Response to RC2: 'Comment on egusphere-2022-926', Anonymous Referee #2

Thank you very much for your careful review and your insightful comments on this manuscript. We will respond to your comments one by one below. Your comments are marked in *blue italics* and follow with our response.

How do the authors estimate the reliability of the anomalies, especially the studies on the same parameter but with the different anomaly occurring time?
About the published papers, their studied time scale are not the same, for some with much longer time than years, for some only a few days before the earthquakes that did not mean without long time anomaly in that parameter. According to the statistical study of De Santis, the ionospheric disturbances were also occurred in a quite longer time during the earthquake preparation phase. How do the authors consider them in a same time scale when their studied time period is not same, is it suitable?
Response: Thanks for your insightful questions. First of all, we need to state that we are not denying or questioning existing research results. All experts and scholars in different fields have their own principles, methods and evaluation criteria. In our study, in addition to the spatio-temporal characteristics of abnormal parameters, we pay more attention to whether the parameter can be correlated with other parameters, which we believe is the basis of coupling analysis. Our study is based on a comprehensive analysis of all available results. For the anomalies of the same parameters at different times (from the same or different researchers), we first judge the correlation between them and the earthquake from the spatial location and occurrence time of the anomalies. If all the anomalies at different times pass the preliminary judgment, then more rigorous screening needs to be carried out, that is, using the related parameters of other geospheres to make further judgement.
In the case of ionospheric anomalies, some anomalies are found to occur much long before the earthquake, such as a month, while others occur days or hours before the earthquake. It is generally believed that ionospheric anomalies are produced by the upward transmission of electro-magnetic signals, generated by the crustal stress filed alteration, to the ionosphere during which the anomalies of the middle geospheres may be aroused and appear before the ionospheric anomalies. For ionospheric anomalies appeared long before an earthquake, it is difficult to find relevant anomalies in coversphere and atmosphere to form a necessary chain with LCAI, but the ionospheric anomalies impending the earthquake can be. This is our logic for picking potential seismic anomalies for systematic analysis, especially the ionospheric anomalies, appeared at different times.

Most anomalies were not detected in the same day, even after the selection of Figure 7, which illustrate indirect relationship between them? Or the coupling process among the lithosphere, atmosphere, ionosphere all needs a few days?
Response: Your question is critical and deserves attention in multi-parameter retrospective studies. We try to answer your question in three aspects. First, all the results in our study were based on previous reports, with different data and different methods and by different researchers. This leads to differences

in time, space, and intensity, even for the same parameters. In that the spatio-temporal features of these abnormalities meet the criteria we set, they are so retained. Second, it is generally believed that only if the fluctuation amplitude of a parameter is significantly beyond the normal range before the earthquake can it be considered as an anomaly. Different data and methods have different sensitivities to such changes, so the time-length to be considered as abnormal varies a lot. Third, when a single parameter is abnormal, it not only needs some time to reach the observable magnitude, but also needs some time to cause the abnormality of subsequent parameters. Although physicochemical reactions can be done in a flash, there are thresholds for satellite observations and seismic anomaly identification.

Line 165: about the figure 3, why only exhibited -20d anomalies around the earthquakes? As described in the text, most parameters exhibited anomalies before that, especially for those in lithosphere? I'd like to suggest a much longer time scale, at least 2-3 months before for a M7 earthquake.

Response: Thanks for your suggestions. As you said, lithospheric anomalies generally have a long period, which is related to the process of crustal stress accumulation. Fluid anomalies and geoelectric anomalies in the lithosphere also basically appear several months or longer before earthquakes. In our study, we focus on the coupling process between different geospheres. These abnormal parameters of the lithosphere, which appeared much long ago might not be strong enough to results in anomalies in the coversphere, atmosphere and ionosphere, so it is not necessary to show the complete time periods of them. As you suggested, the time scale can be extended to 2 months to better present the anomalies in longer time scale, the time axis between 1-2 months was marked with a dashed line and shortened in length in Figure 3.

Line 265: for figure 5, please add the unit for the parameters used in the model.

Response: Thank you for your reminding and we are sorry for our omission. The unit of density is kg/m^3, the unit of Young's Modulus is GPa, the Poisson's ratio has no units, and the unit of viscous coefficient is Pa • s. We've added units in the appropriate places.

Line 360: through the ionosphere?

Response: The VLF signal propagates through multiple reflections between the earth's surface and lower ionosphere (D-region), which forms a natural waveguide known as an earth-ionosphere waveguide. However, because the ionosphere is not an ideal conductor, some VLF signals can still enter the ionosphere. The analysis of the VLF signals radiated by ground transmitters and received on board of the DEMETER satellite confirmed that the transmission process of VLF can be disturbed by earthquakes (Molchanov et al., 2006).

In this study, we believe that the VLF anomaly is formed by ionospheric interference during the propagation process, no matter there is an anomaly in the reflection region of the bottom layer of the ionosphere or an anomaly in the inner ionosphere. Therefore, we need to consider both the two conditions. In line 360, this sentence should be modified to 'hence to impacts on the very low frequency (VLF) signals reflected by or transmitting through the lower ionosphere'.

Molchanov O, Rozhnoi A, Solovieva M, et al. Global diagnostics of the ionospheric perturbations related to the seismic activity using the VLF radio signals collected on the DEMETER satellite[J]. Natural Hazards and Earth System Sciences, 2006, 6(5): 745-753.

Line 310-315: This paragraph discussed the P-pole links, but unfortunately there is no direct evidence or observations to prove it. The authors just list its products in atmosphere, not the real detection on the P-pole effects from geoelectric field, geomagnetic field, underground fluid or something like them in that region. The laboratory results cannot replace the field observations. So it is not so convincing here.

Response: Thanks for your critical comments. In fact, about the existence of P-hole and its effect, we have the corresponding description in the manuscript (line 309-332), and your comments makes us realize that our descriptions are still not clear enough on this issue. We are to explain this problem as follows.

In our previous study, the spatio-temporal evolution of microwave brightness temperature (MBT) anomalies related to the 2015 Nepal earthquakes were uncovered in detail (Qi et al., 2021). A theoretical explanation for seismic MBT anomalies was proposed, i.e. 'crustal stress enhancing—P-hole producing and flowing down stress gradients—surface P-hole accumulating—dielectric constant decreasing—microwave radiation increasing'. This result shows a strong correlation with seismic activity, and the corresponding interpretation has been recognized as a potential mechanism of seismic MBT anomaly. However, there still lacks direct evidence or intuitive presentation of how and where the P-holes was produced, along what routes the P-holes propagated, and where it accumulated on ground surface. Fortunately, the spatial distribution of the simulated crust stress in the study can perfect the theoretical response chain of CSFA, and the simulation results can be mutually confirmed with the MBT anomaly and P-hole theory.

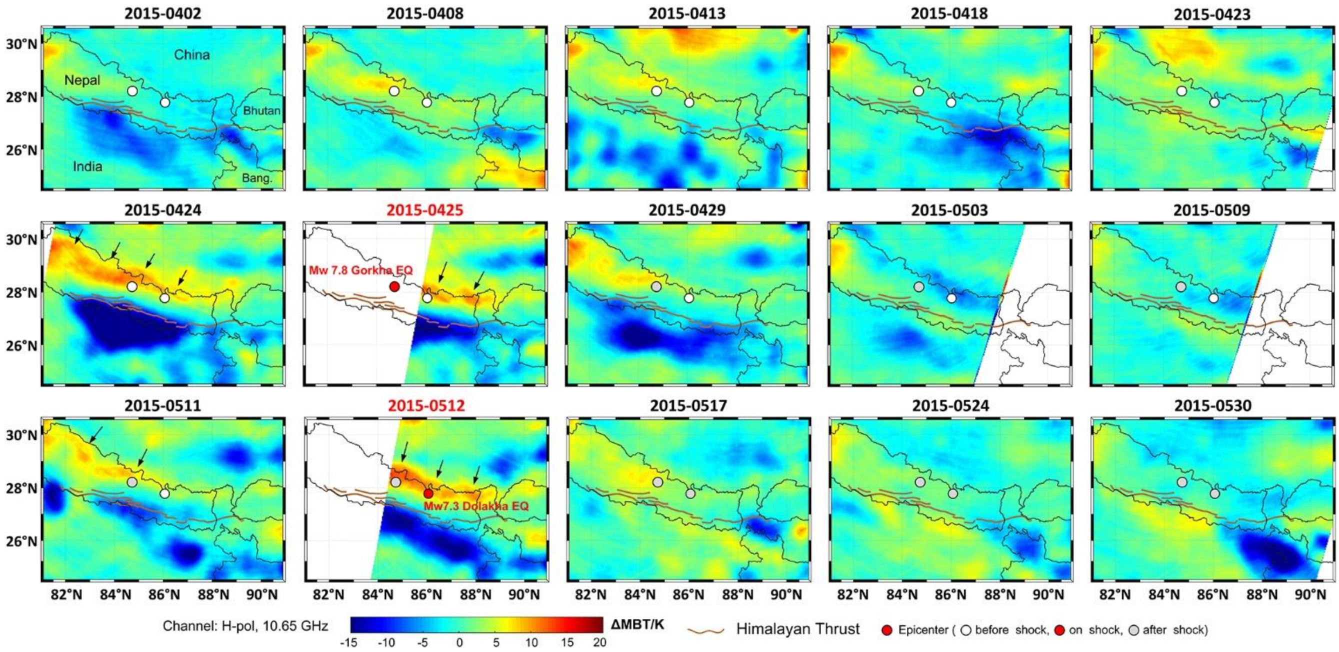

Figure 1: The spatio-temporal evolution of MBT anomalies before, during and after the 2015 Nepal earthquake sequence.

In the manuscript, the equivalent stress distribution shows that the crustal stress, especially on the MHT, was in a highly concentration state before the Nepal earthquake sequence, which benefitted the high comprehensive stress for P-holes activation. The zone between MCT and MBT' belongs to the Lesser Himalaya region, of which the geological lithology is basically composed of low-grade metamorphic and sedimentary rocks (Tater et al., 1983; Burrard et al., 1907). Some amphibolites, volcanic rocks, granites, and augen gneisses exist also within different strata (Dhital et al., 2015). The rock mass in the seismogenic area belong to the type of rocks containing numerous oxygen defects (Freund et al., 2002), which are benefit for P-holes production. This indicates that the great volume of oxygen-defects-embedded crust rock mass in Lesser Himalaya has the ability to produce massive P-holes and transfer to ground surface.

The 3D distribution of uneven stress accumulation indicates that the regional stress gradient developed in vertical from MHT to ground surface and in horizontal from south to north, which determined that P-holes were able to transmit upward and northward along the stress gradient from the hypocenter zone. Therefore, the stress gradient (vertical and horizontal) determined the particular location of P-holes aggregation on ground surface, which overlapped exactly the strips of positive MBT anomalies (Figure 1). Furthermore, the accumulation of P-holes on the mountain surface was bound to form an additional electric field (Freund 2007). Theoretical analysis shows that the lattice ions in the rock material will shift under the action of the additional electric field (Mao et al., 2020), which can reduce the dielectric constant of rock material. This phenomenon was also confirmed by laboratory observation of the dielectric change in non-stressed volume during rock loading (Mao et al., 2020, 2021). According to the microwave remote sensing physics, when the microwave dielectric of a substance decreases, its ability to radiate microwave energy will increase. Therefore, the MBT anomalies occurred with the same spatial pattern of P-holes aggregation on ground surface.

We believe that the combined analysis of the equivalent stress simulation, P-hole theory and microwave remote sensing physics can not only refine and improve the mechanism of seismic MBT anomaly, but also confirm the existence of a chain of CSFA-P-hole activation, migration and aggregation as well as subsequent seismic anomalies before the Nepal earthquakes in 2015.

References in the above paragraphs are same as in the manuscript.

Line 352: About the section 5.1, I cannot agree with the point to firstly retain the negative anomalies in ionosphere. (1) The ionospheric perturbations are always modulated, they cannot be easily defined as increase or decrease; the number of positive anomalies in TEC is almost the same as the negative ones, why the authors remove the positive ones so easily? (2) The disturbances in VLF radio waves are always considered with close relationship of acoustic gravity waves, why the authors connect them to electric field?

Response: Thanks for your comments. Again, we would like to state that the removal of a seismic anomaly is not meant to deny or doubt the results. Based on the established more stringent criteria than in the past, a certain seismic anomaly which might fail to produce such geo-sphere coupling process may not be included in our framework. We admit that there are indeed many types of ionospheric anomalies, which can be regarded as anomalies of different parameters or anomalies of different ionospheric layers. In the stated framework, the concentration of P-holes takes electrons from air molecules, and the ionization at the earth-air interface increases the number of positively charged ions in local atmosphere. The electrostatic action of accumulated charges at the ground-to-air interface would cause the positive ions to move upward with fine particles of light mass and reduce the electron content in the bottom ionosphere, resulting in negative TEC anomaly. This process can explain why ionospheric TEC anomalies have negative values.

However, for the positive anomaly, we have not found an exact explanation to meet with the framework. Actually, we cannot exclude the existence of such a case, the electrons in the ionosphere migrate from one place to another, resulting in the occurrence of negative and positive anomalies in these two places of different altitude or latitude-longitude. If GNSS is effectively used to conduct large scale three-dimensional tomography of the ionosphere, the upward path of ions-and-electrons might be detected and used to determine the positive and negative of the TEC anomalies. However, existing studies often rely on very limited information along the transmission path of GNSS signals to determine the positive and negative changes in TEC, rather than from a holistic perspective. The chain established by P-hole theory can only support the negative TEC anomalies, but this does not mean that seismic TEC anomalies can only be negative, more potential mechanisms definitely exist and need study in the future.

The acoustic-gravity hypothesis considers that some days before the shocking, atmospheric acoustic-gravity waves (AGWs) are excited in the region of earthquake preparation near the Earth's surface, which propagate through the atmosphere and reach ionospheric altitudes. The collisions of the neutral particles with the ions will cause disturbances of the density of the charged particles of the ionosphere. AGWs can affect the propagation of VLF radio waves both directly (in the form of periodic fluctuations in the atmosphere parameters) and through secondary effects arising from wave dissipation (Fedorenko 2021). The received VLF signals contain information about the region of reflection height and its variability (Barr et al., 2000), and ionospheric modifications will lead to changes in the received amplitude and phase of the signals during the process of transmitting over distances of thousands of kilometers (Rodger 2003).

Based on current theory, we know that the VLF transmission is affected by two main factors, i.e., the height of the reflector at the bottom of the ionosphere and the concentration of ionospheric charged particles affect. The AGW theory of atmospheric particles moving up to affect the ionosphere and thus interferes with VLF signals, which does make sense. However, a similar effect can also be achieved by a change in the atmospheric electric field caused by the accumulation of P-holes at the ground surface, which in turn causes charged particles to move upwards and react with the ionosphere. In our framework, the variation of electric field is to affect the propagation of VLF by changing ionospheric parameters, and the abnormal parameters in atmosphere and ionosphere are able to correlate with them, so we choose to use electric field. Since there is no direct or indirect evidence of the AGWs for the Nepal earthquake, this chain cannot be established definitely in this study.

Fedorenko A K, Kryuchkov E I, Cheremnykh O K, et al. Analysis of acoustic-gravity waves in the mesosphere using VLF radio signal measurements. Journal of Atmospheric and Solar-Terrestrial Physics, 2021, 219: 105649.

Barr, R., Jones, D. L., and Rodger, C. J. (2000). ELF and VLF Radio Waves. J. Atmos. Solar-Terrestrial Phys. 62, 1689–1718

Rodger C J. Subionospheric VLF perturbations associated with lightning discharges. Journal of Atmospheric and Solar-Terrestrial Physics, 2003, 65(5): 591-606.