of the HC thus lies in the global distribution of v and the dynamics that govern it. We therefore focus here on the nature of *horizontal* motions involved in the HC. The predicted future drying in the subtropics may be highly sensitive to the poleward extension of the HC, which necessitates a deeper understanding of the dynamics governing the HC, especially near its poleward limit and including the regional complexities introduced by continents and potentially large–scale air–sea interaction.

3 Data sets

We use monthly atmospheric fields based on the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis (Kanamitsu et al. 2002) for the period 1979–2012. In an intercomparison of HC climatology and trends across a range of reanalyses, Stachnik and Schumacher (2011) found considerable

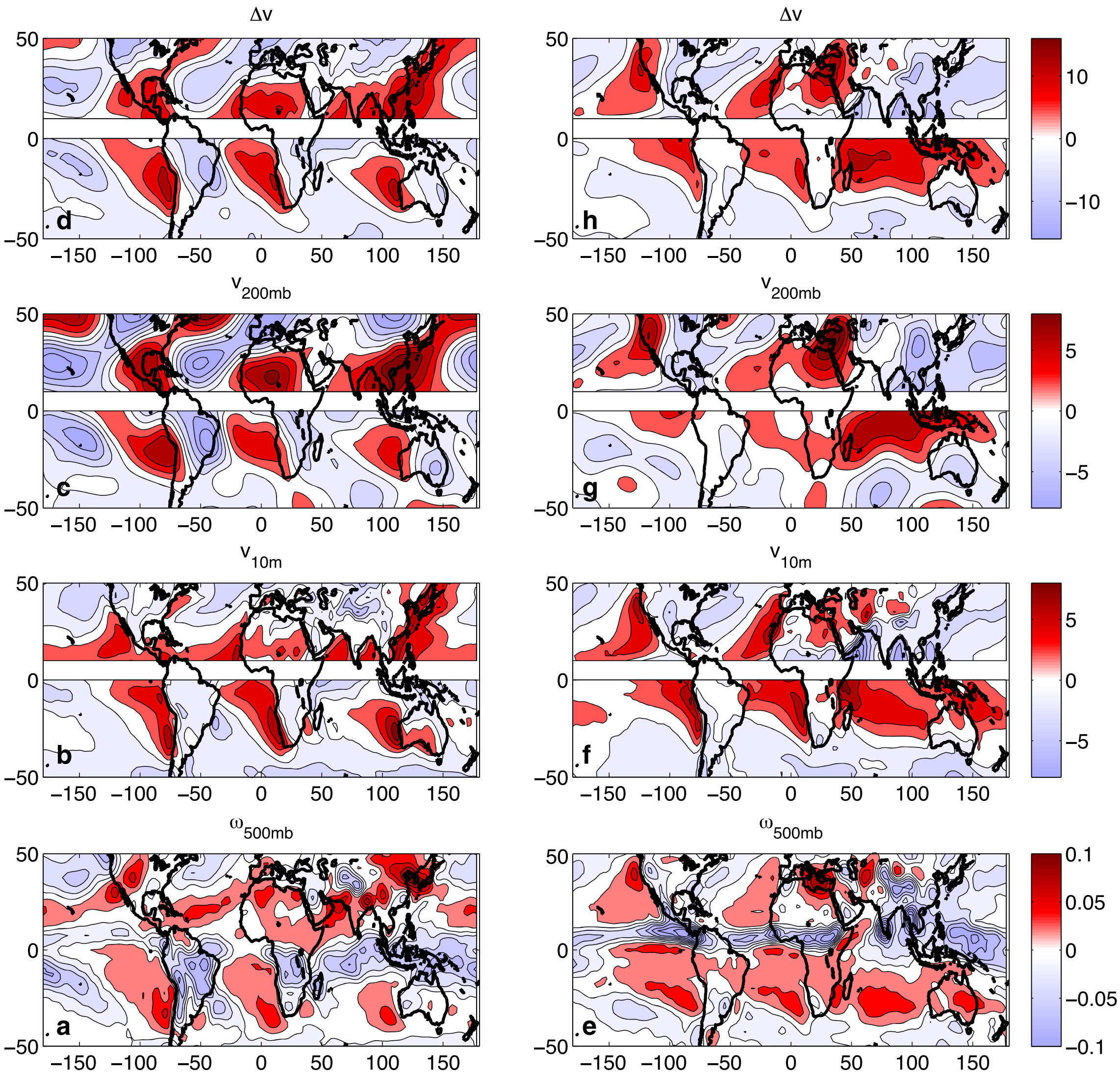

Fig. 2 Global distribution of Hadleywise overturning circulations. Vertical velocity (Pa s^{-1}) at 500 mb (mid–troposphere; 1 mb = 100 Pa) where positive indicates downward (**a**), meridional velocity (m s^{-1}) at the surface (10 m) where positive indicates equatorward or Hadleywise (**b**), upper–tropospheric meridional velocity (averaged 150–200 mb) where positive indicates poleward or Hadleywise (**c**), and the vertical shear of Hadleywise meridional velocity (m s^{-1}) between the surface and the upper troposphere (**d**) for DJF. **e–h** As in **a–d** but for JJA

variability amongst different products with regard to the HC intensity, though less so for the HC width. The NCEP/DOE reanalysis compares well with an ensemble mean of eight reanalysis products for a range of HC metrics (Stachnik and Schumacher 2011).

The analyses presented here have also been repeated with the European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis Interim (ERA–Interim; Dee et al. 2011). Results were qualitatively similar irrespective of the dataset used; so all analyses presented are based on NCEP/DOE.

In the subsequent figures, a convenient sign convention is introduced whereby positive and negative values of v represent "Hadleywise" and "anti–Hadleywise" flow, respectively, where Hadleywise flow is equatorward at the surface or poleward in the upper troposphere.

4 Results

In the Dec.–Feb. (DJF) summer hemisphere, essentially all of the equatorward surface flow is concentrated over the ocean along the western coastlines of the three major Southern Hemisphere landmasses (Fig. 2b). In the winter hemisphere, similar asymmetry is found including concentration of equatorward surface flow along the western coastlines of North America and northern Africa, while weaker Hadleywise flow also extends westward across each of the ocean basins. In the upper–troposphere, the major centers of Hadleywise flow are aligned along similar longitudes as the Hadleywise surface flow but with slightly less deference to the continental coastlines (Fig. 2c). The difference between surface and upper–tropospheric *v* expressed in Hadleywise terms (Fig. 2d) confirms that the zonal asymmetry of the HC is so strong with preference for eastern ocean basins that the meridional overturning circulation is anti–Hadleywise elsewhere. Results for the Jun.–Aug. season (JJA) are qualitatively consistent with the above (Fig. 2e–h). The notable exception is the Indian monsoon, which is such a deep and robust overturning cell driven by summertime heating of the Asian continent that nearby horizontal flow simply bypasses the equator and either partially contributes to or partially interferes with the HC depending on hemisphere and season.

Why is the majority of the Earth's HC concentrated immediately offshore of the major western continental coastlines? On a similar planet without oceanic–continental boundaries such as an aquaplanet, zonally uniform surface temperatures, a zonally uniform equatorial trough of low pressure, and a pair of zonally uniform subtropical high–pressure ridges would prevail and dictate an HC controlled purely by the zonal mean meridional heating gradient. To zeroth order, continents puncture the subtropical ridges with quasi–stationary thermal lows, leading to anticyclones centered over each ocean basin rather than a continuous ridge encircling the subtropical band in each hemisphere. Given the resultant distribution of up–/downwelling favorable winds about the anticyclones, the large–scale response of the subtropical ocean would be a distortion of the SST field such that cooler (warmer) SSTs emerge along the coastlines to the east (west) of each anticyclone. This is indeed observed (Fig. 3a, d). Closing a feedback loop, the subsequent zonally asymmetric subtropical SSTs force the anticyclones to translate asymmetrically eastward (favoring cooler SST), which is also clearly evident (Fig. 3b, e). This juxtaposition of continental lows due to enhanced land surface heating and zonally asymmetric highs due to large–scale air–sea interaction results in elongated strips of very strong zonal pressure gradient (ZPG) following the western continental coastlines. The resultant meridional geostrophic wind (balanced by the ZPG and Coriolis forces) explains nearly all of—and in some cases more than—the Hadleywise flow found in each of the major eastern ocean basins

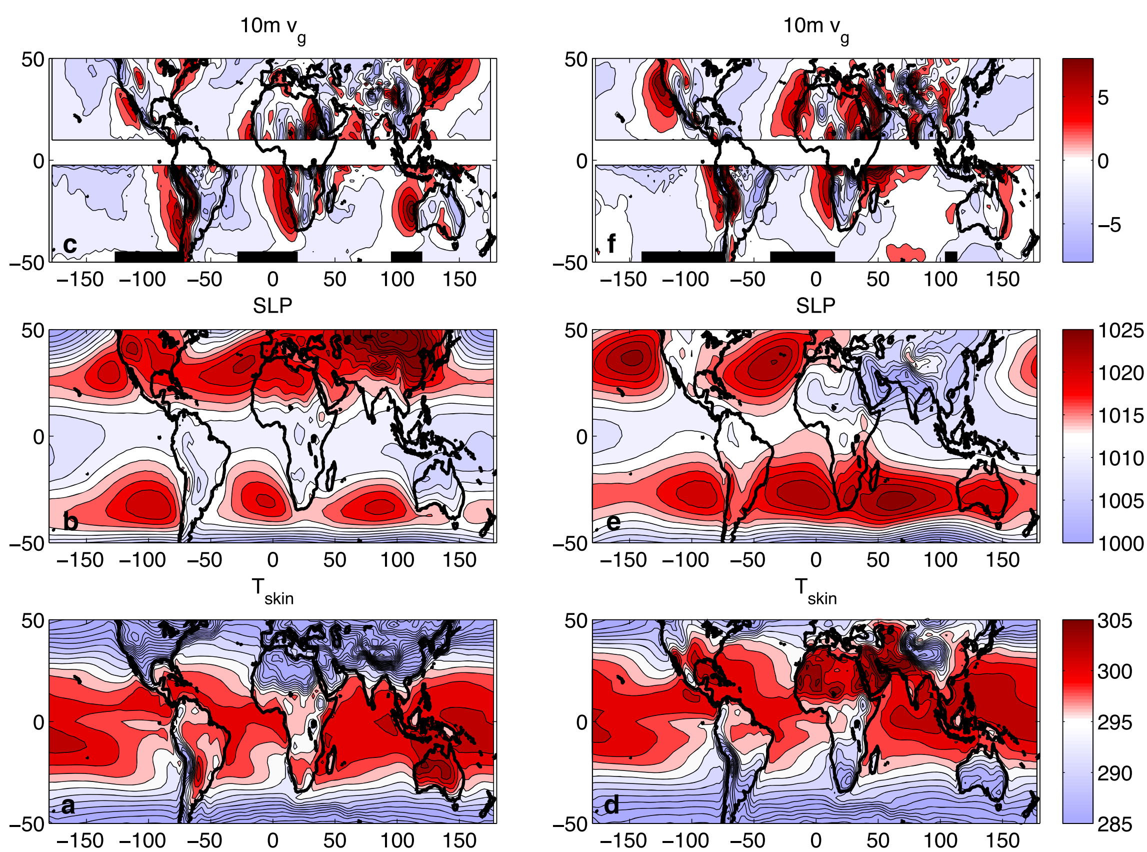

Fig. 3 Dynamic drivers of Hadleywise horizontal flow. Surface skin temperature (K) (**a**), sea level pressure (mb) (**b**), and geostrophic meridional velocity (m s^{-1}) at 10 m where positive indicates equatorward or Hadleywise (**c**) for DJF. **d**–**f**, As in **a**–**c** but for JJA

(Fig. 3c, f). A schematic of this process is provided in Fig. 6b. While the conventional or Halley mechanism likely explains the meridional circulation on an aquaplanet or possibly Venus and Mars (Haberle et al. 1993; Kalnay de Rivas 1975), the geostrophic mechanism described here is clearly only possibly on a planet with oceanic–continental boundaries such as Earth.

The contribution of geostrophy is clearly evident in atmospheric cross–sections (Fig. 4). Extending from the land surface well into the mid–troposphere are marked "bubbles" of warmth relative to surrounding regions, to the immediate west of which are cooler air temperatures that are coupled to a sea surface that is being cooled by coastal upwelling. Associated with these sharp zonal gradients of air temperature are strong ZPGs. In the summer hemispheres (Fig. 4b, c), virtually all of the meridional flow is explained by ZPGs corresponding to sharp thermal contrasts at land–sea margins. In the winter hemispheres (Fig. 4a, d), the equatorward surface flow and poleward upper–tropospheric flow are enhanced by the presence of

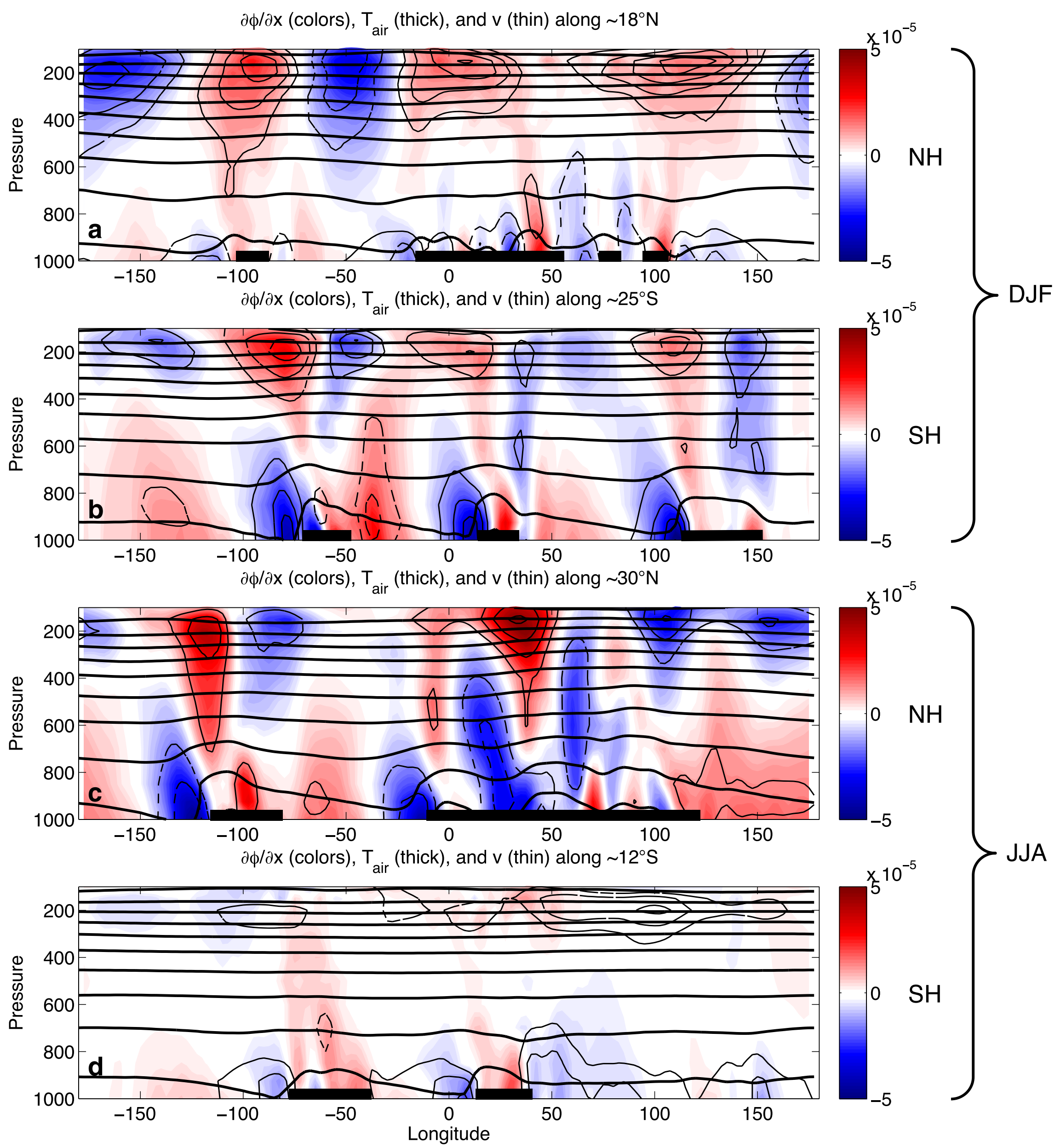

Fig. 4 Vertical structure of atmospheric overturning. **a** Cross–section through the Northern Hemisphere (averaged 10–25°N) during DJF of ZPG (*colors*, Pa m^{-1}), air temperature (*thick lines*, K, every 10 K), and meridional velocity (m s^{-1}, *thin lines*, every 2 m s^{-1}). **b** As in **a** but for 17.5–32.5°S. **c** As in **a** but for JJA and 17.5–42.5°N. **d** As in **c** but for 0–25°S. *Black bars* represent the major landmasses along the median latitude within each cross–section

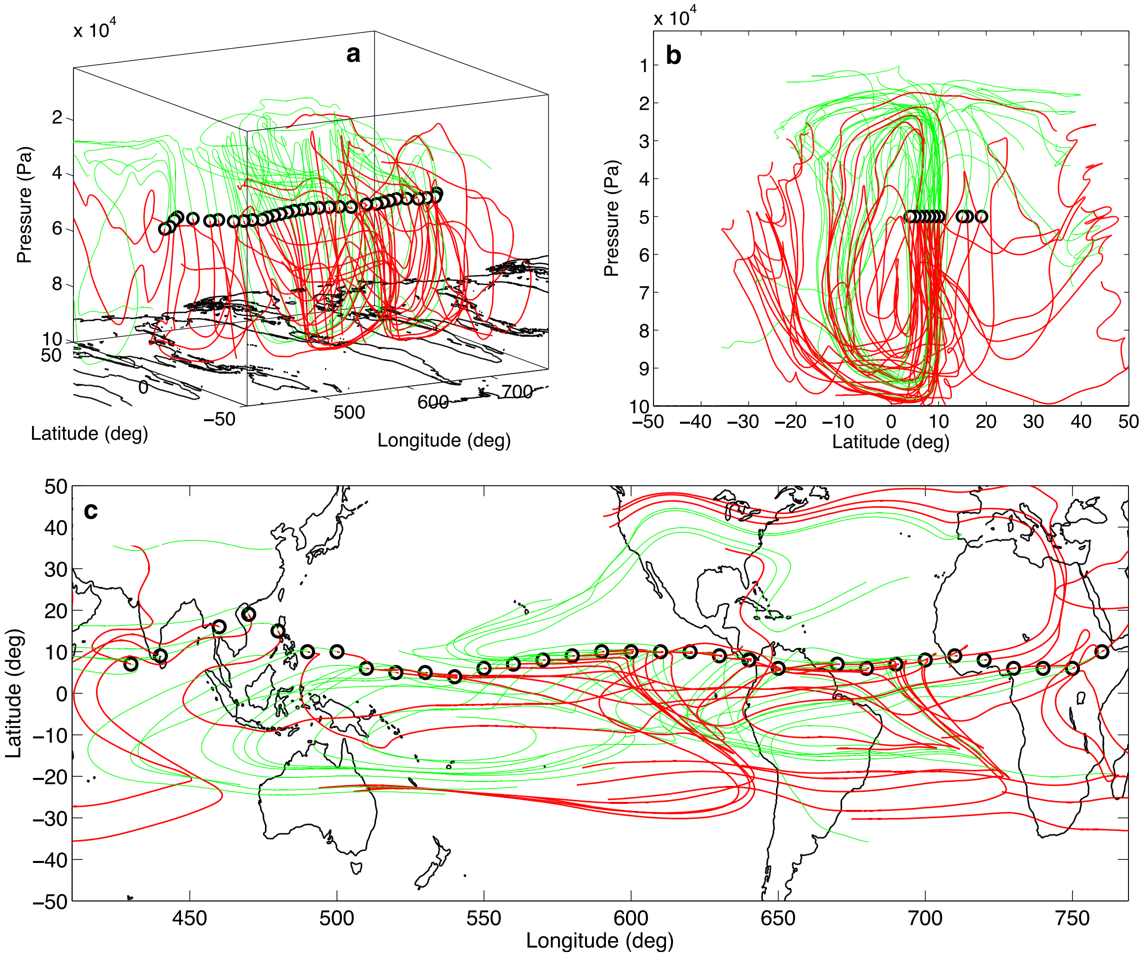

Fig. 5 Velocity streamlines computed using the mean JJA climatology. Forward (backward) three–dimensional streamlines initiated (terminating) at 500 hPa height along the ITCZ in *green* (*red*) for **a** three–dimensional view; **b** latitude–height view; and **c** plan view

ZPGs of the direction that would produce such flow by geostrophic balance in each respective hemisphere. A three–dimensional view of the flow during the JJA season is provided in Fig. 5, which depicts velocity streamlines for air parcels originating and terminating in the ITCZ. The spatial inhomogeneity of the trajectories, highlights the regional aspects of the HC discussed previously: the winter Hadley cell in the Southern Hemisphere is clearly apparent in Fig. 5b, predominantly made up of trajectories off the west coast of the continents representing the surface limb of the HC with enhanced meridional flow (Fig. 5a, c).

It is interesting that regions of subtropical descent (a feature of the HC) are positioned just poleward of the regions of strong equatorward surface flow explained above (Fig. 2). We have shown that a geostrophic mechanism related to regional–scale zonal gradients contributes to the meridional flow in the surface limb of the HC. The geostrophic acceleration away from the subtropics along continental coastlines results in a divergence and is thus a driver—rather than strictly a residual—of subtropical descent by continuity. Likewise, the summer and winter hemisphere Hadleywise cells in these regions would converge near the equator and drive ascent even in the absence of moist convection. Both mechanisms likely contribute to the overall strength of the HC, but the overwhelming zonal asymmetry of Hadleywise circulations in the real atmosphere indicates that land–sea gradients are dominant factors determining the global structure of the HC and strength of its surface limb. As such, these factors have important implications for projected regional variations and trends in the hydroclimate of the subtropics.

5 Summary and discussion

Here, we have expanded on the previous body of work on the regional/seasonal aspects of the HC, in particular how land–sea temperature contrasts contribute to the strength of the HC: we show that the Earth's HC is manifest as three regionally distinct cells along the eastern edges of the

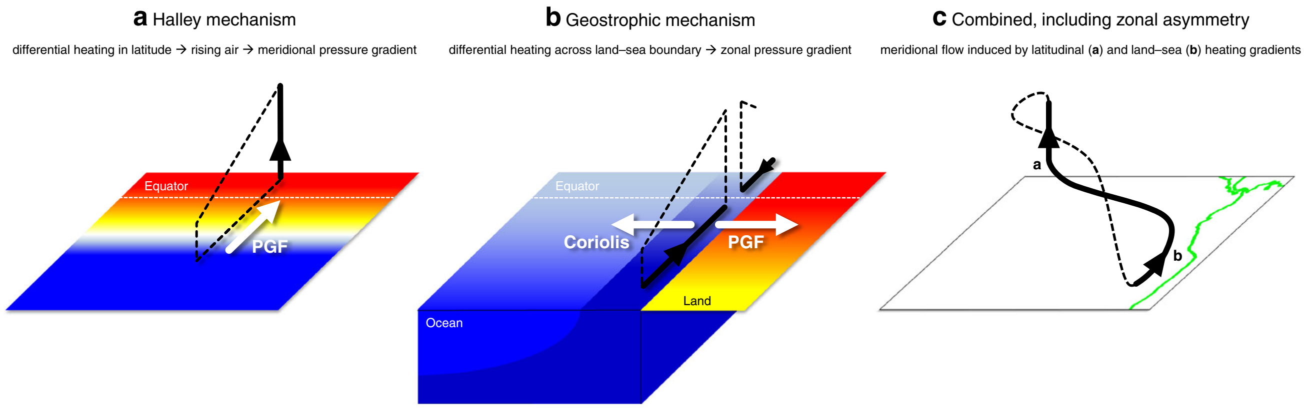

Fig. 6 Diagram of Hadley circulation mechanisms. **a** Conventional mechanism as envisioned by Edmond Halley in 1686, whereby the HC is driven by the latitudinal gradient in solar heating and rising air in the deep tropics (with equatorward surface flow and return flow aloft to conserve mass). *Red* and *blue colors* indicate relatively warm and cool surface temperatures, respectively. **b** Mechanism proposed here, whereby differential heating across the land–sea boundary creates a zonal pressure gradient leading to equatorward geostrophic surface flow and rising air due to convergence with an equivalent cell in the opposite hemisphere. **c** A combination of mechanisms **a** and **b** including the zonal asymmetry of the HC set up by a zonally asymmetric SST field in response to easterly trade winds (which are a result of the Coriolis force, as pointed out by George Hadley in 1735). The schematic is drawn to represent the JJA season

major ocean basins with opposite circulations elsewhere. Moreover, comparable summertime hemisphere cells emerge in each region. The dynamics of the HC near its poleward limit are shown to be largely geostrophic, driven by ZPGs supported by land surface heating and large–scale ocean–atmosphere interaction. By identifying the land–sea thermal contrast as a significant contribution to the HC near its poleward limit, our results offer new insights into the as–yet tenuous links between HC strength or width and future projections of regional hydroclimate, from extreme events to sustained trends in freshwater resources across the vulnerable tropical–subtropical boundary. We can diagnose HC flow in a geostrophic framework because we are moving beyond simply the zonal mean flow (the geostrophic component of which is, of course, zero by construction).

The geostrophic contribution to the meridional flow near the poleward limit of the descending branch of the HC described here highlights the role of ZPGs in driving the Earth's atmospheric meridional overturning. While (Cook 2003) recognized that continents modify the *meridional* pressure gradient, we demonstrate that a substantial part of the Earth's HC is driven by *zonal* pressure gradients that only exist due to continental heating and air–sea interaction. The interplay of different mechanisms—from those envisioned by Edmond Halley in 1686 to that proposed here—is portrayed schematically in Fig. 6. The Halley view of the HC mechanism fundamentally relies on the meridional pressure gradient arising from differential heating in latitude and rising air in the deep tropics (Fig. 6a). This mechanism likely dominates within 5–10° of the equator and in the open ocean sufficiently far from continental coastlines. It must also explain the cross–equatorial component of the HC, as well as its seasonal reversal. Poleward of 5–10° and near continental coastlines, strong equatorward geostrophic flow dominates the meridional velocity field (Fig. 6b). This mechanism cannot explain the HC crossing into the summer hemisphere as the implied geostrophic flow immediately reverses direction across the equator, but does explain the matching cell of opposite sign in the summer hemisphere clearly evident in Fig. 2.

It appears that mechanism *a* is associated with what has been called the "solstitial cell" by Dima and Wallace (2003) after Lindzen and Hou (1988), the stationary cell centered approximately on the equator that reverses seasonally in a sinusoidal manner, while mechanism *b* explains what the same authors referred to as the "seasonally invariant pair of Hadley cells." As the authors noted, the seasonally invariant pair of cells is present year–round (i.e., there is both a winter and summer cell) and has greater meridional extent than the solstitial cell, while both the components contribute roughly equally to the total HC. In the winter hemisphere, where both the solstitial and seasonally invariant cells are of the same sign, the seasonally invariant cell is driven by the geostrophic mechanism and acts to extend the descending branch of the zonal mean HC poleward by $\sim 10°$ latitude. This possibly resolves the finding by Lindzen and Hou (1988) that annual mean heating at the thermal equator cannot explain the size of the annual mean HC, going back to Lorenz (1967). Furthermore, mechanism *b* contributes to the strong zonal asymmetry, as the equatorward geostrophic flow near the poleward limit of the HC is necessarily confined to land–sea boundaries while flow arising from mechanism *a* is not (Fig. 6c). In the summer hemisphere, although the zonal mean overturning is roughly zero by cancellation, strong and coherent Hadleywise cells are present along western coastlines and presumably driven by the geostrophic mechanism and may in some sense be considered "monsoonal" cells. While the summertime cell does not readily emerge in a zonal mean sense, it is nonetheless a prominent regional circulation feature and may prove to be important for understanding projected summertime precipitation changes.

This perspective lends insight into how movement of landmasses and changes in adjacent large–scale ocean–atmosphere interactions are likely to have modified the geostrophic meridional flow and the Earth's HC over geologic timescales. Variations in HC strength on interannual to decadal timescales, as for example associated with the large–scale reorganization of the Indo–Pacific atmosphere during El Niño, need to be reevaluated in light of the modified forcing mechanisms identified here. Finally, projected changes in land–sea temperature contrasts in a warming world due to the relatively low thermal capacity of land will also affect ZPGs and thus need to be considered in understanding changes in HC strength or width, with implications for extremes in hydroclimate and freshwater resources across the increasingly vulnerable subtropics.

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