Authors' response to reviewer #1

First of all, we would like to thank the reviewer for his careful reading and the very insightful and helpful comments. In the following, the reviewers' comments are in black, followed by our replies in blue. Modified and new text is in italic. The main changes in the revised manuscript are related to more thoroughly analysis of the orbit uncertainties related to time variable gravity field modeling and an analysis of the effects of the estimation of the DORIS system time bias on the radial orbit components of ascending and descending satellite passes.

General Comments

* The orbit error analysis is based on orbit differences, which exclude any error common to the orbits. This should be explicitly mentioned in the paper as well as the authors' assumptions in using orbit differences as an error estimate.

We agree with this comment. In addition to the already existing phrases we have included the following statements in the sections 'Introduction', 'Methods' and 'Summary and Conclusions'.

Page 2, lines 61-62: *Note, that our assessment necessarily excludes contributions from errors common to these three orbits.*
Page 4, lines 94-95:*The approach adopted for the estimation of the radial orbit errors implicates that errors common to all three orbits can not be detected. In particular, all three orbits rely on the ITRF2008 reference frame and basically the same set of tracking stations.*
Page 7, lines 190-193: *Since the radial orbit components map directly to the derived sea level heights, we consider the differences presented here to represent estimates of the orbit related sea level error. However, since the orbit error analysis is based on orbit differences, any error common to all three orbits will be lacking in our assessment.*
Page 12, lines 354-355: *We estimate the orbit errors from the radial orbit differences which implies that errors common to all orbits can not be detected.*

* It seems the large and very similar REF-GRGS and REF-GSFC differences shown in Fig 5 could be better explained. Although similar in structure, the REF-Geoid plot features are so much smaller that one may exclude these gravity model differences as the primary cause of the REF-GRGS plot features. I suggest the authors include the GRGS-GSFC plot in the paper for which the orbits have much greater gravity model differences. I suspect much of the annual variability now shown is due to non-tidal station loading for the REF orbit. This contribution is not tested, but the GRGS-GSFC plot may help better identify the source of the annual variations.

We have included the GRGS-GSFC plot in the paper (Fig. 5) as suggested. We now interpret the results in more detail (page 9, lines 256-270) and come to the conclusion that modeling of the non-tidal station loading is a plausible source for part of the observed annual differences.

* I also suggest running a spectral analysis on all the orbit differences to better identify all periodic signals; even if they are not evaluated they can be noted in the paper.

We have included plots of the power spectra of the global mean radial orbit differences for all orbit differences in the elctronical supplement (Fig. S2). We have added a short summary of the relevant periodic signals in Section 3.2.

Page 8, lines 229-233: *A spectral analysis of the global mean radial differences (Fig. S2) exhibits peaks at ~60 days for all but the GSFC and TBias orbit differences and at ~90 and ~170 days for the SLR and DORIS orbit differences. A weak annual component can be observed for the GRGS and Geoid orbit differences.*

* The orbit trend differences are very small (Table 4), however Table 1 indicates substantial differences in the time variable gravity models. I suggest the authors describe/compare which gravity coefficient rates are used over the TOPEX period for all models, and which are defined by SLR.

We have provided in Table 1 more details on the time-variable Earth's gravity field modelling, namely, for which coefficients drift (linear) terms and annual and semi-annual variations are available. Additionally, we have added a new paragraph in Section 2.1 describing the Earth's time-variable gravity modeling for the three orbits (page 3, lines 83-93). To our experience differing drift terms of time variable gravity field models mainly induce dipole like patterns of regional trend differences (Table 5, Fig. 7). On the global mean these signals tend to cancel (Table 4).

* This my main comment. The conclusion ends with a recommendation to try to better determine low-order gravity time-varying terms past the 5x5 field employed by the GSFC orbits using improved techniques with SLR/DORIS. The recommendation is not phrased clearly since the GSFC orbits show the lowest crossover residuals compared to the other test orbits which employ 50x50 and 80x80 time varying terms (Table 1). The problem for improving time variable gravity modeling over the TOEPX period should be an issue for all the orbits tested. The authors should mention this and clarify which time-varying terms are determined with SLR for the EIGEN-6S2 and EIGEN-6S4 fields over the TOPEX period and indicate the origin of the other terms. Furthermore the GSFC and Geoid orbit slightly improved performances over the REF orbit could suggest extrapolation of the higher order GRACE-defined seasonal terms to the TOPEX era may even be harmful. For example is the 5mm REF-Geoid annual signal (Fig 3) due to error in the REF orbit? The authors should clarify the conclusion in consideration of these remarks.

As mentioned in our response to the previous comment, we have specified in Table 1 and additionally described in Section 2.1 the details on modeling the Earth's time variable gravity. We further investigate and discuss the differences between the REF and the Geoid orbits at various places in more detail (page 6, lines 176-179; page7, lines 218-220; page 9, lines 269-270 and lines 285-288). We come to the conclusion that differences of the annual/semiannual terms of EIGEN-6S2 and EIGEN-6S4 for the pre-GRACE period are responsible for the enhanced performance of the Geoid with respect to the REF orbit. Differences of the regional interannual and decadal trends stem most probably from the yearly TVG terms derived from GRACE data starting from August 2002.
Additionally, we have replaced the last sentences of the Section “Summary and Conclusions” in order to clarify the conclusions (page 13, lines 409-419).

Specific Comments

* Any explanation why the DORIS residuals are slightly higher for the DORIS-only orbit? One would expect a decrease in the DORIS residuals compared to the DORIS+SLR orbit DORIS residuals.

We do not think, that the DORIS residuals of the DORIS-only orbit are necessarily smaller than those of DORIS+SLR orbit. In fact, the level of SLR and DORIS residuals for DORIS+SLR orbit is refined by the weighting of observation types (SLR and DORIS). In case, if SLR observations are given higher weight than DORIS observations, the SLR residuals of the SLR-only orbit should be smaller than those of the DORIS+SLR orbit and DORIS residuals of the DORIS-only orbit should be higher than those of the DORIS+SLR orbit. This is the case one observes in Table 2. This is, in fact, what is meant in the sentence "*This is related to the weighting of observations used (3 cm for SLR and 0.05 cm/s for DORIS) and to the number of observations used.*" on page 5, lines 139-140.

* p7 l191 "The annual component of the global mean orbit differences is not included in Table 4, since it is not significant." Insignificant in amplitude, or is the formal error larger than the estimate?

Insignificant in amplitude, we have clarified this.
Page 8, line 232: *Since the annual amplitude is less than 1 mm only, it can be neglected and is not included in Table 4.*

* p7 l212-216 non-tidal station loading for the REF orbits can also be included as a "plausible source" for annual orbit difference variations.

We agree with this comment. We have rephrased the paragraph.
Page 9, lines 265/266: *Another plausible source of the relatively strong signal for the GSFC and GRGS orbit cases are the differences in the annual corrections for station coordinates by geocenter motion corrections and non-tidal atmospheric loading.*

* It is not clear what the REF-DORIS plot in Figure 5 is intended to show?

We have replaced this subplot by the corresponding plot for GRGS-GSFC. The whole paragraph is rephrased and the results are discussed in more detail.

* It is interesting that the Figure 9 REF-DORIS plots show substantial trend differences for the ascending/descending passes. How is the considerable DORIS TOPEX network time bias treated for the various orbits? The SLR network should not have any significant time bias. It has been shown to be closely aligned with GPS time over the Jason-1 period (Zelensky et al. 2006, "DORIS time bias estimated using Jason-1")

In fact, the DORIS system time bias was estimated once per arc for the REF and GSFC orbits, and no bias correction was applied for the GRGS orbit. We have added this information in Table 1 and included a description and a plot of the DORIS time bias estimated with GFZ's orbits in Section 3.2 (Fig S1). Following your suggestions we have expanded our study. We have derived and analyzed an additional test orbit without adjustment of the DORIS time system. The corresponding analyses and results are described in Section 3.4.

* p9 l264 “The most striking feature is that the ascending trends are opposite to the descending trends.” Say one orbit is always ahead of the other and will reach the North pole region (+Z) first, and the trend is positive. After reaching the North pole, the orbits will race South (-Z), and now will not the trend be negative?

We have rephrased the corresponding paragraph. Making use of the new test orbit we introduced, we observe in fact a strong relationship between the estimated DORIS time bias and the global mean radial orbit differences, anti-correlated for ascending and descending tracks. The regional pattern of the decadal trends is a coherent pattern over the Tropics and Subtropics. The same pattern shows up as leading pattern with about 60% explained variance from an EOF-analysis (see attached figure).
The DORIS system time bias is clearly related to along-track orbit position changes. A time bias of the altimeter measurement is known to induce (due to the latitude dependance of the altitude rate) radial errors which are anti-correlated for ascending and descending tracks (e.g. Scharro, R.: A Decade of ERS Orbits and Altimetry, PhD thesis, 2002, Fig. 5.1). However, the corresponding regional patterns would be different from the ones we observe, they should reveal a change of sign somewhere around the Tropics.
Even though our study shows, that uncertainties of the DORIS time bias are capable to induce ascending/descending discrepancies it does not fully explain the mechanism that transfers the along-track errors to radial orbit errors. However this question is beyond the scope of our paper and might be subject of a proper study. We have added a corresponding phrase at page 11, line 330: *This mechanism is not fully understood but a further analysis is beyond the scope of this paper.*

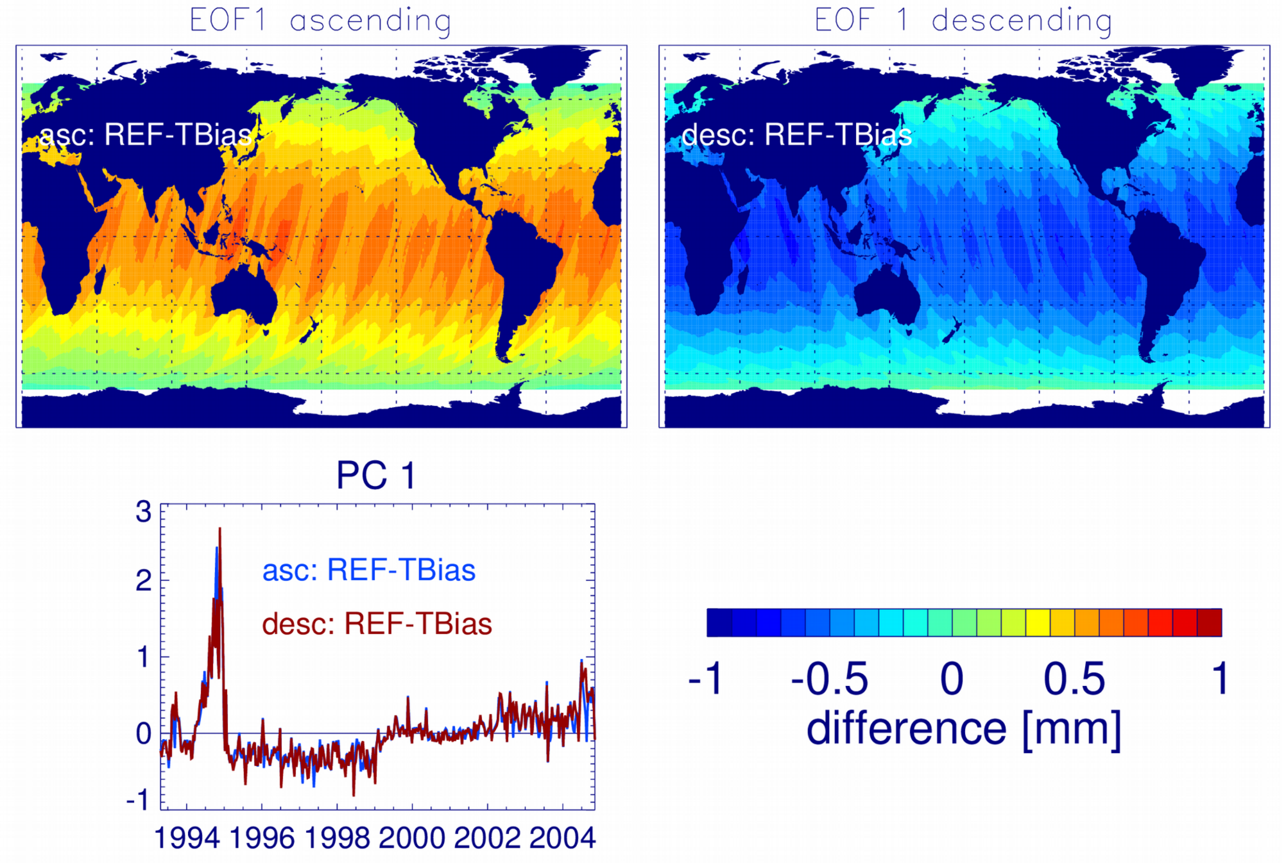

Figure: Leading pattern and time series derived from an EOF analysis of the *REF-TBias* orbit differences for ascending and descending passes.

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