Replies to referees:

We thank both referees for their careful reading of our manuscript. The comments helped us improve the paper. We provide a point-by-point reply to the comments below.

February 5, 2025

Replies to Reviewer 1

We thank the reviewer for the valuable comments and suggestions, which have improved the presentation of the paper.

★ ***General comments:*** *In this manuscript, the authors present a novel methodology on channel selection from FY-3E/HIRAS-II hyperspectral IR to detect SO_2 while eliminating the impact from temperature and moisture in the atmosphere. The topic is interesting and would be beneficial for future applications on SO_2 quantitative retrievals. However, there remains some questions that are not well clarified in the manuscript. My major comment is that the title of this research is kind of misleading as it says 'quantitatively monitor'. This would, to some extent, imply the retrieval of SO_2 levels from satellite observations which never show up in this research. This research is mainly focused on channel selection, but sadly it's not reflected in the title. Therefore, I would suggest the authors revise the title of manuscript to better reflect the key contents of the research, and go through a round of revision to address the specific comments before it is published.*

- Response: Thank you for your careful review and valuable comments on our paper. In this revision, we modified the manuscript title to better reflect the focus of our study on channel selection, making the title clearer and more precise. We have revised the manuscript title to:

  A channel selection methodology for enhancing volcanic SO_2 monitoring using FY-3E/HIRAS-II hyperspectral data

  In the revised manuscript, we reselected the absorption regions for SO_2 and water vapor based on their spectral absorption characteristics. Additionally, we determined appropriate SO_2 perturbation thresholds to ensure that the results more accurately represent the gas distribution features in real volcanic eruption scenarios. Based on this, we obtained the final channel selection results. Furthermore, we conducted additional experiments to validate the sensitivity of the SO_2 channels and their suitability for volcanic SO_2 detection. In response to the issues you raised, we have provided detailed replies in the manuscript, and these revisions and additions are fully reflected in the updated version.

★ ***Specific comments:***

1. *Line 40, the full name of 'UV' should be given here as it appears in the manuscript for the first time.*

- Response: Thank you very much for your comments. In the revision, we included the full name of UV, 'Ultraviolet,' in the manuscript to provide greater clarity in the content. The revised content in the manuscript is as follows:

  Ultraviolet (UV) band sensors are limited to monitoring SO_2 from daytime eruptions due to their reflective nature. (**Revised manuscript line 42**)

2. *Line 49, polar orbiting hyperspectral sounders observe the same area in a period no less than 12 hours, which is not enough to be described as 'continuous observations'.*

- Response: Thank you very much for your suggestions. We agree with the reviewer's opinion and have modified the term 'continuous observation' in the manuscript to improve the rigor and reliability of the content. The explanation is as follows:

  Hyperspectral IR sensors enable observations with finer channel bandwidths that accurately characterize and distinguish each component, thereby reducing interference from other materials. (**Revised manuscript line 51**)

3. *Line 65, the last segment is recommended to be revised as 'with both,,, and ,,, taken into consideration'.*

- Response: Thank you very much for your comments. In accordance with your suggestions, to ensure that the language aligns more closely with academic standards, we have modified the original text as:

  Lipton (2003) developed a method to select atmospheric microwave sounding channels based on the combination of each channel's center frequency, bandwidth, and degrees of freedom for the signal, with both applicability to multiple environmental conditions and providing robust retrieval performance taken into consideration. (**Revised manuscript line 67**)

4. *Line 87, is that a typo of 'Radiative Transfer Model'?*

- Response: We sincerely appreciate your meticulous attention in identifying this typographical error, and we extend our apologies for this oversight. In the revised manuscript, we have rectified the error in question and conducted a thorough review of the entire document to preclude the occurrence of similar inaccuracies. (**Revised manuscript line 90**)

5. *Line 96, there's no T existing in equation (1), with only a T_{sun} which is no 'true atmospheric temperature'.*

- Response: Thank you very much for your insightful comments. In the revised manuscript, we have explicitly indicated the dependence of T and B within the Planck function in the equation (1) accompanied by appropriate annotations and explanations:

$$\mathrm{R} = \varepsilon B_s(T_s)\tau_s - \int_0^{P_s} B(T)d\tau + (1-\varepsilon)\int_0^{P_s} B(T)d\tau^* + 2.16\times 10^{-5}\pi\cos\theta \times \rho_r B_r(T_{sun}) \times {\tau_s}^2$$

Additionally, we have supplemented the definitions of T_{sun}, T_s and θ as they pertain to the equation for clarity, where T_{sun} is solar temperature, T_s is surface temperature and θ is the zenith angle. (**Revised manuscript lines 97-100**)

6. *Line 161, ERA5 has 37 fixed pressure levels vertically, and 137 model levels distributed using hybrid sigma-pressure coordinate system. It seems like you're using the model levels. It is recommended to point this out explicitly in the manuscript.*

- Response: Thank you for your suggestions. We utilized ERA5 hourly specific humidity data on pressure levels from 1940 to present at the 400 hPa level from the 37 fixed pressure levels of ERA5. This data was used to validate that our selected channels combination effectively removes the influence of water vapor interference in sulfur dioxide monitoring. The ERA5 data used in this study can be accessed via the Copernicus Climate Change Service (C3S) Climate Data Store (CDS; https://doi.org/10.24381/cds.adbb2d47). In this revision, we have provided a detailed description of the data types utilized as follows to give a clearer understanding:

Each profile from ERA5 has a horizontal scale of 31 km. and This includes upper-air parameters on 37 fixed pressure levels from 1,000 to 1 hPa and 137 model levels distributed using hybrid sigma-pressure coordinate system.137 vertical levels, ranging from near-surface air pressure to 0.01 hPa. For this study, we interpolate ERA5 400 hPa fixed pressure level data to assess atmospheric water vapor conditions near Mount Ruang concurrent with FY-3E/HIRAS-II observations. (**Revised manuscript line 167**)

7. *Figure 4, on the figure it seems like the selection of water vapor channels only depends on cross-comparison with temperature channels. According to lines 219 to 220, with the selected SO_2 channels being a subset that aligns with the water vapor channels (purple links), there should also be a cyan link between water vapor channels and SO_2 channels which points to water vapor selections. Or as illustrated in the figure, the relevant contents should be like 'the water vapor Jacobian of SO_2 channels must match those of the water vapor channel, while the temperature Jacobian of water vapor channels must match those of the SO_2 channels.'*

- Response: Thank you for your feedback. We fully concur with the reviewer's observations and have comprehensively revised Figure 4 to address these comments. In the updated figure:

  1. SO_2 channel selection was guided by Jacobian analysis.
  2. Atmospheric temperature channels were determined through comparative analysis of temperature Jacobians between the atmospheric temperature absorption region and the pre-selected SO_2 channels.

3. Water vapor channel selection employed a two-stage process:

First, temperature Jacobians from the water vapor absorption region were cross-compared with those from SO_2 channels

Second, water vapor Jacobians from the same region were analyzed against corresponding Jacobians from SO_2 channels.

This systematic approach yielded optimal water vapor channel selections. Note that the selected water vapor channels with similar temperature and water vapor Jacobians of SO_2 channels do not contain SO_2 absorption, meaning there is no overlapping channel between selected water vapor channels and SO_2 channels. **(Revised manuscript Section 3.2, Figure 4)**.

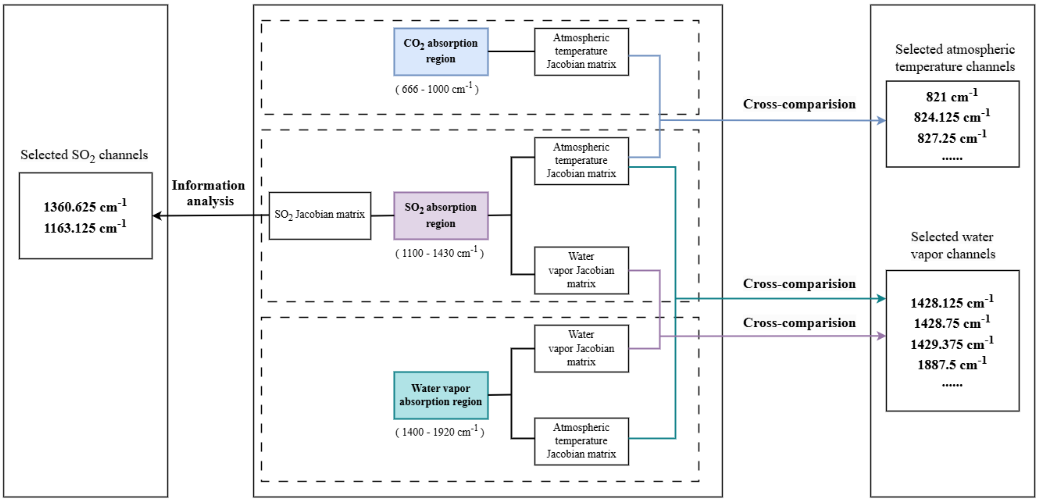

Figure 4: Schematic diagram of channel selection method.

8. *Line 232, it seems like the additional SO_2 signal is around 1125 cm^{-1} rather than 1225 cm^{-1} from Figure 5.*

- Response: Thank you for pointing out the problem. To more comprehensively characterize the absorption capacity of satellite channels for SO_2, we have expanded the SO_2 absorption range in our study to 1100 – 1430 cm^{-1}. Additionally, although the SO_2 signal in the 1100 – 1170 cm^{-1} range is relatively weak, it remains significant for monitoring tropospheric SO_2. Therefore, we have also included SO_2 monitoring channels within the 1100 – 1170 cm^{-1} range to achieve more accurate SO_2 detection. (**Revised manuscript Sec. 3.2.1, Figure 5)**

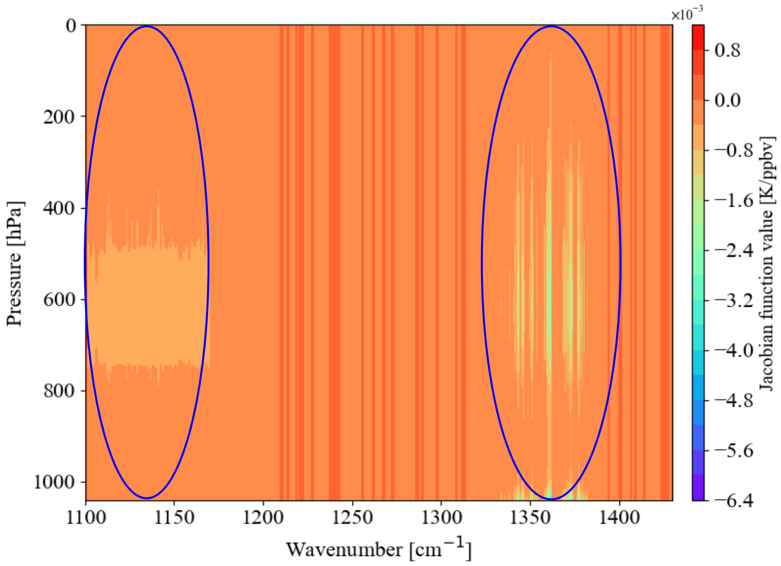

Figure 5: Schematic diagram of the SO_2 Jacobian matrix with atmospheric profiles from the US Standard Atmosphere, 1976.

9. *There should be another set of figures between Figure 6 and 7 showing the temperature Jacobian functions of the channels within SO_2 absorption region.*

- Response: Thank you very much for the constructive feedback. We have redefined the spectral ranges for the SO_2 absorption region and the water vapor absorption region. Following your suggestion, we have supplemented the sections on atmospheric temperature channel selection and water vapor channel selection with Jacobian figures for atmospheric temperature and water vapor within the SO_2 absorption region, respectively. In these figures, we have annotated the SO_2 channels selected in the study to clearly indicate their Jacobian peak values. The following are the temperature Jacobian figures and water vapor Jacobian figures for the SO_2 absorption region. (**Revised manuscript Sec. 3.2.2 and Sec. 3.2.3**)

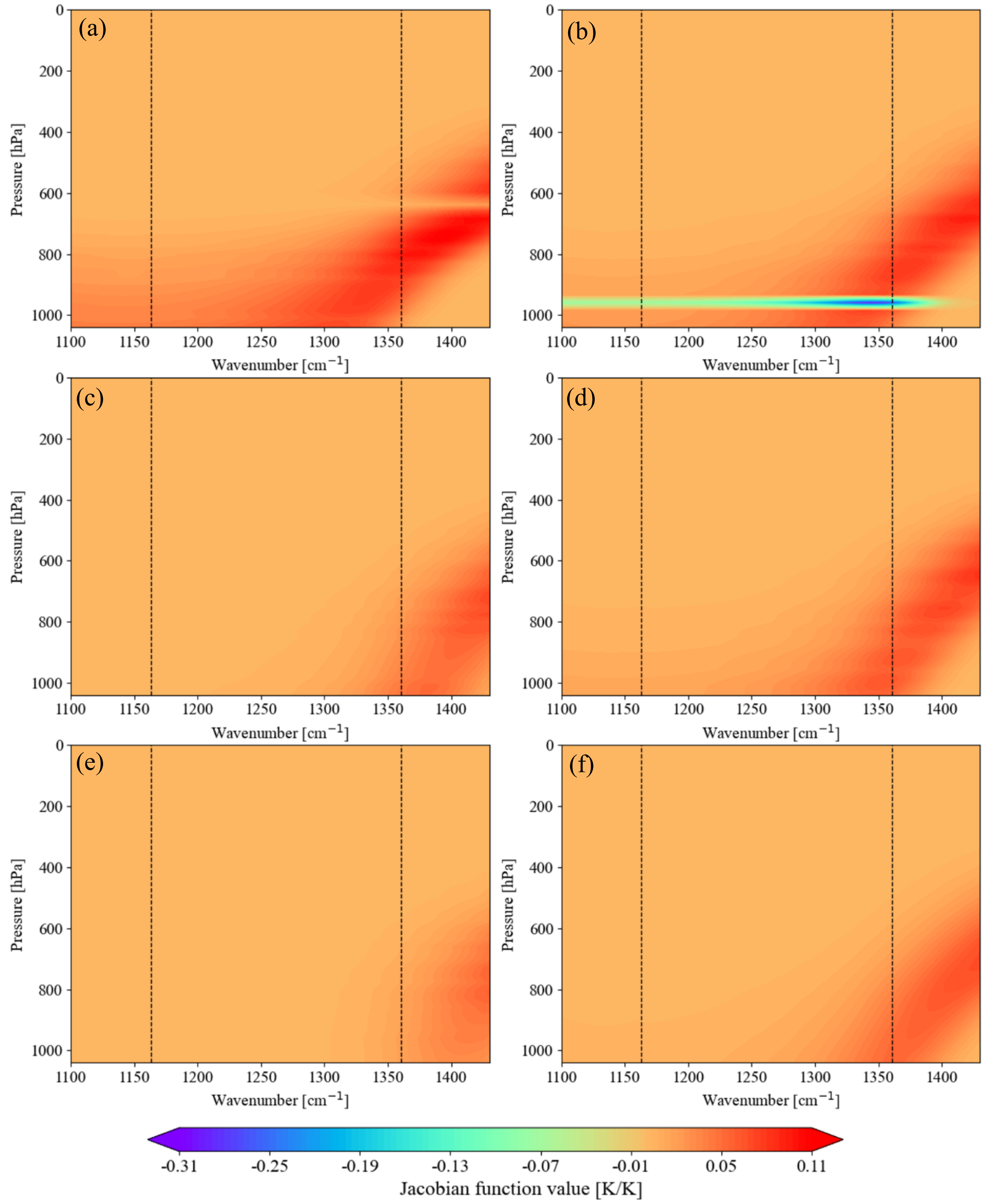

Figure 7: Representations of temperature Jacobian functions at SO_2 absorption region (black dashed lines represent selected SO_2 channels) for the conditions of six atmospheric profiles: (a) tropical atmospheric profile, (b) mid-latitude summer atmospheric profile, (c) mid-latitude winter atmospheric profile, (d) subarctic summer atmospheric profile, (e) subarctic winter atmospheric profile, and (f) US Standard Atmosphere, 1976.

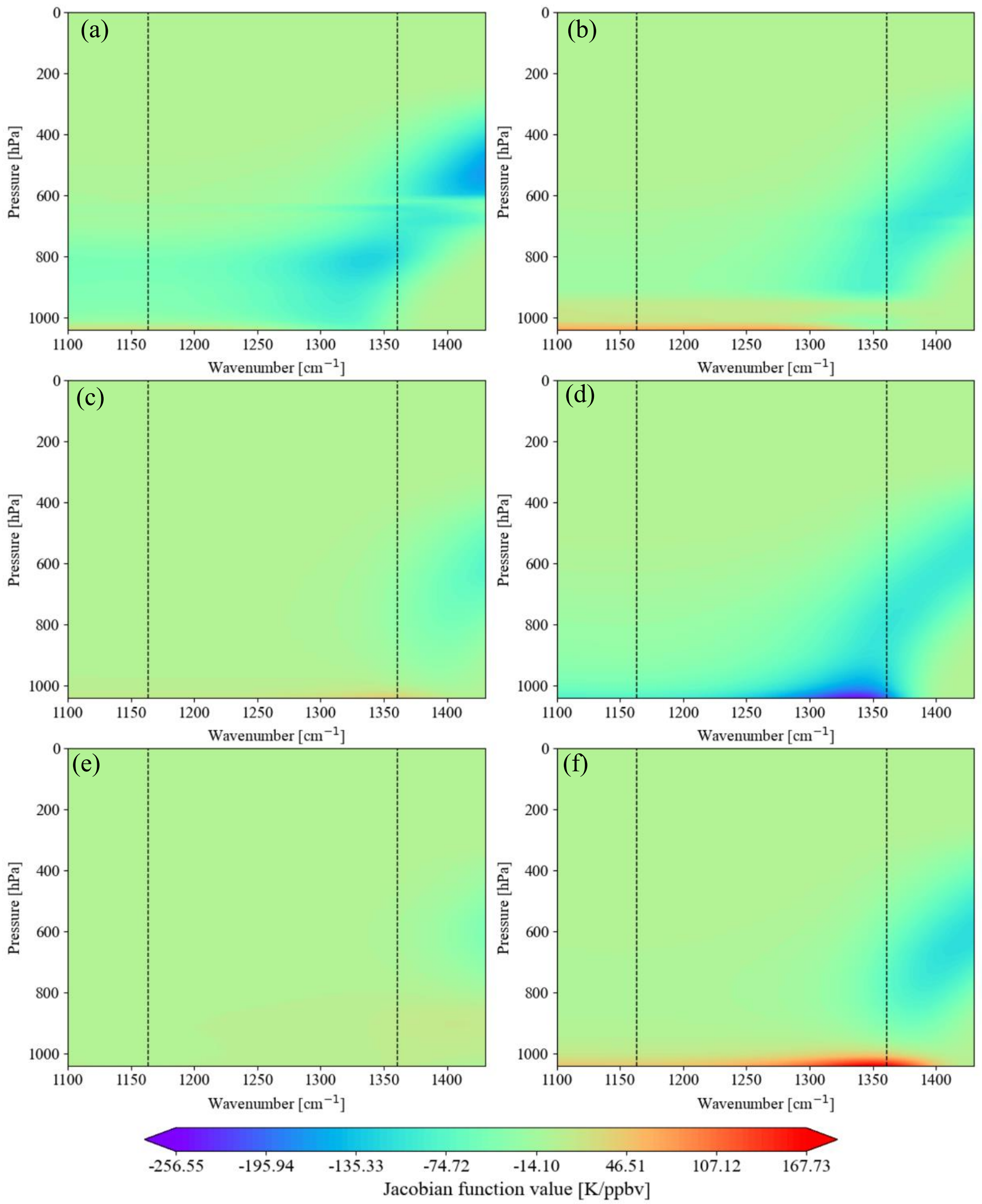

Figure 9: Representations of water vapor Jacobian functions at SO_2 absorption region (black dashed lines represent selected SO_2 channels) for conditions of six atmospheric profiles: (a) tropical atmospheric profile, (b) mid-latitude summer atmospheric profile, (c) mid-latitude winter atmospheric profile, (d) subarctic summer atmospheric profile, (e) subarctic winter atmospheric profile, and (f) US Standard Atmosphere, 1976.

10. *Similar to comment #8, it seems like the left circle in Figure 5 is not around 1225 cm^{-1}, and not included in Figure 8.*

- Response: Thank you for pointing out this problem. We apologize for this oversight. In the revised manuscript, we have expanded the sulfur dioxide absorption spectrum range and selected sulfur dioxide channels in the 1100 – 1170 cm^{-1} spectral range to obtain more comprehensive sulfur dioxide information. Figure 5 has already been presented in the response to comment 8. (**Revised manuscript Sec. 3.2.1**)

11. *Line 307, there should be a more detailed explanation on how a higher BT simulated with positive TD would indicate better SO_2 detection. Isn't it the variation of Jacobian that represent the detection ability better?*

- Response: Thank you for your questions. For a specified wavenumber (ν), the sensitivity of BT to variations in geophysical parameters (X) is represented by the Jacobian matrix for each pressure layer as follows: $J_v(X) = \frac{\partial BT(v)}{\partial X}$. The Jacobian formula defines the relationship between the change in brightness temperature and the perturbation in material concentration. Under consistent atmospheric conditions with fixed SO_2 concentration perturbations and uniform background brightness temperature, the brightness temperature after SO_2 perturbation demonstrates a trend and relative behavior similar to that of the Jacobian value. As a result, brightness temperature can effectively substitute for the Jacobian value in assessing the detection capability of SO_2. Based on your suggestion, we have added a more detailed explanation in the revised manuscript on how a higher BT simulated with positive TD would indicate better SO_2 detection. The modified content in the manuscript is as follows:

  The Jacobian formula defines the relationship between the change in brightness temperature and the perturbation in material concentration. Under consistent atmospheric conditions with fixed SO_2 concentration perturbations and uniform background brightness temperature, the TD after SO_2 perturbation demonstrates a similar trend and behavior to that of the Jacobian value. As a result, TD can effectively substitute for the Jacobian value in assessing the detection capability of SO_2. (**Revised manuscript line 342**)

12. *Line 348, the red box is on Figure 13(c) rather than 12(c).*

- Response: We appreciate your attention to this problem. We have made the necessary correction in the revised manuscript, and the red box is now correctly positioned in Figure 14(b). (**Revised manuscript Sec. 5 Figure 14**)

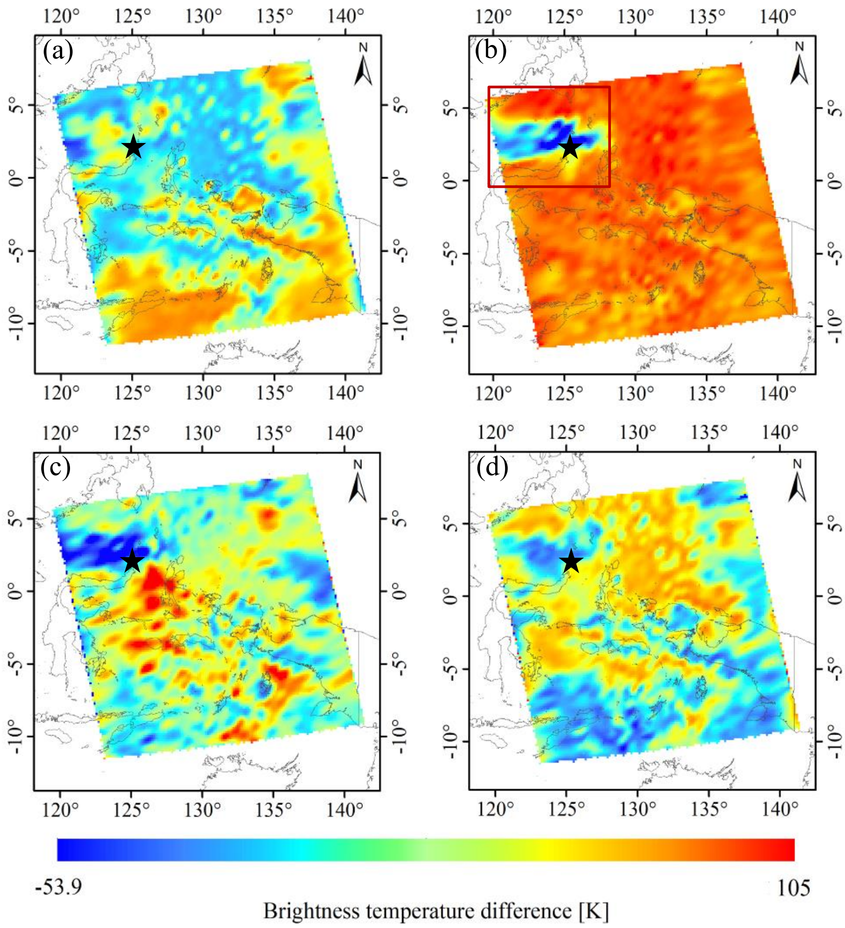

Figure 14: FY-3E/HIRAS-II brightness temperature difference data for the region around Mount Ruang (black star in each image) at 08:55 UT on 18 April 2024 for the channels (a) 1360.625 and 902.5 cm^{-1}, and (b) 1360.625 and 1429.375 cm^{-1}, (c) 1163.125 and 902.5 cm^{-1} and (d) 1163.125 and 1887.5 cm^{-1}.