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Atmospheric Chemistry and Physics Discussions

Interactive comment on "On the role of thermal expansion and compression in large scale atmospheric energy and mass transports" *by* Melville E. Nicholls and Roger A. Pielke Sr.

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Response to referee #1

"Conceptually, eddies in traditional view include waves (e.g., gravity and Rossby waves). Therefore the authors' claim (that the traditional view considers the total energy transfer solely in an advective-like manner by the winds) seems incorrect."

As far as we know, total energy has not been considered to be transported with the phase speed or group velocity of large-scale waves, such as Rossby waves. Rather the meridional component of velocity associated with these waves have been consid-

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ered to cause a meridional transfer of total energy. Large wavelength Rossby waves have westward group velocity and so will transfer energy westward, but this is energy associated with the kinetic energy and potential energy of the wave, rather than the quantity total energy. There are however, many quotes that can be found in the literature alluding to total energy transfer in an advective-like manner by the winds. For example:

1) When discussing heat in sensible form and in latent form exchanged between one latitude and another Priestley (1949) states: “The main agents of meridional transport have been assumed to be the broad and deep northward and southward flowing currents of air whose dimensions are comparable in size to the cyclonic and anti-cyclonic pressure systems.” This suggests transport at the speed of the air currents.

2) Shaw and Pauluis (2012) state: “Advection by the Eulerian mean meridional circulation dominates the total energy transport in the tropics” and “In the region of the Ferrel cell, a poleward energy transport is achieved by atmospheric eddies, which transport both sensible and latent heat poleward”.

3) Liang et al. (2018) state: “In the time mean, the atmosphere carries heat meridionally by moving poleward air parcels with high moist static energy and moving equatorward air parcels with low moist static energy”. Carrying heat meridionally by moving air parcels equatorwards and polewards suggests an advective-like process.

The decomposition of Eq. 3 will include the contribution of expansion and compression to the dry static energy flux. It is the physical interpretation of what causes the flux that we think is brought into question by our results.

“Quantitatively, the authors should show the corresponding results based on the traditional view (i.e., using equations 1-3) in the figures and actually demonstrate the differences of these results versus their results. This would help address the relative importance of thermal compression waves.”

Our simulations are quite simple in that we prescribe a local heat source and examine a short time later the perturbed energy and mass fields. To examine the traditional view we would have to simulate the Hadley cell, Rossby waves and baroclinic eddies etc. That is a good idea, but goes beyond the scope of this work. We agree with the referee that in questioning the traditional view we are hypothesizing and perhaps we should be more cautious in our statements. However, we do need to say something about how these results may be relevant to the traditional view.

The situation is complicated since observational studies and many modeling studies enforce mass balance when computing poleward total energy transport (Trenberth 1991; Masuda 1988; Keith 1995; Magnusdottir and Saravanan 1999; Graversen et al. 2007; Yang et al. 2015; Liang et al. 2018). This typically involves adding a correction to the meridional velocity (e.g. Yang et al. 2015; see appendix). Our line of thinking is that the larger latent heat release at low latitudes than at high latitudes is causing expansion at low latitudes and compression at higher latitudes, which leads to a poleward mass transfer, and that the resultant buoyancy driven circulations and horizontal eddies are bringing mass back from the high latitudes to the low latitudes to give a mass balance. For instance, an eddy that has warm air moving poleward and cold air equatorward may result in an equatorward mass transfer since the warm air tends to be less dense and the cold air more dense. Both thermal expansion/compression and buoyancy driven circulations are all taking place at the same time, which makes the situation complicated. While there must be a mass balance in the long term mean, transfer of total energy by expansion and compression fundamentally involves mass transfer, so this process might not be accounted for properly if a mass balance condition is imposed. However, this is a hypothesis and at this stage we cannot say much about this issue.

As we stated above the decomposition of Eq. 3 will still include the contribution of expansion and compression to the dry static energy flux. Whether the traditional methodology accurately assesses the contribution due to eddies is unclear to us, particularly

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since studies typically employ a mass balance condition. To assess the relative contribution of eddies versus the expansion/compression mechanism would require carefully designed experiments preferably with a fully compressible global model. The referee is correct that we are not able to say how important thermal compression waves are to the total energy transport based on our results. However, given that we find considerable transport of total energy at the speed of sound in our idealized simulations we think the current traditional view is incomplete.

Interestingly a recent paper by Liang et al. (2018) seems to be trying to remove a component involving poleward mass transfer in the total energy transport to come up with a new definition of heat transport. Recognition that considerable mass and total energy transport might be occurring at the speed of sound could provide a different perspective on this problem.

"The presentation is clear. However, for the key points in the manuscript, the use of 28 figures is not justified. The authors could make good use of supplementary material by moving most of the figures there. This would also increase the readability."

We agree that it is a good idea to make use of supplementary material to reduce the number of figures.

Minor comments: "Equation 2: there should be square brackets on the right hand side, to be consistent with equation 3."

Eq. 2 has the factor 2πRecos(phi) which is the distance around the earth at the latitude phi. So that expression on the right hand side is the flux across a circle of latitude. This equation is however usually written as a time average (Starr and White 1954; Oort and Piexóto 1983), although the derivation doesn't require an average in time to be taken. When an average in time is taken there is an approximate mass balance, so the mechanism we are seeing for meridional transfer of total energy that occurs on very short time scales (hours), will not be able to be resolved given the time averaging in observational studies is quite large (days or months). It is possible that by considering time-averaged fluxes this is causing a misinterpretation of how a considerable portion of the energy transport is physically accomplished. However, this is a hypothesis and would have to be subject to a rigorous study.

"Figures 1 and 2: when u' is as large as 5-10 m/s, should a nonlinear model (rather than a linearized model) be used? How does it affect the results?"

The units are cm/s so the velocity perturbation is quite small.

"Figure 9: is the exponent (-5) in “kg mËĘ-3 10ËĘ-5” correct in the figure 9 caption?"

Yes the exponent is correct.

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