# General comments:

## ICA method in general

**To my understanding, an ICA is meant to separate the different sources out of a given signal. This leads me to interpret that each component would thus represent a different source. However, throughout the paper it seems to me that each component is not necessarily a singular source (eg Figure 2). This component is obviously due to some combination of tectonic trend as well as some seasonal signal likely due to hydrology or atmospheric loading. If the point of using an ICA is to separate out different sources so that you can further isolate a specific source, how can you be sure that you are fully capturing the signal you think you are (in this case the tectonic signal or later on NTAL/HYDL)?**

> We are aware that vbICA may not properly separate the tectonic, linear, trend from seasonal non-tectonic signals (Figure 2), as already highlighted by Gualandi et al. (2016). In fact, when the linear trend is not removed from the time series, they result to be highly correlated and this prevents the vbICA algorithm from working efficiently. That is why we removed the linear trend from the time series. We have accomplished this task in a multivariate sense, rather than using standard trajectory models. Nonetheless, even using detrended time series as vbICA input, we cannot separate the NTAL from the HYDL contribution. Considering that they are both a consequence of meteoclimatic forcings, they maintain some interdependence. As a consequence, while NTAL and HYDL are different loading types, they might not be independent from a mathematical point of view and so vbICA is not able to properly separate them. In order to explain that, we add the following part in line 503:
>
> *"The vbICA algorithm is not able to separate NTAL and HYDL because they are not independent from a mathematical point of view. This emerges also from the recent work by Tan et al. (2022), who performed an ICA on GNSS time series of the Yunnan Province of China and interpreted IC1 as the average effects of the joint patterns from soil moisture and atmospheric-induced annual surface deformations. Let us consider for example the case of IC2_NTAL and IC2_HYDL. They have two different temporal evolutions (V2_NTAL and V2_HYDL); but the spatial distributions (U2_NTAL and U2_HYDL) have the same pattern, i.e. they only differ for a weighting factor k. Then, we can write U2_NTAL=k*U2_HYDL.*
>
> *The displacement d resulting from the combined effect of IC2_NTAL and IC2_HYDL is then:*
>
> *d= IC2_NTAL + IC2_HYDL= U2_NTAL*V2_NTAL + U2_HYDL*V2_HYDL= U2_HYDL*(k*V2_NTAL+V2_HYDL).*
>
> *As a result, the displacement due to IC2_NTAL + IC2_HYDL is identified by a single spatial distribution U2_HYDL and a temporal evolution k*V2_NTAL+V2_HYDL. Then, if we do not make any prior assumptions about V2_NTAL and V2_HYDL, it is not possible to separate IC2_NTAL and IC2_HYDL from a statistical point of view.*
>
> *In Sect. 4.2 we show that not only IC2_NTAL and IC2_HYDL have very similar spatial patterns, but also IC1_NTAL and IC1_HYDL, IC3_NTAL and IC3_HYDL have similar spatial responses. Then, the GNSS time-series decomposition in the Alpine area does not allow separating the effect of the hydrological loading from the atmospheric loading with an ICA approach."*

**To this end, why are you decomposing the "source" signals (NTAL and HYDL)? Wouldn't a component from the GNSS decomposition represent the NTAL signal? Or the HYDL signal? And then why do you combine NTAL IC1 and HYDL IC1 and compare them to the GNSS IC1? This implies this component is a portion (and only a portion) of two very different sources. How do you know that's all that's in there? I suppose, what I'm asking is some further clarification in the text about (1) what the different components actually mean in terms of "sources" insofar as are they "sources"? or just spatially independent signals/temporally independent and thus could be heavily influenced by certain things but not necessarily the entire signal (2) further explanation for the motivation behind decomposing the source signals (NTAL/HYDL) and why it's necessary. I realize some of this is not specific to this paper but ICA in these applications in general but I think the text would greatly benefit from further explanation.**

We don't decompose the HYDL and NTAL datasets with vbICA with the goal to separate different sources, but in order to investigate the presence of any spatiotemporal signatures, like the ones emerging from the vbICA analysis of the GNSS data (IC1, IC2 and IC3), that could help in the interpretations of the ICA decomposition.

At the beginning of Section 4.2 we have added some text to further explain the reason why we decompose NTAL and HYDL and what the different components 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 components 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."*

We also decide to change Figure 7, showing the displacement of two different sites, one located in the south-western part of the study region (STV2), the other in the north-eastern side (LYSH), so that the displacement associated with GNSS_IC2 and GNSS_IC3 have opposite sign. This figure show that both the amplitude and the temporal evolution of the GNSS and HYDL+NTAL signals are quite similar in all the three components: while we might have not recognized other sources of deformation generating those signals, atmospheric and hydrological loading seem by far the most relevant processes causing the displacements associated with GNSS_IC1, GNSS_IC2 and GNSS_IC3.

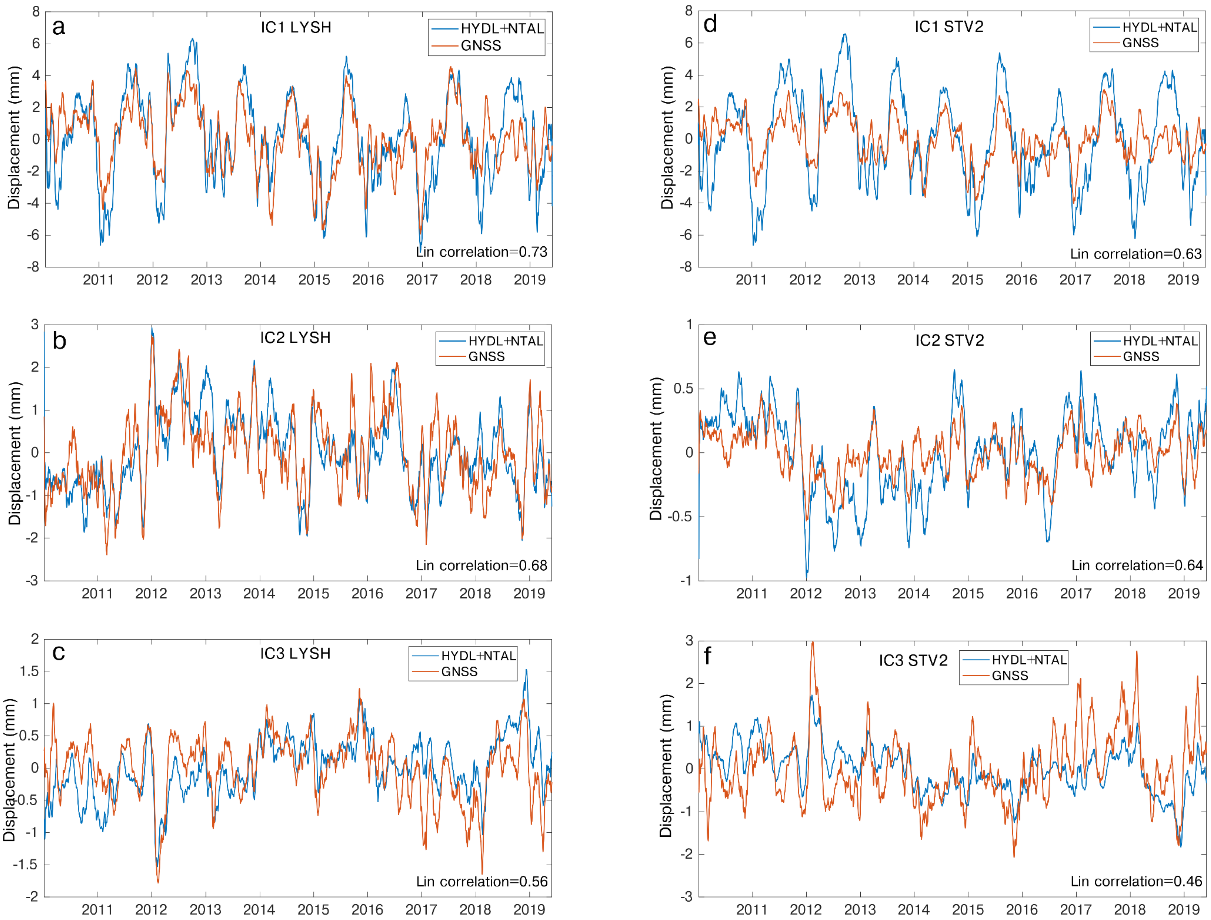

***Figure 7: Comparison, at the LYSH (Lon: 18.45°; Lat: 49.55°) site, between the displacements associated with: a) GNSS_IC1 and NTAL+HYDL_IC1; b) GNSS_IC2 and NTAL+HYDL_IC2; c) GNSS_IC3 and NTAL+HYDL_IC3. d), e), f) are the same as a), b), c), respectively, for the STV2 (Lon: 6.11°; Lat: 44.57°) site.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

## Decomposition of the NTAL/HYDL

**The spatial pattern of the different components from the NTAL and HYDL are incredibly similar. Is this due to how the algorithm works or are these signals just by coincidence showing very similar spatial patterns. How much of the variance due each of these components represent? I think including that, maybe even just in the figures would be helpful for interpretation of the different components.**

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 is caused by their link to a common, meteo-climatic, source. In fact, atmospheric and hydrological loading depend on the climatic conditions, which are spatially and temporally variable.

In section 5.2 we add details about the interconnection between precipitation, atmospheric pressure and hydrological loading:

"*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).*

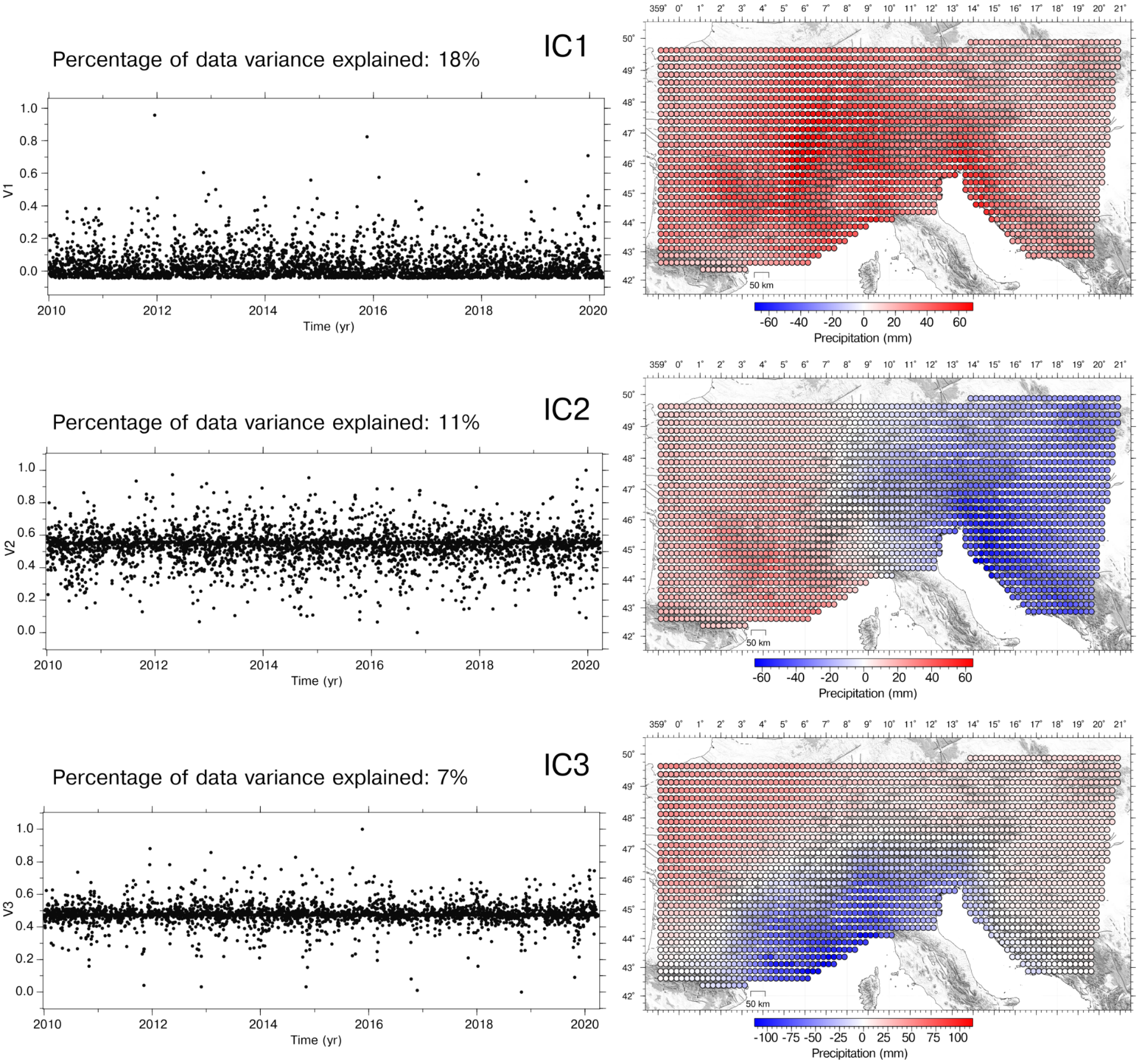

***Figure 14: IC1, IC2 and IC3 of the RAIN decomposition.***

*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).*

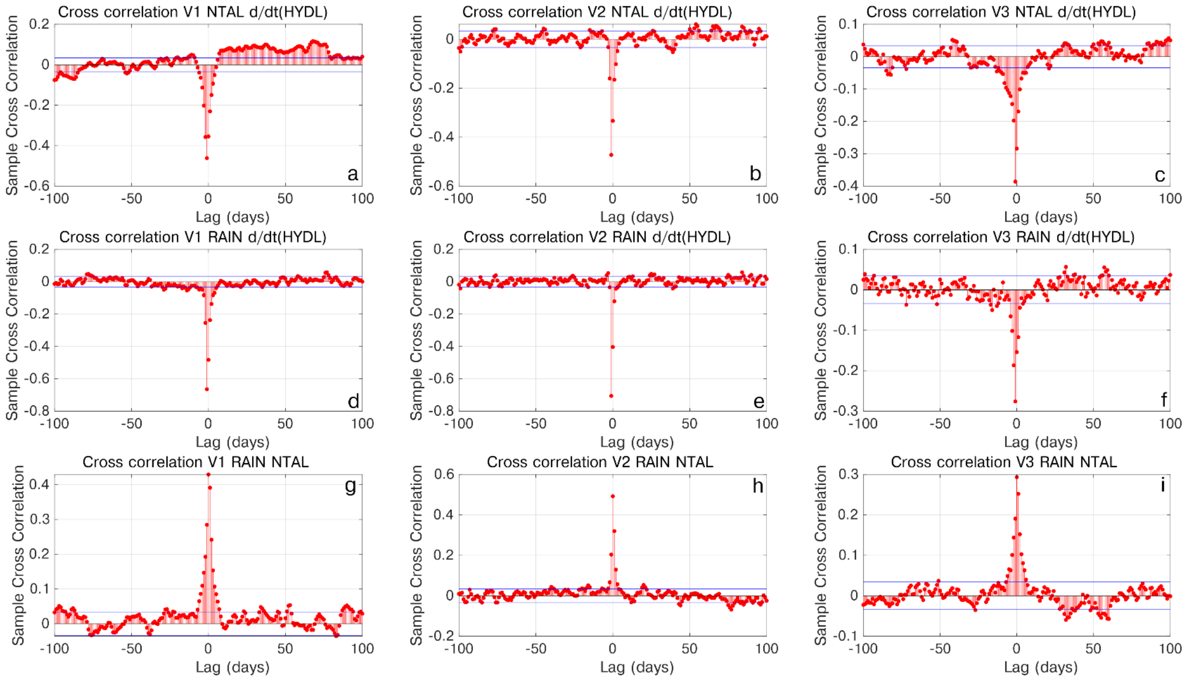

***Figure 15: Cross correlation between:***
***a) the temporal evolution of the IC1 of the NTAL decomposition and the time derivative of the temporal evolution of the IC1 obtained by decomposing HYDL; b) same as a), but considering IC2; c) same as a), but considering IC3;***
***d) the temporal evolution 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.*

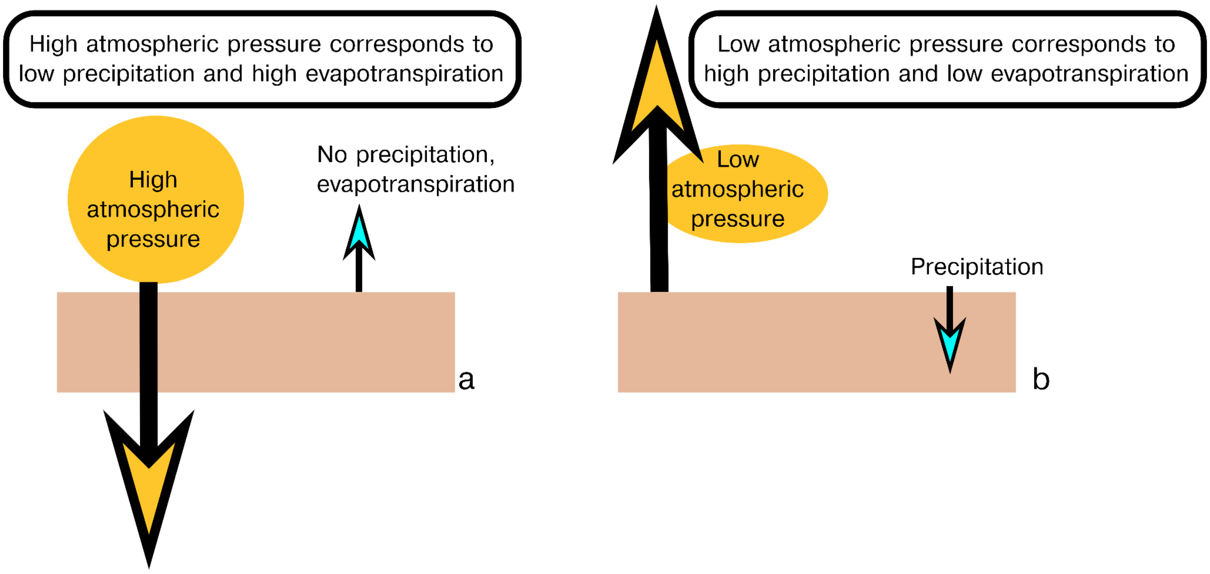

***Figure 16: Schematic representation of the ground vertical displacement due to elastic deformation during high pressure (a) and low pressure (b) conditions. Yellow arrows reflect displacements associated with atmospheric pressure, blue arrows reflect displacements associated with precipitation and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

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 reveals 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 percentage of total variance explained by each component is added to the figures.

## Temperature

**I agree that the fourth component is well correlated with temperature. However, temperature is just a strong seasonal signal so couldn't this signal be something else? In lines 369-370, you mention that when temperature increases the stations in the mountains subside. I'm just confused by what physical mechanism would cause this. The two mechanisms that you list for temperature in lines 505, don't explain why the mountains would experience downward**

**deflection during warm periods. Can you provide further explanation for the physical cause of this? I think in the paper you indicate too heavily that this component is due to temperature fluctuations (especially in Figure 8 and the associated text, the conclusion and abstract) and don't necessarily support this. Correlation does not always indicate causation. I think further data and text is needed to support this finding. Especially since this is mentioned in the abstract (line 16) as well as the conclusion (line 586/593).**

Thanks for this comment. We agree that the conclusions on IC4 are too strong. We modify the abstract, changing a sentence that incorrectly lets the reader suppose that temperature might directly cause the displacement associated with IC4.

In fact, it is more correct to state that the displacements associated with IC4 are caused by processes correlated to temperature, which are discussed in section 5.2, than caused by temperature itself. The contrasting behavior observed for some stations in the Alps and the Adriatic foreland is difficult to explain. Here we propose a possible mechanism, that is now, hopefully, clearly described in Section 5.2 (from line 504):

*"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 response to 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).*

*Conversely, positive vertical displacements as the temperature increases can be caused by monument/bedrock thermal expansion and the drying of the soil, because of the reduction of the hydrological load. While HYDL takes into account the drying of the soil, we cannot exclude that some 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 its spatial distribution, sign, amplitude and relevance in explaining the data variance. In fact, while ~50% of the stations have U4<2mm (Fig. S3d) and explain <1% of the data variance, meaning that IC4 is almost unuseful to reproduce the original data, there is a non-negligible number of stations (~10%) explaining >10% of the data variance and with U4>6mm."*

## Application of vbICA for removing NTAL and HYDL

**Martens et al 2020 (J. of Geodesy) highlighted the importance of removing NTAL and NTOL signals from GNSS time series to reduce scatter/dispersion. In lines 351-353, you mention, vbICA may not be able to separate the NTAL vs HYDL signals. Why not just remove the signals using the GFZ products instead of using the ICA method? Does removing the ICA reduce the scatter more than just removing the signals to begin with?**

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."*

# Minor comments:

**GNSS processing - Do remove signals due to earthquakes? In the supplement you mention removing offsets due to equipment changes but don't mention offsets or post seismic signal removal. Does the ICA capture earthquake signals? Wouldn't this be a good signal to remove to better isolate the uplift?**

Yes, we remove both instrumental and co-seismic offsets and eventually post-seismic signals. However, no co-seismic offsets interest the GNSS stations considered in this work.

**Line 123: grammatical issue - "Since they allow to account"**

Ok, now it is "allow to take into account".

**Line 254: grammatical issue – "its temporal evolution has not a domination frequency"**

Ok, we use "dominant".

**Lines 230: What reference frames are you using for the NTAL and HYDL models?**

Center of figure. We changed the text accordingly.

**Lines 250-251: There are no units for y-axes on the temporal portion of the components. What are the units? Are there any? To construct the signal at a given spot, do you multiply the temporal by the spatial displacement for that point? It would be helpful for understanding the figures.**

In order to answer these questions 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.* $t_1$ *and* $t_2$*, with* $t_2>t_1$*) at the station n is computed as* $V1(t_2)*U1_n-V1(t_1)*U1_n(t_1)$*, where* $V1(t_2)$ *is the value associated with the temporal evolution of the IC at the epoch* $t_2$*.*

$U1_n$ *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,* $V1*U1_n$ *is in mm. It follows that if* $U1_n$ *is positive, as we observe for each station, and V1 is increasing (*$V1(t_2)>V1(t_1)$*), the stations move upward during the* $t_2$*-*$t_1$ *time interval. On the other hand, if* $V1(t_2)<V1(t_1)$ *the stations move downward during* $t_2$*-*$t_1$*.*

*As regards Fig. 2, assuming* $t_1$*=2010.0 and* $t_2$*=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.”*

**Lines 340: For the second component, you list Pearson’s correlation coefficient in addition to the Lin’s. Can you list the Pearson’s for component 1? And in the third component, is this the Pearson’s or the Lin’s coefficient?**

The Pearson correlation between V1_GNSS and V1_NTAL is 0.60, while between V1_GNSS and V1_HYDL is 0.35. In the third component it is the Lin correlation.

**Line 338: How many stations have displacements above 3mm?**

IC2: 411 out of 545; IC3: 414 out of 545.

**Line 389: Is the k value -2 for both?**

Thanks for catching this, we made a mistake. Pink noise k=-1; red noise k=-2. We corrected the text.

**Line 404-408: I think there's a typo here.**

**Consequently, the unfiltered time series are modeled only with the linear trend plus the temporal correlated noise, while the unfiltered time series modeling annual and semi-annual terms are also included.**

**Are both unfiltered? I think the first one should be filtered, yes?**

Thanks for catching this. Yes, the first one is filtered. We corrected the text.

**Section 5.3: If you are removing the linear trend, then are your uplift rates non-tectonic uplift? Or are you adding that back in? Just confusing since in the introduction it seemed like you were settling up to better estimate uplift rates due to tectonics? I think it's fine to remove the linear trend for comparison of stacking methods ect but for Figure 13 and discussion in 5.3 is this with the linear trend removed or included? Is the nontectonic uplift? Or are you adding the linear trend back in? Can you clarify?**

Thanks for this comment that helps to make our goals more clear. In order to answer these questions and make the text more clear, we introduce a new nomenclature for the GNSS time series resulting from the analysis described in lines 169-175: IGb14-time series, which are the raw displacement time-series as obtained from the processing of GNSS data in the IGb14 reference frame, as they come from the GPS data processing (except for the correction of instrumental jumps).

In section 5.3 we compare the IGb14-time series with the ICs filtered time series. The ICs filtered time series, as stated at lines 376-379, are the result of subtracting from the IGb14-time series the combined displacement associated with the first 4 ICs. It follows that in both IGb14-time series and ICs filtered time series the linear trend is not removed, but the linear velocities are estimated independently from the raw (IGb14-time series) and filtered time-series, and compared in terms of vertical velocities and uncertainties.

We modified the text making that more explicit (lines 376-379).

**Many of the figures appear blurry. Additionally, the font on the axes of many of the figures is incredibly difficult to read (eg Figure 3) and would benefit from larger font size.**

We improved the resolution and quality of the figures.