Hunga eruption on 15 January 2022: was there a precursor plume one hour before the eruption?

Bernard Legras (bernard.legras@lmd.ipsl.fr)
Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure / IPSL, Paris, France

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Abstract:

This note is aimed at the examination of a precursor plume one hour before the paroxysmal Hunga eruption on 15 January 2022, following a claim made in Van Eaton et al. (2023). After examination of a number of satellite and meteorological data, it is concluded in agreement with Prata et al. (2024) that this claim results from a misinterpretation of satellite imagery.

1 Introduction

This note was written in response to comments and reviewer responses to Chaper 2 of the APARC report on the atmospheric impact of the 15 Jan 2022 Hunga eruption (2025, to appear) devoted to the initial stage of the plume and the first month after the eruption. During the reviewing process, one of the reviewers who declared to be Alexa van Eaton (AvE) made insisting statements that the report should mention a volcanic plume reported in Van Eaton et al. (2023) as a precursor of the main event one hour before the eruption. It is noticeable that no data is provided in support of this claim in Van Eaton et al. (2023). During the discussion, AvE provided a couple of GOES 17 images using the high resolution channel at 0.64 µm which appeared to be taken from the WorldView site. It does not seem that other data were used by Van Eaton et al. (2023). AvE claimed during the discussion that the plume could not be seen by infrared images due to the limited resolution. This proved to be incorrect. Another claim made Van Eaton et al. (2023) is that the altitude reached by the plume was 15 km. We showed that the brightness temperature was suggesting a much lower altitude of about 6-7 km with which AvE eventually agreed.

In this work, we investigate additional data from the Himawari 8 and GOES West (17) images in the visible and infrared channels and wind profiles from meteorological analysis. We limit our investigation to the time slot 03:00 UTC while AvE also used 02:50 UTC because of the time sampling of the data center from which data were extracted.

This work has been done under the shape of a python notebook, available from the author, which can be primarily run using standard python packages and data available at AERIS data center (https://www.icare.univ-lille.fr/). This text results from the PDF export of the notebook under Jupyter.

As noticed by Van Eaton et al. (2023), the imagers of geostationary satellites take a few minutes to scan a full image. Due to its location, the Hunga is actually scanned 7 minutes after the stamped time of the image. Therefore the image labelled 02:00 UTC contains data collected at 02:07 UTC in the vicinity of the Hunga. This is true for both Himawari 8 and GOES 17. Such a shift is of little relevance here but is to be accounted for a detailed sequencing of observations from different sources.

1.1 Initialization

This initialization step loads the required packages which are all standard and defines the location of the data and the name of the files. Data location should be adapted if this work is to be reproduced. Data have been downloaded from the AERIS data center. The NetCDF version of Himawari 8 and GOES West (17) data is produced by Meteo France at CMS Lannion from data distributed by EumetCAST. The SAFNWC files are a product of the Eumetsat SAFNWC (Satellite Application Facility for NoWCasting) operated by CMS Lannion.

[1]:
```
import numpy as np
from netCDF4 import Dataset
from os.path import join
import matplotlib.pyplot as plt
import matplotlib
from matplotlib.colors import ListedColormap

# data location
himadir = join('..','..','sats','himawari','netcdf','2022','2022_01_15')
safhimadir = join('..','..','sats','himawari','safnwc','2022','2022_01_15')
goesdir = join('..','..','sats','goesw','netcdf','2022','2022_01_15')
safgoesdir = join('..','..','sats','goesw','safnwc','2022','2022_01_15')
```

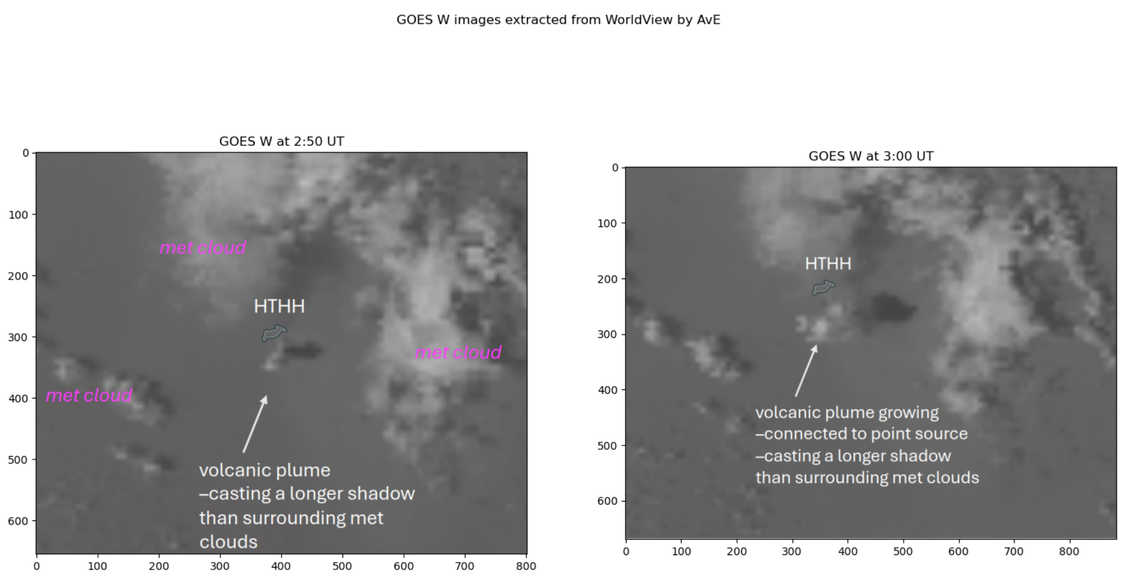
[2]:
```
LRfile = join(himadir,'Jmultic2kmNC4_hima08_202201150300.nc')
HRfile = join(himadir,'Jmultic1kmNC4_hima08_202201150300.nc')
VRfile = join(himadir,'Jmultic500mNC4_hima08_202201150300.nc')
CTfile = join(safhimadir,'S_NWC_CT_HIMA08_globeJ-NR_20220115T030000Z.nc')
CHfile = join(safhimadir,'S_NWC_CTTH_HIMA08_globeJ-NR_20220115T030000Z.nc')
GWfile = join(goesdir,'Wmultic2kmNC4_goes17_202201150300.nc')
CTGWfile = join(safgoesdir,'S_NWC_CT_GOES17_globeW-NR_20220115T030000Z.nc')
CHGWfile = join(safgoesdir,'S_NWC_CTTH_GOES17_globeW-NR_20220115T030000Z.nc')
ncLR = Dataset(LRfile)
ncHR = Dataset(HRfile)
ncVR = Dataset(VRfile)
ncCT = Dataset(CTfile)
ncCH = Dataset(CHfile)
ncGW = Dataset(GWfile)
ncGC = Dataset(CTGWfile)
ncGH = Dataset(CHGWfile)
```

2 Worldview images for GOES West

2.1 From AvE at 2:50 and 3:00

We report here the images provided by AvE in support of the claim for a percursor cloud. The images are in longitude x latitude. The scale of the axis is not described but corresponds to the pixel size of the PNG images provided by AvE.

[46]:
```
from PIL import Image
img1 = Image.open(join('sluggish','WorldViewAvE1.png'))
img2 = Image.open(join('sluggish','WorldViewAvE2.png'))
fig,[ax1,ax2] = plt.subplots(figsize=(18,9),nrows=1,ncols=2)
ax1.imshow(img1)
ax2.imshow(img2)
ax1.set_title('GOES W at 2:50 UT')
ax2.set_title('GOES W at 3:00 UT')
fig.suptitle('GOES W images extracted from WorldView by AvE')
plt.show()
```



The basic argument from AvE is that the image at 02:50 UTC shows a plume attached to the volcano which disperses in the following image at 03:00 UTC. The shadow is estimated to be longer than surrounding clouds.

2.2 Criticism

A detailed examination of the image of the two images shows easily that the clouds located north of the "plume" display shadows of comparable length albeit less dark because they are less opaque. It is shown below that the brightness temperature is similar suggesting the same altitude. The altitude of the "plume" is estimated to be 15 km in Van Eaton et al. (2023) with no data in support. AvE eventually agreed with our estimate of about 6-7 km based on infrared images that were not considered in Van Eaton et al. (2023). Last, and this is possibly the most serious issue, the dispersion of the "plume" to the south west appears to be orthogonal to the south-eastward wind direction determined from the ECMWF analysis, the motion of other clouds and from the dispersion of the plume oberved in the 04:00 UTC image. See below for details.

3 Extraction

Here we extract the geostationary data used in this study.

Position of the volcano: latitude -20.552 & longitude 184.615 or -175.385 (this is the center of the caldera not the location of the Hunga Tonga - Hunga Haapai island which was on the northern edge)
In the native Himawari images the position of the Hunga volcano is
at 2 km resolution (3794,4700): -20.5607, 184.6118 steps 0.02 & 0.03
at 1 km resolution (7588,9401): -20.5557, 184.6176 steps 0.01 & 0.015
at 500m resolution (15176,18801): .... not documented at ICARE In the native GOES images, the position of the Hunga Volcao is at 2 km resolution (3771,953) No other resolution available at ICARE.

```
[4]: fr = {'LR':[3794,4700,100,20],
           'HR':[7588,9401,200,40],
           'VR':[15176,18801,400,80],
           'GT':[3771,953,100,20]}
```

3.1 Extraction from Himawari native files

```
[7]: imLR_IR = ncLR.variables['IR_104'][fr['LR'][0]-fr['LR'][2]:
      ↪fr['LR'][0]+fr['LR'][2]+1,
                                        fr['LR'][1]-fr['LR'][2]:
      ↪fr['LR'][1]+fr['LR'][2]+1]
     imLR_V6 = ncLR.variables['VIS006'][fr['LR'][0]-fr['LR'][2]:
      ↪fr['LR'][0]+fr['LR'][2]+1,
                                        fr['LR'][1]-fr['LR'][2]:
      ↪fr['LR'][1]+fr['LR'][2]+1]
     imLR_V8 = ncLR.variables['VIS008'][fr['LR'][0]-fr['LR'][2]:
      ↪fr['LR'][0]+fr['LR'][2]+1,
                                        fr['LR'][1]-fr['LR'][2]:
      ↪fr['LR'][1]+fr['LR'][2]+1]
     imHR_V8 = ncHR.variables['VIS008'][fr['HR'][0]-fr['HR'][2]:
      ↪fr['HR'][0]+fr['HR'][2]+1,
                                        fr['HR'][1]-fr['HR'][2]:
      ↪fr['HR'][1]+fr['HR'][2]+1]
     imVR_V6 = ncVR.variables['VIS006'][fr['VR'][0]-fr['VR'][2]:
      ↪fr['VR'][0]+fr['VR'][2]+1,
                                        fr['VR'][1]-fr['VR'][2]:
      ↪fr['VR'][1]+fr['VR'][2]+1]
```

3.2 Extraction from GOESW native files

[5]:
```
imGW_IR = ncGW.variables['IR_103'][fr['GT'][0]-fr['GT'][2]:
 ↪fr['GT'][0]+fr['GT'][2]+1,
                                   fr['GT'][1]-fr['GT'][2]:
 ↪fr['GT'][1]+fr['GT'][2]+1]
imGW_V6 = ncGW.variables['VIS_006'][fr['GT'][0]-fr['GT'][2]:
 ↪fr['GT'][0]+fr['GT'][2]+1,
                                   fr['GT'][1]-fr['GT'][2]:
 ↪fr['GT'][1]+fr['GT'][2]+1]
imGW_V8 = ncGW.variables['VIS_008'][fr['GT'][0]-fr['GT'][2]:
 ↪fr['GT'][0]+fr['GT'][2]+1,
                                   fr['GT'][1]-fr['GT'][2]:
 ↪fr['GT'][1]+fr['GT'][2]+1]
```

3.3 Extractions from Eumetsat SAFNWC

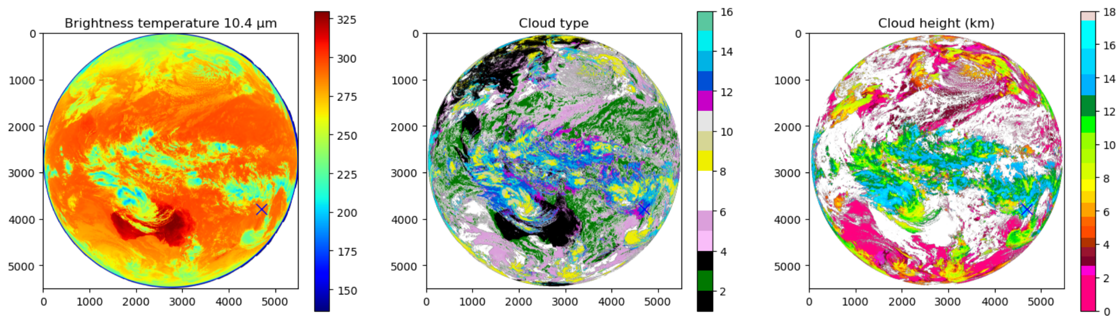
These files are produced by the NoWCasting Satellite Application Facility of Eumetsat operated by Meteo France Centre for Satellite Meteorology (Lannion). They are available at AERIS-ICARE.

[6]:
```
# Cloud type
imCT = ncCT.variables['ct'][fr['LR'][0]-fr['LR'][2]:fr['LR'][0]+fr['LR'][2]+1,
                            fr['LR'][1]-fr['LR'][2]:fr['LR'][1]+fr['LR'][2]+1]
imCTGW = ncGC.variables['ct'][fr['GT'][0]-fr['GT'][2]:fr['GT'][0]+fr['GT'][2]+1,
                            fr['GT'][1]-fr['GT'][2]:fr['GT'][1]+fr['GT'][2]+1]
# Cloud top temperature
imTT = ncCH.variables['ctth_tempe'][fr['LR'][0]-fr['LR'][2]:
 ↪fr['LR'][0]+fr['LR'][2]+1,
                                    fr['LR'][1]-fr['LR'][2]:
 ↪fr['LR'][1]+fr['LR'][2]+1]
imTTGW =  ncGH.variables['ctth_tempe'][fr['GT'][0]-fr['GT'][2]:
 ↪fr['GT'][0]+fr['GT'][2]+1,
                                       fr['GT'][1]-fr['GT'][2]:
 ↪fr['GT'][1]+fr['GT'][2]+1]
# Cloud top height
imHH = ncCH.variables['ctth_alti'][fr['LR'][0]-fr['LR'][2]:
 ↪fr['LR'][0]+fr['LR'][2]+1,
                                   fr['LR'][1]-fr['LR'][2]:
 ↪fr['LR'][1]+fr['LR'][2]+1]
imHHGW =  ncGH.variables['ctth_alti'][fr['GT'][0]-fr['GT'][2]:
 ↪fr['GT'][0]+fr['GT'][2]+1,
                                       fr['GT'][1]-fr['GT'][2]:
 ↪fr['GT'][1]+fr['GT'][2]+1]
# Get colormaps
ct_map = ListedColormap(ncCT.variables['ct_pal'][:15]/256)
hh_map = ListedColormap(ncCH.variables['ctth_alti_pal'][:128].data/256)
```

3.4 Test plot SAFNWC product

This subsection tests the SAFNWC product

[7]:
```
fig,[ax0,ax1,ax2] = plt.subplots(figsize=(18,5),nrows=1,ncols=3)
im0 = ax0.imshow(ncLR.variables['IR_104'][:],cmap='jet')
plt.colorbar(im0)
im1 = ax1.imshow(ncCT.variables['ct'][:],cmap=ct_map,clim=(1,16))
plt.colorbar(im1)
im2 = ax2.imshow(ncCH.variables['ctth_alti'][:]/1000,cmap=hh_map,clim=(0,18))
plt.colorbar(im2)
ax0.plot(4700,3794,'b',marker='x',ms=10)
ax1.plot(4700,3794,'b',marker='x',ms=10)
ax2.plot(4700,3794,'b',marker='x',ms=10)
ax0.set_title('Brightness temperature 10.4 µm')
ax1.set_title('Cloud type')
ax2.set_title('Cloud height (km)')
plt.show()
```



Meaning of cloud type
1: Cloud-free land
2: Cloud-free sea
3: Snow over land
4: Sea ice
5: Very low clouds
6: Low clouds
7: Mid-level clouds
8: High opaque clouds
9: Very high opaque clouds
10: Fractional clouds
11: High semitransparent thin clouds
12: High semitransparent moderately thick clouds
13: High semitransparent thick clouds
14: High semitransparent above low or medium clouds
15: High semitransparent above snow/ice

3.5 Calculation of the Ash product following Eutmetsat recipe

This ash product is produced from three infrared channels using the Eumetsat recipe. See https://user.eumetsat.int/resources/user-guides/ash-rgb-quick-guide for details and a guide for interpretation.

[8]:
```
imLR_IR120 = ncLR.variables['IR_123'][fr['LR'][0]-fr['LR'][2]:
 ↪fr['LR'][0]+fr['LR'][2]+1,
                                      fr['LR'][1]-fr['LR'][2]:
 ↪fr['LR'][1]+fr['LR'][2]+1]
imLR_IR85 = ncLR.variables['IR_085'][fr['LR'][0]-fr['LR'][2]:
 ↪fr['LR'][0]+fr['LR'][2]+1,
                                      fr['LR'][1]-fr['LR'][2]:
 ↪fr['LR'][1]+fr['LR'][2]+1]
clim0 = (243,303)
clim1 = (-4,5)
clim2 = (-4,2)
DBT1 = imLR_IR - imLR_IR85
DBT2 = imLR_IR120 - imLR_IR
# rescaling and clipping
B = np.ma.clip((imLR_IR - clim0[0])/(clim0[1] - clim0[0]),0,1)
G = np.ma.clip((DBT1 - clim1[0])/(clim1[1] - clim1[0]),0,1)
R = np.ma.clip((DBT2-clim2[0])/(clim2[1]-clim2[0]),0,1)
Ash = np.ma.dstack([R,G,B])
# in order to set the masked pixels to white color
Ash.data[Ash.mask] = 1
```

[10]:
```
imGW_IR120 = ncGW.variables['IR_123'][fr['GT'][0]-fr['GT'][2]:
 ↪fr['GT'][0]+fr['GT'][2]+1,
                                      fr['GT'][1]-fr['GT'][2]:
 ↪fr['GT'][1]+fr['GT'][2]+1]
imGW_IR85 = ncGW.variables['IR_085'][fr['GT'][0]-fr['GT'][2]:
 ↪fr['GT'][0]+fr['GT'][2]+1,
                                      fr['GT'][1]-fr['GT'][2]:
 ↪fr['GT'][1]+fr['GT'][2]+1]
clim0 = (243,303)
clim1 = (-4,5)
clim2 = (-4,2)
DBT1 = imGW_IR - imGW_IR85
DBT2 = imGW_IR120 - imGW_IR
# rescaling and clipping
B = np.ma.clip((imGW_IR - clim0[0])/(clim0[1] - clim0[0]),0,1)
G = np.ma.clip((DBT1 - clim1[0])/(clim1[1] - clim1[0]),0,1)
R = np.ma.clip((DBT2-clim2[0])/(clim2[1]-clim2[0]),0,1)
AshGW = np.ma.dstack([R,G,B])
# in order to set the masked pixels to white color
AshGW.data[AshGW.mask] = 1
```

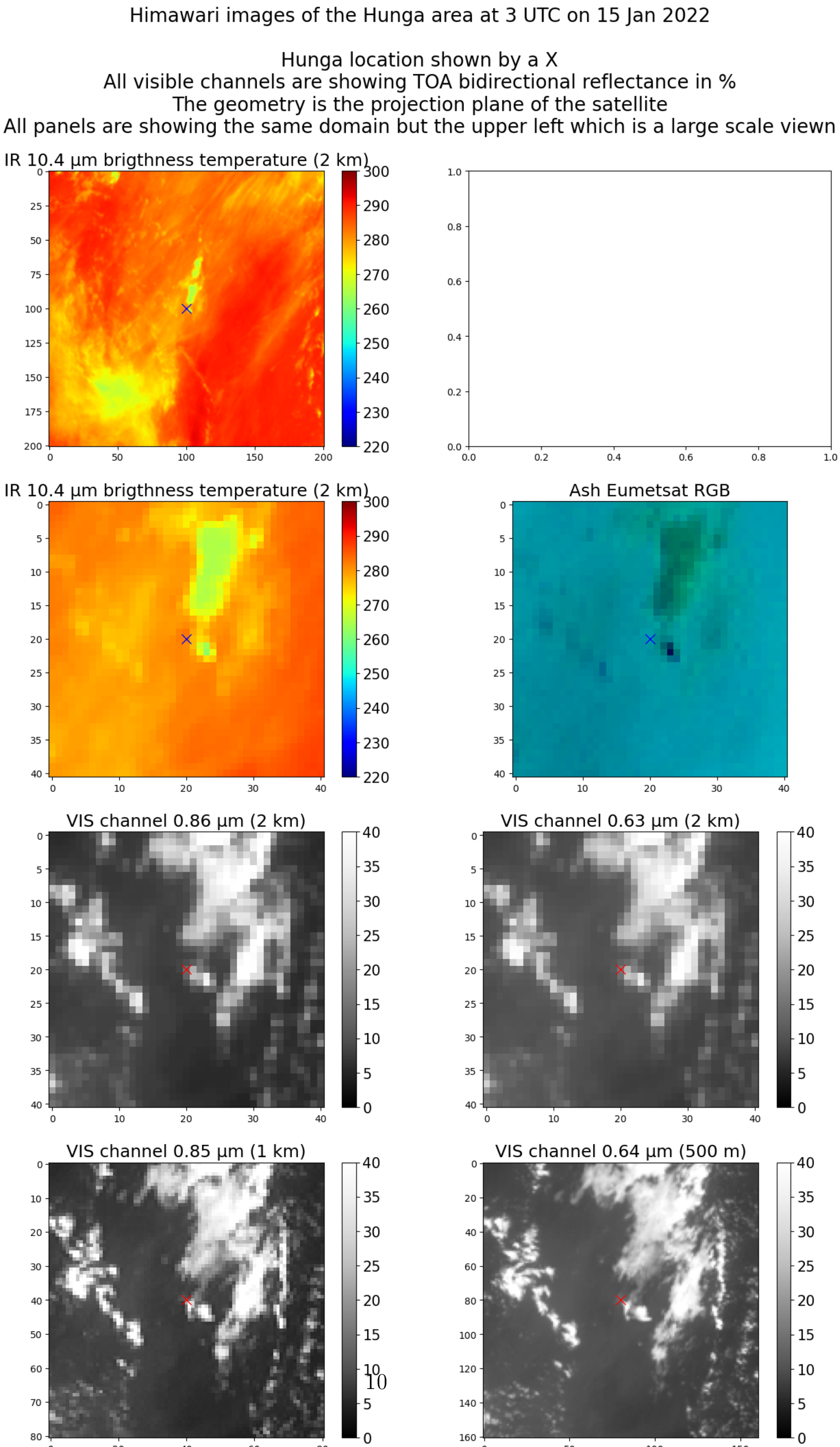
4 Plots

4.1 Plots from Himawari data

Notice the images are shown in the geometry of the satellite and that the number on the axis are pixels in the projection plane of the satellite image (basically polar stereoscopic). The Hunga is centered in all images. Notice also that we do not use any smoothing function like in the WorldView display which tends to confuse and blurr the contours. The resolution indicated in each panel is the nominal resolution of the channel which is the size of the pixel at the nadir of the satellite. The true resolution at the location of the Hunga is reduced.

[10]:
```
fig,[[ax0,axt],[ax1,axash],[ax2,ax3],[ax4,ax5]] = plt.
↪subplots(figsize=(15,24),nrows=4,ncols=2)
matplotlib.rc('xtick', labelsize=15)
matplotlib.rc('ytick', labelsize=15)
plt.rcParams.update({'font.size': 15})
im0 = ax0.imshow(imLR_IR, cmap='jet',clim=(220,300))
l1 = fr['LR'][2]
l2 = fr['LR'][3]
im1 = ax1.imshow(imLR_IR[l1-l2:l1+l2+1,l1-l2:l1+l2+1],cmap='jet',clim=(220,300))
ax0.set_title('IR 10.4 µm brigthness temperature (2 km)')
ax1.set_title('IR 10.4 µm brigthness temperature (2 km)')
plt.colorbar(im0)
plt.colorbar(im1)
ax0.plot(l1,l1,'b',marker='x',ms=10)
ax1.plot(l2,l2,'b',marker='x',ms=10)
imash = axash.imshow(Ash[l1-l2:l1+l2+1,l1-l2:l1+l2+1])
axash.set_title('Ash Eumetsat RGB')
axash.plot(l2,l2,'b',marker='x',ms=10)
im2 = ax2.imshow(imLR_V8[l1-l2:l1+l2+1,l1-l2:l1+l2+1],clim=(0,40),cmap='Greys_r')
im3 = ax3.imshow(imLR_V6[l1-l2:l1+l2+1,l1-l2:l1+l2+1],clim=(0,40),cmap='Greys_r')
ax2.set_title('VIS channel 0.86 µm (2 km)')
ax3.set_title('VIS channel 0.63 µm (2 km)')
plt.colorbar(im2)
plt.colorbar(im3)
ax2.plot(l2,l2,'r',marker='x',ms=10)
ax3.plot(l2,l2,'r',marker='x',ms=10)
l1 = fr['HR'][2]
l2 = fr['HR'][3]
im4 = ax4.imshow(imHR_V8[l1-l2:l1+l2+1,l1-l2:l1+l2+1],clim=(0,40),cmap='Greys_r')
ax4.plot(l2,l2,'r',marker='x',ms=10)
l1 = fr['VR'][2]
l2 = fr['VR'][3]
im5 = ax5.imshow(imVR_V6[l1-l2:l1+l2+1,l1-l2:l1+l2+1],clim=(0,40),cmap='Greys_r')
ax5.plot(l2,l2,'r',marker='x',ms=10)
plt.colorbar(im4)
plt.colorbar(im5)
ax4.set_title('VIS channel 0.85 µm (1 km)')
```

```
ax5.set_title('VIS channel 0.64 µm (500 m)')
fig.suptitle('Himawari images of the Hunga area at 3 UTC on 15 Jan 2022\n\n'+
             'Hunga location shown by a X\n'+
             'All visible channels are showing TOA bidirectional reflectance in␣
 ↪%\n'+
             'The geometry is the projection plane of the satellite\n'+
             'All panels are showing the same domain but the upper left which is␣
 ↪a large scale viewn',
             fontsize = 20)
plt.show()
```

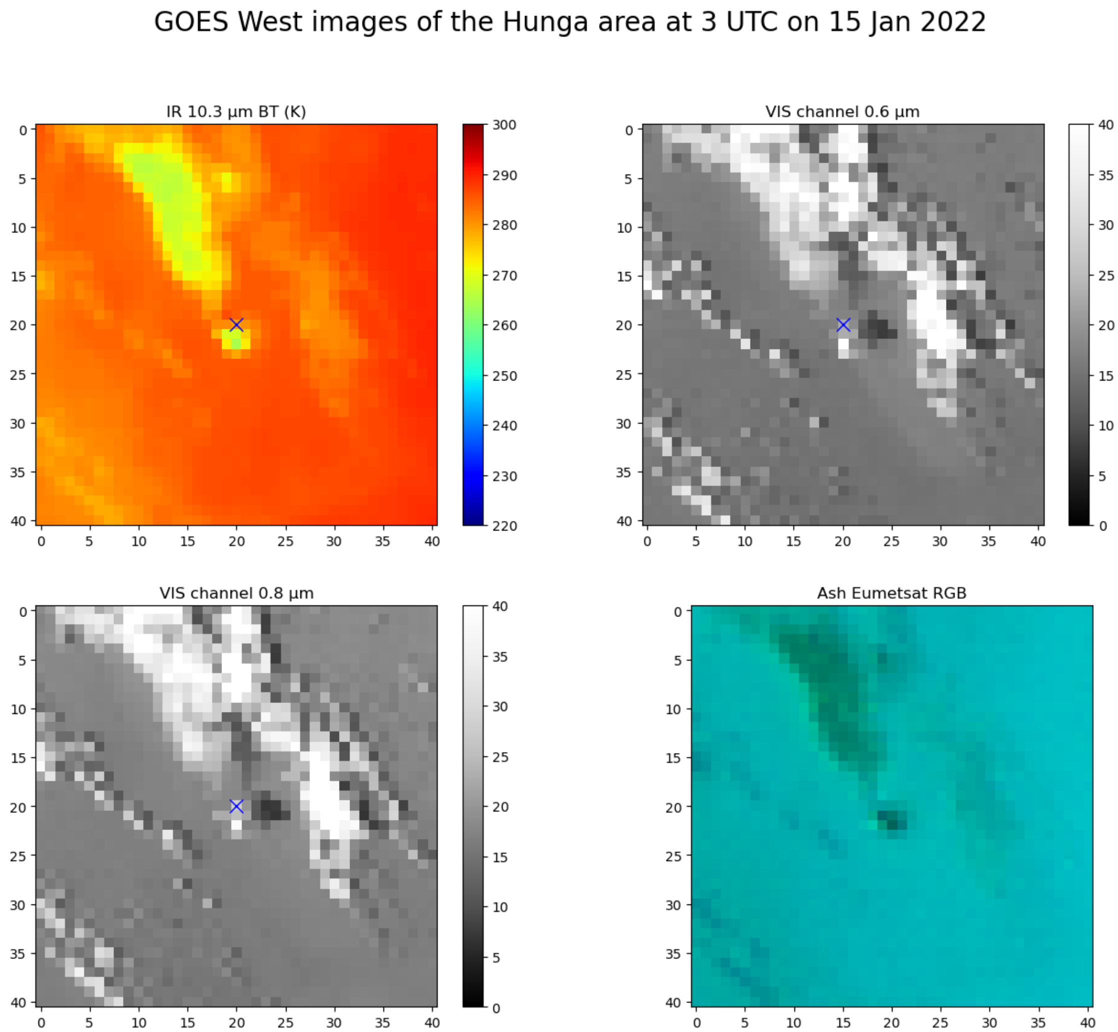

Himawari images of the Hunga area at 3 UTC on 15 Jan 2022
Hunga location shown by a X
All visible channels are showing TOA bidirectional reflectance in %
The geometry is the projection plane of the satellite
All panels are showing the same domain but the upper left which is a large scale viewn
IR 10.4 µm brigthness temperature (2 km)
IR 10.4 µm brigthness temperature (2 km)
Ash Eumetsat RGB
VIS channel 0.86 µm (2 km)
VIS channel 0.63 µm (2 km)
VIS channel 0.85 µm (1 km)
VIS channel 0.64 µm (500 m)

The “plume” is seen on all images albeit with sharper details on the high resolution images. Because of the viewing angle, close to the direction of the sun, the proeminent shadow in the GOES images is hardly visible here. It remains that the brighness temperature is similar to those of clouds located north of the Hunga, suggesting a similar altitude and nature. The clouds located on the east are warmer and possibly lower in agreement with the shorter shadow in GOES images.

4.2 Plots from GOES W data

As the available GOES West (17) archive at AERIS does not contain high resolution data, we only show here images at 2 km resolution.

[14]:
```
l1 = fr['GT'][2]
l2 = fr['GT'][3]
fig,[[ax0,ax1],[ax2,ax3]] = plt.subplots(figsize=(15,12),nrows=2,ncols=2)
im0 = ax0.imshow(imGW_IR[l1-l2:l1+l2+1,l1-l2:l1+l2+1],cmap='jet',clim=(220,300))
im1 = ax1.imshow(imGW_V6[l1-l2:l1+l2+1,l1-l2:l1+l2+1],clim=(0,40),cmap='Greys_r')
im2 = ax2.imshow(imGW_V8[l1-l2:l1+l2+1,l1-l2:l1+l2+1],clim=(0,40),cmap='Greys_r')
im3 = ax3.imshow(AshGW[l1-l2:l1+l2+1,l1-l2:l1+l2+1])
plt.colorbar(im0)
plt.colorbar(im1)
plt.colorbar(im2)
#ax0.plot(l2,l2,'b',marker='x',ms=5)
#ax1.plot(l2,l2,'b',marker='x',ms=5)
#ax2.plot(l2,l2,'b',marker='x',ms=5)
ax0.plot(l2,l2,'b',marker='x',ms=10)
ax1.plot(l2,l2,'b',marker='x',ms=10)
ax2.plot(l2,l2,'b',marker='x',ms=10)
ax0.set_title('IR 10.3 µm BT (K)')
ax1.set_title('VIS channel 0.6 µm')
ax2.set_title('VIS channel 0.8 µm')
ax3.set_title('Ash Eumetsat RGB')
fig.suptitle('GOES West images of the Hunga area at 3 UTC on 15 Jan 2022',
             fontsize = 20)
plt.show()
```

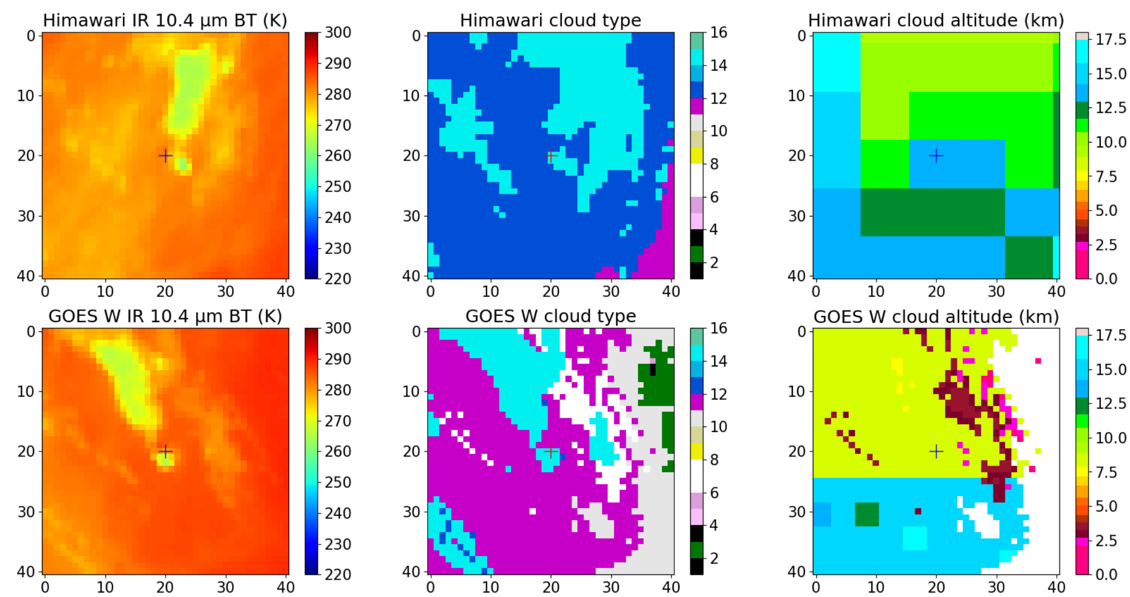


The GOES images agree with the brightness temperature shown in Himawari 8 images with a value of about 265 K which corresponds at such latitude and time to an altitude of about 6-7 km. The casted shadow is somewhat darker at its center than surrounding clouds. It does not appear to be longer than the clouds located north to the volcano, and indeed their brightnass temperature is very similar, but it is longer than the clouds on the east or the weast which are also warmer. The Ash product does not show any signature of volcanic origin.

4.3 Supplement plot using the Eumetsat SAFNWC product

[20]:
```
l1 = fr['LR'][2]
l2 = fr['LR'][3]
fig,[[ax0,ax1,ax2],[ax3,ax4,ax5]] = plt.subplots(figsize=(20,10),nrows=2,ncols=3)
im0 = ax0.imshow(imLR_IR[l1-l2:l1+l2+1,l1-l2:l1+l2+1],cmap='jet',clim=(220,300))
#im0 = ax0.imshow(imLR_IR,cmap='jet',clim=(220,300))
plt.colorbar(im0)
```

```
im1 = ax1.imshow(imCT[l1-l2:l1+l2+1,l1-l2:l1+l2+1],cmap=ct_map,clim=(1,16))
plt.colorbar(im1)
im2 = ax2.imshow(imHH[l1-l2:l1+l2+1,l1-l2:l1+l2+1]/1000,cmap=hh_map,clim=(0,18))
plt.colorbar(im2)
ax0.set_title('IR 10.4 µm BT (K)')
ax1.set_title('Eumetsat SAFNWC cloud type')
ax2.set_title('Eumetsat SAFNWC cloud altitude (km)')
im3 = ax3.imshow(imGW_IR[l1-l2:l1+l2+1,l1-l2:l1+l2+1],cmap='jet',clim=(220,300))
plt.colorbar(im3)
im4 = ax4.imshow(imCTGW[l1-l2:l1+l2+1,l1-l2:l1+l2+1],cmap=ct_map,clim=(1,16))
plt.colorbar(im4)
im5 = ax5.imshow(imHHGW[l1-l2:l1+l2+1,l1-l2:l1+l2+1]/
 ↪1000,cmap=hh_map,clim=(0,18))
plt.colorbar(im5)
ax0.plot(l2,l2,'b',marker='+',ms=15)
ax1.plot(l2,l2,'r',marker='+',ms=15)
ax2.plot(l2,l2,'b',marker='+',ms=15)
ax3.plot(l2,l2,'b',marker='+',ms=15)
ax4.plot(l2,l2,'r',marker='+',ms=15)
ax5.plot(l2,l2,'b',marker='+',ms=15)
ax0.set_title('Himawari IR 10.4 µm BT (K)')
ax1.set_title('Himawari cloud type')
ax2.set_title('Himawari cloud altitude (km)')
ax3.set_title('GOES W IR 10.4 µm BT (K)')
ax4.set_title('GOES W cloud type')
ax5.set_title('GOES W cloud altitude (km)')
plt.show()
```



We see that most relevant clouds are classified as high semi-transparent clouds, which are thin and/or above other clouds. Brighter ones are not necessarily higher but just more opaque than the others. Added to the high zenithal angle of the satellite, this makes very difficult to estimate the altitude and, indeed, the CTH product fails to produce a pattern that makes sense.

5 ERA5 temperature and wind profile at the location of the volcano

The data are here imported from the ERA5 reanalysis in a grib format with a longitude x latitude grid at 1° resolution. All the 137 levels are available. Such data can be easily extracted from the COPERNICUS service. We extract the temperature and the two components of the horizontal wind on the four frid points surrounding the volcanoe. The dry geopotential altitude is then calculated and the profiles are interpolated at the location of the volcanoe. The wind direction is calculated in degree with respect to the east.

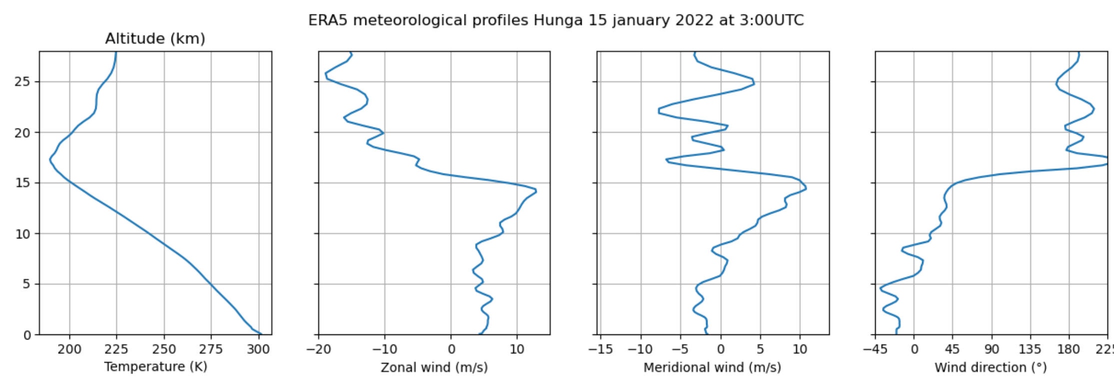
[15]:
```
from ECMWF_N import ECMWF
from datetime import datetime
dat = ECMWF('FULL-EA',datetime(2022,1,15,3))
```

[16]:
```
dat._get_var('U')
dat._get_var('V')
dat._get_var('T')
dat._mkp()
dat._mkz()
```

[17]:
```
lonH = 184.615
latH = -20.552
lo1 = 184
lo2 = 185
la1 = 70
la2 = 71
cx1 = lonH - 184
cx2 = 185 - lonH
cy1 = latH + 21
cy2 = -20 - latH
UH = dat.var['U']
```

[18]:
```
# Interpolation at Hunga location
UH = dat.var['U'][:,la1,lo1]*cy2*cx2 + dat.var['U'][:,la2,lo1]*cy1*cx2 + \
     dat.var['U'][:,la1,lo2]*cy2*cx1 + dat.var['U'][:,la2,lo2]*cy1*cx1
VH = dat.var['V'][:,la1,lo1]*cy2*cx2 + dat.var['V'][:,la2,lo1]*cy1*cx2 + \
     dat.var['V'][:,la1,lo2]*cy2*cx1 + dat.var['V'][:,la2,lo2]*cy1*cx1
TH = dat.var['T'][:,la1,lo1]*cy2*cx2 + dat.var['T'][:,la2,lo1]*cy1*cx2 + \
     dat.var['T'][:,la1,lo2]*cy2*cx1 + dat.var['T'][:,la2,lo2]*cy1*cx1
ZH = dat.var['Z'][:,la1,lo1]*cy2*cx2 + dat.var['Z'][:,la2,lo1]*cy1*cx2 + \
     dat.var['Z'][:,la1,lo2]*cy2*cx1 + dat.var['Z'][:,la2,lo2]*cy1*cx1
ZH = ZH/1000
```

[20]:
```
OR = np.rad2deg(np.atan2(VH,UH))
ym = 28
OR[OR < -100] += 360
fig,[ax0,ax1,ax2,ax3] = plt.subplots(figsize=(15,4),nrows=1,ncols=4,sharey=True)
ax0.plot(TH,ZH)
ax1.plot(UH,ZH)
ax2.plot(VH,ZH)
ax3.plot(OR,ZH)
ax0.set_ylim(0,ym)
ax1.set_xlim(-20,15)
ax3.set_xlim(-45,225)
ax3.set_xticks([-45,0,45,90,135,180,225])
ax0.grid(True)
ax1.grid(True)
ax2.grid(True)
ax3.grid(True)
ax0.set_xlabel('Temperature (K)')
ax1.set_xlabel('Zonal wind (m/s)')
ax2.set_xlabel('Meridional wind (m/s)')
ax3.set_xlabel('Wind direction (°)')
ax0.set_title('Altitude (km)')
fig.suptitle('ERA5 meteorological profiles Hunga 15 january 2022 at 3:00UTC')
plt.show()
```



In the first 6 km, above the surface layer, the wind is fairly uniform to the south-east, at a speed of about 6 m/s. Such wind direction is not compatible with the orientation of the dispersion of the “plume” with is souh-westward.

6 Time sequence of clouds in the vicinity of the Hunga within the 90 minutes before the "precursor" cloud

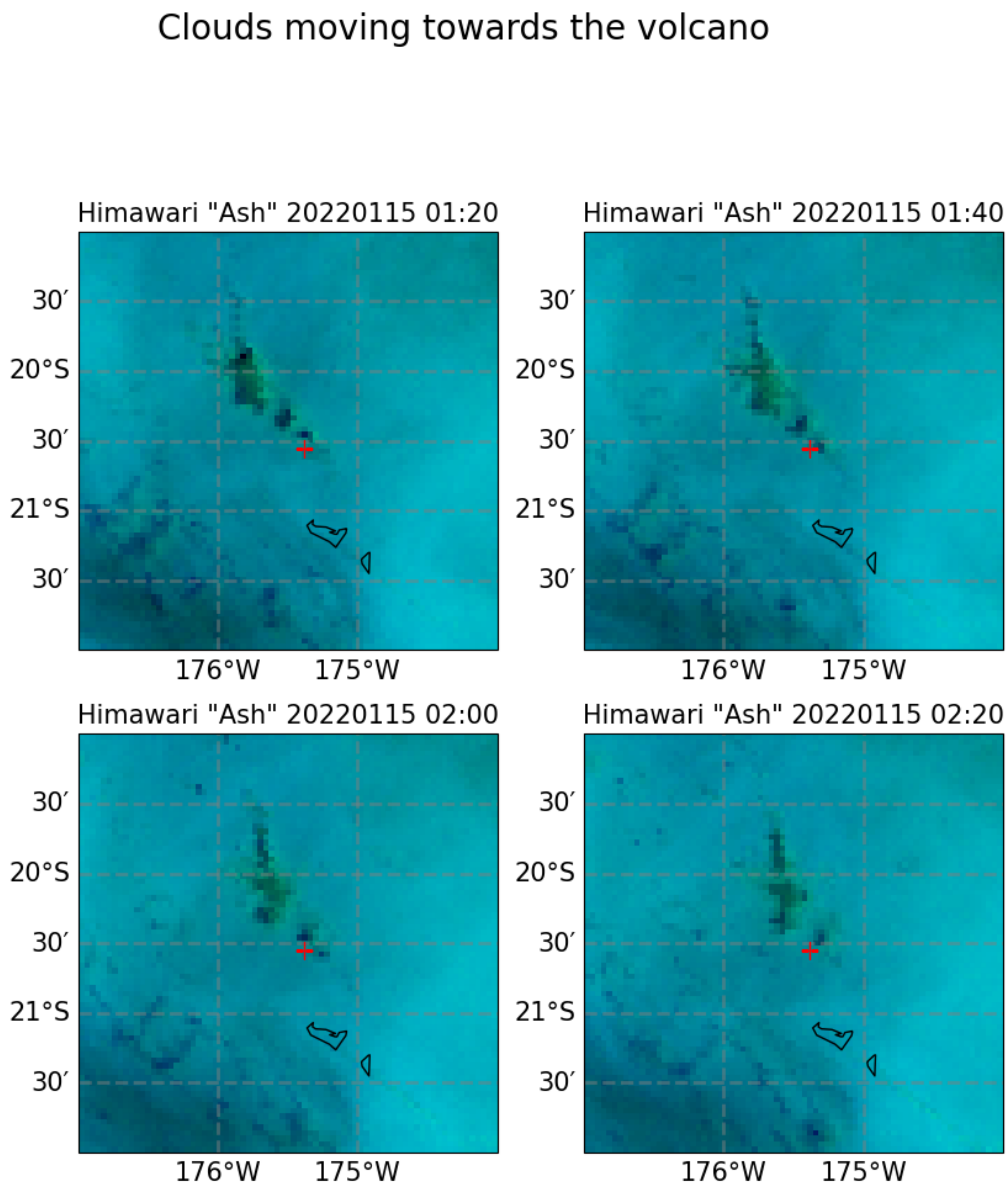
Here we show a sequence of images from Himawari between 01:20 and 2:20 to determine the motion of clouds in the vicinity of the Hunga before the eruption. A main SEward motion emerges which is consistent with mid-level clouds and the warm brightness temperature.

6.1 In renavigated geometry for a map in latitude x longitude

Here we project the Himawari infrared images onto a regular latitude x longitude grid with a resolution of 0,1° by closest neighbour method.

[22]:
```
import geosat
from datetime import datetime
import cartopy.crs as ccrs
proj = ccrs.PlateCarree(central_longitude=180)
wlon = 360-177.
elon = 360-174.
nlat = -19.
slat = -22.
gh = geosat.GeoGrid('HimFull')
ext = [wlon,elon,slat,nlat]
subgh = gh.subgrid(ext)
def HimaGet(dd,var='Ash'):
    ah = geosat.Himawari(dd)
    ph = geosat.SatGrid(ah,gh)
    if var == 'Ash':
        ah._mk_Ash()
    else:
        ah.get_var(var)
    ph._sat_togrid(var)
    return [ph,ah]
dd = (datetime(2022,1,15,1,20),datetime(2022,1,15,1,40),
      datetime(2022,1,15,2,0),datetime(2022,1,15,2,20))
pos = [[0,0],[0,1],[1,0],[1,1]]
fig = plt.figure(figsize=(15,15))
ax = []
for i in range(4):
    ax.append(plt.subplot2grid((3,3),pos[i],projection=proj))
    ph,ah = HimaGet(dd[i],var='Ash')
    ph.chart('Ash',txt=dd[i].strftime('Himawari "Ash" %Y%m%d %H:
 ↪%M'),subgrid=subgh,
             show=False,axf=ax[i],cm_lon=180,xlocs=(-177,-176,-175,-174))
    ax[i].plot(-175.3841+180,-20.5532,'r',marker='+',ms=10)
    ah.close()
fig.suptitle('Clouds moving towards the volcano',size=20,ha='right',va='bottom')
plt.show()
```

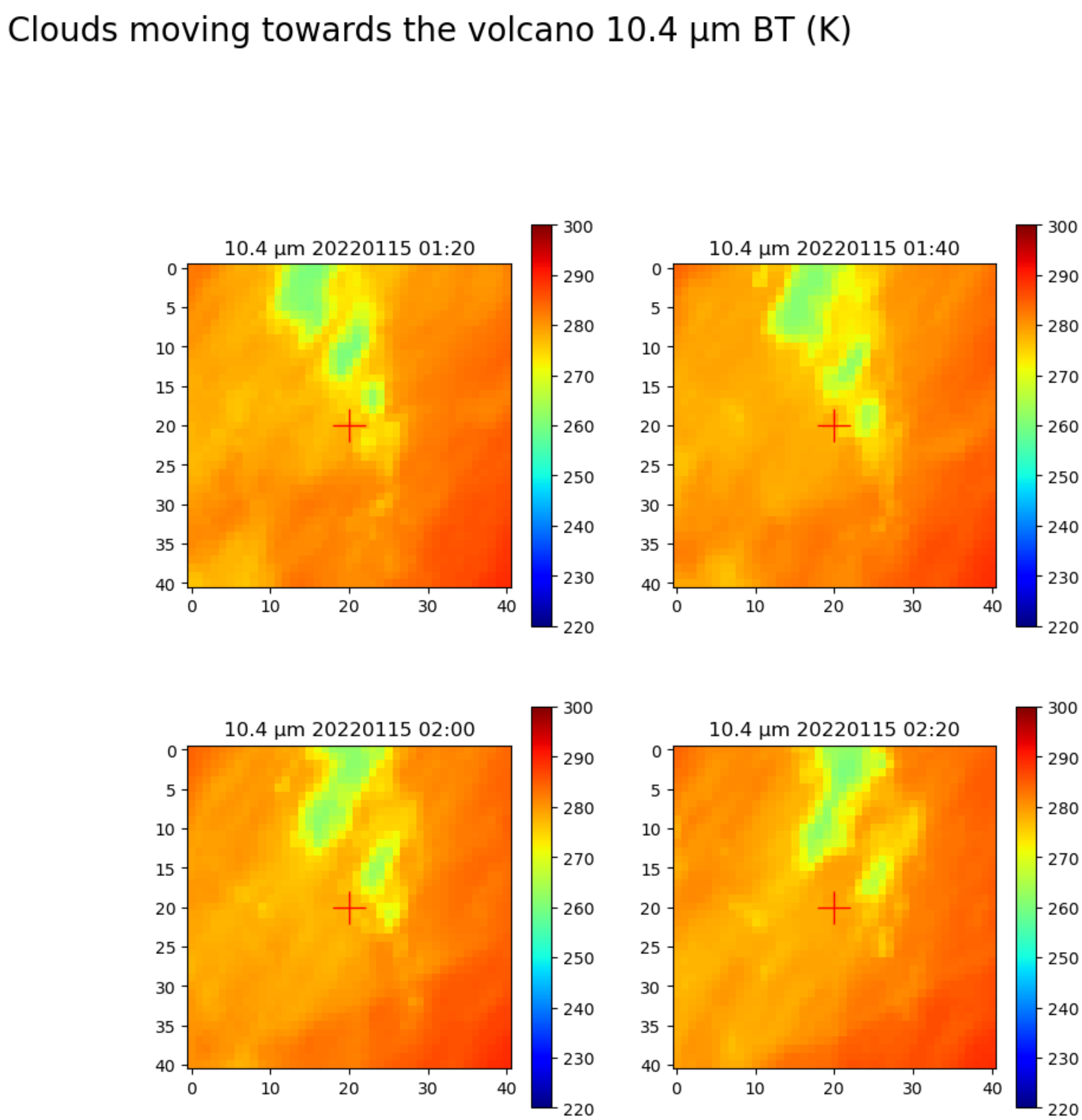
```
3075 3150 1450 1525
lookup table loaded for  himawari_HimFull
```



6.2 In the satellite geometry like other images in this notebook

[23]:
```
fig = plt.figure(figsize=(15,15))
ax = []
l1 = fr['LR'][2]
l2 = fr['LR'][3]
for i in range(4):
```

```
    ax.append(plt.subplot2grid((3,3),pos[i]))
    ph,ah = HimaGet(dd[i],var='IR_104')
    img = ah.var['IR_104'][fr['LR'][0]-fr['LR'][2]:fr['LR'][0]+fr['LR'][2]+1,
                        fr['LR'][1]-fr['LR'][2]:fr['LR'][1]+fr['LR'][2]+1]
    im = ax[i].imshow(img[l1-l2:l1+l2+1,l1-l2:l1+l2+1],cmap='jet',clim=(220,300))
    ax[i].set_title(dd[i].strftime('10.4 µm %Y%m%d %H:%M'))
    ax[i].plot(l2,l2,'r',marker='+',ms=20)
    plt.colorbar(im)
fig.suptitle('Clouds moving towards the volcano 10.4 µm BT (K)',size=20,ha='right',va='bottom')
plt.show()
```



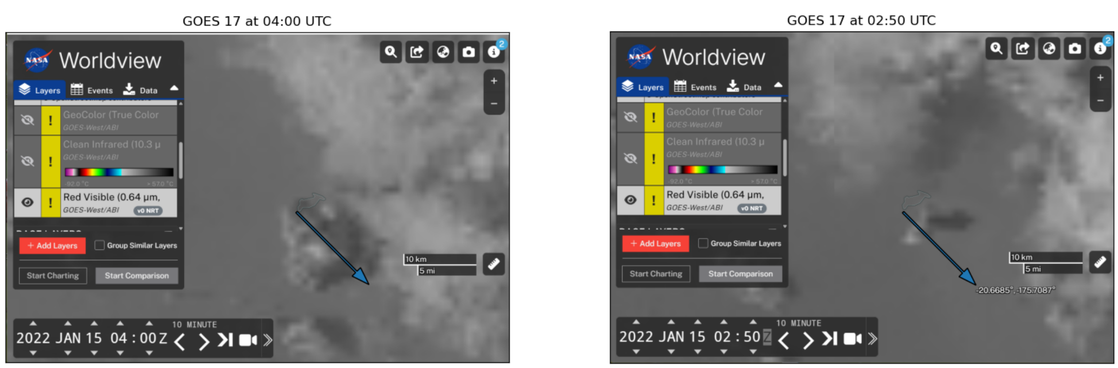
These images taken at 20 minute interval show the motion of mid-altitude clouds in the vicinity of the Hunga before the eruption. Unfortunately the 02:40 UTC image is missing (due to daily Himawari maintenance). Nevertheless, this sequence stronly suggests the "plume" belongs in fact to this ensemble of clouds. The mean motion to the south-east agrees with the orientation of ERA5 winds.

7 Comparison with the precursor at 04:00 UTC

In Gupta et al. (2022), a precursor plume is mentioned to be seen at 04:00 UTC in the GOES 17 image while the plume resulting from the main eruption is first seen at 04:10 UTC.

We show here the GOES 17 0.64 µm images extracted from WorldView for 15 Jan 2022 at 04:00 and 02:50 for comparison. The scale of the longitude x latitude projection is displayed on each panel. An arrow sketches the direction of the wind.

[44]:
```
from PIL import Image
img3 = Image.open(join('sluggish','WV-0400.png'))
img4 = Image.open(join('sluggish','WV-0250.png'))
img5 = Image.open(join('sluggish','WV-0410.png'))
fig,[ax1,ax2] = plt.subplots(figsize=(18,9),nrows=1,ncols=2)
ax1.imshow(img3)
ax1.arrow(730,450,150,150,width=5,head_width=30)
ax2.imshow(img4)
ax2.arrow(730,450,150,150,width=5,head_width=30)
ax1.get_xaxis().set_ticks([])
ax1.get_yaxis().set_ticks([])
ax2.get_xaxis().set_ticks([])
ax2.get_yaxis().set_ticks([])
ax1.set_title('GOES 17 at 04:00 UTC')
ax2.set_title('GOES 17 at 02:50 UTC')
plt.show()
```

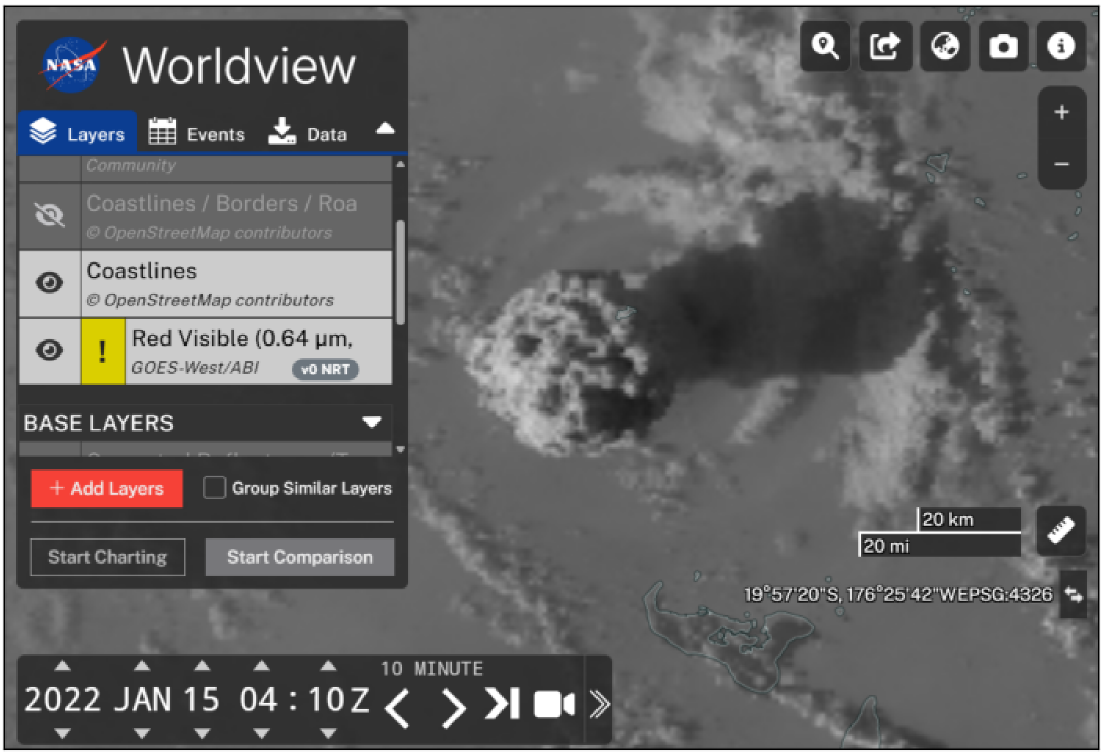


The plume at 04:00 UTC exhibit a conical shape with the tip located on the Hunga Tonga island and extending south eastward in the direction of the wind. The length of this plume which was not visible 10 minutes earlier is compatible with a wind speed of about 10 m/s. We see that on the contrary the "plume" seen in the à2:50 UTC image disperses apparently in a direction orthogonal to the wind. It is more reasonable to assume it is not of volcanic orgin but a cloud possibly triggered by a gravity wave.

We now show for completion the image at 04:10 UTC which is the first of the main plume. Notice that the scale has been enlarged to encompass the hugeness of the plume.

[45]:
```
fig,ax3 = plt.subplots(figsize=(9,9),nrows=1,ncols=1)
ax3.imshow(img5)
ax3.get_xaxis().set_ticks([])
ax3.get_yaxis().set_ticks([])
ax3.set_title('GOES 17 at 04:10 UTC')
plt.show()
```

GOES 17 at 04:10 UTC



Recalling that the data have been collected at 04:17 UTC and that the initiation of the eruption has been at 04:16:00 UTC according to Paoli and Shapiro (2022) based on the surge in the seismic signal, this means that this plume with an apparent shadow 70-80 km shadow developed in about 1 minute. Using teh method of Carr et al. (2022), this shadow corresponds to an altitude of about 20 km, meaning that the plume rose at near the speed of sound.

8 Discussion

We have processed Himawari 8 and GOES 17 data on 15 January 2022 with additional profiles from ERA5 to check whether the claim made in Van Eaton et al. (2023) of a precursor volcanic plume, about one hour before the paroxismal eruption of the Hunga is supported by a thorough analysis. As AvE was a reviewer of the APARC report on the Hunga eruption which was the context of this study, an earlier but essentially identical version of this notebook was used during the discussion that took place during the review process. Although Van Eaton et al. (2023) provide no data in support of the claim, AvE provided a couple of images extracted from the GOES 17 visible channel at 0.64 µm resolution. As these are the only elements of proof, this notebook has focused on a detailed analysis exploiting the other available data. The claim of Van Eaton et al. (2023) comes from the fact that a cloud is visible at 02:50 UTC with a shape compatible with a plume, that persists and develops in the 03:00 UTC image. It is mentioned that it casts a shadow much longer than sussounding clouds, estimating an altitude of 15 km. In the initial stage of the discussion, AvE maintained these claims and mentioned that the plume was too small to be seen by infrared sensors with limited resolution.

WorldView only preserves geostationary data for 90 days but for a selection of exceptional events. GOES 17 visible images are still accessible for Hunga eruption but no other data. The AERIS Icare (https://www.aeris-data.fr/icare/) maintains an online archive of geostationary data with full resolution for Himawari at 20' frequency and with only 2 km resolution for GOES-17 ar 30' frequency. This is why we focused on the data at 3:00 UTC. It is useful to mention here that the nominal resolution is only valid at the nadir. The true resolution is somewhat degraded at large viewing angles as it is the case here. In order to avoid spurious projection effects we only processed here the data in the original satellitte projection plane which is basically stereoscopic.

In the images shown here the "plume" is seen just south of the Hunga with several other larger clouds around. Contrary to the claim of AvE, the IR channels are recording this cloud albeit on a few pixels only. The brightness temperature (BT) put it in the same class as the clouds located NNW of Hunga with a value near 265 K. This indicate an altitude of about 6-7 km which can be considered as a lower estimate since this is valid only for opaque clouds (in the infrared) and the Eumetsat SAFNWC indicates that all clouds in this area are semi-transparent with multi-layer detection in many instances. The details of this classification are not identical for Himawari and GOES as it is often the case at large viewing angles. For the same reason the cloud height product of the SAFNWC is done at too low resolution and is not reliable. Nevertheless the altitude of 15 km put for by Van Eaton et al. (2023) is not conistent with the data.

Another indicator from the IR channel is the ASh RGB Eumetsat composite which exhibits a color for the sluggish cloud which is compatible with a thin ice cirrus. It does not show any sign of the reddish or yellow which indicates ash or SO2. This does not discard by itself a volcanic origin as such plumes can be initially very rich in water but is again an argument lacking in support.

Overall, the IR data do not reveal that the "plume" exhibits any character which differs from nearby clouds and hints to a volcanic nature.

Now we turn the reader's attention to the visible images where the cloud is seen in GOES data as casting apparent shadow to the east. The shadow is hardly visible in Himawari images as the satellite on the west of the volcanoe was, at late afternoon local time, much closer to the sun than GOES located on the east. Nevertheless, the GOES images show that the shadow cast by the "plume" does not extend further from its source than the shadow of the clouds located NNW of the

Hunga. This is consistent with the fact they also display similar brightness temperature. Other clouds located east or SW of Hunga display shorter shadows and, consistently, higher brightness temperature because they are lower.

Let us consider now the orientation of the sluggish plume. It is pointing to the SSW in the image provided by AvE at 02:50UT if we assume the NNE tip is connected to the Hunga. Instead, the ERA5 wind is oriented towards the south-east in the 6 first kilometers and then to the north-east until 15 km. The images of surrounding clouds during the previous 90 minutes also show that they move south-eastward and a (true) precursor, detected at 04:00 UTC in another study (Gupta et al., 2022) but never mentioned by AvE, also flows in this direction. This is not compatible with the interpretation of the 02:50 UTC and 03:00 UTC images as showing a plume blown from the volcano. However, the location of the cloud is compatible with a formation of a cloud triggered by a gravity wave generated by a south-eastward wind passing above the Hunga and this is our preferred interpretation.

Therefore, although the emission of a plume by the Hunga by 2:50 UT on 15 January 2022 cannot be entirely excluded, the reported cloud located south to the Hunga does not exhibit any physical properties that distinguishes it from the meteorological cloud located NNW to the volcano and disperses in the wrong direction according to the wind. It is very likely to be a cirrus formed within the vicinity of the island, possibly triggered by a gravity wave. This analysis reaches the same conclusion as Prata et al. (2025).

In any case, even such a plume would be a manifestation of very superficial activity and cannot be assumed to be the beginning of the plume that was produced about one hour later and climbed the first 20 kilometers in the order of 1 minute.

This notebook is made available publicly upon request of Thomas Aubry who supervised the reviewing of chapter 2 of the APARC report on the atmospheric impact of the Hunga eruption.

Acknowledgments

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