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COMMENT

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Key Points:

- It is necessary to account for the lack of mass conservation in reanalysis data sets when calculating atmospheric heat transport
- Clark et al. (2022) found large trends in atmospheric heat transport that differed among reanalysis data sets due to unrealistic mass fluxes
- Trends in atmospheric heat transport are similar among reanalysis data sets once a mass correction is applied

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Comment on "Moist Static Energy Transport Trends in Four Global Reanalyses: Are They Downgradient?" by Clark et al. (2022)

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Abstract Given the key role that atmospheric heat transport plays in Earth's climate system, efforts to document its changes over the satellite era are valuable. Clark et al. (2022, https://doi.org/10.1029/2022GL098822) calculated trends in atmospheric heat transport among four reanalysis data sets and found substantial disagreements between data sets. However, after accounting for the lack of mass-conservation in reanalysis data sets, we find much smaller magnitude trends, with much better agreement among reanalyses. This highlights the importance of mass corrections when calculating atmospheric heat transport.

Plain Language Summary Atmospheric heat transport plays an important role in our climate system. Reanalysis data sets provide our best representation of how atmospheric heat transport has changed over the last 40 years. A previous study used four different reanalysis data sets to explore how atmospheric heat transport has changed. They found very large changes that disagreed between data sets. We repeat their calculations, but account for known inaccuracies in the reanalysis data sets and find much better agreement between the data sets.

1. Comment

Clark et al. (2022) argue that atmospheric heat transport (AHT) trends differ widely among four atmospheric reanalysis data sets. It is known that atmospheric reanalyses do not conserve mass (Mayer et al., 2021), and that not accounting for this lack of mass conservation can be a source of "major error" (Trenberth, 1997) in the calculation of AHT. Specifically, mass transports can introduce AHT that is not physically realistic if the mass budget is unbalanced. Additionally, the AHT associated with the mass transport will differ depending on if units of Kelvin or Celsius are used (Mayer et al., 2021) and is unrelated to relevant climate variables such as heating of the atmospheric column or connections to ENSO (Liang et al., 2018). For these reasons, a mass budget adjustment is needed when calculating AHT. From correspondence with the authors, we learned that Clark et al. (2022) did not do a mass correction, leading to their finding of large apparent AHT trends (up to 50 TW/year, corresponding to changes in excess of 20% of climatology) that disagree among reanalysis data sets. We show that when mass corrections are done, following standard practices (Marshall et al., 2014), AHT trends are more reasonable (up to 10 TW/year), and that there is much better agreement among reanalysis data sets. The conclusions reached by Clark et al. (2022) thus appear to rest on an incorrect treatment of reanalysis AHT that mostly reflects the non-conservation of mass within the data sets.

We perform our own independent AHT calculations for the four reanalysis products, ERA5 (Hersbach et al., 2020), ERA-Interim (Dee et al., 2011), the Japanese 55-year Reanalysis (Kobayashi et al., 2015), and MERRA2 (Gelaro et al., 2017), for the same time period as Clark et al. (2022), 1980–2018. Just as in Clark et al. (2022), we initially separate AHT, without any adjustments to balance the atmospheric mass budget, into two components: an eddy component coming from the product of zonal-anomalies in both moist static energy (MSE) and the meridional wind, and an overturning circulation component coming from the product of zonal-means in both MSE and meridional wind. We refer to the overturning circulation as the mean meridional circulation (MMC). We calculate these two contributions to AHT at a given latitude (ϕ) at each 6-hourly time as:

$$\text{Total AHT Unadjusted} = \frac{2\pi a\cos(\phi)}{g}\int_0^{\overline{P_s}}\left(\underbrace{[v][\text{MSE}]}_{\substack{\text{MMC AHT}\\ \text{Unadjusted}}} + \underbrace{[v^*\text{MSE}^*]}_{\text{Eddy AHT}}\right)dp, \tag{1}$$

where square brackets [ ] denote zonal averages, asterisks (*) are departures from the zonal average, v is the meridional wind, MSE is the moist-static energy, p is pressure, $\overline{P_s}$ is the climatological surface pressure, and a is the radius of Earth.

We then apply a mass correction to the MMC AHT Unadjusted term to remove the AHT associated with the non-zero mass transport. We do this by subtracting the zonally- and vertically-averaged MSE and meridional wind at each 6-hourly time step (Marshall et al., 2014). We note that the Eddy AHT term in Equation 1 does not require a mass transport correction since $[v^*] = 0$ by definition. A vertical average is defined as:

$$\hat{X} \equiv \frac{1}{\overline{P_s}}\int_0^{\overline{P_s}}(X)\,dp. \tag{2}$$

The MMC AHT Unadjusted term can then be rewritten as:

$$\text{MMC AHT Unadjusted} = \frac{2\pi a\cos(\phi)}{g}\left(\underbrace{[\hat{v}][\widehat{\text{MSE}}]}_{\substack{\text{AHT Mass}\\ \text{Transport}}} + \underbrace{\int_0^{\overline{P_s}}[v]^\dagger[\text{MSE}]^\dagger\,dp}_{\substack{\text{MMC AHT}\\ \text{Adjusted}}}\right), \tag{3}$$

where swords (†) are departures from the vertical average. The first term in Equation 3 is the AHT associated with the mass transport. As we want to exclude the AHT associated with the mass transport, we rewrite the initial Total AHT Unadjusted equation (Equation 1) as:

$$\text{Total AHT} = \frac{2\pi a\cos(\phi)}{g}\int_0^{\overline{P_s}}\left(\underbrace{[v]^\dagger[\text{MSE}]^\dagger}_{\substack{\text{MMC AHT}\\ \text{Adjusted}}} + \underbrace{[v^*\text{MSE}^*]}_{\text{Eddy AHT}}\right)dp. \tag{4}$$

All results shown in this paper come from AHT calculated as in Equation 4, except where we note that the mass correction has not taken place, in which case AHT calculated as in Equation 1 is used.

This formulation of Total AHT is unaffected by any mass imbalance in the reanalysis because: Eddy AHT depends only on the zonal covariance of the zonal anomalies in both meridional wind and MSE and is unaffected by the addition of zonally uniform meridional wind or MSE; and MMC AHT depends only on the vertical covariance of the vertical anomalies in both meridional wind and MSE and is unaffected by the addition of vertically uniform meridional wind or MSE.

Total AHT calculated at each 6-hourly time step is then time averaged over each month. In this formulation, both the Eddy and MMC AHT include energy transport by both the time (monthly) mean circulation and the transient anomalies: (a) the Eddy AHT includes heat transport by both stationary eddies and transient eddies and; (b) the MMC AHT includes contributions from both the time mean overturning circulation and a very small contribution from the transient overturning circulation (referred to as the TOC in Marshall et al. (2014)'s; Equation 1). The transient overturning circulation is one to two orders of magnitude smaller than the other terms in both the time mean and the trends.

In Figure 1, we show trends of Total AHT both with and without the mass correction. Without the mass correction (Figure 1a) our results generally agree well with Figure 1 in Clark et al. (2022) and show large and differing trends among reanalyses. Once the mass correction is made, we find much smaller trends and much better agreement among reanalyses (Figure 1b). The mass transports should be excluded from calculations of AHT as they are primarily a byproduct of the lack of mass conservation in reanalysis data sets and are unreasonably large. To

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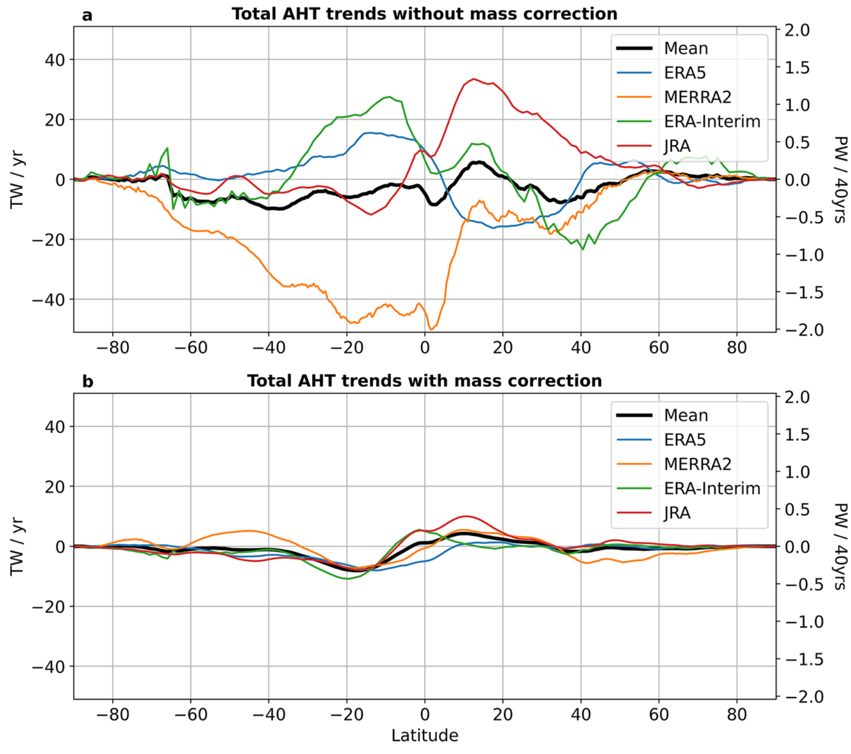

Figure 1. Trends in (a) Total atmospheric heat transport (AHT) without a mass correction; and (b) Total AHT with a mass correction for all four reanalysis data sets. Part (b) and Figure 2a have the same underlying data, albeit with different *y*-axes.

give context to the unreasonable size of the mass transport trends, it would require surface pressure changes over the 1980–2018 time period on the order of 200 hPa to balance the implied mass changes (not shown).

In Figure 2 we take a closer look at trends in AHT after the mass correction has been applied. The largest discrepancies in Total AHT among reanalyses arise in the mid-latitudes and Northern hemisphere tropics (Figure 2a, same as Figure 1b but on a different *y*-scale). However, these discrepancies are much smaller compared to those in Clark et al. (2022). Figure 2b shows trends in Eddy AHT. We see a similar picture to Total AHT trends, with MERRA2 being an outlier in the mid-latitudes. While it is difficult to confirm given the size of the *y*-axis scales in some of the graphs in Clark et al. (2022), there appears to be good agreement between our calculated trends in Eddy AHT and theirs. This is to be expected, as there is no mass-correction applied to the Eddy AHT. In Figure 2c we can see that trends in the MMC AHT are generally in good agreement among data sets with the exception of the Northern hemisphere tropics, where the Hadley cell dominates AHT. Previous work has cast doubt over the validity of Hadley cell trends in reanalysis in this region (Chemke & Polvani, 2019). Additionally, the mismatches among the trends in the Northern hemisphere tropics are small compared to the mismatches in trends in Clark et al. (2022) (their Figures 2a, S1a, S2a, and S3a), which were roughly an order of magnitude larger. In general, while AHT trends between reanalysis products still differ after the mass flux adjustment has been made, there is general agreement amongst data sets at most latitudes i.e., much better than suggested in Clark et al. (2022).

In light of the fact that the AHT trends in Clark et al. (2022) are primarily a result of not mass correcting, and that the mass-corrected AHT trends are much smaller and have better agreement among reanalysis products, it seems premature to draw strong conclusions about whether observed trends in AHT and MSE gradients are consistent. It remains an important question, although we caution it may be difficult to assess given the relatively short period of the record.

In conclusion, the lack of agreement in AHT trends among reanalysis products in Clark et al. (2022) was primarily a result of failing to correct the mass budget of each reanalysis data set. Once the mass budget is corrected, trends in AHT among reanalysis data sets agree better, albeit imperfectly. This highlights the importance of correcting the mass budget whenever calculating AHT.

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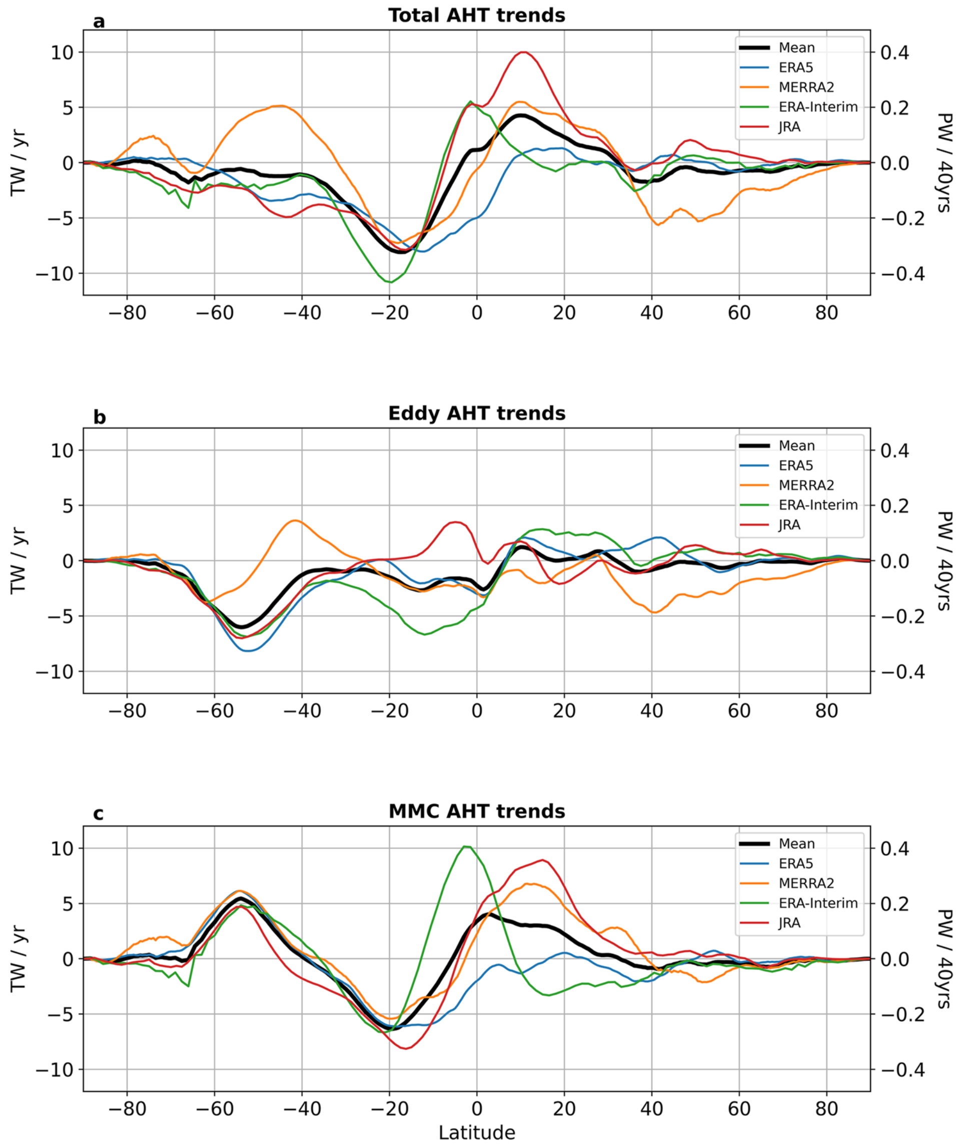

Figure 2. Trends in (a) Total atmospheric heat transport (AHT); (b) Eddy AHT; and (c) mean meridional circulation (MMC) AHT for all four reanalysis data sets after the mass correction has been applied. Figure 1b and part (a) have the same underlying data, albeit with different *y*-axes.

Data Availability Statement

All data used in this comment are publicly available reanalysis data sets. Data can be found at:
ERA5: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5.
ERA-Interim: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim.
MERRA2: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/.
JRA: https://rda.ucar.edu/datasets/ds628.0/.

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