The Hadley Circulation in Reanalyses: Climatology, Variability, and Change

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ABSTRACT

Analysis of the annual cycle of intensity, extent, and width of the Hadley circulation across a 31-yr period (1979–2009) from all existent reanalyses reveals a good agreement among the datasets. All datasets show that intensity is at a maximum in the winter hemisphere and at a minimum in the summer hemisphere. Maximum and minimum values of meridional extent are reached in the respective autumn and spring hemispheres. While considering the horizontal momentum balance, where a weakening of the Hadley cell (HC) is expected in association with a widening, it is shown here that there is no direct relationship between intensity and extent on a monthly time scale.

All reanalyses show an expansion in both hemispheres, most pronounced and statistically significant during summer and autumn at an average rate of expansion of $0.55 \pm 0.1$ decade$^{-1}$ in each hemisphere. In contrast, intensity trends are inconsistent among the datasets, although there is a tendency toward intensification, particularly in winter and spring.

Correlations between the HC and tropical and extratropical large-scale modes of variability suggest interactions where the extent of the HC is influenced by El Niño–Southern Oscillation (ENSO) and the annular modes. The cells tend to shrink (expand) during the warm (cold) phase of ENSO and during the low (high) phase of the annular modes. Intensity appears to be influenced only by ENSO and only during spring for the southern cell and during winter for the northern cell.

1. Introduction

The Hadley circulation is a thermally driven circulation that features ascent of equatorial air to a height of about 15 km, transportation aloft toward the poles, descent at the subtropics, and a return flow near the surface. These features offer an explanation for the persistence and extent of the trade winds and the subtropical high pressure belt that dominate the climate of the tropics and subtropics. The descending branch of the Hadley cell (HC) is associated with subsidence in each hemisphere. At the surface, this coincides with the subtropical ridge (STR), a region of high pressure encircling the globe associated with low precipitation and high evaporation rates. Indeed, the climate of many of Earth’s arid and semiarid regions is dominated by the location of the STR and the descending branch of the HC. The HC has a seasonal cycle (e.g., Oort and Yienger 1996; Dima and Wallace 2003). During the solstitial seasons, a single cell associated with cross-equatorial flow tends to dominate, whereas during equinoctial seasons a distinct cell exists in each hemisphere. The interhemispheric distance between the two regions of descent may be referred to as the “width” of the HC or the width of the tropics (e.g., Johanson and Fu 2009; Stachnik and Schumacher 2011, hereafter SS11). Various theoretical studies of the HC (e.g., Walker and Schneider 2006; Schneider 2006; Frierson et al. 2007; Lu et al. 2009) suggest that the width scales with a variety of parameters, including the broad-scale static stability, the height of the tropopause (tropical or extratropical), and/or the equator-to-pole temperature difference. Over recent years, attention has been focused on the expansion and strengthening of the HC in the context of a changing climate, with potentially important implications for the surrounding climatic zones (Seidel et al. 2008; Reichler 2009).

While the HCs can readily be defined from dynamic variables such as velocity potential, the vertical velocity at specific pressure levels (Kumar et al. 1999; Wang 2002; Tanaka et al. 2004), or the meridional component of the divergent wind (Song and Zhang 2007), it is the mass-weighted zonal-mean meridional streamfunction (ZMSF) that is most commonly used (e.g., Oort and Yienger 1996; Trenberth et al. 2000; Dima and Wallace...
hemispheres combined, to be on the order of between 2007; Davis and Rosenlof 2012). However, Johanson little difference between the hemispheres (Hu and Fu have shown expansion rates of about 0.8

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diagnostic variability on various time scales.

Previous studies using the annual average ZMSF have shown expansion rates of about 0.8\textdegree} decade\textsuperscript{−1}, with little difference between the hemispheres (Hu and Fu 2007; Davis and Rosenlof 2012). However, Johanson and Fu (2009) and SS11 find expansion rates, for both hemispheres combined, to be on the order of between 1.1\textdegree} and 3.2\textdegree} decade\textsuperscript{−1}. On a seasonal basis, trends are largest in the summer and autumn seasons of each hemisphere (Hu and Fu 2007; Davis and Rosenlof 2012). This widening has been linked to increasing greenhouse gases (GHG) (Lu et al. 2007) and/or ozone depletion since 1979 (Kang et al. 2011; Polvani et al. 2011).

Levine and Schneider (2011) noted that despite a large body of observations and numerous studies with GCMs, it remains unclear how the width and intensity of the Hadley circulation are controlled. Current literature highlights differing opinions as to whether expansion of the HCs is directly related to intensification. Modeling results indicate that changes in intensity and width of the HC are inversely related (Mitas and Clement 2006). For example, Lu et al. (2007) noted a consistent weakening associated with a poleward expansion of the diagnosed Hadley circulation within climate models forced by enhanced GHG concentrations. However, the simulated expansion rate for the late twentieth century is less than that of the observed (Johanson and Fu 2009). While many models indicate a weakening of the HC under expansion, this is not always the case. In reality, these changes are more complex, and even the direction of the change is not necessarily consistent across all the studies. While an observed intensification of the Northern Hemisphere winter cell is inferred from several studies (Tanaka et al. 2004; Quan et al. 2004; Song and Zhang 2007; SS11), it is suggested that discrepancies can be accounted for by considering the different cloud parameterization and convective schemes used in the reanalysis models (Mitas and Clement 2005). Song and Zhang (2007) found significant differences between two reanalysis datasets and claimed this to be due to differences over the tropical western Pacific, where observations are sparse. In particular, the upward (ascending) branch of the HC is sensitive to these components, and there are relatively few direct observations in the tropics, especially over oceans, to validate the reanalysis schemes. Despite this, Mitas and Clement (2006) argued that reduced static stability can explain an intensification of the Hadley circulation in order to maintain the required heat transport for energy balance.

Large-scale modes of variability, such as El Niño–Southern Oscillation (ENSO) and the annular modes, can also impact the intensity and extent of the HC. Oort and Yienger (1996) showed that the HC intensity tends to increase during the warm phases of ENSO events and weaken during cool phases and that variability in the subtropical jets is associated with HC variability. However, Mitas and Clement (2005) found little relationship between the Northern Hemisphere (NH) wintertime Hadley circulation and ENSO events, citing that correlation values differed greatly among the datasets. Furthermore, Tanaka et al. (2004) showed that peak values in the NH winter exhibits weak interannual variability, contrasting large variability in the NH summer. They also found that there was no significant correlation with ENSO. More recently, SS11 identified a weak yet statistically significant strengthening of the NH HC in winter during El Niño events.

Observations of the southern annular mode (SAM) indicate a positive trend over the past few decades, indicating a strengthening of the subpolar westerlies coupled with a weakening mean jet stream at lower latitudes. These observations directly impact the general circulation, particularly during the active seasons where the high polarities of the annular modes act to displace the HC extent poleward (Thompson et al. 2000). In agreement with this, Kang and Polvani (2011) found a strong relationship between the position of the Southern Hemisphere (SH) eddy-driven jet and the edge of the HC in austral summer; they show a 1° poleward shift of the HC extent in association with a 2° shift of the eddy-driven jet, a feature that is strongly related to the annular mode (Robinson 2007).

One major issue highlighted by the various studies to date is that different results in terms of observed trends of the HC can arise depending on which method is used to define various indices: which datasets are analyzed or which parameter is used. Davis and Rosenlof (2012) clearly showed the sensitivity of the results in their comparison of the tropical width diagnosis. They highlighted large discrepancies from several subjective and objective definitions of the tropical edge using both reanalyses and satellite observations. If the width of the tropics has been shown to expand, it is unclear how much of the expansion is implicit to each hemisphere. Thus, given the asymmetry and seasonality of the Hadley circulation in each hemisphere, we consider the northern and southern hemispheric contribution separately.

With regard to previous studies, three main questions remain to be answered concerning the HC, particularly the following:

1) What is the hemispheric seasonal cycle in the different sets of reanalysis?
2) What are the annual and seasonal trends, their significance and robustness, and their causes?

3) How does ENSO and annular modes (AMs) influence the HCs in each hemisphere?

The objective of this study is to answer these questions by the means of all available reanalyses and objective definition of the Hadley cells.

2. Data and methods

The eight reanalysis datasets examined here are the NCEP-1; NCEP-2; CFSR; ECMWF data (ERA-40 and ERA-Interim); the NASA reanalysis (MERRA); the Japanese 25-yr Reanalysis Project (JRA-25); and the NOAA–CIRES Twentieth-Century Reanalysis version 2 (20CR). Reanalysis datasets are a hybrid of numerical weather prediction model output and assimilated data from various observational platforms. In general, reanalyses adequately reproduce many mean “dynamic” quantities like wind and temperature, albeit with some systematic errors (e.g., Reichler and Kim 2008). It is especially crucial to examine an ensemble of reanalysis datasets to validate a climate signal estimate (Thorne and Vose 2010). It is therefore important, as shown by SS11, to use all available reanalysis datasets.

The datasets comprise monthly means but have different spatial resolutions and span different periods. These different characteristics are summarized in Table 1 together with references for a description of each dataset. In addition, an ensemble mean is computed (across all eight datasets) to highlight the biases and discrepancies discussed above. Notable differences worth mentioning are as follows:

- While all reanalyses utilize conventional data sources (e.g., radiosondes, satellite, soundings, surface observations), the assimilation technique, the models, and the spatial and temporal resolution of the archived data vary.
- All reanalyses use a three-dimensional variational (3Dvar) assimilation scheme, except ERA-Interim, which employs a full 4Dvar system, corresponding to a temporal extension of the 3Dvar.
- NCEP-2 is an upgrade from NCEP-1, which incorporates corrections of errors, notably in the snow cover, which repeatedly used the 1973 data for the entire 1974–94 period.

### Table 1. Reanalysis datasets used in the study. The resolution includes spatial (longitude, latitude, and pressure levels) and time interval of the archived quantities (wind in this study). Details for each dataset can be found in the associated reference.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Length</th>
<th>Reference</th>
<th>Temporal resolution</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEP-1</td>
<td>1958–present</td>
<td>Kalnay et al. 1996</td>
<td>6 h</td>
<td>2.5° × 2.5° × 17 levels</td>
</tr>
<tr>
<td>NCEP-2</td>
<td>1979–present</td>
<td>Kanamitsu et al. 2002</td>
<td>6 h</td>
<td>2.5° × 2.5° × 17 levels</td>
</tr>
<tr>
<td>CFSR</td>
<td>1979–present</td>
<td>Saha et al. 2010</td>
<td>1 h</td>
<td>0.5° × 0.5° × 36 levels</td>
</tr>
<tr>
<td>ERA-40</td>
<td>1957–2002</td>
<td>Uppala et al. 2005</td>
<td>6 h</td>
<td>2.5° × 2.5° × 23 levels</td>
</tr>
<tr>
<td>ERA-Interim</td>
<td>1979–present</td>
<td>Dee et al. 2011</td>
<td>6 h</td>
<td>0.75° × 0.75° × 37 levels</td>
</tr>
<tr>
<td>MERRA</td>
<td>1979–2009</td>
<td>Rienecker et al. 2011</td>
<td>3 h</td>
<td>2/3° × 1/2° × 42 levels</td>
</tr>
<tr>
<td>JRA-25</td>
<td>1979–2009</td>
<td>Onogi et al. 2007</td>
<td>6 h</td>
<td>1.25° × 1.25° × 23 levels</td>
</tr>
<tr>
<td>20CR</td>
<td>1871–2008</td>
<td>Compo et al. 2011</td>
<td>6 h</td>
<td>2° × 2° × 24 levels</td>
</tr>
</tbody>
</table>
CFSR is the only fully coupled land–ocean–atmosphere reanalysis, while all the others use observed sea surface temperature (SST) to drive the atmospheric model.

ERA-Interim is an upgrade of ERA-40, in terms of resolution and the use of a 4Dvar scheme.

The MERRA dataset further assimilates instantaneous rain rate observations through satellite measurements.

The JRA-25 includes additional Chinese snow cover data that are not part of the prior reanalyses.

Finally, the 20CR includes only surface pressure, SSTs, and sea ice in its assimilation, with no upper-air or satellite observations.

As can be seen in Table 1, the length of period differs among the various datasets. The most common period spans from 1979 through 2009; ERA-40 and 20CR end in August 2002 and December 2008, respectively. For these latter datasets, a basic one-dimensional multiple linear-scaling technique is applied to the HC indices monthly time series from the other six datasets in order to obtain a common period of 1979–2009 for all eight datasets. This is done by solving the following system of equations:

\[
[Y] = [b] \times [X],
\]

where \(Y\) is a one-dimensional array of length \(N\) containing the dependent variable \([y(N)]\); \(X\) is a two-dimensional array of size \([x(M + 1, N)]\), where \(M\) is the number of independent variables; and \(b\) is a one-dimensional array, with the same length as the leftmost dimension of \(x\), which contains the partial regression coefficients. In our case, \(b\) is obtained with the overlap period of the dataset (i.e., 1979–2002 for ERA-40 and 1979–2008 for 20CR).

Here, \(N\) corresponds to the overlap length and \(M\) corresponds to the number of datasets available over the full period of study. Then, \(b\) is used together with the \(M\) datasets over the nonoverlap period to extrapolate the ERA-40 and 20CR “missing” periods. We verified that the method is robust by comparing for instance the reconstructed HC indices from ERA-Interim for the first 10 yr (1979–88), with the “real” datasets that only became available recently (not shown).

The zonal-mean meridional streamfunction derived from the meridional wind fields is chosen to diagnose the HC. Not only is this dynamic quantity more likely to be well reproduced by the models, but the identification of the HC is based on physically meaningful occurrences of the quantity (i.e., maximum and zero value of the streamfunction), as noted by Davis and Rosenlof (2012).

The monthly zonal-mean meridional streamfunction \(\psi\) is computed from monthly-mean data (Buja 1994, B17–B18),

\[
\psi(p, y) = \frac{2\pi a \cos(y)}{g} \int_p^{P_s} V(p, y) \, dp,
\]

where \(V\) is the zonal-mean meridional wind, \(y\) latitude, \(p\) is pressure, \(P_s\) is surface pressure, \(a\) is the average radius of Earth, and \(g\) is the gravitational acceleration.

Figure 1a shows the annual-mean \(\psi\) determined from the NCEP-2. The circulation is depicted by alternating negative and positive cells. The HCs are the two strongest cells positioned directly adjacent north and south of the equator, with negative/positive values indicative of anticlockwise/clockwise rotation. The other cells correspond to the weaker Ferrel cells in the midlatitudes and the even weaker polar cells at high latitudes.
We define the extent (or edge) of the HCs by the zero isoline for $\psi$ on the poleward side of these cells, averaged between 400 and 600 hPa, although, as noted by SS11, the results are not strongly sensitive to the pressure levels chosen to determine the zero line. SS11 defined the width of the Hadley circulation as the distance between the first latitudes poleward of the cell centers in which the 700–400-hPa average value of $\psi$ equals zero, which is the width of both cells together. Here, the width of each cell is defined by the difference between these extents and the intersection between the two cells. The intersection represents the latitude of zero value of $\psi$, averaged between 400 and 600 hPa, near the equator (i.e., when $\psi$ changes sign as it passes from positive value in the NH cell to negative value in the SH cell), that separates the NH and SH cells. The seasonal cycle of extent, intersection, and width of the cells are illustrated in Fig. 1b. The seasonal cycle here highlights the difference in hemispheric behavior and justifies the need to consider the southern and northern cells of the Hadley circulation separately. The notable difference in evolution between extent and width also highlights the need to consider both indices for specific analyses such as interannual variability.

Here, the intensity is defined as the vertically averaged maximum value of $\psi$ between 900 and 200 hPa, marking the lower and upper limits of the cell (as indicated in Fig. 1). This avoids the introduction of possible disturbances at the surface and top of the atmosphere (e.g., friction). In most studies, the peak value of $\psi$ has been used to characterize the intensity of the HC. However, Mitas and Clement (2005) suggested that one cause of the discrepancies is that the $\psi$ maxima are at different levels in various reanalyses. In agreement to this, SS11 also mentioned the presence of anomalous northward velocities in JRA-25, CFSR, and NCEP-1 that are associated with a higher (altitude) location of the streamfunction maxima. Vertically averaging the maximum values at each level offers a way to minimize such discrepancies. We have also verified (not shown) that the results for intensity were relatively insensitive to the definition (i.e., whether using absolute maxima or vertically averaged values).

Time series of the annual-mean 200–900-hPa vertical mean $\psi$ together with the extents and intersection of the HC are displayed in Fig. 2 for all eight reanalysis datasets used in this study. The intensities of the HC are monitored by maximum $\psi$. First, interannual variability of the extent and intersection in all datasets is very similar to those of the zero lines of the 200–900-hPa average $\psi$, confirming the robustness of the definition regarding the choice of number of pressure levels. Second, strong interannual variability is evident in all indices and all datasets. In particular, the temporal evolution of the HC edges is markedly different between the two hemispheres, highlighting clear non-linearity. Finally, discrepancies between the datasets are clearly observable. These are analyzed in detail in the following sections. Figure 2 also exhibits a tendency toward long-term trends in both intensity and extent of the HC. This will be investigated in greater detail in section 4.

Long-term linear trends of the above HC indices are computed as the difference between the last 15 yr (1995–2009) and the former (1980–94). This is applied to monthly-, seasonal-, and annual-mean indices of the HC. Statistical significance of the resulting trends is assessed using Student’s $t$ test at the 95% significance level, using the null hypothesis that the trend is zero.

Tropical and extratropical effects on changes in HC indices are assessed by simple correlation analysis (section 5). The effect of ENSO on the HC is assessed using correlation coefficients computed between the indices of HC extent and intensity and the Southern Oscillation index (SOI). Extratropical variations are assessed by examination of the relationships with the AMs, using the SAM and the northern annular mode (NAM) indices. SOI and AM indices were obtained from the U.S. National Weather Service Climate Prediction Center (CPC; http://www.cpc.ncep.noaa.gov/products/).

As the two Hadley cells are characterized by opposite sign of $\psi$, we will keep the convention of positive values for the northern cell and negative for the southern cell. Because of this, the associated anomalies will also be of opposite sign. For example, a negative anomaly in extent describes a contraction in NH, while in SH it is associated with an expansion. Seasons here refer to the hemispheric seasons where summer corresponds to June–August (JJA) in NH and to December–February (DJF) in SH.

3. Overview of the Hadley circulation in the reanalyses

a. Annual cycle

The annual cycle of the Hadley cells in each hemisphere is shown by a plot of mean monthly extent versus intensity for all eight reanalysis datasets in addition to the ensemble mean (Fig. 3a). As expected, all datasets show a very similar large annual cycle. The two cells vary out of phase with one another, with the more poleward (stronger) cell located in the summer (winter) hemisphere. The southern cell is generally more intense but varies in latitudinal extent less on the seasonal time scale (cf. from 28°–38°S to 25°–44°N). The northern cell is characterized by relatively rapid poleward shift during summer followed by a gradual retreat equatorward and
FIG. 2. The 200–900-hPa vertical average $\psi$ ($10^5$ kg s$^{-1}$) for eight reanalysis datasets. Zero contours are indicated by black bold lines for the 200–900-hPa $\psi$ values and by gray bold lines for the 400–600-hPa $\psi$ values. Black bold dashed lines indicate the location of $\psi$ maximum.
an increase in maximum intensity by winter. This is then followed by a relatively sudden decrease in intensity so that the seasonal cycle can be described as triangular. The annual cycle of the southern cell is characterized by a crossover in the trace between winter and summer, drawing an asymmetrical lemniscate curve as shown in Fig. 3a. The configuration of the continents plays a crucial role in determining the properties of the HC (Cook 2003).

While the general behavior of the cells is similar in all datasets, there are some differences. For example, the NCEP-1, JRA-25, and 20CR datasets indicate a relatively more poleward NH cell during the winter to summer transition while the ERA-40 and CSFR datasets indicate the most equatorward extent at this time. The NCEP-1 dataset also indicates a low winter maximum intensity. The ERA-Interim dataset resembles the ensemble mean.

There is a greater consistency among the eight datasets in their representation of the SH cycle with all but two resembling the ensemble mean. The NCEP-1 dataset shows a weaker winter cell yet the summer intensity is

Fig. 3. Annual cycle of HC intensity ($10^9$ kg s$^{-2}$; negative for the SH and positive for the NH) vs (a) extent ($^\circ$S for the SH and $^\circ$N for the NH) and (b) width (degrees) from eight different reanalyses as indicated on the figure. The ensemble mean across the eight datasets is also shown (dashed black bold).
similar in all. The JRA-25 dataset shows the annual cycle shifted roughly 2° poleward compared to the others despite having a similar intensity. There is little consistency in the correlations (not shown) between the monthly indices of extent and intensity, consistent with SS11.

Another way to look at the temporal evolution of the HC is through the annual cycle of intensity versus width (Fig. 3b). This is motivated by the fact that the annual cycle of the intersection is large and tends to lead extent by a month, with extreme positions at about 15°S (15°N) in January (July) (Fig. 1b). Figure 1b shows that the width is at maximum in the winter hemisphere while the intersection is farthest poleward in the summer hemisphere. Figure 3b reveals a more linear evolution characterized by a rapid transition from winter to summer and back for both hemispheres. In this case, the monthly evolution of the two cells is fairly symmetrical about the equator. In contrast with the out-of-phase evolution between intensity and extent (Fig. 3a), the annual cycle is such that the maximum intensity is associated with maximum width and vice versa. This covariation between intensity and width of the HC is explained by the annual movement of the intersection from one hemisphere to the other. Lindzen and Hou (1988) showed that, for a given hemisphere, both the strength and width of the HC increase as the maximum heating is displaced poleward in the opposite hemisphere. Further, Plumb and Hou (1992) showed that the HC also strengthens and expands if the surface heating at the equator intensifies.

b. Interannual variability

Figure 4 shows the time series of the annual-mean intensity anomalies in terms of the percentage of the mean values given in Table 2 for both cells. There is a high degree of consistency in the variability with a range of values between −15% and +18% in the SH and between −20% and +25% in the NH and a slight tendency for both cells to vary similarly (i.e., anomalously strong NH and SH cells tend to be found in the same year). Some differences between the datasets include the fact that the variability within 20CR is weakest in both hemispheres throughout the period, with anomalies less than 10%. In contrast, the ERA-40 and MERRA anomalies are much higher, with maxima about twice the magnitude of those in 20CR. The time series of the ensemble mean anomalies indicate an increase in the NH cell but little change in the SH cell.

Figure 5 shows time series of the ensemble mean anomalies for each season together with the annual mean. Strong seasonality can be seen in both hemispheres. An

<table>
<thead>
<tr>
<th>Data</th>
<th>SH</th>
<th>NH</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEP-1</td>
<td>−91</td>
<td>84</td>
</tr>
<tr>
<td>NCEP-2</td>
<td>−112</td>
<td>95</td>
</tr>
<tr>
<td>CFSR</td>
<td>−134</td>
<td>96</td>
</tr>
<tr>
<td>ERA-40</td>
<td>−134</td>
<td>117</td>
</tr>
<tr>
<td>ERA-Interim</td>
<td>−121</td>
<td>102</td>
</tr>
<tr>
<td>MERRA</td>
<td>−122</td>
<td>91</td>
</tr>
<tr>
<td>JRA-25</td>
<td>−127</td>
<td>101</td>
</tr>
<tr>
<td>20CR</td>
<td>−114</td>
<td>95</td>
</tr>
<tr>
<td>ENS</td>
<td>−119</td>
<td>98</td>
</tr>
</tbody>
</table>
annual feature is apparent with strongest anomalies occurring in both the winter hemisphere (consistent with previous studies) and the spring hemisphere when the intensity transition is most pronounced (see Fig. 3). In contrast, the variability in the summer and autumn hemispheres is small and tends in phase opposition.

Annual-mean edge anomalies of the HCs (extents and intersection) are shown in Fig. 6. With a few exceptions, there is greater consistency compared with intensity. On occasion, marked differences from one or two datasets are observed compared to the others. There is some evidence for a poleward shift of the extent of both cells after 1997 that is also associated with some intensification. This poleward shift is accompanied by more scatter among the datasets, especially in the NH. JRA-25 and CFSR appear to be the outliers in both hemispheres, with strongest anomalies for the former and weakest values for the latter. The intersection time series show no significant trend, which is not surprising given that the intersection represents the location of the ascending branch of the HC and coincides with the zonal-mean intertropical convergence zone (ITCZ), which has no evident long-term trend. The correlation between intersection and extents is not significant (not shown). The distinct behaviors of the intersection and the extents suggest that, while the former is dominated only by tropical variability, the latter could also be influenced by extratropical variability.

The interannual evolution of the HC widths is shown in Fig. 7. In comparison with interannual variability of the extent (Fig. 6), most of the variability in extent is captured by variability in width. The main difference with the extent is that the outliers noticed previously in the extents such as MERRA and JRA-25 are now markedly amplified, which is contributed by the same outliers noted in the interannual variability of the intersection (Fig. 6). The correlations between extent and width are significant for both hemispheres ($r > 0.6$). This suggests that, while intraseasonal variability of intersection and extent can be explained by their respective locations (i.e., tropical versus polar), the nature of interannual variability and long-term changes are similar.

Time series of ensemble mean seasonal extent anomalies (Fig. 8) reveal largest variability during JJA [March–May (MAM)] in the NH (SH), which tends to dominates annual-mean variability (except post-1995 in the SH). During these seasons, the largest NH anomalies are about twice as large as those in the SH. The apparent expansion after 1997 seen in the annual mean appears to be a feature of all seasons in both hemispheres. The time series of the ensemble mean seasonal width behave similarly (not shown).

Correlations between annual-mean features from 1979 to 2009 are displayed in Table 3. Some values are statistically significant among some datasets, but there is no consistency on the sign of the relationships across all datasets. The relationship between intensity and width of the HC is consistent among most datasets but not always statistically significant. The sign of the correlations implies intensification in association with expansion of the
cells. There tends to be a significant negative relationship between the extents of the cells in each hemisphere, indicating out-of-phase behavior. In contrast, there is no consistent relationship in the behavior of the intensity of the cells. The relationship between the widths of the cells is generally negative but not significant.

4. Observed long-term trends in the HC

Time series of the HC indices (Figs. 4–8) suggest both an intensification and an expansion of the cells after 1997. More details of these trends are indicated by composite annual cycle of intensity versus extent (Fig. 9a)
for the 15-yr periods 1980–94 and 1995–2009. Although the anomalies are small, there is a distinct trend toward the poles for both cells and for most months, especially in the SH. Only October and December exhibit retreat toward the equator in the NH. In general, an intensification of the northern cell is observed, with the exception of a slight weakening in December and January. In contrast, the southern cell intensifies from October to April and weakens afterward. The annual cycle for intensity versus width is shown in Fig. 9b. While in the NH a poleward shift of the extent is associated with expansion, this is less evident in the SH.

This general overview is detailed further by quantifying the change between the two periods (i.e., the long-term trends; Fig. 10). The trends in intensity shown in Fig. 10a highlight some inconsistencies between the datasets. Five datasets show intensification of the NH cell (three of which are statistically significant), ranging between +3.6% (NCEP-1) and +22% (MERRA). Two (NCEP-2 and ERA-Interim) show small weakening trends (absolute values ≤3.3%) and one (20CR) shows no trend. Trends in the SH are similarly inconsistent, with three datasets showing intensification (NCEP-1, ERA-40, and MERRA); three weakening (CFSR, ERA-Interim, and JRA-25); and two showing no trend (NCEP-2 and 20CR). Only the ERA-40 dataset shows a statistically significant intensification of +12.2%. These differences between the datasets have been noted previously.

Table 3. Correlation coefficients computed using annual-mean values from 1979 to 2009 between intensity and extent $r_{SH_E}$ and $r_{NH_E}$ and between intensity and width anomalies from the Southern $r_{SH_W}$ and Northern $r_{NH_W}$ Hemisphere and for extent $r_E$, intensity $r_I$, and width $r_W$ anomalies between the two hemispheres. The ranges are indicated by the “min” and “max” signs in parentheses.

<table>
<thead>
<tr>
<th>Data</th>
<th>$r_{SH_E}$</th>
<th>$r_{NH_E}$</th>
<th>$r_{SH_W}$</th>
<th>$r_{NH_W}$</th>
<th>$r_E$</th>
<th>$r_I$</th>
<th>$r_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEP-1</td>
<td>0.46*</td>
<td>0.32</td>
<td>-0.62* (min)</td>
<td>0.51*</td>
<td>-0.7*</td>
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* Correlation values significant at the 95% level (Pearson’s $r$ test).
by Mitas and Clement (2005) and SS11. SS11 suggested that the inconsistency in the SH might be related to the different representation of stratospheric ozone in the models.

In contrast, a poleward shift in both hemispheres is evident in all datasets (Fig. 10b). The expansion varies between 0.4° (ERA-Interim) and 1.3° (JRA-25) for the NH and between 0.4° (CFSR) and 1.4° (JRA-25) for the SH (as shown by SS11). All but one of the SH trends (CFSR) are significant, whereas only one (JRA-25) of the NH trends is significant. This is due to higher interannual variability of the NH (see Fig. 7).

A poleward shift of the HC extent does not necessarily imply an expansion of the cell. As shown by the trends of the HC width (Fig. 10c), only the NH consistently shows expansion among all datasets, although only two datasets are statistically significant (MERRA and JRA-25). The trends in MERRA and JRA-25 are more than twice as large as the trends in extent, indicating an additional trend in the intersection. This difference is also seen in CFSR dataset. The other datasets exhibit trends very similar to their associated extents, indicating that there was no trend in the intersection. The same differences between extent and width are also seen in the SH. In the datasets where NH trends in width were larger than extent, the southern cell trends are reduced. This highlights the fact that a poleward shift of the HC extent does not necessarily imply its expansion but rather could be the effect of its counterpart cell expanding and “pushing” it poleward from its climatological position or even shrinking it. Therefore, in the SH, trends in CFSR and MERRA exhibit shrinkage while the JRA-25 dataset is close to neutral. By contrast, the other datasets show expansion. The lack of statistical significance here

Fig. 9. As in Fig. 2, but for the ensemble mean (over the eight reanalysis datasets) for different periods: 1980–94 (gray) and 1995–2009 (black).

Fig. 10. Trend (difference between the 1980–94 and 1995–2009 periods) of HC (a) intensity (% of the climatology), (b) extent (degrees of latitude), and (c) width (degrees of latitude). Gray filled bars are for SH and black empty bars are for NH. Trends significant at the 95% level are indicated by a star.
compared to the extent trends may be related to a larger interannual variability (Fig. 7). Note that the conservation of the combined trends of both cells from either extent or width indicates tropical expansion is consistent in all datasets.

The trends are not uniform throughout the year but vary with season (Fig. 11). In the NH, the intensification is most evident during the cool seasons [DJF, MAM, and at a lesser extent through September–November (SON)], whereas JJA shows a small weakening. In the SH, three datasets (ERA-40, MERRA, and NCEP-1) indicate intensification across all seasons peaking in winter (JJA). However, the other datasets are less consistent, indicating both increases and decreases from one season to the other. In summer (DJF), most datasets exhibit statistically significant but small intensification (<7%). These results are consistent with Quan et al. (2004), who suggested that the intensification of the NH winter HC was associated with tropical SST warming trends and increased rainfall in the Pacific warm pool. They also showed that the NH winter HC intensification did not have an equivalent during the SH winter because SST warming trends were very weak through winter. The different behavior between the Northern and Southern Hemisphere winter ultimately results in an observed intensification of the northern HC but not the southern during their winter season.

We investigate this hypothesis by comparing the seasonal trends in observed Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) v1.1 SST from the Met Office Hadley Centre (available from http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_hadisst) and Global Precipitation Climatology Project (GPCP) precipitation [provided by the NOAA/Oxford of Oceanic and Atmospheric Research (OAR)/Earth System Research Laboratory (ESRL)/Physical Sciences Division (PSD), Boulder, Colorado, from their website at http://www.esrl.noaa.gov/psd/] data for the period 1980–2009. Figure 12 shows linear trends for DJF and JJA together with the trend difference between the two seasons for these variables. SST trends over the tropical Indian and western Pacific Oceans are smaller in DJF than in JJA despite increasing precipitation trends north of the equator along the tropical belt, coinciding with the HC intersection (or ITCZ). Strong cooling trends associated with drying trends in the equatorial eastern Pacific dominate in DJF but tend to fade in JJA. An intensification of the HC implies acceleration of the mean meridional circulation and in the ascending branch of the HC, thus offers an explanation for increased rainfall. However, the SST trends pattern in DJF is rather similar to a La Niña pattern, which would contribute to decrease the HC intensity (Oort and Yienger 1996; SS11).

Perhaps more relevant to the NH winter cell intensification is the stronger SST warming in the subtropics at around 30°C in both the Pacific and Atlantic Oceans (Fig. 12). In a zonally symmetric model study where maximum thermal forcing is collocated with the northern extent of the HC, Plumb and Hou (1992) showed that, for a certain heating rate threshold, not only had the HC intensified but it also expanded to the opposite hemisphere. This, together with the SST trend difference, shows that the SST gradient in the subtropics might be a more likely mechanism to intensify the HC.

Consistent with the annual-mean trends (Fig. 10), seasonal trends of the HC extent also show better agreement between the datasets than for the intensity. As observed in the ensemble mean composite annual cycle (Fig. 9), the strongest poleward shift trends occur in summer and autumn hemispheres, with maxima of +2.3°C in SH for NCEP-2 and +2.8°C in NH for JRA-25 in summer. In the other seasons there is some slight evidence of poleward shift, except in winter hemisphere when the trends are smallest.
Seasonal trends of the width also show largest expansion in the hemispheric winter. These expansion trends are generally statistically significant. Trends for most seasons are consistent with those of the extent, except in JJA and SON, where the MERRA and JRA-25 exhibit the NH HC width expansion that is twice as large as extent trends. Seasonal trends of the intersection (Fig. 13) confirm that this discrepancy is due to the particularly large southward trend of the intersection during these seasons shown only in these two datasets. The trends in the HC intersection from MERRA and JRA-25 can also be seen in Fig. 6, where the intersection time series are marked by strong positive anomalies in the early 1980s and negative anomalies in late 1990s and early 2000s. A general southward shift of the intersection in MAM of about 0.5° on average is consistent with a reduced trend in the SH width compared to the extent.

5. The impact of large-scale modes of variability on the Hadley circulation

a. ENSO

To capture the effect of ENSO, we calculate an annual cycle from July of one year to June of the following year. This timing better approximates the natural ENSO cycle and avoids combining the effects in different ENSO cycles. Hence the period analyzed spans from July 1979 to June 2009. La Niña and El Niño events are
defined when SOI values magnitudes exceed +1 or −1, respectively. Composites are formed using the four strongest events in each category (Fig. 14a). El Niño events are more common in the first part of the record; La Niña events are more frequent in the latter part. To remove any potential effect of this sampling bias, the HC indices (i.e., extent, width, and intensity) are detrended using the least squares linear regression technique. The resultant composite annual cycles shown in Fig. 14b indicate a tendency for the HC extent to shift equatorward (poleward) during El Niño (La Niña), more markedly in SH. These shifts are associated with shrinkage/expansion of the HC (Fig. 14c). Changes in intensity during the cool seasons include a slight intensification/weakening associated with warm/cold phases of ENSO.

Correlations between HC indices (intensity, extent, and width in each hemisphere and intersection) and SOI values at annual and seasonal time scales are displayed in Table 4. Linear detrending of the HC indices was performed. Here, only the correlation coefficients associated with the ensemble mean and the range of values across the eight datasets are shown. These indicate statistically significant relationships between ENSO events and all HC indices but SH width and intersection in the
calculation. The reanalyses for the minimum and maximum values are shown in parentheses.

**Annual mean**
- Min: 0.06 (MERRA)
- Max: 0.54* (CFSR)

**Annual min**
- Min: 0.05 (MERRA)
- Max: 0.31 (ERA-25)

**Annual max**
- Min: 0.14 (CFSR)
- Max: 0.32 (MERRA)

**DJF mean**
- Min: 0.26 (JRA-25)
- Max: 0.34* (ERA-25)

**DJF min**
- Min: 0.04 (ERA-25)
- Max: 0.22 (MERRA)

**DJF max**
- Min: 0.32 (NCEP-2)
- Max: 0.29 (20CR)

**MAM mean**
- Min: 0.13 (MERRA)
- Max: 0.33 (CFSR)

**MAM min**
- Min: 0.21 (JRA-25)
- Max: 0.15 (20CR)

**MAM max**
- Min: 0.01 (NCEP-2)
- Max: 0.37* (NCEP-2)

**JJA mean**
- Min: 0.04 (MERRA)
- Max: 0.24 (CFSR)

**JJA min**
- Min: 0.04 (MERRA)
- Max: 0.37* (NCEP-2)

**JJA max**
- Min: 0.05 (20CR)
- Max: 0.43* (CFSR)

**SON mean**
- Min: 0.08 (MERRA)
- Max: 0.07 (ERA-25)

**SON min**
- Min: 0.02 (ERA-25)
- Max: 0.03 (20CR)

**SON max**
- Min: 0.06 (20CR)
- Max: 0.29 (CFSR)

* Correlation values significant at the 95% level (Pearson’s r test).

The intensification is associated with contraction of the HC consistent with the findings of Lu et al. (2008) using the phase 3 of the Coupled Model Intercomparison Project (CMIP3) models. The intensification in association with contraction here has been linked to an increase in meridional temperature gradient, which results in an intensification of the thermally driven HC (Reichler 2009). The expansion might be caused by a reduction in baroclinicity in the subtropics driven by an increase in (dry) static stability and/or by an increase in the phase speed of upper-tropospheric baroclinic waves (Lu et al. 2008). The negative correlation (r = −0.32) between the SOI and intersection, though not statistically significant, suggests that the location of the ITCZ is likely to be affected by ENSO in the way that it moves northward during warm events and southward during cool events.

At seasonal time scales in the NH, these correlations remain statistically significant only through DJF for intensity when interannual variability is greatest (see Fig. 5). Oort and Yienger (1996) also showed an intensification of the NH cell during DJF of between 10% and 20%. This rate is stronger than that found by SS11 (6%). Seasonal correlations with extent are statistically significant though only in JJA as interannual variability is greatest. This is in stark contrast with the width, which is statistically significant in DJF, likely because of the statistically significant negative correlation between SOI and intersection (r = −0.64). In DJF, the intersection is in the SH and a negative correlation with SOI indicates that it will tend to move equatorward during a warm phase and consequently contribute to a contraction in the northern HC. The opposite occurs during cool phase.

This picture is less clear in the SH. Links to intensity are statistically significant only during SON. However, links to extent are significant in all seasons but JJA. This can partly be explained by the seasonality of the SH HC indices. Although their differences are not as marked as in the NH, intensity and extent anomalies in the SH tend to dominate in the seasons when correlations with SOI are statistically significant (Figs. 5, 8). The fact that correlations between SOI and HC SH intensity were significant only in SON may explain the results in SS11 that ENSO impact on the southern cell in JJA was not significant or consistent among the datasets.

Similar to the NH in DJF, in the SH winter, correlation between SOI and width is statistically significant in...
JJA ($r = -0.41$). This is explained in terms of statistically significant correlation between SOI and intersection ($r = 0.4$) with the same arguments as in DJF for the NH, with the intersection now located in the NH.

b. Annular modes

The annular modes are the leading patterns of climate variability in the extratropics (Baldwin and Dunkerton 1999). They are characterized by geopotential height perturbations of opposing signs in the polar cap region and in the surrounding zonal ring around 45° latitude (Thompson and Wallace 2000). They exist all year round, being most active during midwinter (JFM) in the NH (NAM) and late spring (November) in the SH (SAM) and most inactive during JJA in both hemispheres (Thompson and Wallace 2000). Their impact on the tropical troposphere is mainly evident with midtropospheric temperature anomalies around 20° latitude and opposing mean meridional circulation anomalies (Thompson and Lorenz 2004).

Here correlations between HC indices (intensity, extent, and width of each hemisphere) and NAM and SAM indices for the annular modes were computed at annual- and seasonal-mean time scales (Table 5). Both cells tend to be more extensive when the annular modes are more intense and vice versa. This is seen in all seasons with the weakest relationship seen during JJA when the AMs are most inactive. In contrast to this clear signal, there is no obvious relationship between the intensity of the cells and the AM indices.

When the AM index is positive the HC expands farther. Physically, the linkage is plausible. A positive AM suggests a displacement of the storm track and the associated eddy-driven jet stream. This is consistent with the interannual relationship identified by Kang and Polvani (2011) in both the CMIP3 multimodel database and the NCEP–NCAR reanalysis during DJF, but not in JJA. The results here agree and extend this to the equinoctial seasons, which were not examined in their study.

Expansion of the HC cells could be associated with positive trends in AMs over the last few decades, particularly in the SH. Several studies (e.g., Thompson and Solomon 2002; Gillett and Thompson 2003; Arblaster and Meehl 2006) have attributed trends in SAM to the formation of the Antarctic ozone hole during austral spring (SON). Son et al. (2008) showed that twentieth-century simulations in CMIP3 containing ozone forcing had greater tropical expansion. They directly confirmed this result using chemistry climate models (Son et al. 2010). Model simulations have clearly shown that stratospheric ozone depletion can result in a distinct poleward shift of the HC edge (Polvani et al. 2011). It

**Table 5.** Correlation between annual-mean ensemble mean HCI and HCE and annular modes (NAM for the NH and SAM for the SH) index. The reanalyses for the minimum and maximum values are shown in parentheses.

<table>
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*Correlation values significant at the 95% level (Pearson’s r test).
should be noted that these trends are more robust in the SH (Thompson and Solomon 2002; Marshall 2003; Fu et al. 2006) in contrast to its northern counterpart, which was ambiguous (Marshall et al. 2001; Cohen and Barlow 2005; Overland and Wang 2005; Hurrell et al. 2001).

While ozone is expected to recover by the mid-twenty-first century, tropical expansion and positive AM trends are expected to continue. Simulations from CMIP3 clearly show a widening by the end of the twenty-first century (Lu et al. 2007). Previdi and Liepert (2007) used CMIP3 models to suggest that changes to the AM account for about half of the projected changes in the HC and subtropical regions. Similarly, Sobel and Camargo (2011) identified robust changes to the tropical SST and trade winds from CMIP3 models associated with an expansion and weakening of the HC. They hypothesized that the HC is not the driver of these changes but ultimately a response to the changing character of the extratropical baroclinic eddies in an enhanced-GHG climate. Yin (2005) indicated a poleward shift of the storm track and associated change in the AM of both hemispheres in GCM simulations using SRES emission scenarios. This change is associated with a warming of the tropical upper troposphere and a poleward shift in the baroclinicity. Lim and Simmonds (2009) further found that the increased temperature gradient in high latitudes also plays a role in the poleward shift of the storm tracks.

6. Concluding remarks

A detailed analysis has been conducted into the behavior of the Hadley circulation as it is represented in eight existing reanalysis datasets. Indices such as intensity, edges, and width of the Hadley cells in each hemisphere were defined from the most commonly used zonal-mean meridional streamfunction. The complete annual cycle of the HC in each hemisphere was documented. This analysis offers as complete a view of the HC as is possible with current reanalyses. In addition to the annual-mean view of the HC as in SS11, a month-to-month evolution of the HC indices was highlighted. We also show that the extent and width of each cell can evolve differently; variability in the NH cell can be twice as strong as the SH. Finally, long-term trends of the annual average are consistent with previous studies: namely, the total smallest/largest expansion is obtained from CFSR/JRA-25. These trends are more complex in seasonal averages and indicate the need to consider each cell separately. For instance, we showed that, in autumn, the SH is marked by an average poleward shift of the intersection by 0.6° and of the extent by 1.2° over 30 yr.

While results from the reanalyses show a general qualitative agreement with one another, significant differences exist in the strengths and tendencies of the analyzed features, both within a given season and over the longer-term. This is clearly seen in the annual cycle of the HC. One source of uncertainty appears to be the different formulations of “model physics” like radiation and clouds. Another possible source of uncertainty is the different methods used in assimilating the observational data, particularly the satellite radiances. Changing observing systems and introduction of significant satellite systems around 2000 raise the question of whether the reanalyses are suitable for use in long-term climate studies. The role of inhomogeneities in reanalysis data still remains very unclear (Lucas et al. 2012). The historical radiosonde data also have uncertainties, in part due to changing instrumentation over the course of the record (Lazante et al. 2003). The large parts of the globe, primarily the oceans that are unobserved but also make up the observing network, introduce uncertainty. These “data voids” affect the interpolation and gridding of the data, which, along with the homogeneity adjustments, do not appear to maintain the appropriate dynamical balance between the wind and temperature fields (Allen and Sherwood 2008).

Finally, the relationship with ENSO and annular modes was tested. In annual-mean, intensity and extents are significantly correlated with ENSO, suggesting shrinking together with intensification during warm phases of ENSO and the opposite behavior during cool phases of ENSO. These relations become more complex at seasonal time scales. The correlations between seasonal-mean values of HC indices and the SOI do not remain statistically significant for all seasons. SS11 showed that, while intensity was influenced by ENSO in winter hemispheres, there was no significant relationship with the width. They also suggested that the less evident relationship between SH intensity and ENSO could be related to other influences such as stratospheric ozone. However, we showed here that highest correlation between SH intensity and ENSO index was not in winter but spring, which may explain their poor relationships. In addition, they only compared calendar annual-mean HC width (including both SH and NH) with ENSO. Yet our results show strong correlation with annual-mean values centered on the increasing phase of ENSO (i.e., centered on December) and a hemispheric asymmetry in terms of seasonal-mean correlations.

In addition, the statistically significant correlations between SOI and HC intersection in DJF and JJA suggest that the location of the ITCZ is influenced by ENSO during these seasons. In particular, it tends to
move equatorward/poleward from its hemisphere summer position during warm/cool events.

A statistically significant relationship exists between indices of the AMs and the extent and width of the cells in both hemispheres and all seasons. This implies that the HC intersection is not affected by the AMs. This is partly understandable since the annular modes reflect the redistribution of pressure between middle and high latitudes, which, in turn, will have an effect on the zonal average winds and position of the cells. Previous studies have attributed the expansion of the cells to increasing greenhouse gas concentrations (Lu et al. 2009), aerosol (Allen et al. 2012), ozone depletion (Lu et al. 2009; Kang et al. 2011; Polvani et al. 2011), SST warming, and their combined effects (Staten et al. 2011). Sigmond et al. (2011) showed through a model study that the main drivers of positive trends in SAM index were both greenhouse gases and ozone depletion, with the first factor tending to strengthen the SAM in April–June and the second tending to strengthen it in summer. Indeed, positive trends in the SAM index (Thompson and Solomon 2002) and SH ozone depletion in summer since early 1980s (Son et al. 2008; Polvani et al. 2011) may partly explain the observed relationship between HC expansion and the annular mode. Therefore, hypothetically enhanced greenhouse gases intensify the SAM and expand the Southern Hemisphere cell in April–June, while ozone depletion intensifies the SAM and expands the southern cell in summer. This hypothesis is currently under investigation.

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