Pintori et al. use a version of the ICA method (called variational Bayesian ICA) to decompose vertical GPS position time series and hydrology/atmospheric predicted loading time series around the European Alps. They study the agreement between the ICs extracted from the GPS series and from the loading models for the period from 2010 to 2020. Their main conclusions are that 1) the vertical GPS series can be separated in a tectonic linear motion and variations caused by temperature and atmospheric/hydrology loading; and that 2) improved tectonic velocities are obtained by correcting the GPS series using ICs obtained from the GPS series themselves.

While the volume of work is of note, especially concerning the GPS data processing, I do not think the conclusions are supported by the data and methods used by the authors. It is reasonable to say that temperature variations, atmospheric pressure variations and hydrology load variations contribute to the variations observed in vertical GPS time series, especially at the annual period, as GPS positions react to these and many other phenomena together. A completely different thing is to say that the observed GPS variations of vertical position *are* originated or explained by these processes, as the authors repeatedly state in the manuscript. This is a clear misinterpretation of their analysis and I develop my reasoning in the paragraphs below.

Thanks for this comment. We are aware that GPS stations react to many processes at the same time and that the changes in the GPS positions we highlighted are the response of the solid Earth to several multiscale processes. We made the relationship between observed signals and possible causative processes less strong over the text.

Before that, and assuming conclusion 1 is right, it's very surprising that the authors do not try to remove the modeled loadings from the GPS series to test the impact on the estimated velocities. Instead, conclusion 2 is based on removing the GPS ICs from the GPS series, i.e., conclusions 1 and 2 are totally unrelated. The GPS ICs were obtained from GPS series that were previously detrended, explaining the small change of the estimated velocities from the filtered series. The ICA filtering also explains the reduction of the noise in the series and, therefore, of the estimated velocity uncertainty from the filtered series.

The comment about removing the modeled loading from the GNSS time series was made also by Referee #1, we answer as follows:

Our goal is to remove signals associated with meteo-climatic processes using vbICA, instead of subtracting modeled displacements, such as those made available through loading services like GFZ, from the measured displacements. This approach minimizes biases due to the mismatch between the actual signal caused by atmospheric and hydrological loading and the modeled ones. Larochelle et al. (2018) reached similar conclusions by comparing GRACE measurements and the results from ICA decompositions of GNSS displacements, which resulted to be more accurate in correcting GNSS from seasonal displacements than removing GRACE displacements, which smooth local effects in the data acquisition and processing.

This is now described at the beginning of Section 5.1:

"Our goal is to estimate the tectonic velocity of the GNSS stations, then we seek to remove signals associated with meteo-climatic processes. Instead of subtracting from the IGb14-time series the modeled displacements, such as those made available through loading services like GFZ, we prefer to subtract the displacements associated with the ICs. This approach minimizes biases due to the mismatch between the actual signal caused by atmospheric and hydrological loading and the modeled ones. Larochelle et al. (2018) reached similar conclusions by comparing GRACE measurements and the results from ICA decompositions of GNSS displacements, which resulted to be more accurate in correcting GNSS from seasonal

displacements than removing GRACE displacements, which smooth local effects in the data acquisition and processing.

In order to support the approach followed, we estimated the scatter of the GNSS displacement time series by computing the mean standard deviation of 1) the time series given as input to vbICA (IGb14-time series), 2) the IGb14-time series minus the combined displacement associated with the first 3 ICs and 3) the IGb14-time series minus the displacements due to HYDL+NTAL from GFZ models. The resulting standard deviation is 5.32, 4.10 and 4.73, respectively. This demonstrates that removing the displacement associated with the first four ICs is more effective in reducing the scatter than removing the HYDL+NTAL contribution."

Where I think this approach fails is that the raw series (used to estimate the velocity, the filtered velocity being very similar) and the filtered series (used to re-estimate the velocity uncertainty) are not consistent and therefore the velocity and its "improved" uncertainty are not consistent either. The authors could have tried a more aggressive filtering, like a band-pass filter leaving the trend and high-frequency noise only, or could have not consider colored noise in the velocity estimation (both ways are equivalent) and they will get even smaller velocity uncertainties. Unfortunately, this will not give any valuable information on the quality of the velocity and your ability to extrapolate it to understand tectonic physical processes. The only way to improve velocity estimates is to understand and reduce variability in the GPS series with proven corrections and models. If the white noise is more visible in the filtered series is probably because the GPS ICs absorb together a significant portion of the power-law noise that typically dominates the variance of the detrended GPS series, though this is not very clear from the IC PSDs in Fig. 3. Precisely, the power-law noise in the GPS series is only mentioned briefly and its influence on the GPS ICs and on the correlation with the loading ICs is not discussed at all.

We do not understand what the reviewer means by "not consistent". Filtering Common Mode Signals or Common Mode Errors from GPS time-series is a very commonly adopted step, performed in many different ways (and our work discusses one possible approach) when research topics require improvement of the signal to noise ratio, and there is a vast literature on that. We agree that filtering the time series by applying, for example, a pass-band filter, does not give any valuable information on the quality of the velocities, and, in particular, on the nature of the signals filtered out. We partially disagree with the sentence that "the only way to improve velocity estimates is to understand and reduce variability in the GPS time-series with proven corrections and models". We agree that the common goal is to reduce the "variability" in daily positions, but adopting "proven corrections and models" is one way to reach that goal, not the "only way". For example, Dong et al. (2002) well described how to reduce variability in GPS time-series by adopting several models, however, in more recent papers similar results have been obtained by applying multivariate statistical methods (eg., Tan, Chen, Dong et al., Remote Sensing, 2020; Yan, Dong et al. JGR, 2019; Tan, Dong and Chen, Advances in Space Science, 2022, to cite a few from the same author). Larochelle et al., 2018, also, found that an approach that uses results from multivariate statistical methods is more accurate in filtering out seasonal signals than using proven models. See also our response to the next comment.

We discuss the effect of time series filtering on the noise in lines 432-435, 484-495 and in Figure 11.

With respect to the GPS ICs and their attribution of a geophysical origin, I enumerate below several points raising concerns on the authors' approach. Generally, many past publications have shown than GPS series and loading models do not see the same thing, except partly for the annual variation.

This latter sentence would provide further justification for the approach we have used in this manuscript. However, we agree that comparisons between models and geodetic observations greatly help in the interpretations, and this is exactly what we have done in Section 4.2.

Most of the variance in the loading model series is concentrated at the annual period. Compared to the PSD of the loading models, the GPS series contain a relatively higher variance at long periods with a distinct PSD slope and a PSD much richer in periodic artifacts at short periods. The authors briefly comment on the systematic errors that are present in the GPS series, but they do not try to make the GPS series more consistent with the model series. For instance, it is known the annual draconitic variation could significantly affect the comparison to the solar annual variation of the loading models.

The analysis of the PSD does not show the presence of frequencies associated with the draconitic signal in any of the ICs. While the draconitic signal frequency (~1.04 cycles per year) might be hidden in the annual frequencies of the ICs resulting from the GNSS data analysis (Fig. 3), it is much less relevant to explain data variance then the processes we discussed to interpret the GNSS_ICs (temperature-related processes, atmospheric and hydrological loading), whose frequencies are exactly 1 cycle per year. Otherwise, we would have observed an IC with a PSD of ~1.04 cycles per year, but this is not the case.

The results obtained by the authors are confusing (see points below) and do not refute findings from past publications, contrary to their claims to successfully separate geophysical signals from the GPS series. For instance, authors show no evidence that the HYDL series significantly explain variations in their GPS series. The GPS and NTAL annual seem to partly agree (see points below), so the authors introduce a thermal annual component in the discussion without providing strong evidence nor explanation of its spatial pattern.

NTAL is the most relevant cause of the displacements observed by GNSS, but also HYDL plays a role. This is proven by the correlation between HYDL and GNSS and by the increasing correlation with GNSS when considering NTAL+HYDL instead of HYDL only.

We are not introducing a thermal annual component, IC4 is a result of the vbICA analysis. We tried to better explain and interpret its spatial pattern in the main text:

"Air temperature increase can induce both positive and negative vertical displacements. In the alpine valleys the water content increases as the temperature increases because of the snow and ice melting. It follows that in those areas the elastic hydrological load is higher during summertime than winter (Capodaglio et al., 2017), so that negative vertical displacements are observed when the temperature increases. Then, it is not surprising that in the alpine valleys the stations affected by large IC4-related displacements move downward as temperature increases. This may be an example of a small-scale hydrological process that is likely badly reproduced by the global HYDL, which does not have a spatial resolution fine enough to represent hydrological loading displacements at the scale of the alpine valleys. Other site-dependent processes that can potentially induce uplift during winter are the ice formation, and subsequent melting, in the antenna and antenna mount (Koulali and Clarke, 2020) and soil freezing (Beck et al., 2015).

Conversely, positive vertical displacements as the temperature increases can be caused by monument/bedrock thermal expansion and by the drying of the soil, because of the reduction of the elastic hydrological load. While HYDL takes into account the drying of the soil, we cannot exclude that some very local, unmodeled, environmental conditions can amplify this effect at some sites. This might explain why most of the sites affected by uplift during temperature *increases are located in plain areas, like the northern sector of the Paris Basin and in the Po plain, instead of the mountainous ones.*

The relation between IC4 and local processes is also suggested by the heterogeneity of this signal in terms of spatial distribution, sign, amplitude and relevance in explaining the data variance. In fact, while ~50% of the station have U4<2mm [...]"

It is also probably worth mentioning that, if the GPS series were effectively explained by the combination of atmospheric/hydrology loading and temperature variations, as the authors claim, we should get the same GPS series out of the same GPS data when using different software, different strategies and different corrections. However, this is often not the case, especially when comparing global and regional GPS solutions.

Comparing the GPS solutions obtained using different software and strategies is out of the scope of this work. Section 5.2 is updated with additional content that we think helps to interpret the correlations shown in Section 4.2 between GNSS_ICs and NTAL+HYDL_ICs. Furthermore, in the introduction we point out that

"Excluding tectonic and volcanological processes, and once removed the effect of tides associated with solid earth, pole and ocean, variations of atmospheric pressure loading and fluid redistribution in the Earth crust are the main cause of vertical ground displacement recorded by GNSS stations worldwide (Liu et al. 2015)" .

It follows that we are not surprised to find the contribution of HYDL+NTAL in our GNSS data.

Other general points:

1) While I understand the objective of the ICA applied to the GPS series is to separate the variability into independent processes, I cannot understand the rationale for applying ICA to the NTAL and HYDL series. What are the independent processes to be separated in the atmospheric pressure loading or water loading? Even more confusing are the results from the comparison of a single GPS IC to a single NTAL/HYDL IC and the claim that the GPS series are explained by both.

The goal of applying vbICA to HYDL and NTAL time-series is not that of separating possible different sources, but to investigate the presence of possible spatial and temporal signatures in the model datasets to be compared with results from GPS decomposition, such as the ones discusses in this work (IC1, IC2 and IC3).

At the beginning of 4.2 we add some text to better and, hopefully, more clearly explain why we decompose NTAL and HYDL and what the different component mean in terms of "sources":

"As discussed in the introduction, atmospheric and hydrological loading are likely the main sources of vertical displacement in the great Alpine region. Since they are both uniform in terms of spatial response, showing smooth spatial variations, we decided to check if the first 3 ICs of the GNSS decomposition are associated with the displacements due to atmospheric and hydrological loading, and with their pattern of variability.

The vbICA analysis separates the data into statistically independent signals, which is useful because independent signals are often caused by different and independent sources of deformation. Nonetheless, a single source of deformation, such as atmospheric or hydrological loading, can be spatially heterogeneous and characterized by peculiar spatio-temporal patterns. In this case, the vbICA separates a single source of deformation in different signals associated with different spatio-temporal patterns. As a consequence, we decided to apply a vbICA decomposition on HYDL and NTAL model displacement time series in order to check if

> *they show any pattern and if they resemble the spatial distribution of IC1, IC2 and IC3 of the GNSS decomposition."*

The ICA analysis is forcing the NTAL/HYDL series into non-gaussian independent components, even if they do not exist physically. This probably explains why the total NTAL annual is split across ICs with spatial patterns as orthogonal as possible.

> It is worth noting that the similarities between the spatial patterns of the NTAL and HYDL independent components do not depend on how the algorithm works: the relative position of the sites is never taken into account during the analysis.
>
> The presence of N-S and E-W gradients in the ICs of both NTAL and HYDL, and also of the precipitation data, is likely caused by their link to a common, meteo-climatic, source. In fact, precipitation, atmospheric and hydrological loading depend on the climatic conditions, which are spatially and temporally variable. Besides IC1, which is a spatially uniform signal explaining more than the 90% of the total variance in either NTAL or HYDL decomposition, IC2 and IC3 probably reveal the spatio-temporal features of the weather regimes that cause atmospheric and hydrological loading on the surface: the Atlantic Ridge and the North Atlantic Oscillation. In section 5.2 we added the following part:
>
> *"It is then likely that weather regimes like the NAO and the Atlantic Ridge influence both NTAL and HYDL, which is mainly forced by precipitation, so that the spatial patterns of the ICs associated with atmospheric and hydrological loading are the same of NAO (N-S) and Atlantic Ridge (E-W)."*

The same spatial patterns are found for the GPS series, probably because once the trend, offsets and annual are removed from the GPS series, what is left is a Gaussian or near Gaussian series with temporal & spatially correlated noise and also the above-mentioned systematic periodic errors. It may be that the easiest way for the ICA to force the separation of these residual series into ICs is by making their spatial patterns orthogonal (see another possible explanation in point 5 below). The authors' conclusion that GPS and loading see the same spatial patterns is therefore not very solid.

> We would agree if the N-S and E-W patterns weren't found in NTAL and HYDL. Anyway, since we observe these kinds of patterns, and there is also temporal correlation between NTAL+HYDL_IC2(3) with GNSS_IC2(3) what we are observing is more likely a signal than noise. See also the updated Figure 7.

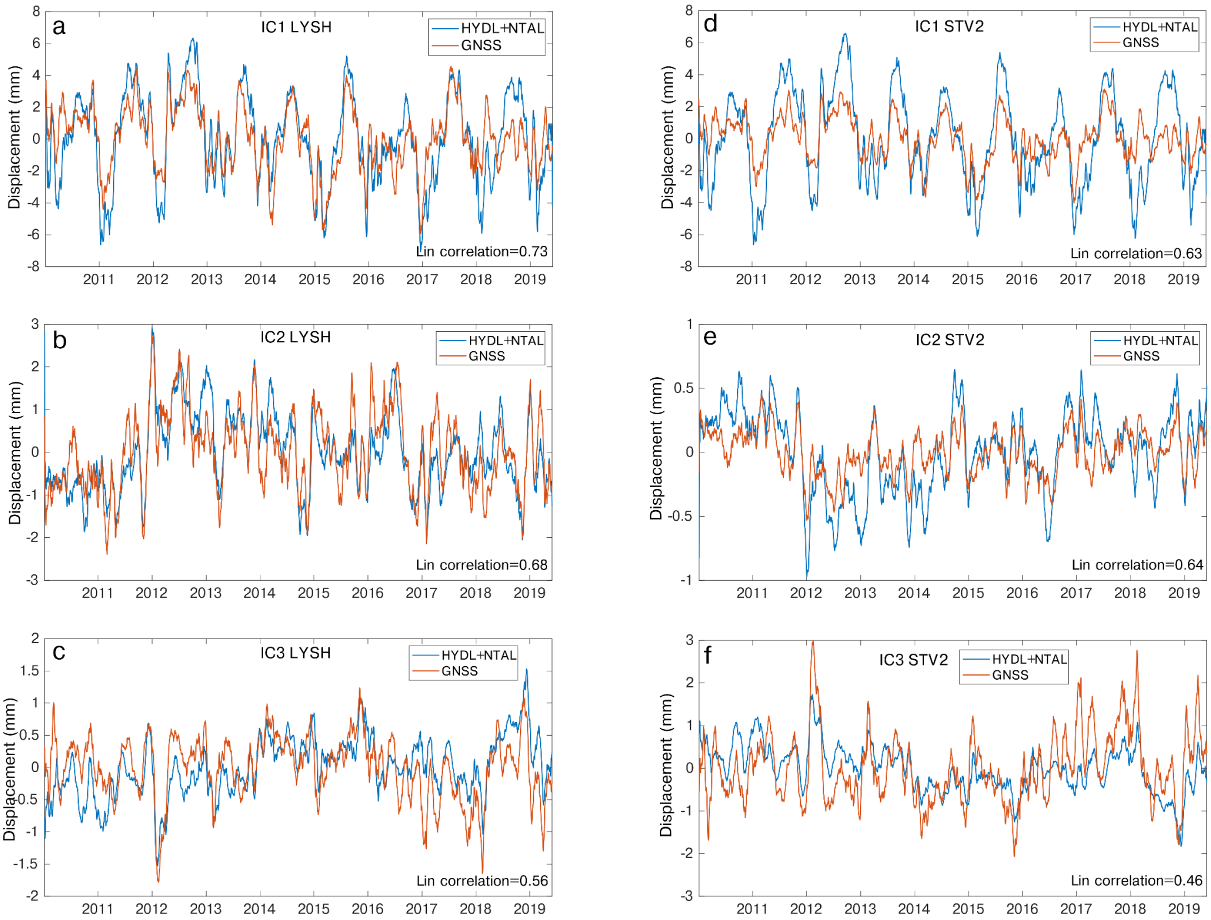

Figure 7: Comparison, at the LYSH (Lon: 18.45°; Lat: 49.55°) site, between the displacements associated with: a) GNSS_IC1 and NTAL+HYDL_IC1; b) GNSS_IC2 and NTAL+HYDL_IC2 ; c) GNSS_IC3 and NTAL+HYDL_IC3. d), e), f) are the same as a), b), c), respectively, for the STV2 (Lon: 6.11°; Lat: 44.57°) site. A 30-days moving average filter is applied to better visualize the data.

2) The GPS and NTAL/HYDL series have different spatial samplings, which must complicate the interpretation of their comparison. Also related to the spatial sampling, it must be difficult to extract accurate NTAL values in the Alps due to the pressure model resolution and the short-scale changes in topographic gradient, making its comparison to the GPS series even less trustworthy. I suspect similar limitations exist when comparing GPS and HYDL model series in a mountain range.

We do agree, and we are aware that at some GNSS sites probably HYDL do not correctly model the displacements caused by hydrological loading because of very local scale processes. We make that more explicit in the text when discussing the interpretation of IC4:

"In the alpine valleys the water content increases as the temperature increases because of the snow and ice melting. It follows that in those areas the elastic hydrological load is higher during summertime than winter, as observed by Capodaglio et al. (2017), so that negative vertical displacements are measured when the temperature increases. Then, it is not surprising that in the alpine valleys the stations affected by large IC4-related displacements move downward as temperature increases. This may be an example of a small-scale hydrological process that is likely badly reproduced by the HYDL displacement dataset, which does not have a spatial resolution fine enough to represent hydrological loading displacements at the scale of the alpine valleys. Other site-dependent processes that can potentially induce uplift during

winter are the ice formation, and subsequent melting, in the antenna and antenna mount (Koulali and Clarke, 2020) and soil freezing (Beck et al., 2015).”

On the other hand, the concordance between NTAL and GNSS time series seems very good, in particular when considering IC1 (Fig. S8), which explains the largest percentage of variance of the data. The overall agreement between HYDL+NTAL with the displacements associated with the first 3 ICs seems robust to us and we believe that this justify the approach of estimating environmental-induced displacements directly from the data and not from the models, which are used only for comparison.

3) Each dataset used by the authors is decomposed in different numbers of ICs: 7 for GPS, although only 4 are discussed, and 3 for the model loadings. Then they compare the first 3 individual ICs and find weak correlations between them.

IC5, IC6 and IC7 are discussed in the Supplementary Material, as we find that these are more localized features associated with local processes, not of interest for the Alpine area.

We do not agree with the word “weak” to define the correlation between the first 3 ICs of the GNSS and of HYDL+NTAL (Fig. 6). We provide additional details about the correlation between the displacements associated with the ICs, including not only the Lin, but also the Pearson correlation coefficient as suggested by Referee #1.

The authors conclude on the origin of the individual GPS ICs based on their correlation to the individual loading ICs. However, this criterion is very weak, especially with correlation values around 0.6. As an example, similar (Pearson’s) correlation values would be obtained between a pure sinusoidal and the same sinusoidal delayed almost pi/3, which is roughly two months if the sinusoidal has a period of one year. When subtracting one sinusoidal from the other, it is clear that we are not correcting much. The ratio of explained variance between the different ICs would have been more appealing, but, it is not clear that the individual ICs from different datasets correspond to the same fraction of the total signal (see point 1).

We added the percentage of explained variance in the figures.

We show histograms with the maximum displacement associated with each IC in the supplementary material (Fig. S4, which we now moved in the main text as suggested by Rev#3), while the spatial response in Fig. 3 shows the displacement associated with each station for each IC.

We agree that two sinusoidal signals can be correlated even if they are out of phase. Nonetheless in our case, especially when considering the displacements associated with atmospheric loading, which are larger than the ones caused by atmospheric loading, we observe temporal evolutions (Fig. 4) which are far from a pure sinusoid. It follows that it is very unlikely that a signal is by chance correlated, both in terms of amplitude and temporal evolution, with the ones shown in Fig. 4. Further evidences about that are shown in Fig. 7, where the correlations between IC1 (Fig. 7a 7d), which are around 0.6, are not the result of two sinusoids out of phase.

So maybe the ICA method is not well adapted to this problem or should not be applied to the NTAL/HYDL series (see point 1). A band-pass filtered comparison of GPS and loading series would probably be more informative here. Also rather than filtering the GPS series, I think it would have been better if the authors had shown how the loading models change the variance of the GPS series, as it is done in many other publications. The loading would need to be computed

at the station locations. It would have been even better to show how the GPS variance changes (not necessarily reducing) all along its power spectrum when correcting the loads.

We estimated the scatter of the time series by computing the mean standard deviation of the time series given as input to vbICA (IGb14-time series); IGb14-time series minus the combined displacement associated with the first 3 ICs; IGb14-time series minus the displacements due to HYDL+NTAL. The resulting standard deviation is 5.32, 4.10 and 4.73, respectively. This demonstrates that removing the displacement associated with the first four ICs is more effective in reducing the scatter than removing the HYDL+NTAL contribution.

4) The authors are processing a regional network and aligning it to a global linear frame (IGb14) that does not include seasonal variations. The frame alignment of the daily solutions from regional networks acts as another CME-like filtering of the series, not discussed by the authors, but probably similar to the SFM method. The filtering is more efficient as the network size is smaller, but the authors do not provide enough information on this point. It is then difficult to interpret the common network-wide annual signal shown by the GPS IC1. I would expect the regional frame alignment would absorb part of this common GPS annual signal, making it difficult to compare to the loading model and also leaving an amplitude much smaller than the residual station-dependent annual signal that is probably captured by the IC4. However, the numbers in table 1 indicate the opposite, assuming the average "of the amplitude of the maximum displacement" is somehow related to the annual amplitude, which is not clear either. The annual variation is the most prominent signal in NTAL with amplitudes typically of a few mm, less than 1 cm at the center of large continental masses. So it's not clear what the authors mean with atmospheric loading amplitudes larger than 2 cm. It is also not mentioned which frame was used to create the loading series and whether they were detrended like the GPS series, especially the HYDL series.

The position time-series used in this work do not come from a regional GNSS solution. As explained in Section 3.1 and in the Supplementary Material, the Alpine time-series are part of a much larger solution that includes data from >4000 continuous GNSS stations distributed mainly in the Eurasian and African plates. It is worth considering that seasonal terms in ITRF have been introduced only with ITRF2000. The IGb14 frame is determined by a robust "quasi-global" network of ~250 IGb14 core sites + some regional high-quality stations (see figure below, where blue circles show the sites used to define the IGb14 reference frame). For this reason, we are quite confident that if some CME is absorbed by the daily alignment to IGb14, this is a fraction of the one in case of regional solutions. The N-S and E-W gradients in spatial patterns of common ground displacement components were found in Serpelloni et al. (2013), who used a continental-scale solution, by combining regional solutions with global MIT SINEX and using 246 IGS stations for the reference frame definition (Fig. S1). Figure S1 is now included in the Supplementary Material.

We added, from line 209, a more detailed explanation on how to interpret the temporal evolution, the spatial distribution and the displacement associated with the ICs.

"Before discussing the vbICA results, we briefly explain how to interpret the temporal evolution and the spatial distribution of the ICs, so that it is possible to retrieve the displacements associated with them.

The color of each GNSS site in Fig. 2 represents the IC2 spatial response (U2), which indicates the maximum displacement associated with the IC2, while the temporal function V2 is normalized between 0 and 1. The displacement associated with IC2 between two epochs (e.g. t1 *and t2, with t2>t1) at the station n is computed as V1(t2)*U1n-V1(t1)*U1n(t1), where V1(t2) is the value associated with the temporal evolution of the IC at the epoch t2.*

*U1n depends on the site, but not on the epoch; its unit of measurement is mm, while V has no units of measurement. As a result, V1*U1n is in mm. It follows that if U1n is positive, as we observe for each station, and V1 is increasing (V1(t2)>V1(t1)), the stations move upward during the t2-t1 time interval. On the other hand, if V1(t2)<V1(t1) the stations move downward during t2-t1.*

As regards Fig. 2, assuming t1=2010.0 and t2=2020.0, the displacements associated with IC2 are ~30 mm upward at the "red" GNSS stations, ~30 mm downward at the "blue" GNSS stations and ~0 mm at the white ones."

We also modify lines 255-256:

"IC1 is a spatially uniform signal characterized by an annual temporal signature, as shown by the power spectral density (PSD) plot in Fig. 3a. The mean of the maximum amplitudes is 26 mm, while the histogram showing the distribution of displacement amplitudes is shown in Fig. S3a.

IC2 shows a spatial response characterized by a clear E-W gradient, but, differently from IC1, its temporal evolution has not a dominating frequency. The spatial response U2 of the eastern stations (in blue) is mainly negative, while the U2 of the western stations (in red) is mainly positive."

We used the Center of Figure reference frame and the time series were not detrended; we added this information in the text.

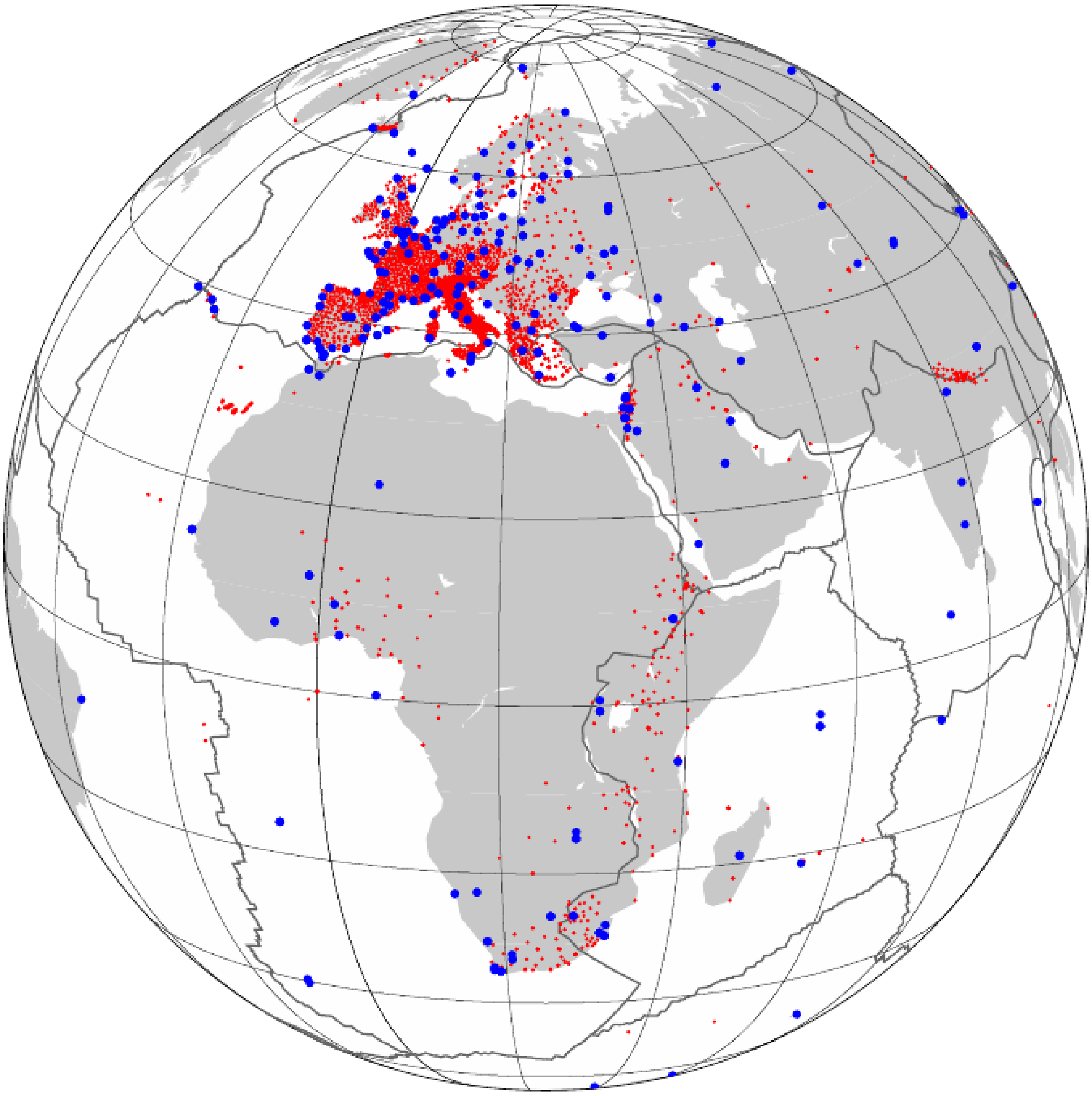

Figure S1: Distribution of the continuous GNSS stations analyzed (red dots). The blu circles show the sites used to define the reference frame, including all IGb14 core sites, integrated by additional, high-quality, IGS stations.

5) The 2nd and 3rd GPS ICs are particularly interesting. These represent daily E/W and N/S network tilts with a rather flat spectrum. The NTAL and HYDL show similar spatial tilts, but their physical meaning is dubious (see point 1) and their spectral content is completely different: mostly seasonal for NTAL and mostly interannual for HYDL. The origin of these network tilts is very likely not the same among the datasets, as stated by the authors. In addition, if the whole GPS network is truly moving like these two ICs and it is not an artifact of the ICA separation, I would first think of a problem with the reference frame alignment. As said in point 4, network-wide common mode signals, including daily tilts and annual up & downs, should be at least partly (if not totally) absorbed by the frame alignment as these signals are not included in the linear reference frame and the network size is probably not large enough. Figure 7b must be wrong as there is no annual variation in the GPS IC2.

We updated Fig. 7 considering different stations: one located in the south-western part of the network (STV2), the other in the north-eastern side (LYSH), so that the displacement associated with GNSS_IC2 and GNSS_IC3 have opposite sign.

In section 5.2 we discuss with more details the interconnection between precipitation, atmospheric pressure and hydrological loading. We hope that this part helps to make more clear that what GPS is recording is mostly caused by the environmental contribution (atmospheric + hydrological loading) and not by data processing errors like the reference frame alignment or the draconitic variation:

"*We also performed a vbICA analysis on precipitation data (RAIN) recorded over the study region, using 3 ICs. The spatial pattern of the ICs is analogous to the ones associated with NTAL and HYDL (Fig. 14).*

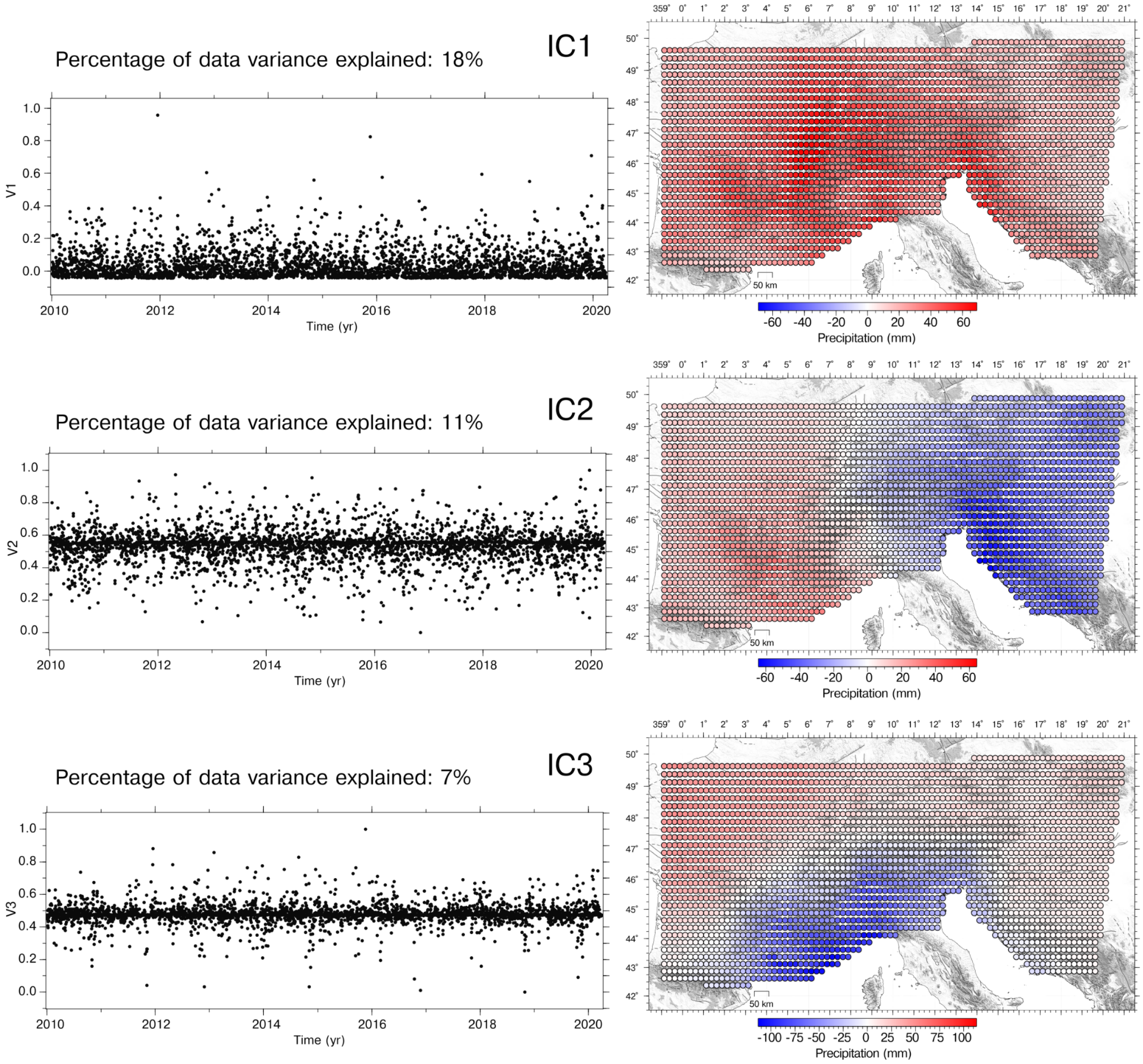

Figure 14: IC1, IC2 and IC3 of the RAIN decomposition.

This supports the hypothesis that precipitation, atmospheric pressure, hydrological loading and ground displacement are somehow interconnected and characterized by a common climate-related forcing, whose characteristics of spatial variability are described by the NAO and Atlantic Ridge weather regimes.

We point out that HYDL, NTAL and GNSS are models or measurements of vertical displacement, which is positive when upward and negative when downward; while RAIN is the amount of fallen rain per unit area.

Let us consider for the sake of simplicity the IC1 case, but what we are going to discuss holds true also for IC2 and IC3.

The temporal evolution of NTAL_IC1 (NTAL_V1) is correlated with the temporal evolution of RAIN_IC1 (RAIN_V1, Fig. 15g-i) and anti-correlated with the time derivative of the temporal evolution of HYDL_IC1 (HYDL_V1, Fig. 15a-c). HYDL_V1 is also highly anti-correlated with RAIN_IC1 (Fig. 15d-f).

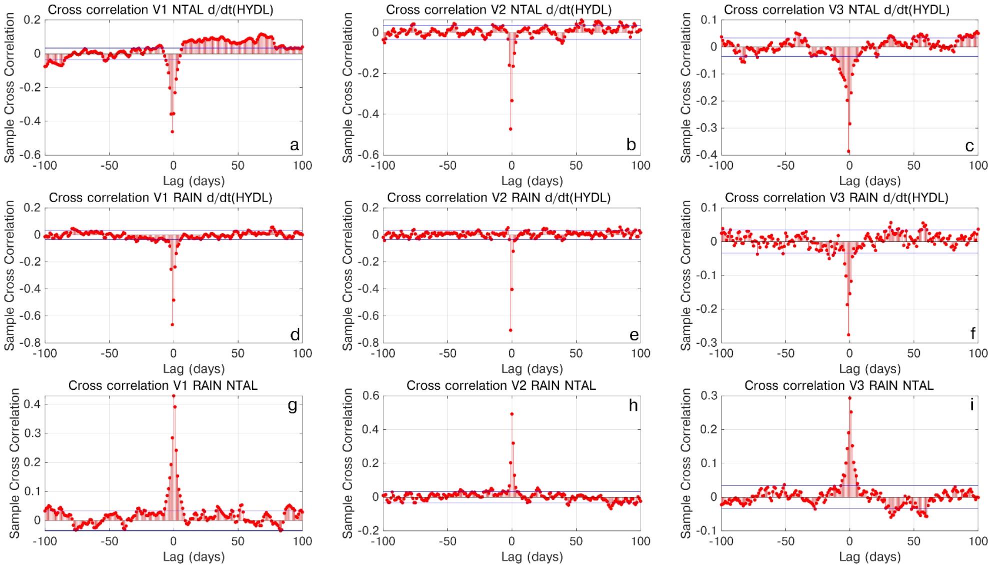

Figure 15: Cross correlation between:

a) the temporal evolution of the IC1 of the NTAL decomposition and the time derivative of the temporal evolution of the IC1 obtained by decomposing HYDL; b) same as a), but considering IC2; c) same as a), but considering IC3;

d) the temporal evolution of the IC1 of the precipitation data decomposition and the time derivative of the temporal evolution of the IC1 obtained by decomposing HYDL; e) same as d), but considering IC2; f) same as d), but considering IC3;

g) the temporal evolution of the IC1 of the NTAL decomposition and the temporal evolution of the IC1 of the precipitation data decomposition; h) same as g), but considering IC2; i) same as g), but considering IC3.

Our interpretation of the correlations discussed above, schematically represented in Fig. 16 is the following: when the weather goes from a low pressure to a high pressure regime, the increasing pressure causes a downward displacement of the ground (Fig. S8). Anyway, low pressure regimes are often associated with precipitation, and that is why IC1_RAIN and IC1_NTAL are correlated. It follows that when we go from high pressure to low pressure conditions, the ground motion, if we assume a pure elastic process, is affected by two forces acting in opposite directions: the decreasing atmospheric pressure induces uplift, while the precipitation load causes downward motion. Rain also affects hydrological loading, increasing it and causing a downward ground motion. As a consequence, the temporal derivative of HYDL_IC1, which is more sensitive to small but fast variation of hydrological loading than HYDL itself, is negative and anti-correlated with IC1_RAIN.

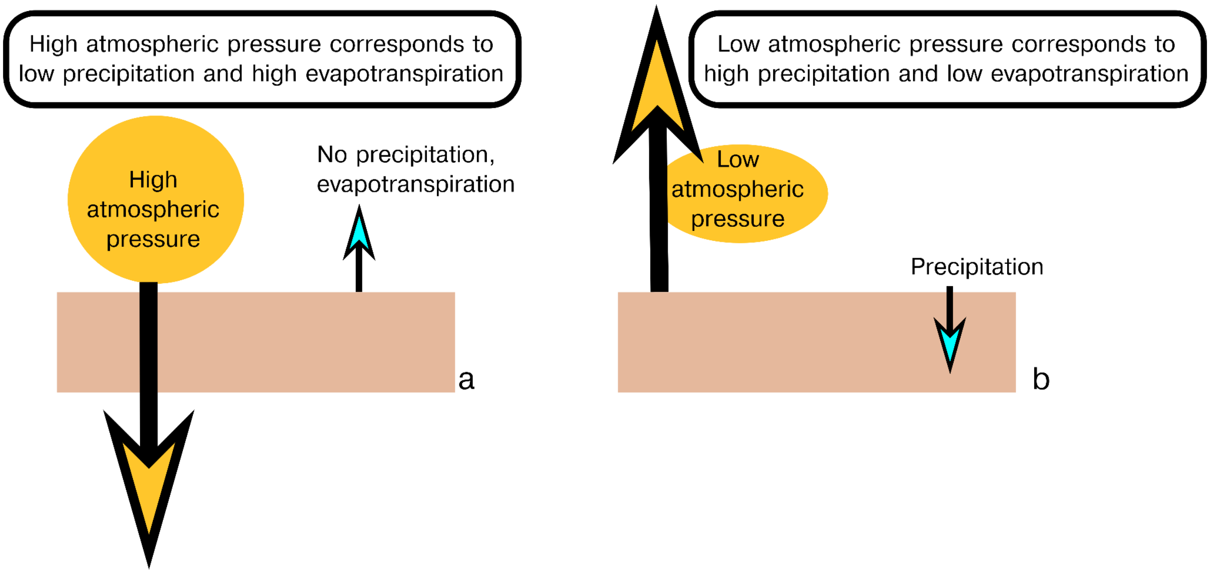

Figure 16: Schematic representation of the ground vertical displacement due to elastic deformation during high pressure (a) and low pressure (b) conditions. Yellow arrows reflect displacements associated with atmospheric pressure, blue arrows reflect displacements associated with precipitation and evapotranspiration.

Atmospheric pressure variations happen at fast temporal scales, then the switch from high to low pressure conditions (and vice versa) can happen in a few days and cause quite large (centimetric) ground vertical displacements. Hydrological loading acts at longer timescales and there are several factors to consider besides precipitation, in particular the temperature, which causes evapotranspiration. Nonetheless, computing the time derivative of the hydrological loading allows to detect "fast" variations due to the change of the atmospheric pressure and the precipitation events often associated with it."