INVESTIGATION OF TRENDS IN THE MOISTURE BUDGET OF THE TROPICAL ATMOSPHERE

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ABSTRACT

Recent studies have found contradicting results regarding the tropical atmospheric circulation (TAC) has intensified or weakened in the recent past. We here conduct a preliminary study to investigate changes in TAC and in tropical moisture transports.

We divided the tropics between +/- 30° latitude into regions with upward and downward vertical wind motion, representing the ascending (ASC) and descending (DESC) branches of TAC. Typically moisture is advected from DESC into ASC at the lower levels of the atmosphere and from ASC into DESC at the upper levels. The moisture budget of ASC has been calculated in terms of the difference between precipitation and evaporation (P-E) and in terms of moisture fluxes along the boundary separating ASC and DESC.

In addition to mean values often used for calculating moisture transports we here also used instantaneous moisture values and wind vectors. Between both ways of calculating the moisture budget we found large discrepancies not only in the total water budget, but also in the annual cycle and in the vertical profiles highlighting the importance of using instantaneous values instead of mean values over time.

1 INTRODUCTION

The tropical atmospheric circulation (TAC) carries huge amounts of moisture and thus constitutes an important component of the Global Water Cycle. Some elements of the TAC, such as the Hadley Cell, can even extend to the extra-tropics. Changes in the intensity of TAC can affect the tropical moisture transports and can impact the characteristics of precipitation inside as well as outside the tropics.

TAC patterns are typically characterised by regions of rising air, e.g. due to more pronounced surface heating. The supply of continuously rising air causes horizontal divergence of air at upper levels. While being moved away this air cools again and sinks some distance from the region of rising. Low level flow is typically directed towards the region of rising. The most prominent example of such a pattern is the Hadley Circulation, extending over the tropical region of the whole globe.

Different answers, whether TAC has intensified or weakened in the past are given in literature, with e.g. *Vecchi et al.* [2006] finding a weakening, but *Sohn and Park* [2010] finding a strengthening. We here reinvestigate recent trends in the TAC applying mean as well as instantaneous values by means of the moisture transport. So far we have not distinguished between changes in atmospheric moisture amounts and changes in wind strength.

2 DATA AND METHOD

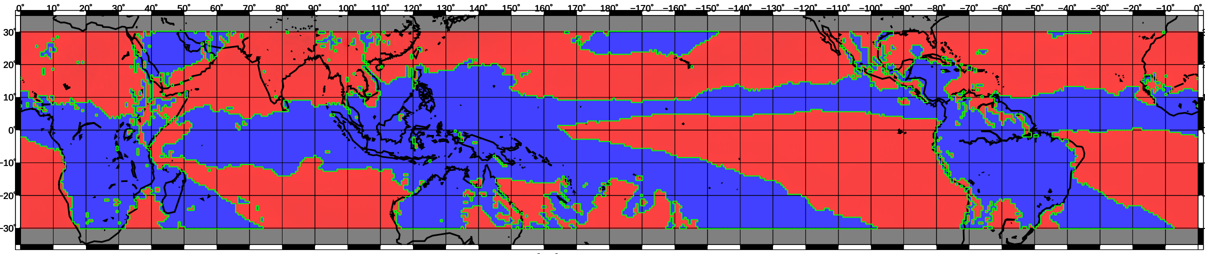
To investigate moisture fluxes of the TAC we applied global reanalysis data from ERA-interim[*Simmons et al.*, 2007] developed at the European Centre for Medium-Range Weather Forecast (ECMWF). From ERA-interim horizontal and vertical wind vectors (U,V and ω), specific humidity (Q) and vertical pressure information were used for the period 1989-2008 and between $\pm 30^\circ$ latitude, representing the tropics. Calculations were restricted to the lowest 30 model levels (representing the atmosphere up to an altitude of ≈ 200hPa), which contain almost all of the atmospheric moisture. Additionally, precipitation (P) and evaporation (E) were used as a reference to confirm the resulting moisture budgets.

The change of TAC in our study is characterized by means of changing transports along a boundary separating regions of upward (ASC) and downward (DESC) vertical wind motion in the tropics. Accordingly our calculations were subdivided into two steps:

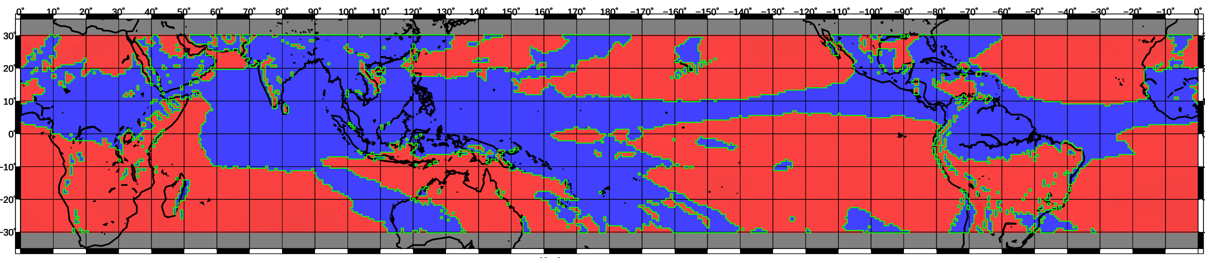
- first, the boundary along the ASC regions has to be defined,
- then, the transport of water vapour over this boundary is calculated.

2.1 DEFINITION OF BOUNDARY SEPARATING ASCENDING AND DESCENDING BRANCH OF THE TROPICAL CIRCULATION

The regions of upward and downward vertical wind motion (ascending (ASC) and descending (DESC) regions), and thus the branches of the Hadley cell, vary over time. Although ASC and DESC are highly variable even on the six hourly timescale of ERA-interim, we in this first study used monthly mean ω for their identification. To distinguish between ASC and DESC ω at 500hPa level has previously been used [*Allan and Soden*, 2007]. Here vertically averaged monthly mean ω was calculated for each grid box, weighting ω by the thickness of each layer, respectively. Whenever we find different directions of this averaged ω in two neighbouring grid boxes, a boundary segment is defined between these two boxes. Two resulting examples of the computed boundary are given in Fig. 1 for northern and for December 1995 and Jun 1996.



(a) Dec 1995



(b) Jun 1996

Figure 1: Direction of vertically averaged monthly mean ω per grid box in Dec 1995 (a) and Jun 1996(b). Regions with ascending (blue) and descending (red) vertical motions in the tropics and boundary (green line) separating both.

2.2 ESTIMATION OF THE MOISTURE BUDGET

To estimate the moisture budget, the moisture flux (MF) is calculated along all the n_b boundary segments b between ASC and DESC (green line in Fig. 1) each month. Therefore the perpendicular wind vector (WP) and the precipitable water content (PWC) are estimated along each boundary segment on each of the n_l model levels l. For each segment on each level, MF then is the product of WP and PWC. The total moisture budget at time t then is the sum of MF at each segment on each level:

$$MF_t = \sum_{b}^{n_b} \sum_{l}^{n_l} WP_{bl} * PWC_{bl} \tag{1}$$

This total moisture budget is calculated based on monthly average values for Q and U and V (MFmm) as well as based on (6-hourly) instantaneous values (MFhr).

Additionally, precipitation and evaporation are used for all ASC grid boxes and the moisture budget is estimated from P-E.

3 RESULTS

Fig.2 shows the yearly time series and the yearly cycle of the moisture budget. Calculations are based on instantaneous (MFhr) wind and humidity on the one hand and based on monthly means (MFmm) on the other. Also given is the moisture budget estimated from precipitation minus evaporation as a reference.

There is a large offset between MFhr and MFmm. The influx into ASC is $\approx 25\%$ higher when mean values are applied. However, the yearly time series of MFhr and MFmm take a similar course: years of peak or minimum influx are usually the same, no matter if mean or instantaneous values are applied. This situation is different in the yearly cycle. While in MFhr there are two peaks in the respective hemispheres' summers, in December/January and July/August, there is only one distinct peak found in MFmm, in southern summer. In other words: there is a relatively high correlation coefficient $r = 0.94$ between the yearly time series, but a considerably lower one of $r = 0.50$ in the yearly cycle.

Also shown in Fig.2 are the yearly time series and the yearly cycle of the moisture budget calculated from P-E. There is a similar mean budget in P-E and MFhr (323 and $320\ \frac{km^3}{day}$) and also the respective yearly and monthly values differ little. Differences may just be related to numerical reasons or to changing atmospheric moisture content (AMC). Note, that MF may either affect P-E or the total AMC over a given region, as

$$MF = P - E + \Delta AMC \tag{2}$$

The budgets from P-E and MFhr share the large offset compared to MFmm.

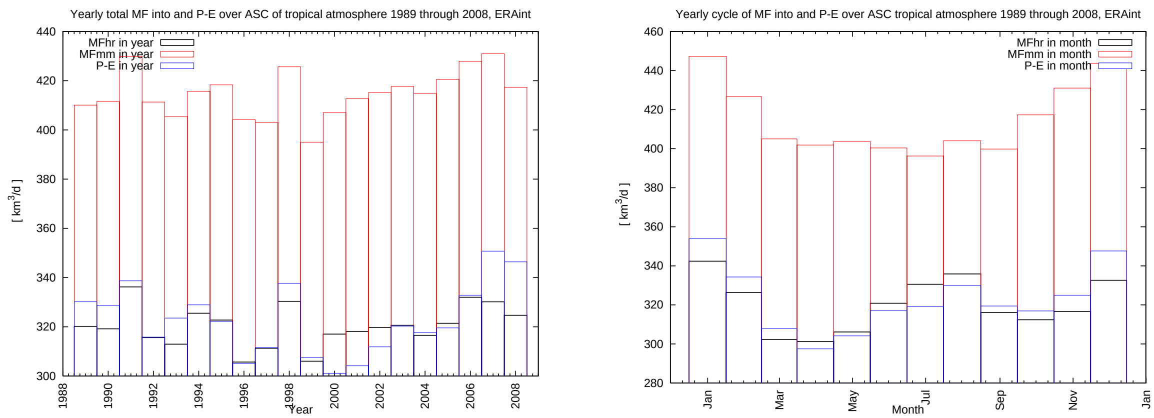
We calculated trends for all the three data sets based on the least squares method:

- P-E : $0.27\frac{\frac{km^3}{day}}{year}$
- MFhr : $0.24\frac{\frac{km^3}{day}}{year}$
- MFmm : $0.51\frac{\frac{km^3}{day}}{year}$

All the trends are positive, but none of them is significantly (according to a t-test based on the yearly values) different from 0. We found the trend in MFhr and P-E to be of a similar strength, whereas the trend in MFmm is approximately twice as large.

To find out the reason for the large discrepancies between MFmm and MFhr/P-E, we investigated closer the vertical profile of moisture fluxes along the boundary. A plot of the mean MFmm and MFhr over the whole time period is shown in Fig.3. In accordance to the lower level convergent flow (trade winds) of the Hadley Circulation, both data sets reflect the equator ward motions, indicated by inward fluxes of moisture into ASC. At the medium height and uppermost levels, fluxes are directed poleward in also accordance to the Hadley Cell's upper level divergence.

There is one substantial difference between the vertical profiles: while the lower level influx is of similar magnitude for both, MFhr and MFmm, there is a much lower outflow at



(a) yearly values (b) seasonal cycle

Figure 2: Yearly moisture budget calculated as atmospheric moisture transports based on instantaneous (MFhr) and monthly mean wind and humidity as well as on precipitation and evaporation. Time series (2(a)) and monthly mean values (2(b))

the upper levels in MFmm. This lower outflow probably is the reason for the higher values in the moisture budget in MFmm. So far, we can only speculate about the reasons for this difference. We suggest, that largest upper level outward fluxes of moisture occur, when high amounts of PWC and high wind speeds directed outwards occur at the same time. This coincidence of high wind speeds and moisture are 'averaged out', when only monthly values are applied. Recall, that despite the relatively regular pattern of the Hadley Cell, wind speeds can be very variable and even directed inwards to the ASC at upper levels, thus reducing the average strength of the outward directed wind speed.

4 SUMMARY AND OUTLOOK

In our effort towards a reassessment of changes in the tropical moisture budget and changes in the tropical circulation, we have calculated the moisture transports using wind vectors and atmospheric humidity from ERA-interim. For the moisture flux calculations, we applied monthly mean values on the one hand, and 6 hourly instantaneous values on the other. We found a large offset in the calculations based on the monthly values as compared to those based on 6 hourly values. Unlike the budget from the monthly values, that of the 6 hourly values is close to a reference budget derived from the difference of precipitation and evaporation. We conclude, that there is a systematic error in the moisture budget calculated from the monthly mean values, which originates from badly represented fluxes in the upper model levels. This error does not only influence the amount of the budgets, but also leads to an inaccurate annual cycle of the budget as well as to an overestimated trend.

We conclude for our further investigations, that mean values are inadequate for the

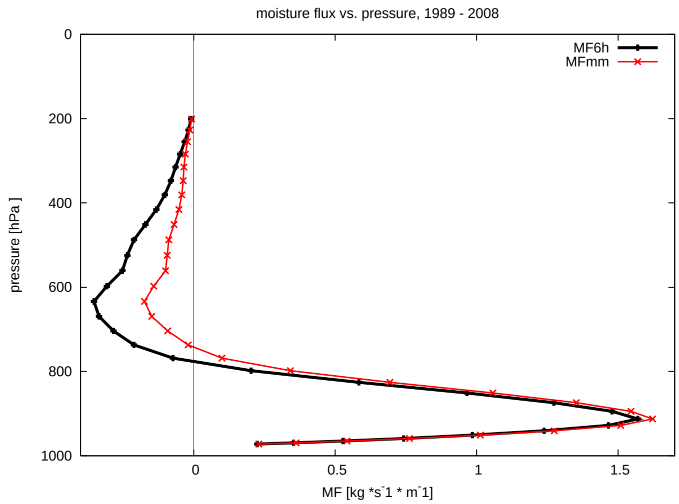


Figure 3: Average vertical profile of moisture transport (moisture transport against pressure) into ascending regions of the tropics calculated based on instantaneous (black) as well as on monthly mean (red) values.

moisture budget calculations. For the sake of simplicity we in this study have applied a mask for regions of rising and sinking motion which is based on monthly mean vertical winds. To what extent the usage of mean values for the definition of regions and the boundary line over which the moisture transports are calculated remains to be investigated.

Further future tasks will be to compare moisture fluxes in ERA-interim with satellite data for validation purposes. Changes in moisture transports can be due to changing wind patterns or changes in atmospheric moisture content. Thus, another branch of investigations will be to relate changes to either of these options.

References

Allan, R. P., and B. J. Soden, Large discrepancy between observed and simulated precipitation trends in the ascending and descending branches of the tropical circulation, *Geophys. Res. Lett.*, *34*, 2007.

Simmons, A., S. U. J., D. Dee, and S. Kobayashi, Erainterim: New ECMWF reanalysis products from 1989 onwards, *Newsletter 110*, ECMWF, 2007.

Sohn, B. J., and S.-C. Park, Strengthened tropical circulations in past three decades inferred from water vapor transport, *J. Geophys. Res.*, *11*, 2010.

Vecchi, G. A., B. J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison, Weakening of tropical pacific atmospheric circulation due to anthropogenic forcing, *Nature*, *441*, 73–76, 2006.