AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

REPLY

10.1029/2023GL104020

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

Joseph P. Clark[1,2], Steven B. Feldstein[1], and Sukyoung Lee[1]

[1]Department of Meteorology and Atmospheric Science, The Pennsylvania State University, State College, PA, USA, [2]Now at Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA

Key Points:

- After mass correction, reanalysis moist static energy (MSE) transport trends are not downgradient
- After mass correction, reanalysis dry static and latent energy transport trends oppose each other over most latitudes
- The MSE transport trend is not in a poleward direction north of 30°N

Correspondence to:

J. P. Clark,
jc7377@princeton.edu

Citation:

Clark, J. P., Feldstein, S. B., & Lee, S. (2023). Reply to comment on "moist static energy transport trends in four global reanalyses: Are they Downgradient?" by Clark et al. (2022). *Geophysical Research Letters*, *50*, e2023GL104020. https://doi.org/10.1029/2023GL104020

Received 6 APR 2023
Accepted 12 JUL 2023

Abstract

In a previous study, we investigated whether reanalysis moist static energy (MSE) transport trends over the 1980 through 2018 period are consistent (a) with each other and (b) with the finding that these transport trends are downgradient, as found in climate models. Regarding point (a), our conclusion was that MSE transport trends were dependent on the reanalysis data set. However, Cox et al. (2023) correctly point out that the reanalysis dependence is reduced dramatically if a barotropic mass flux correction is applied at a monthly mean timescale prior to computing the MSE transport trends. In our reply below, we revisit point (b) after applying this correction. We find that even after the correction, reanalysis MSE transport trends are not downgradient nor poleward in the Northern Hemisphere extratropics. However, reanalysis does show a compensation between dry static and latent energy transport trends, which has been shown in climate models historically.

Plain Language Summary

Energy is transported poleward by the atmospheric circulation. As the climate warms, the amount of energy transported poleward is projected to increase. In a previous study, we investigated whether this holds in reanalysis data sets (data sets that obtain global coverage by combining measurements with numerical models). However, as pointed out by Cox et al. (2023), we did not account for the fact that reanalysis products do not respect mass conservation. Correcting for this, MSE transport trends do not exhibit a reanalysis dependence to the degree we previously found. Nevertheless, reanalysis MSE transports are not associated with changes in the surface MSE gradient, as models suggest, nor are these fluxes poleward in the Northern Hemisphere extratropics. An aspect that becomes more consistent between models and reanalysis after correcting the mass budget is an anticorrelation between dry static and latent energy transports trends.

1. Reply to Cox et al. (2023)

Given the important role that moist static energy (MSE) transports play in shaping the climate, how MSE transports will change in a warming climate is an important question. Climate models suggest that poleward MSE transports will increase under climate change. This has previously been conceptualized as a downgradient response to changes in the near surface MSE (e.g., Armour et al., 2019; Hwang & Frierson, 2010). In our previous study (Clark et al., 2022), we concluded that reanalysis products displayed trends over the 1980 through 2018 period that were neither downgradient nor poleward. Cox et al. (2023), however, point out that our original study did not account for the fact that reanalysis products do not respect mass conservation, and justifiably raised a question on the validity of our original conclusions. Cox et al. (2023) applied a monthly mean vertically uniform correction to the zonal mean mass flux following previous work (Marshall et al., 2014) and found that the reanalysis dependence is significantly reduced, demonstrating the importance of correcting the mass imbalance prior to investigating trends in MSE transports. Therefore, in this reply, we revisit our earlier conclusions after applying the same correction as Cox et al. (2023).

In Figure 1, we display the zonal mean vertically integrated MSE trend (as in our original study) and the near surface MSE trend assuming a constant 80% relative humidity (as in Armour et al., 2019; Hwang & Frierson, 2010) from each reanalysis (ERA-Interim, Dee et al., 2011; ERA5, Hersbach et al., 2020; JRA-55, Kobayashi et al., 2015; MERRA2, Gelaro et al., 2017). These two quantities are fairly similar (Figure 1). Using Figure 1, we assess whether reanalysis MSE transports follow a flux-gradient relationship. Comparing to Figure 2a of Cox et al. (2023) which shows trends of the meridional MSE flux, it is evident that reanalysis products a do not closely follow a flux-gradient gradient relationship even after correcting the mass imbalance. Focusing on

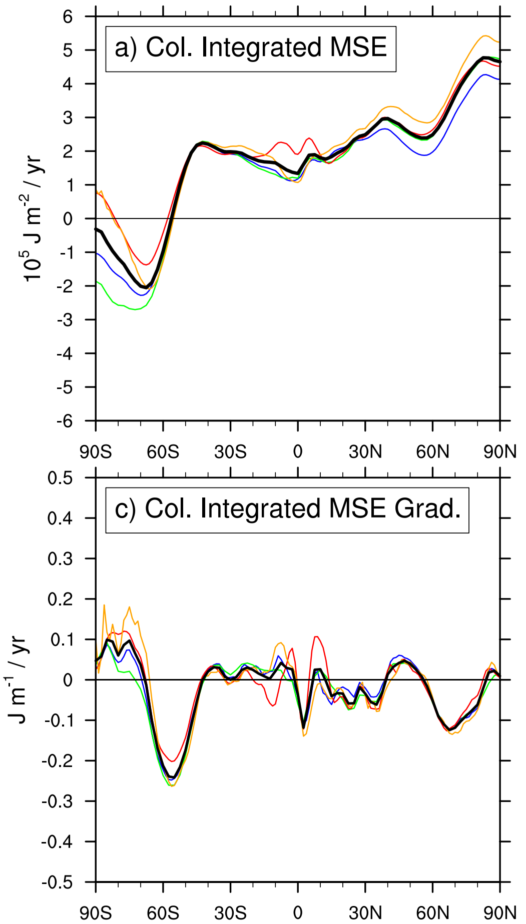

Figure 1. Trends in zonal mean (a) vertically integrated and (b) surface moist static energy (MSE), where the surface MSE is computed following Hwang and Frierson (2010) by assuming a constant relative humidity of 80% and a flat, constant pressure (p = 1,000 hPa), surface. Panels (c) and (d) show $-\frac{\partial}{\partial y}$ of panels (a) and (b), respectively.

the average of the four reanalysis products (the black line), our Figure 1d shows that $-\frac{\partial(MSE)}{\partial y}$ is mostly negative between 60°S and 30°S, undergoes several sign changes between 30°S and 30°N, positive between 30°N and 50°N, and again negative between 50°N and 80°N. Figure 2a of Cox et al. (2023) shows that the average MSE flux trend is negative between ~70°S and ~5°S, positive between ~5N and ~30°N, and weakly negative between ~30°N and ~70°N. Therefore, the fluxes are downgradient between 60°S and 30°S, and between 50°N and 70°N. However, between 30°S and 50°N, the flux-gradient relationship does not hold (Note that the MSE flux trend does not satisfy the flux-gradient relationship with the vertically integrated MSE either (Figure 2c)). It is worth mentioning that the equatorward MSE transport trend between 50°N and 80°N, coincides with significant Arctic warming that has occurred over the 1980 through 2018 period.

We next applied the mass budget correction as in Cox et al. (2023) to reproduce our Figure 2 in the original manuscript for the readers who may wish to know how the mass correction changes our original Figure 2. Specifically, in Figure 2, we split the mass-corrected MSE transport trend from ERA5 into various components (Clark et al., 2022). The formulation not only splits the MSE transport into parts associated with the overturning circulation and eddies, but also into parts associated with changes in the circulation, changes in the MSE field, and their covariance (i.e., nonlinearities). We also decompose the MSE transports into contributions from latent and dry static energy transports (see the Data and Methods of Clark et al. (2022) for complete detail).

First, it is important to evaluate our original conclusion that MSE transport trends are not poleward. In Cox et al. (2023), it can be seen that the reanalysis mean MSE transport trend is poleward between 75°S and 5°S and between the equator and 30°N. Poleward of 30°N, the MSE transport trend is equatorward. Compared to our original finding (Figure 2 in Clark et al., 2022), for the ERA5 reanalysis, the mass-corrected MSE transport

10.1029/2023GL104020

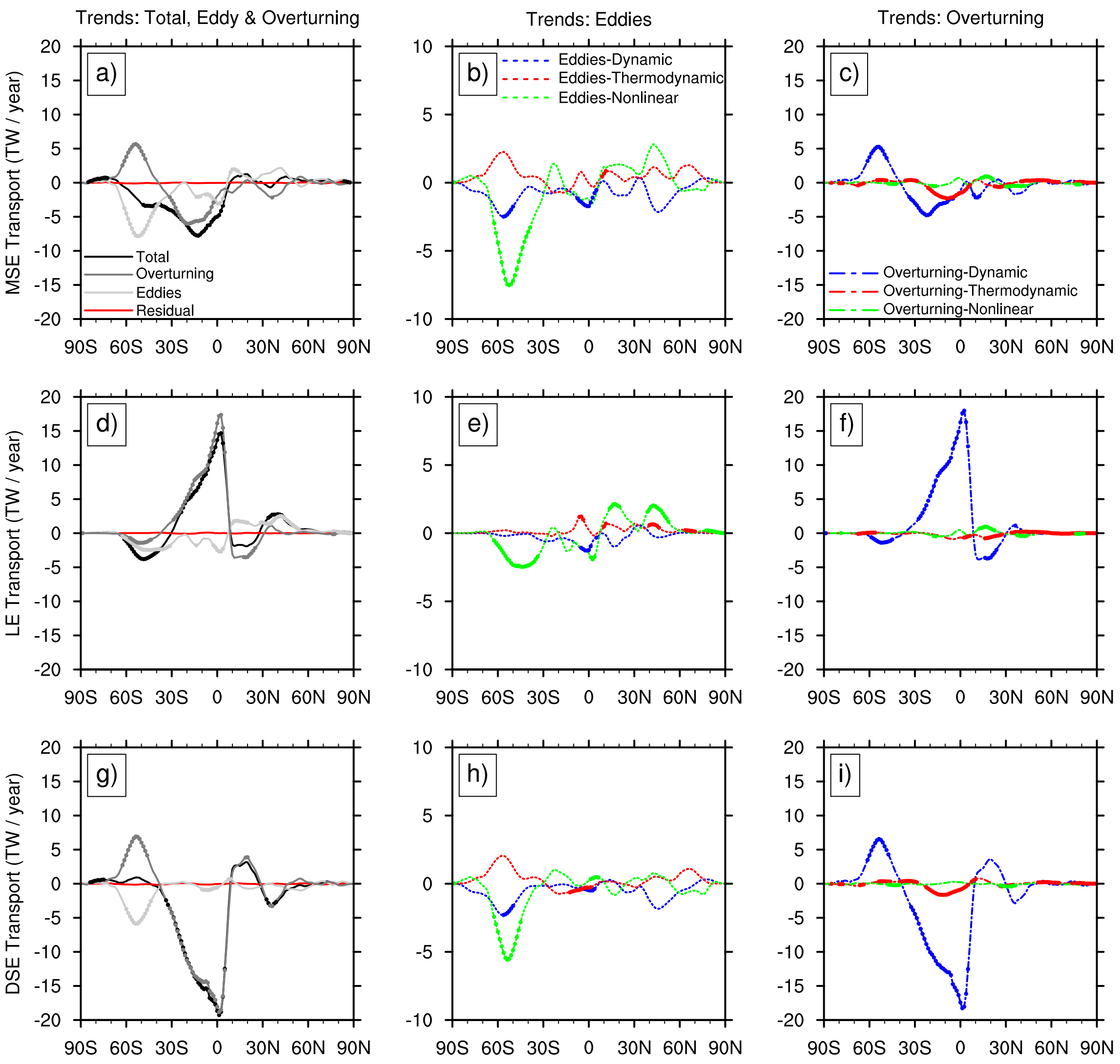

Figure 2. ERA5 northward moist static energy transport trends (top) decomposed into parts associated with latent energy transport (middle) and dry static energy transport (bottom). The gray shading in the leftmost column further splits the energy transport trends into eddy and overturning parts, respectively. The middle column further splits the eddy energy transport into a part associated with circulation (dynamic) anomalies, energy (thermodynamic) anomalies, and their nonlinear interaction. Similarly, the rightmost column further splits the overturning energy transport into parts associated with the circulation, energy and their nonlinear interaction (see Clark et al. (2022)) for a complete discussion). The red line in the leftmost columns indicates a residual. Filled circles denote statistical significance at the 95% confidence level.

trend is significantly reduced in amplitude. The MSE transport is trending southward between 70°S and 10°N, and trending negligibly elsewhere (Figure 2a). We also find that eddy MSE transports dominate in the Southern Hemisphere (SH) between 70°S and 45°S (Figure 2b) while the overturning circulation opposes the eddies in this region and dominates between 45°S and 10°N (Figure 2c). Although the MSE transport trend is not poleward at all latitudes in ERA5 (Figures 2a) and Cox et al. (2023) show that some reanalysis products exhibit MSE transport trends that are more poleward than ERA5.

For the ERA5 reanalysis, splitting the trend into contributions from the latent energy transport and dry static energy transport, we find that the mass flux correction does not significantly impact the latent energy transport (cf. Figure 2 here with that of Clark et al. (2022)).

Instead, the correction significantly changes the dry static energy transport such that it becomes broadly anti-correlated with the latent energy transport (Figures 2f and 2i and 2d and 2g). An additionally interesting finding is a near balance between trends in transient eddy dry static energy transports and overturning dry static energy transports over the SH (between 70°S and 45°S; Figures 2g–2i). Meanwhile, between 45°S and 10°N, the latent and dry static energy transport trends also oppose each other, however, at these latitudes, both the latent and dry static energy transports driven by changes in the zonal mean meridional wind (Figures 2f and 2i).

That the dry and latent energy transport trends are anticorrelated in the ERA5 reanalysis is interesting because climate models historically suggest the same anticorrelation for the two transport trends under warming (e.g., Held & Soden, 2006). An early example of this finding can be seen in Figure 12 of Manabe and Wetherald (1975). Held and Soden (2006) examined the response to 2xCO_2 equilibrium simulations by GFDL's AM2/LM2 and archives of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (SRES) A1B. Their Figure 10 (which is replotted in Figure 2 of their corrigendum (Hwang et al., 2011)) shows that in midlatitudes of both hemispheres the magnitude of the latent heat transport change is roughly twice that of the sensible energy transport. The net result is increased poleward transport of MSE in both simulations. It is interesting that in the ERA5 trend that we examined, the trends of the two fluxes cancel each other in the Northern Hemisphere (NH) midlatitudes. Figure 2a of Cox et al. (2023) shows that in NH midlatitudes, the reanalysis mean is also close to zero. In the SH midlatitudes, however, the mean trend is negative which is consistent with the model simulations. The cause of this contrasting behavior between the two hemispheres is worth further investigation in the future.

2. Closing Remarks

For the 1980 through 2018 period, reanalysis MSE transport trends are not downgradient at most latitudes nor are they poleward between 30°N and 90°N. However, while these aspects do not perfectly line up with expectations developed from climate model simulations, ERA5 shows a trend toward increased poleward dry static energy transports in the subtropics and decreased poleward dry static energy transports in the extratropics, compensated by opposite behavior from the latent energy transports. Such a compensation has been shown in climate model simulations historically.

Overall, the results presented here prompt further work on the topic of MSE transports over the historical period. In particular, future work on the topic of MSE transport trends in reanalysis may consider whether reanalysis falls into the climate model spread (Hwang & Frierson, 2010) and whether the MSE and moisture budgets are closed following the mass budget correction (e.g., Bangalath & Pauluis, 2020).

Data Availability Statement

ERA5 data is available at: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5.

ERA-Interim data can be obtained from the following archive: https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/.

JRA-55 data is available at the NCAR-UCAR Research Data Archive: https://rda.ucar.edu/. MERRA2 data used in this study can be obtained at: https://goldsmr5.gesdisc.eosdis.nasa.gov/data/MERRA2/M2I6NPANA.5.12.4/.

Acknowledgments

We thank two anonymous reviewers for their comments that greatly improved the quality of this manuscript. We also thank Tyler Cox for bringing to our attention the consequence of neglecting to correct for mass conservation when using reanalysis data to investigate moist static energy transports. This work was funded by National Science Foundation grant AGS-1948667.

References

Armour, K. C., Siler, N., Donohoe, A., & Roe, G. H. (2019). Meridional atmospheric heat transport constrained by energetics and mediated by large-scale diffusion. *Journal of Climate*, *32*(12), 3655–3680. https://doi.org/10.1175/jcli-d-18-0563.1

Bangalath, H. K., & Pauluis, O. M. (2020). A new mass flux correction procedure for vertically integrated energy transport by constraining mass, energy, and water budgets. *Geophysical Research Letters*, *47*(22), e2020GL089764. https://doi.org/10.1029/2020gl089764

Clark, J. P., Feldstein, S. B., & Lee, S. (2022). Moist static energy transport trends in four global reanalyses: Are they downgradient?*Geophysical Research Letters*, *49*(20). e2022GL098822. https://doi.org/10.1029/2022gl098822

Cox, T., Donohoe, A., Armour, K. C., Frierson, D. M., & Roe, G. H. (2023). Comment on "moist static energy transport trends in four global reanalyses: Are they downgradient?" by Clark et al., 2022. *Geophysical Research Letters*. https://doi.org/10.1029/2023GL104020

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). *Journal of Climate*, *30*(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate*, *19*(21), 5686–5699. https://doi.org/10.1175/jcli3990.1

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hwang, Y. T., & Frierson, D. M. (2010). Increasing atmospheric poleward energy transport with global warming. *Geophysical Research Letters*, *37*(24). https://doi.org/10.1029/2010gl045440

Hwang, Y. T., Frierson, D. M., Soden, B. J., & Held, I. M. (2011). CORRIGENDUM: Corrigendum for Held and Soden (2006). *Journal of Climate*, *24*(5), 1559–1560. https://doi.org/10.1175/2010jcli4045.1

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., et al. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. *Journal of the Meteorological Society of Japan. Series II*, *93*(1), 5–48. https://doi.org/10.2151/jmsj.2015-001

Manabe, S., & Wetherald, R. T. (1975). The effects of doubling the CO2 concentration on the climate of a general circulation model. *Journal of the Atmospheric Sciences*, *32*(1), 3–15. https://doi.org/10.1175/1520-0469(1975)032<0003:TEODTC>2.0.CO;2

Marshall, J., Donohoe, A., Ferreira, D., & McGee, D. (2014). The ocean's role in setting the mean position of the Inter-Tropical Convergence Zone. *Climate Dynamics*, *42*(7–8), 1967–1979. https://doi.org/10.1007/s00382-013-1767-z