Below please find the Point-by-point response to both reviews. Please note that following the suggestions from referee #4 (Dr. Laliberté) we rearranged the Results section. According to this rearrangement, the order of the figures changed (and additional figures/panels are included).

Referee #4 (Dr. Laliberté)

Review for "The impact of oceanic heat transport on the atmospheric circulation" by M.-A. Knietzsch, A. Schröder, V. Lucarini, and F. Lunkeit

The authors use an intermediate complexity model with coarse resolution to quantify the impact of artificially changing poleward oceanic heat transport in a slab ocean. It follows a suite of similar studies that appeared in recent years and innovates by using advanced diagnostics to measure the impact of oceanic heat transport on the atmospheric circulation. Among other diagnostics, it describes the atmospheric circulation using the concept of the "climate machine". It is my impression that the conclusions that follow from this climate machine perspective will help readers gain physical intuition about what makes the atmospheric circulation weaken when ocean heat transports are increased.

For these reasons I think this manuscript will be an important contribution to climate science. I have however serious concerns about parts of the Ferrel cell analysis. These will be discussed later in my first and second major comments. I have also the impression that the manuscript lacks a clear focus with none of their many results really standing out. Because this will likely affect the potential impact of this manuscript, I would suggest that the authors pick one of their results and then organize their development to clearly emphasize that result. In my third major comment the authors will find a more extensive explanation for this suggestion. For these reasons, I would recommend that the manuscript undergo a round of major revisions.

The authors should feel free to contact me if they have any questions about my review.

Frederic Laliberte

We thank Dr. Laliberté for his thorough evaluation and his valuable suggestions. In the following we answer (in normal text) his remarks (in *italic*).

Major Comments:

1. On lines 170, 295, 550 and 660, the authors refer to Czaja and Marshall (2006, hereafter CM2006) but seem to mischaracterize their work. CM2006 did not show that "the atmospheric heat transport can be represented by the product of the strength of the TEM residual circulation and the vertical contrast in moist static energy if the eddy transport of the theta is replaced by the transport of theta_e" as claimed on line 660. Instead they have shown that this statement is true only if in addition the vertical gradient of theta in the equation on line 655 is replaced by the vertical gradient of theta_e. This can be easily verified.

Indeed, as noted by the reviewer, Czaja and Marshall (2006) showed that the atmospheric heat transport can be presented by the product of the strength of the TEM residual circulation and the vertical contrast in moist static energy if both the eddy transport and the vertical gradient of Θ are replaced by the respective values utilizing Θe . We are sorry to confuse this conclusion. We changed the respective statements.

The problem is that in Earth-like conditions the vertical gradient of theta_e vanishes in the free troposphere from the tropics to well within the midlatitudes. Because of these two features, Figure 10b would look drastically different: It would be negative in the lower troposphere, be undefined in the lower free troposphere, and positive in the upper free troposphere. In fact, this problem was discussed in Pauluis et al. (2011, "A Statistical generalization…") and to a lesser extent in Laliberte et al. (2012). The conclusion at the moment is that there is no simple way to represent a well-defined (all its values finite) moist isentropic circulation in the latitude-pressure plane.

It is also true that the distribution of moist static stability precludes a diagnostics of the moist isentropic circulation in pressure coordinates similar to the dry case. In addition, beside the fact that the vertical gradient of Θ_e appears in the denominator, one may notice that deriving a Kuo-Eliassen type of equation involves (i) quasi-geostrophic scaling and (ii) the thermal wind balance. But, for (i) the stability needs to be large which for the moist case cannot be assumed, and (ii) thermal wind balance employs the horizontal gradient of Θ (and not Θ_e) introducing additional complications.

We note the principle problem by referring to Pauluis et al. (2011) and Laliberté and Pauluis (2010) in the diganostics section

' However, Pauluis et al. (2011) and Laliberté and Pauluis (2010) pointed out that there is no simple way to represent a well-defined moist isentropic circulation in the latitude-pressure plane.'

and in the results section

'Unfortunately, as pointed out by Pauluis et al. (2011) and Laliberté and Pauluis (2010), there is no simple way to represent a well-defined moist isentropic circulation in the latitude-pressure plane. This prevents a diagnostic similar to the dry case.'

If I understand well, the analysis to create Figure 10b involved only replacing the eddy transport of theta with the eddy transport of theta_e and not replacing the vertical gradient of theta with the vertical gradient of theta_e. In this case, Figure 10b gives the moist atmospheric heat transport only if multiplied by the vertical gradient of theta (or the dry static stability) and not if it is multiplied by the vertical gradient of theta_e (or the moist static stability), as claimed on line 325. As a consequence, the discussion of Figure 11 might not be right in this context. If the residual moist streamfunction was not computed using the vertical gradient of theta_e (or, more accurately, the STEM of Pauluis et. or an equivalent approximation) then its strength and the way it evolves under increased ocean heat transport might not be right. Although I am not expecting an increase as in Figure 3 (upper left) of Laliberte and Pauluis (2010), the moist circulation might not collapse as much as implied in Figure 11.

We recognize that using Θ_e for the transport und keeping Θ for the stability, as we did, can lead to misleading or even wrong results. In principle, the statistical transformed Eulerian mean (STEM) introduced by Pauluis et al. (2011) provides a method to apply a TEM-like formalism to the moist circulation and, thus, to distinguish between Eulerian mean and eddy circulation. However, we decided not use STEM but to compare the dry and the moist case by simply discussing the (total) meridional circulation (mass transport) on surfaces of constant dry and moist isentropes, respectively.

We modified the respective part of results section:

' To tackle this problem, Pauluis et al. (2011) introduces a statistical generalization of the transformed Eulerian mean circulation for arbitrary vertical coordinates. However, here we restrict ourselves by diagnosing and comparing the total atmospheric circulation on dry and moist isentropes.
Figure 18 displays the respective circulations for OHT_{max} = 0 PW and 3 PW, as well as the maxima of the respective streamfunctions for different OHTs. The circulation on dry isentropes corresponds well with the residual circulation except that it is closed and has smaller maxima, mainly due to misrepresentation of near–surface values in pressure–coordinates. It shows one single overturning cell with (for small OHT) a tropical and a mid-latitude maximum. In contrast to the dry case, the circulation on moist isentropes shows one maximum only for all OHTs which located in the mid–latitudes. In addition, the moist isentropic circulation is narrower and exhibits higher values, illustrating the impact of the moisture transport.
For increasing OHT both the dry and the moist isentropic circulation slow down, and the maxima shift poleward. Consistent with the findings by Czaja and Marshall (2006) this agrees well with changes in the transport of dry and moist static energy, respectively (cf. Fig. 11). However, the relative decreases of the transports are smaller than those in the circulations. This is explained by a narrowing of the isentropic circulation for larger OHT (cf. Fig. 18 for 0 and 3 PW) which corresponds to a decrease of static stability.'

2. I found the analysis of the Kuo-Eliassen equation slightly confusing and I would have greatly benefitted from a clearer connection between the Eulerian-mean decomposition (Fig. 8) and the TEM decomposition (Fig. 10a,c,e). Here's a suggestion: Rewrite equation on line 620 by adding and removing the last term on the RHS of the equation on line 650. This will split the eulerian-mean circulation into 5 terms instead of 4: heating, friction, eddy heating minus vertical EP flux, eddy momentum minus horizontal EP flux, and the EP flux. This way the TEM reconstruction then becomes simply equal to the sum of the first, second and last term. In the TEM framework, the third and fourth term are therefore representing the effective mass transport by eddy heat fluxes and eddy momentum fluxes, respectively. This would likely put much more physical intuition into Fig. 9 because the different terms will have a clearer physical meaning. At the moment, it seems that heat and momentum transport do not change (Fig. 9b) with increased ocean heat transport and yet the residual streamfunction (which is basically driven by the heat and momentum transports) changes appreciably (Fig. 11, here I'm assuming that the picture for the dry residual streamfunction looks more or less similar).

As the reviewer indicates, the connection between the Eulerian mean decomposition and the TEM decomposition is given by the role of the eddies. In the Eulerian mean view, the Eddies only act as seemingly independent forcing of the mean meridional circulation (right hand side of the Kuo Eliassen equation) due to their transport of heat and momentum. In the TEM view, the residual mean circulation, i.e. the part of the mean meridional circulation which is not balanced by the convergence of the eddy heat transport, is forced by the combined effect of the eddy heat and momentum transport (given by the E-P flux) illustrating the interrelation between both. In our case, the combined effect of the eddies is to set up the eddy related Stokes circulation.

Indeed this link can be made visible by rewriting the Kuo-Eliassen equation as suggested by the reviewer. However, perhaps we misunderstood the reviewers comment but the terms resulting from the proposed manipulation are: heating, friction, the E-P flux forcing and the circulation due to the eddy heat transport (sometimes referred to as Stokes streamfunction).

We added this link between Eulerian mean and TEM in Appendix A:

' Though representing a different view of the circulation, and, in particular of the role of the eddies, the Kuo-Eliassen equation and the TEM equation represent the same physics. This can be seen by rearranging the terms of the Kuo–Eliassen or the TEM equation (and neglecting differences between globally and zonally averaged stability) to give

eq.

We see that considering the combined effect of eddy heat and momentum transport leads to a second circulation defined by the eddy heat transport:

eq.

where Ψ_E is sometimes referred to as Stokes streamfunction.'

And explain the difference in the Eulerian and the TEM view in the results section:

'We note that in the Eulerian mean view (Fig. 15) the eddy forcing does not appear to be very important by being of small magnitude and low sensitivity. The huge impact of the eddies on the circulation only becomes clear when considering der combined effect of the eddies which sets up an eddy related (Stokes) circulation, as visible in the TEM view.'

3. As indicated above, I find that there are many interesting results but that they are not tied together. My understanding is that most of the results are in support of Figs. 14-18 but at the moment it feels more like three sets of disjoint results. One set is about the circulation, the second set is about the Lorenz cycle and the last is about the climate machine. One suggestion would be to begin with Figs 1-4 and then discuss Figs. 12-14 and Fig. 15a. These fit nicely with Fig. 2. Then the authors could present Fig. 17 and Fig. 18, their main results. Fig. 18 should be followed by Fig. 5 because the responses are consistent. Then Figs. 6-11 explain what is happening to the circulation and Fig. 16 confirms its role in the Lorenz energy cycle. Then Fig. 15b shows that what is happening in the cycle is consistent with the efficiency, thus confirming the relevance of the climate machine perspective. I feel that this would make it easier for the authors to clearly emphasize their innovative point of view on the atmospheric circulation.

We are very grateful for these suggestions, and rearranged the result section.

Minor comments:

1. I know that publication was concurrent but it would seem relevant to relate some of these results to the recently published Laliberte et al. (2015).

We added to the summary and discussion:
'Recently, Laliberté et al. (2015) proposed a different thermodynamic point of view with respect to what used here, indeed confirming the relevance of looking at the climate system as a heat engine. They studied using models and reanalyses the work output of the climate

engine and showed that the equivalent Carnot cycle is constrained by the power necessary to maintain the hydrological cycle which accounts for the moisture inefficiency related to the addition of water vapor to unsaturated air. For a warmer climate they found a reduction of the work output consistent with our results for increasing OHT. Laliberté et al. (2015) attributed most of the response to an increase of the moistening inefficiency. There is strong indication that this is also true in our case due to a large increase in near-surface specific humidity and evaporation with only moderate changes in near-surface relative humidity. However, further diagnostic is necessary to quantify the impact of moistening inefficiency.'

2. See my minor comments / questions / typos in the annotated pdf attached to this review. Better to view with Adobe Reader.

- We did our best to correct the typos and the wording.

- Accounting for the referees comments/questions (...) we modified '...'. Please note that the line numbers refer to the old version:

l5 (Very confusing sentence): ' The atmosphere compensates the imposed oceanic heat transport changes to a large extent, and significant modifications of the atmospheric general circulation can be noted.'

l11 (maybe avoid two words like decline and increasing right next to each other..): 'For increasing oceanic heat transport both the Hadley and Ferrel cell show a decline and a poleward shift of their maxima.'

l27 (This sentence is not completely sound. Try: "Over a global and long-term average all the supplied energy is emitted to space..."): 'Over a global and long–term averages all supplied energy is emitted to space, so that the incoming shortwave radiation is balanced by the outgoing longwave radiation (Peixoto and Oort, 1992; Lucarini and Ragone, 2011).'

l39 (the idiom "to draw a line" means "to separate one thing from another". Here, the author means "to draw line" in the sense of "connecting two things". Rewrite.): ' Recently, using tools of macroscopic non–equilibrium thermodynamics, a connection has been drawn between a measure of the efficiency of the climate system, the spatio–temporal variability of its heating and temperature fields, the intensity of the Lorenz energy cycle and the material entropy production (Johnson, 2000; Lucarini, 2009; Lucarini et al., 2011).'

l44 (Again two words that are very similar. Why not drop "integrated"): '...that the sum of the incoming entropy flux...'

l57 (Hanging sentence. Is it Stone that said that features can be related?): ' Stone concluded that features of the meridional heat transport can be related to the solar constant, the radius of the Earth, the tilt of the Earth's axis and the hemispheric mean albedo.'

l66 (Again, this sentence is hanging. It should be explicitly connected to the previous sentence.): ' Enderton and Marshall concluded that Stone's result is a good guide for ice–free climates. However, they also noted that the effect of the related meridional gradients in albedo on the absorption of solar radiation need to be taken into account if polar ice caps are present.'

l70 (what affects the flow? The changes in OHT directly? Or is it the atmospheric circulation that affects?): 'The atmospheric compensation implies a significant impact of changes in OHT on the atmospheric circulation as a whole. These changes in the atmospheric circulation concern the zonally symmetric flow, the zonally asymmetric (eddy) flow and the interplay between both.'

l250 (three "and"s here. It makes it confusing.): 'The total mean flow transport is the result of a large compensation of the equatorward transport of heat (sensible and latent) and the poleward transport of potential energy. '

l258 (what are the "processes" here? I'm lost. Did you mean the components?): 'Although changes in OHT are very large it appears that the role of the different mechanisms in controlling the total heat transport remains unchanged: In the inner tropics eddy transport is not important and the poleward energy transport is due to the transport of potential energy by the zonal mean flow. Here, the transport of sensible and latent heat by the zonal mean flow is directed towards the equator reducing the net transport. Starting in the outer tropics eddy transport becomes dominant. The importance of eddy latent transport increases for increasing temperatures due to higher moisture content according to Clausius–Clapeyron, i. e. latent heat transport is more important for lower latitudes. Eddy transport of potential energy is negligible while the transport of potential energy by the zonal mean flow in the mid–latitudes is equatorward and counteracts the eddy transport.'

l68+l69 (linear decrease -> I expect a rate of change, e.g. 21.5%/PW)): 'The decrease in strength of the Hadley cell is virtually linear and amounts to about 1.8×10^{10} kg s^{-1} per PW. The Ferrel cell strength decreases by about 0.4×10^{10} kg s^{-1} per PW with stronger decreases for smaller OHT_{max}.'

l324 (I'm not sure that's what they showed.): 'Czaja and Marshall (2006), based on work by Held (2001), showed that the atmospheric heat transport can be represented by the product of a moist TEM residual circulation and the vertical contrast in moist static energy (or equivalent potential temperature, Θe). Here, both the eddy transport and the vertical gradient of of Θ in the TEM formalism are replaced by the respective values utilizing Θe'

l460 (I don't know what a contributive process is.): 'This includes latent and sensible turbulent heat fluxes and frictional dissipation of kinetic energy.'

l644 (What is \theta_s here?): ' With Θs denoting the constant, global mean potential temperature at a given pressure level according to quasi–geostrophic scaling.'

Anonymous Referee #5

We thank the referee for his/her comments. In the following we answer (in normal text) the remarks by the referee (in *italic*). Please note that the line numbers refer to the old version of the paper.

This is the review of the paper entitled "The impact of oceanic heat transport on the atmospheric circulation" by Knietzsch et al. This paper studies what is the impact of an increased OHC to the atmospheric circulation and heat transport, and analyzes the dynamical and thermodynamical responses in the atmosphere. For this they use a simplified aquaplanet/slab ocean model with prescribed ocean heat content.
This paper is well written, and explores in depth the momentum and heat budgets in the atmosphere.
My opinion is that this paper should be published after minor revisions. This paper has improved considerably from the initial submission, and I believe the authors addressed the main points raised by the reviewers in the first draft of the manuscript.
My major point would be for the authors to explain and give some more physical insights about the results found in this paper. I suggest some in the minor comments below. Specially, approximately in the lines 235 to 260 there is not too much physical explanation on the underlying processes. In my opinion this would benefit the paper considerably.

With respect to the underlying mechanisms for the heat transport (former lines 235-260), we added:
'Although changes in OHT and, thus, the atmospheric compensation are very large it appears that the role of the different mechanisms in controlling the total heat transport remains unchanged: In the inner tropics eddy transport is not important and the poleward energy transport is due to the transport of potential energy by the zonal mean flow. Here, the transport of sensible and latent heat by the zonal mean flow is directed towards the equator reducing the net transport. Starting in the outer tropics eddy transport becomes dominant. The importance of eddy latent transport increases for increasing temperatures due to higher moisture content according to Clausius-Clapeyron, i.e. latent heat transport is more important for lower latitudes. Eddy transport of potential energy is negligible while the transport of potential energy by the zonal mean flow in the
mid-latitudes is equatorward and counteracts the eddy transport.'

Here are some minor comments:

l.215 - by lowest and highest temperatures you mean equator and 90N? Please specify.

We modified:
'Here, the equator-to-pole gradient is defined by the difference between the values at the lowest and highest latitude of the model's grid which are located at about 0.9° and 85.8°, respectively.'

l.236 - Took me some time to figure out what I had to observe in Figure 4. The authors should clarify that the small differences in the total heat transport profiles indicate atmospheric compensation.

We modified:
'Despite the difference in sea-ice extent (i.e. planetary albedo), the atmospheric heat transport compensates the changes in OHT to a large extent, as can be inferred from the small

differences in total meridional heat transport diagnosed from the energy budget at the top of the atmosphere (Fig. 4).'

l.238 - What is the zonally averaged atmospheric meridional transport? Isn't it just the meridional heat transport or is the same as the zonally symmetric part?

It is just the 'atmospheric meridional heat transport'.

l.247 - Please explain why latent heat explains the eddy part.

We modified:
'For the eddy transport in the tropics, only the latent heat transport is of appreciable magnitude.'

l.248 - Extra "f" in the sentence.

Corrected

l.250 - Why the word "however" in this sentence?

Omitted

l.254 - I do not understand the reason why geostrophic eddies do not transport potential energy. Please clarify.

We added:
'(i.e. the meridional velocity is given by the zonal gradient of the geopotential, and thus the zonal average of the product of velocity and geopotential vanishes).

l.266 - How does it compare to observations, at least broadly? Since the maximum OHT was selected to be close to the observed, the location and strength of the cells should be similar given similar maximum OHT strength.

We added:
'Considering the idealized setup, both the position and the strengths of the simulated cells are in reasonable agreement with observations for OHT_{max}=2 PW which is about the observed OHT strenth (e.g. Peixoto and Oort, 1992).'

l.267 - Please clarify that this decrease of 85% is for an increase of 4PW (I guess), or the slope of cell strength?

We clarified:
The decrease in strength of the Hadley cell is virtually linear and amounts to about $1.8 \cdot 10^{10}$ kg s^{-1} per PW. The Ferrel cell strength decreases by about $0.4 \cdot 10^{10}$ kg s^{-1} per PW with stronger decreases for smaller OHT_{max}.

l.269 - Is this a shift or expansion poleward? Please clarify this and how this parameter is estimated (core or boundary of cell?).

We clarified:
The core of the Ferrel cell shifts poleward.

l.272 - Why is it a thermally indirect cell? Is it friction dominated?

Actually, this additional (weak) cell is thermally direct (warm air rising, cold air sinking) although it is rotating counter-clockwise (on the Northern hemisphere). It is a virtual cell caused by averaging an almost vanished Hadley cell in summer and a winter hemisphere Hadley cell which has its maximum on the summer hemisphere. We thank the reviewer to point us to this mistake. We corrected the respective part:

'For OHT_{max}=4PW, an additional (weak) cell can be observed close to the equator with counter-clockwise rotation. However, this (virtual) cell is caused by averaging an almost vanished Hadley cell in summer and a winter hemisphere Hadley cell which has its maximum on the summer hemisphere.'

l.277 - Any idea on why the magnitudes of the reconstructed cells are underestimated? Is this because the forcings are not mutually independent?

It is not clear why the reconstruction overestimates the magnitudes of the cells. Independence of the forcing terms is not necessary to derive the Kuo-Eliassen equation (Appendix A) and, thus, should not lead to a systematic error. Possible sources of the differences are the numerical procedure to solve the equation (e.g. the representation of the derivatives) and, in particular, the quasi-geostrophic assumption.

We added:
' It is not clear why the reconstruction overestimates the magnitudes of the cells. Possible sources of the differences are the numerical procedure to solve the equation (e.g. the representation of the derivatives) and, in particular, the quasi-geostrophic assumption.'

l.285 - Why friction is more important at lower levels? Is this because of the friction is strong within the Ekman layer close to the surface?

Yes. We modified:
'.. which indicates the dominance of frictional dissipation close to the surface'

l.333 - heating is correlated to temperature "differences".

In our thermodynamic perspective we consider the energetics of the system. To gain (potential) energy, and to sustain the circulation against frictional dissipation, a positive correlation between heating and temperature is needed (heating needs to take place at relatively high temperatures while relatively cold regions need to cool further).

We modified:
'Such reservoirs are constructed in such a way to substantiate the fact that heating and temperature fields are positively correlated to gain potential energy (see Appendix B)'

l.589 - This is an important point about the potential role of ocean dynamics to the negative feedback explained in the paper. Apart from the MOC in the north Atlantic, there are also responses due to the equatorial thermocline. Previous works show that in warmer climates there is a response similar to an El Nino in the Pacific (e.g., Some of Alexey Fedorov's papers). Slab ocean models do not capture the same magnitude of signal in the tropics. Additional words have to be said about the potential role of ocean dynamics in the model.

We added:
'Apart from the meridional overturning circulation in the Atlantic, significant modifications of the oceanic circulation in a warmer climate can also be found in the equatorial Pacific strongly linked to El Nino-Southern Oscillation (ENSO) variability (e.g. Collins et al, 2010; Fedorov et al, 2006). This gives rise to an additional potential feedback mechanism related to oceanic dynamics which is not captured by slab ocean models (e.g. Boer and Yu, 2003).'

Figure 8 - there are two letter (e) panels.

corrected

References: There are several references missing in the main text.

We double-checked and corrected the references.