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Changes in the strength and width of the Hadley circulation since 1871

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Abstract

Recent studies demonstrate that the Hadley Circulation has intensified and expanded for the past three decades, which has important implications for subtropical societies and may lead to profound changes in global climate. However, the robustness of this intensification and expansion that should be considered when interpreting long-term changes of the Hadley Circulation is still matters of debate. It also remains largely unknown how the Hadley Circulation has evolved over longer periods. Here we present long-term variability of the Hadley Circulation using the 20th Century Reanalysis. It shows a slight strengthening and widening of the Hadley Circulation since the late 5 1970s, which is not inconsistent with recent assessments. However, over centennial timescales (1871–2008), the Hadley Circulation shows a tendency towards more intense and narrower state. More importantly, the width of the Hadley Circulation has not yet completed a life-cycle since 1871. The strength and width of the Hadley Circulation during the late 19th and early 20th century show strong natural variability, exceeding 10 15 variability that coincides with global warming in recent decades. These findings raise the question that the recent change of the Hadley Circulation is primarily attributed to greenhouse warming or a long-period oscillation of the Hadley Circulation substantially longer than that observed in previous studies.

1 Introduction

20 The Hadley Circulation (ascent near the equator and subsidence in the subtropics) is a fundamental regulator of the Earth's energy budget, e.g. redistribution of energy from tropics to higher latitudes. The Hadley Circulation determines the precipitation pattern in the tropics and subtropics, e.g. the prevalence of rain in the moist inner tropical regions and the dry conditions in the subtropical regions (e.g. Diaz and Bradley, 2004).
25 In recent years, there has been a substantial interest in the decadal change of the Hadley Circulation, focusing on its two aspects: strength and width. Satellite

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Randel, 2007). The IPCC AR4 climate model simulations also showed Hadley Circulation widening in response to increased greenhouse gases (Lu et al., 2007; Johanson and Fu, 2009). However, the widening appears to be nearly an order of magnitude smaller in the IPCC AR4 simulations than those in the observations (Johanson and Fu, 2009). This suggests that further studies are necessary to confirm long-term changes in the meridional extent of the Hadley Circulation.

To date, it is unclear what observational and model biases cause the above discrepancies of the strength and width of the Hadley circulation in response to climate change, e.g. reanalyses and models show fundamentally different thermodynamic structures in the tropical troposphere (Mitas and Clement, 2006), and radiosonde observations and its assimilation in reanalyses might be one of the problems (Santer et al., 2005; Sheppard, 2007). The modern reanalyses now available extend from no earlier than 1948 to the present (e.g. the National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis, NCEP/NCAR, starts from 1948; Kistler et al., 2001), leaving many important climate events uncovered. It remains largely unknown how the strength and width of the Hadley Circulation have evolved over longer periods, and how future climate change may affect the Hadley Circulation. Here we analyze long-term variation of the Hadley Circulation using the Twentieth Century Reanalysis version 2 (20CR2), which provides the first estimates of global tropospheric variability from 1871 to 2008 (Compo et al., 2011). Preliminary validations suggest that the 20CR2 depicts more realistic vertical structures of temperature trends in the tropics and subtropics, and probably suffers less from spurious trends than any previous reanalyses (see more detailed discussion of the key differences between the 20CR2 and previous reanalyses, and the evaluations of the 20CR2 in Sect. 2).

2 Data and method

In this study, our results and conclusions are based on the 20th Century Reanalysis Version 2. Previous reanalyses assimilate the available observations using 3D-Var

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the tropics and subtropics, and to reduce the uncertainties in our conclusions, we have compared the 20CR2 and NCEP/NCAR with observations for 1958–2010. We have used the annual-mean temperature anomalies in the tropics and subtropics (30° S–30° N) from the radiosonde atmospheric temperature products for assessing climate (RATPAC, Free et al., 2005), which is less influenced by the temporal inhomogeneities due to historical changes in instruments and measurement practices. Linear trends and their uncertainties were calculated as a function of height. The same procedure is applied to the 20CR2 and NCEP/NCAR temperature anomaly fields. As shown in Fig. 1, the observations display a warming trend extending from surface to the upper troposphere, and the upper troposphere is warming faster than the surface. At all levels, temperature trends in the 20CR2 are considerably closer to the observations than that of the NCEP/NCAR. The improved accuracy in the 20CR2 compared to the NCEP/NCAR is most pronounced in the lower and upper troposphere. There are quantitative differences between the trends in the 20CR2 and observations. However, the magnitudes of the trends in the 20CR2 and in the observations are not significantly different when their uncertainties are taken into account as compared to those of the NCEP/NCAR.

A conventional way to depict the Hadley Circulation is to calculate the mass stream function (MSF, Oort and Yienger, 1996), which is defined by $\Psi = \frac{2\pi a \cos \varphi}{g} \int_0^P \bar{v} dp$, where Ψ is MSF, \bar{v} is the zonally-averaged north/south (meridional) velocity, a is the earth's radius, g is gravity, φ is latitude, and P is pressure level. The MSF at a given latitude and pressure level is equal to the rate at which mass is being transported meridionally between that pressure level and the top of the atmosphere. Note that the Hadley Circulation is a zonal-mean quantity, although there is considerable zonal asymmetry of the Hadley Circulation.

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3 Results

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winter and spring, and poleward in summer and autumn (Fig. 3b). The southern edge of the southern Hadley Circulation shows a significant equatorward-moving tendency since 1871 (1° in latitude, >99 % significance), although a poleward shift is found starting from the late 1970s (Fig. 2c). The equatorward shift of the southern edge of the southern Hadley Circulation occurs in all the seasons (Fig. 3b). We note that the northern and southern edges of the Hadley Circulation tend to diverge starting from the late 1970s, which is consistent with the identified expansion of the Hadley Circulation in the aforementioned studies.

Figure 2d shows the width of the Hadley Circulation, which is defined as the distance between the northern and southern edges of the Hadley Circulation. It appears that the width of the Hadley Circulation has not yet completed a cycle since 1871. Specifically, the Hadley Circulation shrunk by $\sim 4\text{--}5^{\circ}$ in latitude from the 1870s to the mid-1920s, followed by two major expansion periods (from the mid-1920s to the mid-1940s and from the late 1970s to the present), which are in accordance with two major warming periods (1925–1944 and 1978–present) found in the observations (Jones et al., 1999; Hansen et al., 2010). Overall, the Hadley Circulation shows a tendency toward a narrower state during 1871–2008 (-1.44° in latitude, >99 % significance).

Despite a large number of observational and modeling studies, it remains unclear how the strength and width of the Hadley Circulation are related (Schneider et al., 2010). As shown in Table 1, significant out-of-phase relationships are found between the strength, and the width and northern edge of the Hadley Circulation, even with the trends removed. By contrast, no strength-width relationship exists for the southern counterpart, although significant correlation is found between the strength and the southern edge of the southern Hadley Circulation. This indicates that the northern Hadley Circulation might dominate the southern counterpart in modulating the meridional extent of the Hadley Circulation.

It is instructive to analyze the relationship between the covariability of the strength and width of the Hadley Circulation and surface temperature. The Global Historical Climatology Network (GHCN) data (<http://www1.ncdc.noaa.gov/pub/data/cmb/>

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ghcnm/ghcnm-v3.pdf) shows that the global-mean surface temperature has warmed by 0.06 °C for 1880–2008 (Fig. 2e). Compared to the observations, the global-mean near surface air temperature of the 20CR2 shows comparable warming trend (0.06 °C for 1880–2008), and coherent variation (the correlation between the 20CR2 and GHCN is 0.94, >99 % significance).

It has been suggested that the Hadley Circulation would weaken associated with global warming (Diaz and Bradley, 2004; Lu et al., 2007; Vecchi and Soden, 2007), which is based on the relationship between the meridional surface temperature gradient and the strength of the Hadley Circulation (Diaz and Bradley, 2004), and the 10 IPCC AR4 model projected decrease of convective overturning in the tropics as climate warms (Vecchi and Soden, 2007), but some studies demonstrate that the Hadley Circulation has strengthened in recent decades, particularly in winter. Here our analysis shows the Hadley Circulation has strengthened in accordance with the increase of the global-mean surface temperature since 1871, but the northern Hadley Circulation shows substantial multi-decadal fluctuations.

It has also been suggested that the meridional extent of the Hadley Circulation would expand associated with greenhouse warming. This is based on the postulation that the extent of the Hadley Circulation is determined by the latitude of baroclinic instability. Under global warming conditions, the subtropical static stability increases due to an 20 established consequence of moist thermodynamics, which pushes the baroclinic instability zone poleward, and consequently, the outer boundary of the Hadley Cell extends poleward (Lu et al., 2007). Here our analysis shows that the Hadley Circulation has shrunk by 1.44° in latitude in accordance with surface warming during 1871–2008.

The sustained increase in the width of the Hadley Circulation for the past few 25 decades that have occurred simultaneously with a significant positive trend in the global-mean surface temperature has led to the speculation that the changes in both fields are the result of greenhouse warming. Meanwhile, examination of the strength and width of the Hadley Circulation shows substantial changes during the late 19th and early 20th century, which features low atmospheric concentration of greenhouse gases.

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We further divide the entire period (1871–2008) into (1) cold period (1871–1925), which features a slight decrease or no increase in the global-mean surface air temperature, and (2) warm period (1926–2008), which is characterized by a quite persistent rise in the global-mean surface air temperature (Fig. 2e). As shown in Fig. 5, the strength 5 of the northern Hadley Circulation decreases with the increasing surface air temperature, although such dependence during the cold period is not statistically significant (Table 1). The opposite is the case for the strength of the southern counterpart, which increases with the increasing surface air temperature. This suggests that the northern and southern components of the Hadley Circulation have opposite strength- 10 temperature relationship. The width of the Hadley Circulation does show an expansion with the increasing surface air temperature during the warm period, but no dependence on surface temperature is found during the cold period. The width of the Hadley Circulation changes non-monotonically with surface temperature, showing different sensitivity to cold and warm conditions.

15 4 Conclusions

We conclude that the 20CR2 does indicate a slight strengthening and widening of the Hadley Circulation for the past three decades, corroborated by the results of recent analyses. However, over longer periods (1871–2008), the Hadley Circulation has become stronger and narrower. Moreover, the width of the Hadley Circulation has not 20 finished a full life-cycle since the 1870s, which indicates the observed expansion in recent decades might be a reflection of a long-period oscillation. To further confirm the identified secular variability, we perform a spectral analysis on the time series of the width of the Hadley Circulation. The spectral analysis indicates that the width of the Hadley Circulation exhibits a clear secular peak indicative of centennial-scale variability 25 that is distinct from the null hypothesis of a red-noise stochastic process, statistically significant (>99 %, not shown). Moreover, a growing paleoclimatic proxy evidence indicates centennial-scale oscillatory behavior of the position of the Intertropical

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Convergence Zone (ITCZ, a tracer of the horizontal scale of the Hadley cell, Hu et al., 2007) for the past several millennia, i.e. the planktic foraminifer *Globigerinoides sacculifer* in Gulf of Mexico sediments shows distinct century-scale cyclicity of ITCZ (Poore et al., 2004). The strength and width of the Hadley Circulation during the late 19th and 5 early 20th century experience substantial changes that exceed changes associated with global warming in recent decades. A simple relationship between the strength and width of the Hadley Circulation, and surface temperature is not supported. These findings are intriguing and raise the question that the recent changes of the Hadley Circulation is primarily due to greenhouse warming or long-term change of the Hadley 10 Circulation (e.g. variability of the Hadley Circulation at centennial timescales). Attributions of those changes require a deeper understanding of how the strength and width of the Hadley Circulation is controlled under various dynamical regimes, even in the present climate state.

Acknowledgements. This research is supported by 973 program (2011CB309704 and 15 2010CB428606) and NSFC (41176169 and 41025018).

References

Bengtsson, L., Hodges, K., and Hagemann, S.: Sensitivity of the ERA-40 reanalysis to the observing system: Determination of the global atmospheric circulation from reduced observations, *Tellus A*, 56, 456–471, 2004.

20 Brönnimann, S., Compo, G. P., Spadin, R., Allan, R., and Adam, W.: Early ship-based upper-air data and comparison with the Twentieth Century Reanalysis, *Clim. Past*, 7, 265–276, doi:10.5194/cp-7-265-2011, 2011.

Chen, J., Carlson, B., and Del Genio, A.: Evidence for strengthening of the tropical general circulation in the 1990s, *Science*, 295, 838–841, 2002.

25 Compo, G., Whitaker, J., Sardeshmukh, P., Matsui, N., Allan, R., Yin, X., Gleason, B., Vose, R., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R., Grant, A., Groisman, P., Jones, P., Kruk, M., Kruger, A., Marshall, G., Maugeri, M., Mok, H., Nordli,

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Ø., Ross, T., Trigo, R., Wang, X., Woodruff, S., and Worley, S.: The Twentieth Century Reanalysis Project, *Q. J. Roy. Meteorol. Soc.*, 137, 1–28, 2011.

Diaz, H. and Bradley, R.: The Hadley Circulation, Present, Past and Future, Kluwer Academic, Dordrecht, 511 pp., 2004.

5 Free, M., Seidel, D., Angell, J., Lanzante, J., Durre, I., and Peterson T.: Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC): A new dataset of large-area anomaly time series, *J. Geophys. Res.*, 110, D22101, doi:10.1029/2005JD006169, 2005.

Fu, Q., Johanson, C., Wallace, J., and Reichler, T.: Enhanced mid-latitude tropospheric warming in satellite measurements, *Science*, 312, 1179, doi:10.1126/science.1125566, 2006.

10 Hansen, J., Ruedy, R., Sato, M., and Lo, K.: Global surface temperature change, *Rev. Geophys.*, 48, RG4004, doi:10.1029/2010RG000345, 2010.

Hu, Y. and Fu, Q.: Observed poleward expansion of the Hadley circulation since 1979, *Atmos. Chem. Phys.*, 7, 5229–5236, doi:10.5194/acp-7-5229-2007, 2007.

15 Hu, Y., Li, D., and Liu, J.: Abrupt seasonal variation of the ITCZ and the Hadley circulation, *Geophys. Res. Lett.*, 34, L18814, doi:10.1029/2007GL030950, 2007.

Hudson, R., Frolov, A., Andrade, M., and Follette, M.: The total ozone field separated into meteorological regimes, Part I: Defining the regimes, *J. Atmos. Sci.*, 60, 1669–1677, 2003.

Johanson, C. and Fu, Q.: Hadley cell widening: Model simulations versus observations, *J. Climate*, 22, 2713–2725, 2009.

20 Jones, P., New, M., Parker, D., Martin, S., and Rigor, I.: Surface air temperature and its variations over the last 150 years, *Rev. Geophys.*, 37, 173–199, 1999.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., and Fiorino, M.: The NCEP-NCAR 25 50-Year Reanalysis: Monthly Means CD-ROM and Documentation, *B. Am. Meteorol. Soc.*, 82, 247–268, 2001.

Lu, J., Vecchi, G., and Reichler, T.: Expansion of the Hadley cell under global warming, *Geophys. Res. Lett.*, 34, L06805, doi:10.1029/2006GL028443, 2007.

Mitas, C. and Clement, A.: Has the Hadley cell been strengthening in recent decades?, *Geophys. Res. Lett.*, 32, L03809, doi:10.1029/2004GL021765, 2005.

30 Mitas, C. and Clement, A.: Recent behavior of the Hadley cell and tropical thermodynamics in climate models and reanalyses, *Geophys. Res. Lett.*, 33, L01810, doi:10.1029/2005GL024406, 2006.

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Table 1. Correlations between the strength, width and edge of the Hadley Circulation, and regressions of the strength and width of the Hadley Circulation on the averaged 20CR2 surface air temperature in the tropics and subtropics (TSSAT).

	Correlation			Regression
	Width	Edge (<i>N</i>)	Edge (<i>S</i>)	($10^{10} \text{ kg s}^{-1} \text{ }^{\circ}\text{C}^{-1}$) TSSAT
Strength (<i>N</i>)	-0.59	-0.59	-0.17	-0.66 (-0.88)
Strength (<i>S</i>)	-0.06	0.19	-0.46	1.67 (1.28)
Width	1	0.88	0.48	-0.25 (2.09)

Note: >99 % significance is in bold type.

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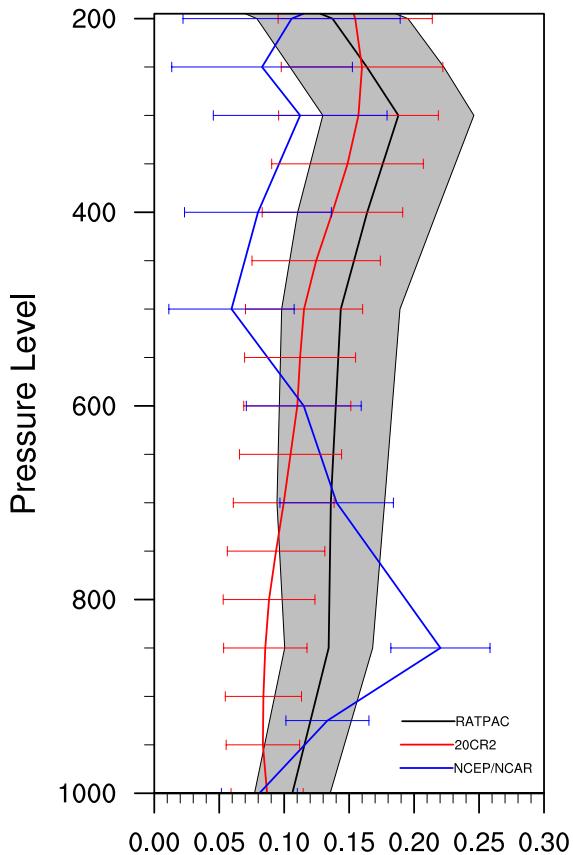


Fig. 1. Comparison of the vertical structures of the annual-mean temperature trends ($^{\circ}\text{C}$ per decade) in the 20CR2, NCEP/NCAR and observations (RATPAC) for 1958–2010. Also shown are the 95 % confidence intervals (grey bands for observations and error bars for the 20CR2 and NCEP/NCAR).

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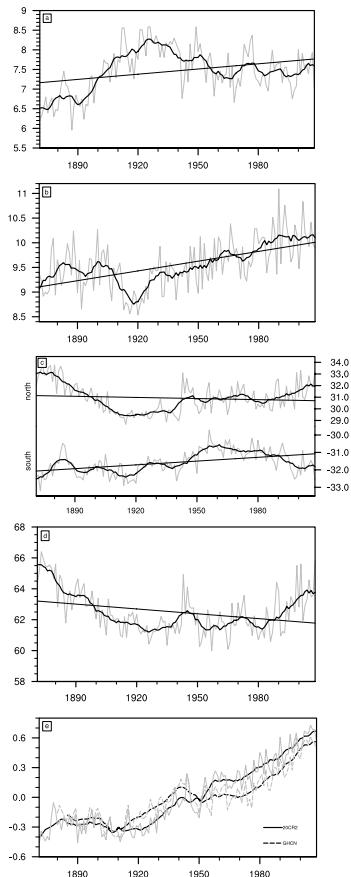


Fig. 2. Time series of the annual-mean (grey line) and 10-year running mean (black line) strength, edge and width of the Hadley Circulation for 1871–2008: **(a)** the strength of northern component, **(b)** the strength of the southern component, **(c)** the poleward-edge of the northern and southern components, and **(d)** the width, and **(e)** time series of the annual-mean GHCN surface temperature and 20CR2 surface air temperature for 1871–2008.

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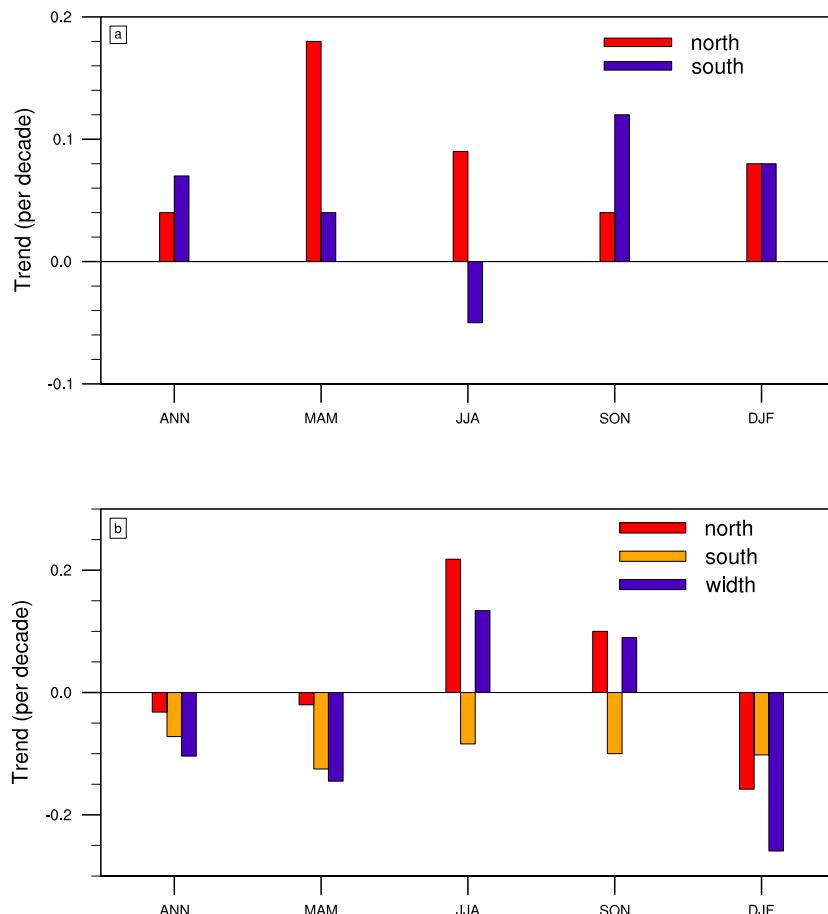


Fig. 3. Annul and seasonal trends of (a) the strength of the northern and southern Hadley Circulation ($\times 10^{10} \text{ kg s}^{-1}$ per decade), and (b) the poleward-edge and width of the Hadley Circulation (latitude per decade) for 1871–2008.

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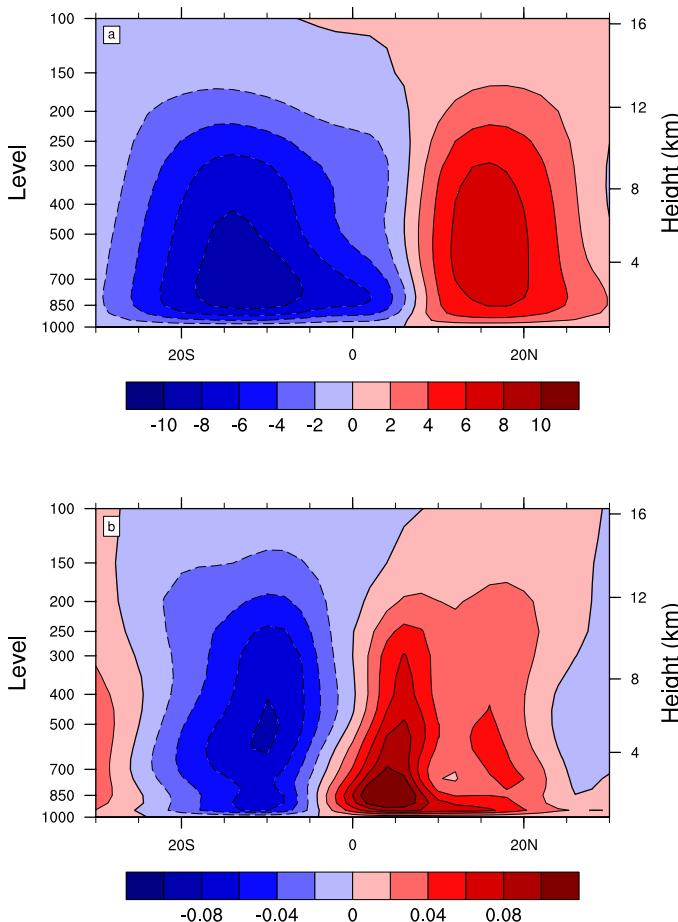


Fig. 4. (a) Climatology ($\times 10^{10} \text{ kg s}^{-1}$) and **(b)** trend ($\times 10^{10} \text{ kg s}^{-1}$ per decade) of the mass stream function of the Hadley Circulation for 1871–2008.

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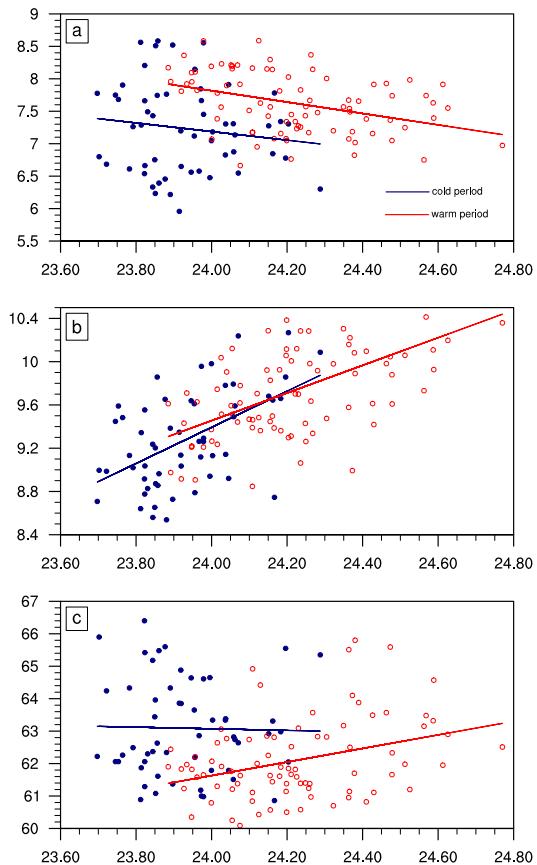


Fig. 5. Scatter plots of the strength and width of the Hadley Circulation versus the averaged 20CR2 surface air temperature in the tropics and subtropics (30° S– 30° N) during the cold (1871–1925, blue) and warm (1926–2008, red) periods: **(a)** the strength of the northern component, **(b)** the strength of the southern component, and **(c)** the width.