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Reconciling Hadley Cell Expansion Trend Estimates in Reanalyses

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Key Points:
- Hadley cell expansion trends in early-generation reanalyses are larger than those in modern reanalyses
- The majority of these larger trends are impacted by mass nonconservation in the mean meridional circulation
- When this is corrected, Hadley cell expansion trends in early-generation reanalyses converge toward those in modern reanalyses

Supporting Information:
- Supporting Information S1

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Abstract Numerous studies have concluded that historical Hadley cell expansion simulated in reanalyses is much larger than the future expansion predicted by climate model simulations. Is Hadley cell expansion too weak in climate models, or are the trends in reanalyses spuriously large? This study shows that the mean meridional circulation in reanalyses generally does not conserve mass. The mass imbalance projects onto trends in the Hadley cell edge latitudes by modifying both the mean and anomalous circulation. In correcting for the imbalance, the majority of Hadley cell expansion trends in early-generation reanalyses in both hemispheres are revised to be smaller in magnitude, bringing them into closer agreement with the trends in modern reanalyses and climate models. While the methodology presented here is statistical in nature, it produces quantitatively similar results to a more sophisticated mass budget correction method.

Plain Language Summary Reanalyses are weather forecast models that use observations to constrain hindcasts of the past evolution of Earth's atmosphere. They are one tool used to study the Hadley cells, two large circulation cells in the tropics with far-reaching impacts on Earth's climate. The amount the Hadley cells expanded in older reanalysis products was much larger than what was simulated in climate models. However, some of this expansion is due to the violation of a basic physical law. When this is corrected, the expansion in older reanalyses is closer to the expansion in more modern reanalyses. It is possible that some of the supposed discrepancy between models and reanalyses was due to these sorts of problems in the older reanalyses.

1. Introduction

While differential solar heating of Earth's surface leads to the meridional variation of temperature, the Hadley circulation shapes the climate of Earth's tropical belt by redistributing heat and water vapor. Deserts and stratocumulus decks form at the belt's northern and southern edges on the eastern side of ocean basins, where subsidence dries and stabilizes the atmosphere. Water vapor in these subtropical dry zones is converged onto the equator by the trade winds, where it heats the air through condensation and drives the upward motion in the Hadley cells. Divergent flow aloft carries this warm air poleward, where it can be tapped by eddies and transported into the midlatitudes (Trenberth & Stepaniak, 2003).

Models predict that the Hadley cell edges will expand poleward in response to radiative forcings (Davis et al., 2016; Grise & Polvani, 2016; Hu et al., 2013; Lu et al., 2007), and there is emerging evidence that such changes may have already occurred (Choi et al., 2014; Davis & Rosenlof, 2012; Lucas et al., 2014; Seidel et al., 2008; Tselioudis et al., 2016). With strong gradients in temperature, humidity, precipitation, and wind at the belt's edges, any poleward shift in the circulation could project strongly onto the surface climate of Earth's most populous latitudes (Birner et al., 2014). As there are insufficient observations to study the mean meridional circulation directly (Waliser et al., 1999), reanalyses have been used to estimate past trends in the Hadley cell edge latitudes (Allen et al., 2012; Davis & Birner, 2013; Hu & Fu, 2007; Johanson & Fu, 2009; Nguyen et al., 2013; Stachnik & Schumacher, 2011). These studies have shown a statistically significant poleward movement of the Hadley cell edge latitudes in both hemispheres over the last ~30 years, and a number of studies have concluded that climate model trends are much weaker than those in reanalyses (Johanson & Fu, 2009; Quan et al., 2014). However, a recent study using modern reanalyses suggests that the disagreements, if they exist, are potentially small (Davis & Birner, 2017), especially in light of the magnitude of internal variability (Garfinkel et al., 2015).

This paper addresses the extent to which these seemingly conflicting conclusions are driven by the use of early-generation versus modern reanalyses (defined in the next section), and why the results might be reanalysis dependent. It is well known that reanalyses may have spurious trends, as the combination of model biases and inhomogeneities in the observing/assimilation system may lead to unphysical jumps and violations of mass/energy conservation (Bengtsson et al., 2004; Berrisford et al., 2011; Long et al., 2017; Quan et al., 2014). Here we explore the possibility that Hadley cell expansion trends in early-generation reanalyses are spuriously large and that the modern reanalyses more accurately reflect past changes in Hadley cell width. To the extent possible we want to know whether inhomogeneities in reanalysis mass conservation relate to spurious changes in the mean meridional circulation, and what effect this might have on Hadley cell edge latitude time series and their derived trends. We will also examine possible corrections for mass nonconservation and how these corrections relate to the previously reported discrepancies among reanalysis trend estimates of Hadley cell expansion.

2. Data

We use vertical and meridional winds from nine reanalyses: the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al., 1996), the NCEP/Department of Energy (DOE) reanalysis (Kanamitsu et al., 2002), and the Climate Forecast System Reanalysis Version 2, hereafter *CFSR* (Saha et al., 2010); the European Centre for Medium-Range Weather Forecasting (ECMWF) 40-year Reanalysis, hereafter *ERA-40* (Uppala et al., 2006), and the ECMWF Interim Reanalysis, hereafter *ERA-Interim* (Dee et al., 2011); the Japanese Meteorological Agency 25-year Reanalysis, hereafter *JRA25* (Onogi et al., 2007), and the Japanese Meteorological Agency 55-year Reanalysis, hereafter *JRA55* (Kobayashi et al., 2015); and the National Aeronautics and Space Administration (NASA) Modern Era Retrospective Analysis for Research and Applications (Rienecker et al., 2011), hereafter *MERRA*, and the Modern Era Retrospective Analysis for Research and Applications 2 (Gelaro et al., 2017), hereafter *MERRA2*. We use the assimilation, or *asm* product, rather than the analysis, or *ana* product, from MERRA and MERRA2 (the resulting trends are sensitive to the output product [Garfinkel et al., 2015]). For further information on these reanalyses, see Table 1 of Fujiwara et al. (2017).

JRA55, MERRA2, CFSR, and ERA-Interim are designated here as modern reanalyses, as they represent each agency's most recent reanalysis product. NCEP/NCAR, NCEP/DOE, ERA-40, JRA25, and MERRA are referred to here as early-generation reanalyses. We recognize this distinction is somewhat arbitrary for MERRA, as MERRA is just as modern as ERA-Interim. Nevertheless, MERRA is NASA's first-generation reanalysis product and has since been supplanted by MERRA2, so it is no longer NASA's state-of-the-art product.

We also use 36 Coupled Model Intercomparison Project—Phase 5 (CMIP5; Taylor et al., 2012) Historical and 23 CMIP5 RCP8.5 simulations, with the models listed in the supporting information.

Our period of analysis is 1980 through 2009, though ERA-40 ends in 2001 and JRA25 ends in 2004.

3. Methods

The mean meridional stream function (MMS) is the standard variable for examining the Hadley cells. It is defined as the meridional mass flux between a given level and the top of the atmosphere, that is,

$$\Psi(p,\phi) = \frac{2\pi a\cos\phi}{g}\int_p^0 [v]\mathrm{d}p, \tag{1}$$

where $\Psi(p, \phi)$ is the MMS at pressure p and latitude ϕ, a is the radius of the Earth, g is the gravitational acceleration, and $[v]$ is the zonal mean meridional wind where brackets indicate the zonal mean. We define the Hadley cell edge latitudes as the latitudes of the zero crossing of the MMS at 500 hPa in each hemisphere poleward of each hemisphere's maximum absolute MMS.

For a meridional circulation that conserves mass, the vertical velocity is a function of the meridional gradient of the MMS and is given by

$$[\omega](p,\phi) = -\frac{g}{2\pi a^2\cos\phi}\frac{\partial\Psi(p,\phi)}{\partial\phi} \tag{2}$$

where $[\omega]$ is the zonal mean vertical pressure velocity. For the purposes of this study, it is worth emphasizing that by construction the stream function is able to simultaneously describe the vertical and meridional flow

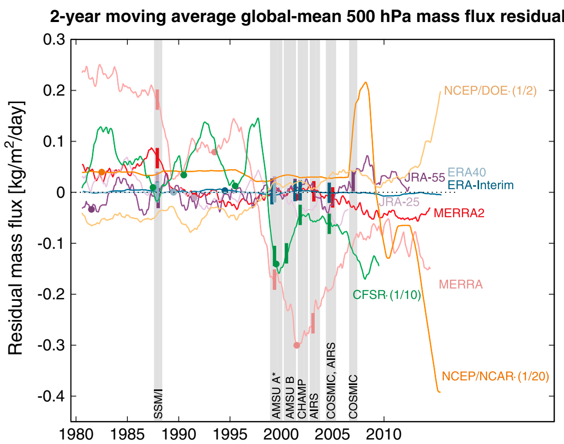

Figure 1. Twenty-four-month running mean residual mass flux at 500 hPa from the nine reanalyses. Dots indicate data stream transitions; vertical bars indicate the assimilation of new satellite observations, with vertical gray bars indicating the particular satellite mission. Dates of both data stream and satellite transitions and color scheme from Fujiwara et al. (2017). NCEP/NCAR, NCEP/DOE, and CFSR scaled by factors of 1/20, 1/2, and 1/10, respectively. For the AMSU A transition, MERRA and MERRA2 begin to assimilate both AMSU A and B. For the COSMIC and AIRS transition, CFSR and ERA-Interim begin to assimilate AIRS, while MERRA2 begins to assimilate COSMIC.

only if mass is conserved. Without this constraint, two-dimensional flow cannot be described by a single variable.

As isobars in a hydrostatic fluid are surfaces of constant vertically integrated mass, the globally integrated vertical mass flux on an isobar must be 0 (the mass flux is equivalent to the vertical pressure velocity divided by g). Otherwise, mass conservation is violated. One might be tempted to use the vertical velocity derived from the MMS to test whether the MMS conserves mass. But by construction, the vertical pressure velocity derived from the MMS will be exactly what is required to conserve mass given any meridional wind field.

This presents a conundrum, as we cannot use the MMS itself to test whether the MMS conserves mass. Instead, we examine the global mean of the vertical mass flux at 500 hPa in the reanalyses. As it should be 0 if the circulation conserves mass globally, we refer to this quantity as the global mean *mass flux residual*. Five hundred hectopascals is chosen as it is most relevant for the Hadley cell edge latitude metric. In models the vertical pressure velocity is generally diagnosed from the surface pressure tendency and the divergence of the horizontal winds (e.g., it is the vertical mass flux necessary to close the column mass budget). It is therefore at minimum as well constrained as the zonal mean meridional wind.

It may be the case that a reanalysis conserves mass, at least as measured by the global mean surface pressure (e.g., Gelaro et al., 2017) but does not conserve mass locally as measured by the global mean mass flux residual at 500 hPa. Local inconsistencies between the vertical and horizontal circulation may arise because of the analysis tendencies imposed on the horizontal winds and the geopotential. Regardless of whether the reanalysis conserves global mean mass or not, any local mass nonconservation in the circulation could project onto variability and trends in the Hadley cell edge latitudes.

4. Results

We first examine the 2-year moving average monthly mass flux residual at 500 hPa (Figure 1; the raw time series are shown in Figure S1 in the supporting information). Here positive values indicate a net downward mass flux—the same sign as the pressure velocity. For reference, the values shown here range from 0.5% to 3.0% of the root-mean-square 500 hPa mass flux in the reanalyses (or approximately on the order of parts per hundred of the atmospheric mass on daily timescales). In many cases, the variability in mass balance across reanalyses is uncorrelated, which could be taken as characteristic of a nonphysical process.

In addition to the mass flux residual, Figure 1 notes data stream transitions and satellite transitions to aid in the interpretation of variability in the mass flux residual. During a satellite transition, a reanalysis begins to assimilate a new set of satellite observations with new biases and coverage statistics. These changes to the observing system can introduce artificial changes into the simulated climate. During a data stream transition, two different reanalysis simulations are stitched together to a form a complete record of the climate system, which can create similar discontinuities. The satellite transitions indicated include the Special Sensor Microwave/Imager (SSM/I), Advanced Microwave Sounding Unit (AMSU) A and B, the Atmospheric Infrared Sounder (AIRS), and the Challenging Minisatellite Payload (CHAMP) and Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC) Global Positioning System-Radio Occultation sytems. Further information, including the dates of most of these transitions, can be found in Fujiwara et al. (2017). We will comment on the coincidence of these transitions and peculiar behavior in the mass flux residual, but we do not assess the plausibility of these transitions in causing such behavior.

ERA-Interim and ERA40 are nearly indistinguishable, in part because their mass flux residual is essentially 0 throughout the data record. There does appear to be a minor trend in the mass flux residual in ERA-Interim.

MERRA transitions from a positive to near-zero mass flux residual after the SSM/I transition and then to a negative mass flux residual during a data stream transition and during the period when AMSU A, AMSU B, Atmospheric Infrared Sounder, and COSMIC began to be assimilated. MERRA2 is clearly an improvement over MERRA, though it exhibits a long-term drift over the record, in part due to a reduction in the mass flux residual after the SSM/I transition.

Improvement is also evident between JRA25 and JRA55. JRA25 has a positive mass flux residual in the late 1980s, before a data stream transition and when SSM/I began to be assimilated. Later, it transitions from near zero to negative after it began to assimilate AMSU data. In contrast, JRA55 maintains relative mass balance throughout the modern era, with minor variability around the SSM/I and COSMIC transitions. Even in the early 2000s, when there were substantial changes to the observing system, JRA55 exhibits little variability.

NCEP/NCAR, which must be scaled by a factor of 1/20 to fit within the plot axes, exhibits several abrupt shifts in mass flux residual after the year 2006 (see also Figure S1). Perhaps because of the improvements in the representation of physical processes between NCEP/NCAR and NCEP/DOE, the mass flux residual in NCEP/DOE is smaller over most of the observational period. In the 2010s the mass flux begins to rapidly diverge toward larger values. However, the connection between satellite transitions and unphysical behavior in NCEP/NCAR and NCEP/DOE is not as straightforward to assess as it is in other reanalyses. NCEP/NCAR and NCEP/DOE assimilate temperature retrievals, unlike the other reanalyses that assimilate radiance measurements. While CFSR does not have such abrupt changes in its mass flux residual, it does have the largest root-mean-square mass flux residual with a substantial long-term trend. Like MERRA, it displays a rapid shift from positive to negative values in the late 1990s and early 2000s, coincident with the AMSU transitions. However, it appears that CHAMP may reanchor CFSR to a lower mass flux residual shortly thereafter.

We have examined the impact of horizontal resolution on the mass flux residual to test whether the mass flux residual is a numerical artifact (Figure S2). Here we examine the root-mean-square mass flux residual, rather than the mean or standard deviation, as we are interested in quantifying representative values of the mass flux residual regardless of sign. In subsampling the reanalyses to coarser resolutions, we find that the root-mean-square mass flux residual does not increase. This suggests that the mass flux residuals are not artifacts of insufficient horizontal resolution but are instead large-scale features of the modeled climate in reanalyses. As a measure of calculation uncertainty, we also calculated the root-mean-square mass flux residual in the JRA55-AMIP simulation and in the CMIP5 Historical simulations. In these simulations, the underlying model is not coupled to an assimilation system and is expected to better conserve mass. The CFSR, NCEP/NCAR, NCEP/DOE, and MERRA reanalyses have mass flux residuals greater than the estimates from the CMIP5 and JRA55-AMIP simulations, suggesting that their mass flux residuals are likely to be manifestations of mass non-conservation. On the other hand, the mass flux residuals in the remaining reanalyses are indistinguishable from our estimate of calculation error.

To gain some insight into the impact of this mass flux residual on the circulation, we regress the MMS onto the monthly standardized, detrended mass flux residual (i.e., with zero mean and standard deviation of 1) in each reanalysis using a standard linear least squares regression (Figure 2). We do not assume that the climatological circulation in the reanalyses conserves mass, so we do not deseasonalize the index. For both the NCEP/NCAR and NCEP/DOE regressions, we exclude all values of the mass flux residual past 2006 when the abrupt changes occur. The regressions are marginally different if the regression is performed through 2009 (see Figure S3). For NCEP/NCAR, the regression pattern appears more similar to the others if one scales the regression by more than one standard deviation, for example, representative of the abrupt shifts (also see Figure S3).

In general, the mass flux projection is dominated by a single negative cross-equatorial cell in the tropics of the same sign as the Southern Hemisphere winter cell. In most reanalyses the projections also have two positive-signed cells along the zero contour of the MMS of the same sign as the Northern Hemisphere Hadley cell (Figure 2). These anomalies project oppositely onto the Hadley cell edge latitudes in each hemisphere. For example, given a positive mass flux residual the regressions indicate that the residual is associated with an anomalously poleward Northern Hemisphere Hadley cell edge and an anomalously equatorward Southern Hemisphere Hadley cell edge. CFSR is an outlier as it indicates opposite-signed impacts to the two hemispheres. ERA-Interim is also an outlier with no projection onto the Southern Hemisphere subtropical circulation. While the mass flux residual is small in ERA-Interim, its projection is concentrated at the Northern Hemisphere Hadley cell edge. Crucially, the projection in ERA-Interim for a given standard deviation change in the mass flux residual is quantitatively similar to the other reanalyses. In every reanalysis except

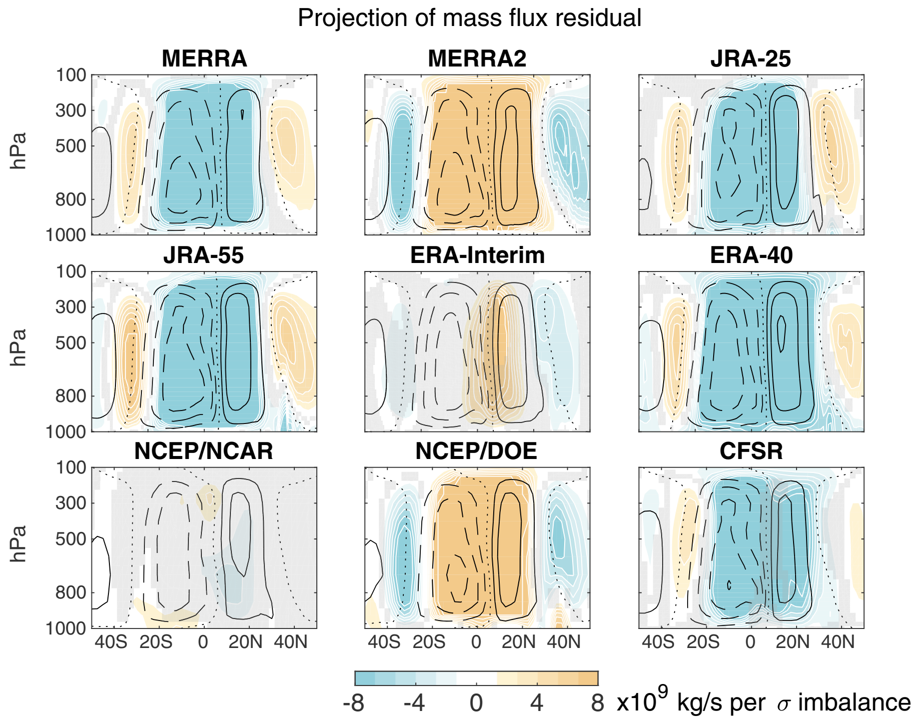

Figure 2. The projection of the mass flux residual onto the mean meridional stream function from the nine reanalyses (shading). Also shown is the annual mean meridional stream function (black contours, positive values in solid, negative values in dashed, zero line in dotted, every 30×10^9 kg/s) from each reanalysis. Gray shading indicates coefficients not statistically significant at the 95% confidence level. Projections (and mass flux residuals in Figure 1) for the MERRA2, ERA-Interim, and NCEP/DOE reanalyses multiplied by -1 for ease of comparison.

NCEP/NCAR and ERA-Interim, the projections are mostly statistically significant wherever the values are contoured.

As the mass flux residual projects onto the MMS, it is possible to correct for the impact of mass nonconservation on the MMS by removing the projection of the mass flux residual at each time step. We derive the projection of the monthly mean mass flux residual on the MMS for each month, remove this from the monthly mean MMS to construct the *corrected* monthly mean MMS, and average the corrected monthly mean MMS into the corrected annual mean MMS. While this correction is entirely statistical in nature, we will corroborate some of our results using the more rigorous mass correction methodology of Trenberth (1991).

As noted before, we do not deseasonalize the mass flux residual or MMS, and for the correction we also do not detrend, either, though the regression coefficients used to correct the MMS are based on the detrended regression. Trends in the Hadley cell edge latitude are not a function of MMS anomalies alone but instead the superposition of MMS anomalies and the climatological MMS. For different meridional gradients in the climatological MMS, a given MMS anomaly will produce different changes in the Hadley cell edge latitude. It is therefore important to consider the impact of the mass flux residual on both the MMS anomalies and climatology.

Our focus is the impact of this correction on trends in the Hadley cell edge latitudes calculated from the annual mean MMS. Past studies have generally focused on these annual mean trends as the edge latitudes are often poorly defined in the summer months on monthly timescales. For NCEP/NCAR and NCEP/DOE, we use the regression pattern from Figure 2, which was only calculated based on data through 2006, on the full time series through 2009.

Correcting for the mass flux residuals generally decreases Northern Hemisphere and Southern Hemisphere expansion trends, although the impact differs by reanalysis product and is less robust in the Southern Hemisphere (Figure 3). In the Northern Hemisphere, the substantial and statistically significant poleward

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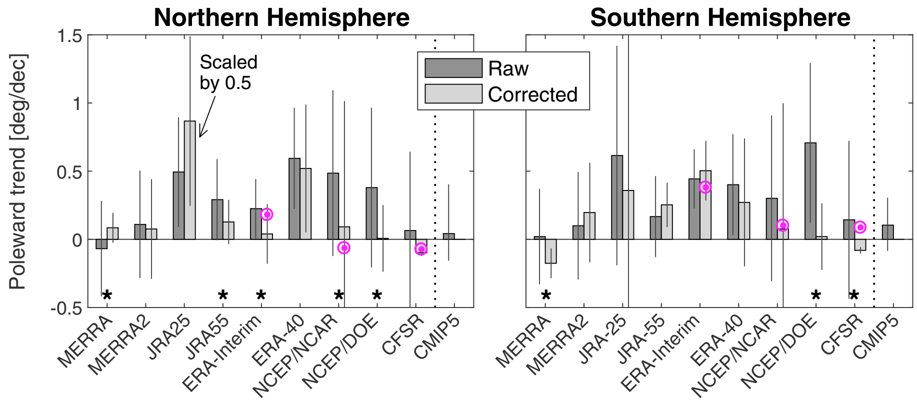

Figure 3. Raw and corrected poleward trends in the Hadley cell edge latitudes in the Northern (left) and Southern (right) Hemispheres in the annual mean. Whiskers indicate 95% confidence intervals using the effective degrees of freedom, or, for CMIP5, the range of model trends. Stars indicate that the raw and corrected trends in the given reanalysis are statistically significantly different at the 95% confidence level. Magenta circles indicate the poleward trends in the Hadley cell edges using the Trenberth (1991) mass correction method—see text. Note that ERA-40 trends are through 2001, JRA25 trends are through 2004, and all others are through 2009.

trends in NCEP/NCAR and NCEP/DOE are reduced by over 80% using the corrected data. In JRA55 and ERA-Interim, the already-low trends are halved, and in MERRA the slightly negative trend is corrected to be more positive. For all of these reanalyses, the raw and corrected trends are statistically significantly different at the 95% confidence level (assessed as in Lanzante, 2008). The trends are not significantly different in MERRA2 or CFSR. Somewhat surprisingly, there are no statistically significant trend revisions for either ERA-40 or JRA25 in either hemisphere. Both reanalyses have spurious trends and biases in their precipitation and temperature fields that may contribute to their expansion trends, regardless of whether the circulation is corrected to conserve mass (Kobayashi et al., 2015). Despite this, the average expansion trend in the Northern Hemisphere decreases from 0.34 ± 0.08° to 0.17 ± 0.07° per decade. Ignoring JRA25, the trend decreases from 0.29 ± 0.08° to 0.13 ± 0.07° per decade.

In the Southern Hemisphere, the poleward trends in NCEP/DOE and CFSR decrease, and the poleward trend in MERRA decreases so as to become equatorward. There are no other statistically significant changes. The average expansion trend decreases from 0.32 ± 0.08 to 0.19 ± 0.07° per decade, meaning that the average expansion trends are nearly identical in both hemispheres whether one examines the raw or corrected data. It is worth noting that in NCEP/DOE and ERA-40, the raw trend was statistically significant but the corrected trend is not. In the Northern Hemisphere, this is also true for ERA-Interim and NCEP/DOE. On the other hand, in JRA55, CFSR, and MERRA in the Southern Hemisphere the trends are revised to be significant. Of note is that the corrections to MERRA, MERRA2, JRA25, JRA55, and ERA-Interim are of opposite sign in the two hemispheres. In MERRA2 and JRA-55, the corrections are of nearly the same magnitude such that the correction in the total (north plus south) expansion trend is small.

Also displayed in Figure 3 are the Hadley cell expansion trends assessed from the MMS corrected using the methodology of Trenberth (1991). Trenberth (1991) describes a barotropic correction to the horizontal winds, which corrects for mass nonconservation in global analyses by taking into account the column-integrated mass budget residual. This scheme must be implemented on the highest time resolution reanalysis output available and so is costlier to perform than the statistical technique used here. We have therefore performed this correction using budget data readily available for three of the reanalyses from the National Center for Atmospheric Research and described in Trenberth and Fasullo (2018; see Acknowledgements). The Trenberth (1991) correction gives quantitatively similar results to our statistical correction method in the ERA-Interim, NCEP/NCAR, and CFSR reanalyses. For example, in both hemispheres the Trenberth (1991) method produces similarly drastic reductions in Hadley cell expansion trends in NCEP/NCAR, from significantly poleward to indistinguishable from 0. For ERA-Interim, the Trenberth (1991) correction is small but so is our statistical correction. The minor differences in the corrected trends may be the result of the different vertical structure of the two methods. The Trenberth (1991) method is barotropic and partitions the mass flux necessary to close the mass budget equally at all levels; the projection patterns we find tend to be concentrated in the midtroposphere, where the Hadley cell edge latitude is calculated. In spite of this, the time-mean Trenberth (1991) correction to the MMS (Figure S4) is similar in structure to our correction for the three reanalyses (Figure 2; the projection of the mass flux residual is the correction).

Excepting ERA-Interim in the Southern Hemisphere, the modern reanalysis trends fall within the range of CMIP5 model trends. Here the CMIP5 model trends are taken from 1980 through 2009 by combining the Historical and RCP8.5 simulations for 23 models. Regarding the early-generation reanalyses, in the Southern Hemisphere the uncorrected trends in JRA25, ERA-40, and NCEP/DOE fall outside of the range of model trends, while in the Northern Hemisphere the uncorrected trends from JRA25, ERA-40, NCEP/NCAR, and NCEP/DOE fall outside of the range of model trends. Once corrected, the trends in the Southern Hemisphere in ERA-40 and NCEP/DOE and the trends in the Northern Hemisphere in NCEP/NCAR and NCEP/DOE fall within the range of model trends. Even after being corrected, the trends in JRA-25 and the Northern Hemisphere trend in ERA-40 remain outside of the range of model trends.

5. Conclusions

Mass is not conserved by the meridional circulation in reanalyses. Residual vertical mass fluxes project onto Hadley cell expansion trends, artificially inflating trends in both hemispheres. The characteristics of the mass flux residual suggest it is not simply a function of horizontal resolution, but instead a result of errors introduced by the assimilation system and/or the representation of physical processes within the reanalysis models. Detection of these errors and their correction was accomplished without the use of any observational constraints and with only monthly mean reanalysis output. As further evidence of the reliability of this method, the Trenberth (1991) correction technique provides similar results. However, the mechanisms that may drive the imbalance and its projection onto the circulation remain uncertain.

While the corrected expansion trends in early-generation reanalyses are generally closer to those in modern reanalyses and CMIP5 model simulations, some persistent differences remain. These remaining differences could be associated with other errors and biases that are beyond the scope of this analysis. Though modern reanalyses still have difficulty conserving mass, these errors tend to not project as strongly onto trends in the Hadley cell edge latitudes as they do in early-generation reanalyses. For these reasons it would seem prudent to exclude early-generation reanalyses from future analyses of derived circulation quantities such as the MMS, except as historical reference points to past literature.

Johanson and Fu (2009) found that Hadley cell expansion in reanalyses was larger than in the worst-case scenario climate model experiments. However, they used the NCEP/NCAR, NCEP/DOE, and ERA-40 reanalyses. Grise et al. (2018) have noted that the NCEP/NCAR reanalysis is an outlier in regards to its stream function-based tropical expansion trends. Here we have additionally shown that in general a substantial fraction of the expansion trends in these particular reanalyses are associated with violations of mass conservation. Our correction technique revises these trends to be smaller and in closer agreement with model trends. Considering the substantial impact of natural variability on the observed rates of expansion (Allen & Kovilakam, 2017; Amaya et al., 2017), more work is warranted to determine if there truly are differences between the rates of expansion simulated in models and reanalyses.

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