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Atmospheric forcing mechanisms of polar motion

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Abstract. The polar motion consists of free and forced oscillations which are influenced by mass variations in the Earth system. The contribution of the atmosphere to the excitation of the polar motion is investigated by forcing the dynamic Earth system model DyMEG with atmospheric angular momentum (AAM) and by multivariate statistical analyses of the regional representation of the AAM. The analyses are performed with the ECHAM3-T21 and the ECHAM4-T42 global circlation models, which are only forced by observed sea surface temperatures. For validation, the NCEP-reanalysis is used. The model results of DyMEG show, that the annual oscillation of polar motion is predominantly due to atmospheric pressure forcing, while the motion component is less important. A regional statistical analysis of the AAM due to mass variations presents an anomaly pattern which consists of strong annual pressure variations located over Asia, in particular at the Himalaya. This annual atmospheric pushing and pulling on the Earth above the Asian continent turns out to be the primary component responsible for accelerating the forced polar motion. These pressure variations are also active on higher frequencies connected with rapid polar motions. The results reveals, that atmospheric forcing is sufficient to excite the Chandler wobble (CW). Neither a significant nor at least an increased signal in the frequency domain of 14 to 16 months exists and regional statistical analysis of AAM give no hint for an oscillation with a typical time scale of 14 to 16 months. Hence, the CW seems to be excited by stochastic processes in the atmosphere.

1 Introduction

The polar motion of the Earth features variations which are caused by mass redistributions in the Earth system, ranging from diurnal to interdecadal time scales (Lambeck, 1980). The most prominent variations of polar motion are the annual and the Chandler oscillation. The former is mainly caused by mass redistributions in the atmosphere, but also the hydrosphere including the oceans show a relevant contribution to the annual signal (Nastula et al., 2003, Seitz et al., 2004). The Chandler wobble is a free oscillation of the Earth. It is well known, that the amplitude of the Chandler wobble would vanished due to frictional effects (Moritz and Mueller, 1987). However observations show an undamped oscillation in the Chandler frequency domain. Thus, the Chandler wobble must be permanently excited. The most likely primary components responsible for accelerating the forced polar motion are frequent mass variations in the Earth subsystems, namely the atmosphere and the hydrosphere (Wahr, 1983; Furuya et al., 1996, 1997). Seitz et al. (2004) have shown, that consistent atmospheric and oceanic forcing is sufficient to excite the simulated Chandler wobble of the Dynamic Model for Earth Rotation and Gravity (DyMEG, Seitz and Kutterer, 2002). Gross (2000) and Celaya et al. (1999) have pointed out, that oceanic and atmospheric excitation series exhibit enough spectral power in the Chandler frequency range to excite the Chandler wobble by resonant forcing. But nevertheless, the physical forcing mechanism of the Chandler wobble are still unknown.

In the case of the annual oscillation (Nastula et al., 2003) and high frequency variations (Salstein and Rosen, 1989), some regional analyses of the atmospheric mass variations were performed. But the physical processes of exchanging the angular momentum between the atmosphere and the solid Earth on these time scales are also still unknown.

Therefore the regional contributions of the atmospheric mass variations are analysed to detect typical variability patterns of the atmospheric mass, which are connected with polar motion. In addition, regional torques are analysed to understand the exchange processes between the atmosphere and the underlying solid or fluid Earth. This is done by analysing the atmospheric angular momenta (AAM) and torques of climate simulations with the ECHAM model (DKRZ, 1992; Roeckner et al., 1992; Roeckner et al., 1996) in different versions. Also, the NCEP reanalysis data are used for validation. To show the effect of atmospheric mass variation, DyMEG is forced with atmospheric data alone. Thus, if dominant mass variations occur, the resulting time series will give an impression of atmospheric contributions to polar motion.

2 Datasets, models and methods

This analysis will focus on the atmospheric forcing mechanisms of polar motion. We used atmospheric datasets based on climate simulations with the ECHAM model in different update versions and with different forcings. The ECHAM3-T21 global circulation model was forced with the Global Ice coverage and Sea Surface Temperature dataset (GISST, Parker et al., 1994) for the period from 1949 to 1994. These boundary conditions represent observed and analysed monthly mean data. The horizontal resolution of ECHAM3 amounts to 5.6^o corresponding to the spectral triangular truncation at the wave number 21. It has been shown, that this forcing provides a realistic climate variability (Glowienka-Hense, 1999; Stuck, 2002) Additionally we have used the more recent model version of the Max Planck Institute for meteorology (MPI), the ECHAM4-T42 model. This version is forced with the recent GISST2.2 dataset (Rayner et al., 1996) with improved and extended analysis of the monthly observed boundary conditions for the period from 1903 to 1994. The horizontal resolution amounts to 2.8^o due to the spectral T42 representation. The vertical resolution for both models is given by 19 vertical levels. Five runs of each model version were carried out with the same forcing but different initial conditions. To validate these models the datasets of the NCEP/NCAR reanalysis (Kalnay et al., 1996) are also used here. Those reanalysis data are interpolated to coarser grids, corresponding to each ECHAM model resolution (T21, T42).
To study the influence of atmospheric mass variations on polar motion, the non-linear model DyMEG is forced with the relative atmospheric angular momentum and the complete atmospheric tensor of inertia of the above described atmospheric data. The time resolution of the forcing amounts to 12 hours in the case of the ECHAM simulations and to 6 and 24 hours in the case of the NCEP/NCAR reanalysis. Comparisons between the model results for the different forcings are discussed in detail by Seitz et al. (2004).
The analyses in this paper are performed with multivariate statistics like the Empirical Orthogonal Functions (EOF, Kutzbach, 1967; Preisendorfer, 1988; von Storch, 1999) and the Canonical Correlation Analysis (CCA, Barnett and Preisendorfer, 1987; Bretherton et al., 1992). Time spectral analysis is done by Wavelet Transformation with the Morlet wavelet (Weng and Lau, 1994; Torrence and Compo, 1998).

3 Annual oscillation

The dominant excited signal of polar motion is the annual oscillation. Together with the Chandler wobble, it generates the typical observed beat of polar motion. Accountable for this annual forcing is the climate system, in particular the atmosphere (Celaya et al., 1999; Ponte and Stammer, 1999; Nastula et al., 2003; Seitz et al., 2004). Nevertheless, the underlying process which forces the annual oscillation of polar motion has still not been determined in detail.
One advantage of DyMEG is the ability to test different forcings and therefore to receive an impression which forcing is accountable for certain impacts on polar motion. Fig. 1 shows the resulting x-component of polar motion simulated with DyMEG from 1962 to 1994. The model was solely forced by atmospheric mass variations (matter term) (Fig. 1a)), and relative AAM (motion term) (Fig. 1b). The data were deduced from the ECHAM3-T21 global circulation model. Both time series confirmed the results of previous studies (Nastula et al., 2003), that the atmospheric matter term seems to be more important for forcing polar motion than the motion term. The time series of the x-component forced with the atmospheric matter term only (Fig. 1a) shows the typical characteristics of polar motion, according to the superposition of Chandler and

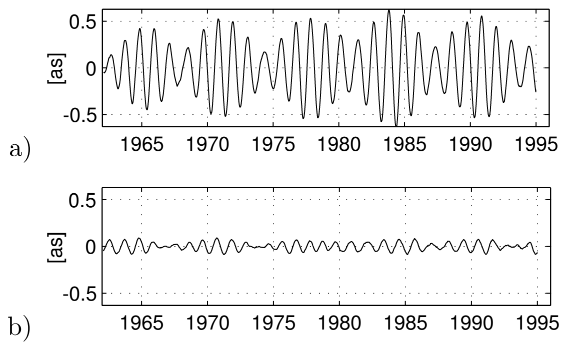

Figure 1: Resulting DyMEG time-series of the x-component of polar motion regarding atmospheric ECHAM3 excitation a) matter, b) motion.

annual frequency. Compared with the observed polar motion (not shown) the amplitude of polar motion, forced with the matter term is overestimated. This could be expected, since the atmospheric pressure variations over the oceans are not compensated by the barometric response of the oceans in this atmosphere-only experiment. Nevertheless, the simulated timeseries reveals an undamped Chandler wobble. This denotes, that atmospheric pressure variations contribute significantly to the excitation of the Chandler wobble.

The wind contribution to polar motion (Fig. 1b) is much weaker than the pressure contribution. After a few years the motion term produces an oscillation that features a collapsing beat. Thus, wind variations obviously play a minor role in exciting the Chandler wobble. The results of DyMEG forced with NCEP reanalysis data show a very similar behaviour (Seitz et al., 2004).

A spectral analysis of the forcing functions, i.e. the atmospheric matter term of the ECHAM3 and ECHAM4, reveals neither a significant nor an enhanced variability in the Chandler frequency range. The figure 2 shows the Morlet wavelet transformed atmospheric angular momentum due to pressure variations (matter term) of the x- and y-component of the ECHAM4 model (the results for ECHAM3 look alike). This spectral analysis is based on monthly mean values without the predominant annual oscillation which was removed by the long term monthly mean. Nevertheless, both spectra reveal significant high frequency variability for the whole period.

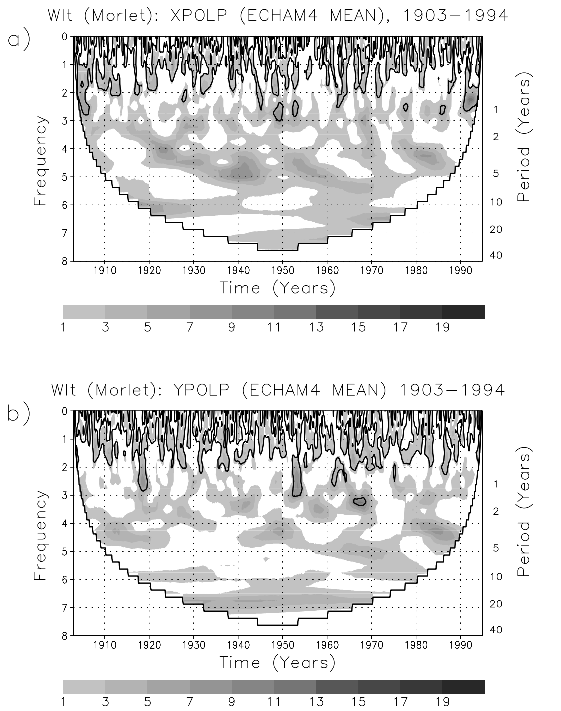

Figure 2: Morlet wavelet power spectra (normalized by variance of time series) of atmospheric angular momentum (matter) of ECHAM4 a) x-component, b) y-component. Annual variability is removed. Values of variances < 1 are masked out, values significant at the 1% level are marked in bold outline.

Regional analysis. Since pressure forcing is prominent for the excitation of polar motion, a regional analysis of the grid point representation of the atmospheric matter term is performed. The local atmospheric pressure is weighted according to the estimation of the global mean matter term (e.g. Bell et al., 1991) with the sine and cosine depending on the geographical latitude and longitude. Thus, only the horizontal integration is omitted. First, the Empirical Orthogonal Functions (EOF) of this local atmospheric matter term are estimated in order to detect the typical modes of space-time variability. Fig. 3 and Fig. 4 show the first EOF of the local matter term of the x-, and y-component of the ECHAM3 and the NCEP reanalysis data respectively. The patterns of the x-component (Fig. 3a, 4a) show a strong negative anomaly above the North Pacific and a positive anomaly above the North Atlantic. Beside these anomalies, some weaker signals over East Asia, Australia and Africa are visible. In general, the main

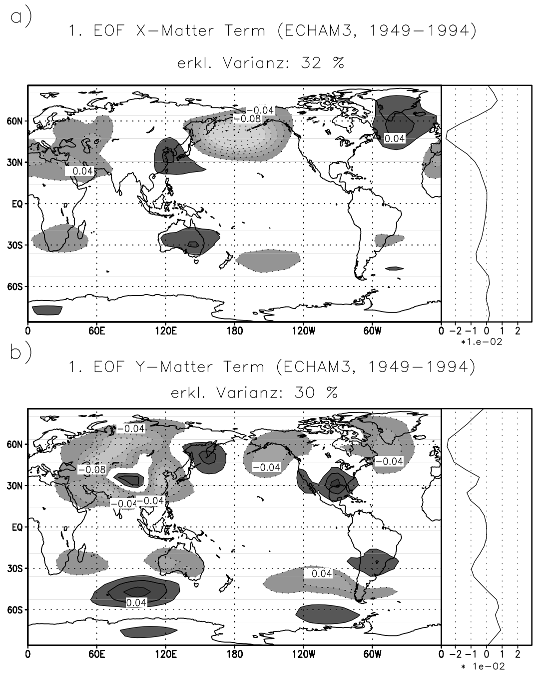

Figure 3: 1. EOF of the atmospheric matter term based on monthly means of one simulation of ECHAM3-T21 GCM (1949-1994), a) x-component, b) y-component.

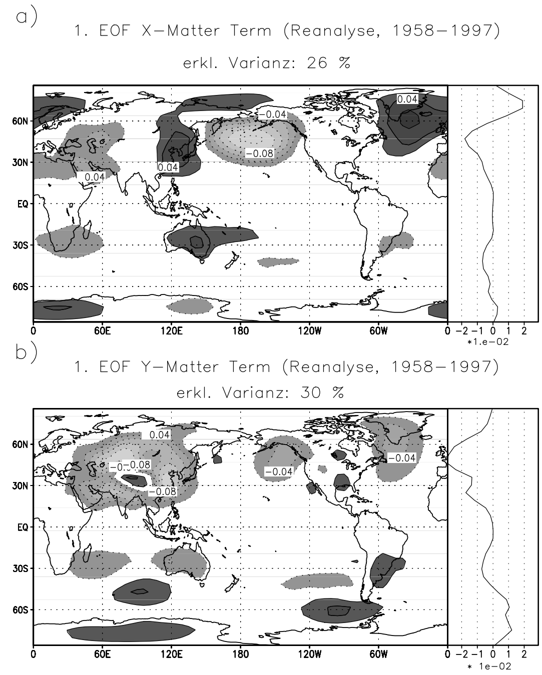

Figure 4: Same as Fig. 3 with NCEP reanalysis data (1958-1997), a) x-component, b) y-component.

anomalies are located over the oceans, which means, that those pressure variations should be compensated by the barometric response of the oceans. In contrast, the y-component (Fig. 3b, 4b) shows only one prominent anomaly pattern over central Asia in each dataset. Above the Tibetean Plateau is a positive anomaly. It is surrounded by a strong negative anomaly over the remaining mountainious regions of Asia. It is obvious, that these mass variations affect polar motion, since the variations are over land. This pattern of the atmospheric y-component (herein after called "'Himalaya mode"') turns out to be the main mechanism of polar motion excitation by pushing and pulling the Earth, in respect to the mean conditions. Due to the fact that the patterns explain roughly 30% of the total space-time variability, it is expected, that these pattern represent the annual oscillation of the pressure variation. Eventually, climatological variables offer a strong annual cycle.

The spectral analysis of the corresponding amplitude (principal component) of the 1.EOF affirm this assumption (not shown). Thus, only the annual oscillation is illustrated by the EOF pattern. In conclusion, the atmospheric mass variations excite the annual component of polar motion by pushing and pulling the solid Earth within an annual cycle over central Asia in the Himalaya region.

To give an impression how the atmospheric angular momentum is exchanged with the solid Earth via torques, a canonical correlation analysis is performed between the y-component of the local atmospheric matter term and the mountain and friction torque of both (x,y) components. The highest canonical correlation ($\tilde{\rho} = 0.97$) is reached for the combination with the x-component of the mountain torque. Both canonical correlation pattern are shown in figure 5. The upper panel (Fig. 5a) presents the variations of the mountain torque, which are highly canonical correlated with the variations of the y-component of the atmospheric matter term which is presented in the panel below (Fig. 5b). Since the pattern of the matter term looks absolutely similar to the Himalaya mode (Fig. 3b) this correlation occurs on the annual time scale. A spectral analysis of the corresponding amplitudes confirms this obvious similarity (not shown). The mountain torque pattern illustrates

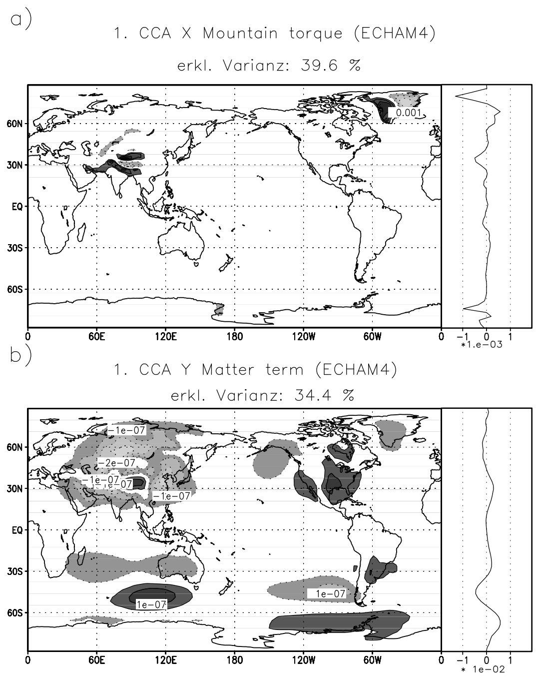

Figure 5: 1.CCA of a) mountain torque (x-component) and b) atmospheric matter term (y-component) based on monthly means of ECHAM4 simulation (1903-1994). Canonical correlation: 0.97

the exchanging processes of angular momentum due to annual pressure variations. As expected, very strong mountain torque variations occur at the Himalaya mountains, where the strongest pressure variations can be found. Suprisingly, there are also some obvious mountain torque anomalies at Greenland while the mass variations are only weak.

The CCA with the friction torque produces no significant correlation in the space time domain. This denotes, that the mountain torque is in particular responsible (at least on the annual time scale) for the transfer of atmospheric angular momentum into the solid Earth and vice versa.

4 High frequency variations

Besides the annual and the Chandler oscillation, polar motion is characterised by high frequency variations, too. As an impression, Fig. 6 shows the x-component of the simulated polar motion. In times when annual and the Chandler oscillation efface each other (i.e. the amplitude of polar motion is weak), high frequency oscillations are dominant (e.g. in 1980 and 1981). These variations are existent in both the observations

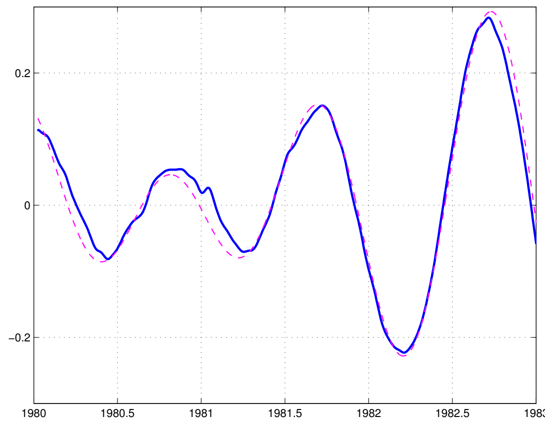

Figure 6: x-pol coordinates simulated with the DyMEG model forced with ECHAM3 (solid) and an idealized oscillation of annual and Chandler oscillation (dashed) for the period 1980-1983.

and the simulation. The atmosphere contributes significanly to these variations.

The analysis of the high frequency local atmospheric mass variations is based on the 12-hourly data of the ECHAM3 model for the year 1981. The 1.EOF of the 12-hourly data y-component of the atmospheric matter term (not shown) shows nearly the same pattern as the 1.EOF of the 46 years monthly mean series, i.e. the Himalaya mode (Fig. 3b). Only the explained variance of this pattern is reduced (12%). Since almost one annual cycle is included in this EOF-analysis, this similarity is not surprising. But the corresponding amplitude of this 1.EOF (Fig. 7b, solid) suggests also a connection of high frequency variability with the Himalaya mode. In particular in the beginning of 1981 a strong shift from negative to positive values and back to negative values within just a few days occurs. This fast variation reaches 2/3 of the amplitude of the seasonal cycle, which documents its importance compared with the annual variation. The time series of the global mean AAM and the global mean matter term (Fig. 7a) show also a strong anomaly in the beginning of 1981. Thus, anomalies of the global mean AAM are obviously produced by mass variations which are mainly due to the Himalaya mode.

Considering the amplitude of the 1.EOF of the matter term, one striking feature is the occurence of extreme amplitudes in the boreal winter season, while the amplitude in summer is much

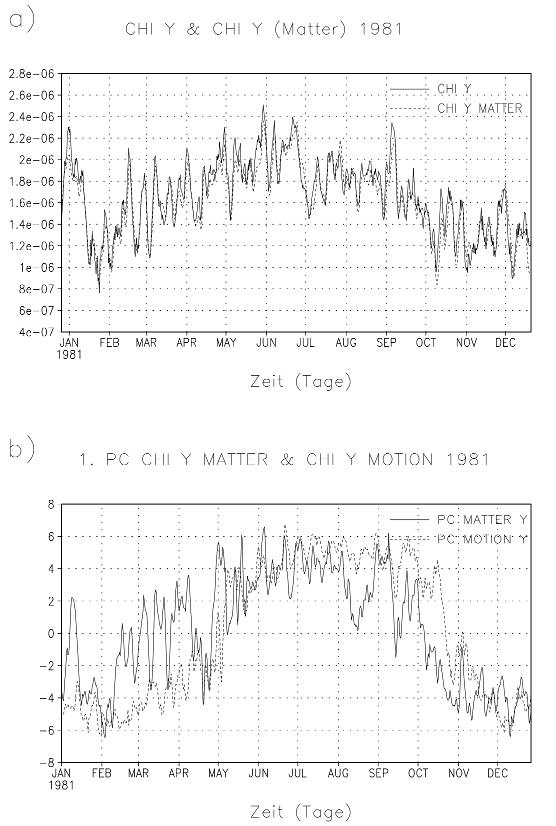

Figure 7: Time series of ECHAM3 y-component (1981): a) global mean AAM (solid) and global mean matter term (dashed), b) amplitude of 1.EOF matter term (solid) and amplitude of 1.EOF motion term (dashed).

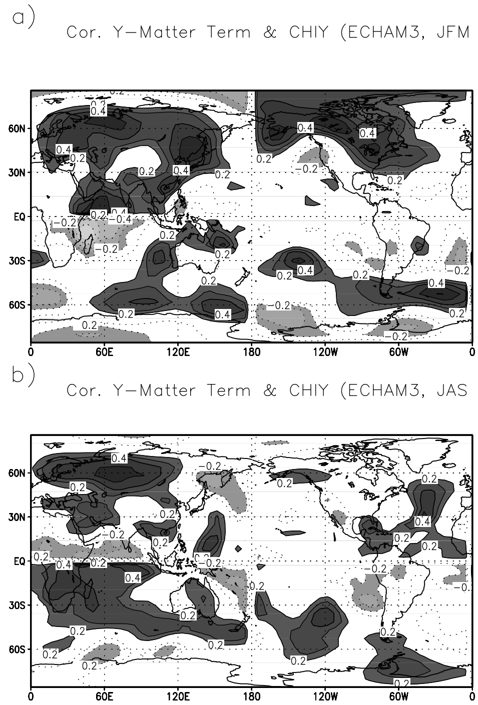

Figure 8: Local correlation coefficient of atmospheric matter term and global mean AAM, a) January, February, March; b) Juli, August, September; significant values (5%) are shaded.

weaker. Hence, the local matter term is correlated with the global mean AAM in winter and summer respectively (Fig. 8). In the winter season, the highest correlation occurs over Asia with a similar structure of the Himalaya mode and over North America. Some additional local correlations can be found over the southern oceans. Likewise in the summer season the strongest correlation occurs over Asia. Most of the other significant correlations are over the oceans, which may compensate these pressure variations. The correlation patterns confirm the EOF analysis of the 12-hourly data as it shows a significant influence of the Himalaya mode to the global mean AAM. Consequently, the Himalaya mode affects polar motion on high frequencies, too, especially during winter.

5 Conclusions

Atmospheric mass variations contribute to both Chandler and annual oscillations. Besides, they are responsible for high frequency variations of polar motion, too. The motion component (relative angular momenta) is generally less important for polar motion. In particular the pressure variations over Asia (Himalaya mode) play an important role for polar motion excitation. The results of DyMEG, forced with simulated atmospheric data, show that the Chandler wobble is excited by the atmosphere. Even though neither significant nor enhanced spectral power exists in the corresponding frequency range of the atmospheric angular momenta. The dominant part of the annual oscillation is caused by atmospheric mass variations at the Himalaya. Besides, subseasonal pressure variations in this region possibly contribute to high frequency polar motion. The pressure variations accumulate in boreal winter, where strong mass variations over North America occur, too. In summer, the highest pressure variations are compensated by the oceans. The anomalies of AAM due to the Himalaya mode are predominantly exchanged by the mountain torque at the Himalaya. But also some exchanging processes occur at Greenland via mountain torque.

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