

Introducing HYDRA2 – a Multispectral Data Analysis Toolkit for Suomi NPP and EOS

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Abstract

A freeware based multispectral data analysis toolkit for satellite data has been developed to assist research and development of remote sensing applications as well as education and training of remote sensing scientists; it is called HYDRA2 - HYper-spectral data viewer for Development of Research Applications version2. HYDRA2 provides a fast and flexible interface that allows users to explore and visualize relationships between sensor measurements (displayed as brightness temperatures for infrared and reflectances for visible and near infrared) and wavelength (or wavenumber) using spectra diagrams, cross sections, scatter plots, multi-band combinations, and color enhancements on a pixel by pixel basis with full access to the underlying metadata of location and time.

HYDRA2 enables interrogation of multispectral (and hyperspectral) fields of data so that (a) pixel location and spectral measurement values can be easily displayed; (b) spectral bands can be combined in linear functions and the resulting images displayed; (c) false color images can be constructed from multiple spectral band combinations; (d) scatter plots of spectral band combinations can be viewed; (e) pixels in images can be found in scatter plots and vice versa; (f) transects of measurements can be displayed, and (g) soundings of temperature and moisture as well as spectra from selected pixels can be compared.

HYDRA2 is a toolkit that can be used with direct broadcast and archived data from Suomi NPP and the EOS Aqua and Terra platforms.

This paper describes some of the procedures for displaying multispectral data using HYDRA2 and presents some examples with VIIRS, MODIS, CrIS, and ATMS data.

1. Design Philosophy of HYDRA

HYDRA2 (Hyper-spectral data viewer for Development of Research Applications version 2) grew out of the necessity to provide research scientists and educators with freely available software that could display and investigate remotely sensed multispectral and hyperspectral data. HYDRA2 is a fourth generation application produced at the University of Wisconsin's Space Science and Engineering Center (SSEC). The first three were based on commercial packages IDL, Matlab, and Java; they served as a testbed to refine the operations and functionality requested by the users.

When considering the design of HYDRA2, the most important requirements were that the

software must be (a) freely available to the global community, (b) computer platform independent, and (c) extendable. Computer platform independence has been elusive in so far as HDF libraries still are required to view the data. To this end the Java-NetCDF library from Unidata, which provides a platform independent, multi-array access API to a wide range of file storage formats, is employed to provide access to HDF4/5, used for NASA EOS and SuomiNPP. The VisAD (Visualization for Algorithm Development) Java library was selected as the basis for HYDRA2; Hibbard et al (2002) has more information about VisAD. This library allows applications to be written in either Java or Jython, the Java implementation of the popular Python scripting language; more details are available in Bill (2002) and Lutz et al (1996). The core of the VisAD library is a unified Data Model, which allows for the representation of literally any numeric data in a consistent manner. This is very important when integrating data from a variety of sources that may have different sampling topologies in space or time. The Data Model also has built-in metadata for parameters such as units and error estimates. Because these metadata are an integral part of the data, they can be easily used to verify the validity of computations (the software detects invalid combinations, such as adding a temperature to a pressure) and to estimate the reliability of computations.

HYDRA2 is a standalone client application organized into a simple hierarchy of Java classes leveraging the VisAD library, the aforementioned Java-NetCDF library and a higher level, VisAD based library from Unidata for handling map projections and geo navigated displays. HYDRA2's design layout separates classes responsible for generating displays, interactive data interrogation, custom analysis tools and provides a programmatically extendable interface for adapting physical data to VisAD's abstract data model.

The programmatic interface to the data files has been designed so that emerging new file types or formats will be easy to support without changing the core of the applications. The key was to abstract the reading of the files so that the application makes the same function or method calls regardless of the file being read. This same philosophy is used in packages such as OpenDAP and ESML, which have the notion of a plug-in.

Appendices 1 and 2 offer more details on getting HYDRA2 started and how to use the command structure to stage and interrogate multispectral data. The following sections illustrate some of the HYDRA2 capabilities for analyzing data from the Suomi National Polar orbiting Partnership (SNPP) that include the multispectral Visible Infrared Imaging Radiometer Suite (VIIRS), hyperspectral Cross track Infrared Sounder (CrIS), and Advanced Technology Microwave Sounder (ATMS) – see eoPortal <https://directory.eoportal.org/web/eoportal/satellite-missions/s/suomi-npp>.

HYDRA2 is also capable of viewing and interrogating data from the Earth Observing System (EOS) Terra and Aqua platform sensors that include the Moderate resolution Imaging Spectro-radiometer (MODIS) and the Atmospheric Infrared Sounder (AIRS) – see eoPortals <https://directory.eoportal.org/web/eoportal/satellite-missions/a/aqua> and <https://directory.eoportal.org/web/eoportal/satellite-missions/t/terra>. In addition data from the MetOp (Klaes et al., 2007) Infrared Atmospheric Sounding Interferometer (IASI) can also be displayed with HYDRA2 – see eoPortal <https://directory.eoportal.org/web/eoportal/satellite-missions/m/metop>.

2. Examples of Spectral Band Applications with HYDRA2

HYDRA2 enables display and interrogation of the available spectral bands for any pixel within a granule of data (21 for VIIRS and 36 for MODIS); more information about VIIRS can be found in Murphy et al (2006) and about MODIS in Barnes et al (1998). Measurements values (in reflectance or brightness temperature as selected) can be displayed for individual pixels within the granule; transects from one location to another can be constructed for a given spectral band to determine min/max values as well as gradients in between.

Figure 1a shows the VIIRS water vapor sensitive spectral band M9 (1.38 μm) reflectance image for 422 UTC on 30 August 2012 over Korea and Japan (dark is less reflecting and drier and white is the opposite). Using the HYDRA2 commands, measurement values and latitude/longitudes for any of the pixels for all of the spectral bands can be displayed.

Figure 1b presents an RGB image (created using the “RGB” option under “Tools” in the HYDRA2 window). A false color image has been composed from the VIIRS spectral band combination (M5 at 0.67 μm in the red, M4 at 0.56 μm in the green, and M3 at 0.49 μm in the blue) that comes closest to providing an image akin to what the human eye would see. RGB allows any three bands to drive the red, green, and blue enhancements.

Figure 1c shows a transect superimposed on the infrared window M15 image (initiated by using “Transect” under “Tools”) and the associated brightness temperature values going from west to east; clouds at 230 and ocean surface at 290 are readily apparent.

When two windows are open, “Scatter” (under “Tools”) allows one to generate scatter plots of one set of spectral band (or band combinations) measurements versus another (the first window chosen for the scatter display will appear on the x-axis and the second on the y-axis). The values within the scatter plot can be located in the window images and conversely regions within the window image can be displayed in the scatter plot. This is very useful in locating features in the images and determining threshold values for discriminating them from the rest of the image (e.g. clear sky versus cirrus clouds). Figure 2 shows screens associated with the scatter tool. Visible reflectances are plotted on the y-axis against infrared window 11 μm brightness temperatures on the x-axis in a scatter plot. Pixels in the scatter plot are high-lighted in different colors and their locations are marked in the infrared window brightness temperature image. Purple highlights cold and reflecting, green warm and reflecting, and blue warm and non-reflecting. Conversely, pixels in the images can also be high-lighted and their locations in the scatter plot marked (not shown).

Figure 3 shows an example of an image created using Band Math (initiated by using the “Band Math” option under “Tools” in the HYDRA2 window) on VIIRS spectral bands; the normalized vegetation index is shown as calculated from reflectances [band M7 (0.87 μm) – band M5 (0.67 μm)] / [band M7 (0.87 μm) + band M5 (0.67 μm)]. The vegetation index is based on the relatively low leaf and grass reflectance from spectral bands below 0.72 μm and relatively high reflectance from spectral bands above. Regions with some vegetation are clearly distinguished from those with little. Regions without significant vegetation have indices below 0.3; vegetated regions show indices above 0.6.

Figure 4 illustrates the capability to compare infrared window measurements from VIIRS (I4) and MODIS (B31) over Asia Oceania separated by less than 20 minutes. The advanced spatial resolution of VIIRS (380 m) versus MODIS (1 km) is readily apparent. Detailed comparison of brightness temperatures in transects, overlays, and scatter plots provide good confidence of the calibration and geo-location of the two data sets.

HYDRA is also programmed to display several MODIS derived product files; they include

- MOD06: various cloud properties
- MOD04: optical depth
- MOD28: SST
- MOD35: Cloud Mask
- MOD14: Fire Mask

Figure 5 shows the MODIS cloud top pressures from MYD06 associated with the 30 Aug 2012 pass over Asia Oceania. An effective display for these derived products is often an overlay with a spectral band image (e.g IR window band 35 or visible band 1). The capability to display VIIRS derived products will soon be added.

3. Hyperspectral data analysis with HYDRA2

HYDRA2 is also used to analyze granules of hyperspectral CrIS data; the spectral selection is now indicated by wavenumber, a prevalent indicator in the infrared region of the spectrum which equals the number of wavelengths that fit into one centimeter. CrIS takes infrared measurements from 650 to 2550 cm^{-1} (15.4 to 3.9 μm) in 1305 spectral channels at spectral resolutions as high as 0.5 cm^{-1} .

Figure 6a shows the HYDRA2 display of CrIS data over the Pacific Ocean and parts of China, Korea, and the Philippines on 30 August 2012. The top panel displays two spectra measured by CrIS over a pixel in clear skies (marked by the turquoise cross and displayed as the turquoise spectra) and over a nearby pixel in high clouds (marked by the red cross and displayed by the white spectra); the spectral gaps in CrIS between 1087 to 1205 cm^{-1} (9.2 to 8.3 μm) and 1754 to 2174 cm^{-1} (5.7 to 4.6 μm) are bridged by HYDRA2 with a straight line. The clear sky spectrum shows those regions where the atmosphere has CO₂ absorption (between 650 and 750 cm^{-1} as well as between 2350 and 2450 cm^{-1}), H₂O absorption (between 1265 and 1625 cm^{-1}), and O₃ absorption (near 1050 cm^{-1}). Pacific Ocean brightness temperatures in the infrared window region (902.25 cm^{-1}) are near 292 K while the cloud top temperatures are about 236 K. The spectral brightness temperatures measured over the cloud are relatively constant as one would expect over an opaque blackbody-like cloud in the long wavelength region (the spectra is relatively flat between 650 and 1150 cm^{-1}). No significant moisture is evident above the cloud (indicated by the flatness in the water vapor sensitive region between 1265 and 1625 cm^{-1}). In contrast there is strong absorption by atmospheric water vapor over the surface of the Pacific Ocean (resulting in significantly colder brightness temperatures from 1300 to 1600 cm^{-1} since the sensor is seeing less deeply into the troposphere) and absorption by atmospheric ozone (seen in the colder temperatures near

1050 cm⁻¹). The reflected solar contribution over the cloud in the short wavelength region is evident by the temperature increase from 220 to 260 K (going from 2450 to 2550 cm⁻¹). However there is no significant solar contribution from the Black Sea pixel.

Figure 6b demonstrates the capability to zooming in on a portion of the spectra. As one nears the center of the ozone absorption region it is expected that the satellite is sensing less deeply into the atmosphere. As the cloud temperatures get warmer by about 10 K in going from the periphery of the ozone absorption band at 1020 cm⁻¹ to the center of the absorption band at 1055 cm⁻¹, it is suspected that the cloud top is likely in the stratosphere where temperatures get warmer with altitude (unlike the troposphere where they get colder with altitude).

Figure 7a zooms in to some clouds east of the Philippines and the spectra between 1380 and 1410 cm⁻¹. Figure 7b shows the result from the Band Math tool enabling investigation of spectral channels on and off water vapor absorption features; this illustrates how the spectral and spatial sensitivity of the CrIS measurements is readily explored with HYDRA2. Brightness temperature differences between 1387.5 cm⁻¹ (off the water vapor rotational absorption line hence sensing mostly the sea surface) minus 1390.0 cm⁻¹ (on the water vapor rotational absorption line hence sensing some of the lower tropospheric moisture) of more than 30 K (red regions) indicate very dry regions of the lower troposphere; dry regions (blue) with less than 1 K difference are evident over the opaque high clouds.

4. Microwave data analysis with HYDRA2

HYDRA2 is also used to analyze granules of microwave sounder ATMS data; the spectral selection is now indicated by frequency in GHz, the prevalent indicator in the microwave region of the spectrum (where 300 GHz equals a wavelength of 0.1 cm). ATMS is a cross-track scanner that combines all the channels of the preceding AMSU-A1, AMSU-A2, and AMSU-B sensors into a single package with considerable savings in mass, power, and volume. 22 spectral bands from 23.8 GHz through 183 GHz are included.

Figure 8a shows the display of ATMS data over the Pacific Ocean on 30 Aug 2012 coincident with the VIIRS and CrIS data shown earlier. In the top panel, the ATMS measured brightness temperatures as a function of spectral frequency are shown for measurements just off the coast of China (turquoise cross) and over the Pacific Ocean (white cross); the spectral variations are caused by absorption due to H₂O at 31 GHz and O₂ at 60 GHz and H₂O again at 183 GHz. In the bottom panel of Figure 8a, there is the image of the microwave window brightness temperatures measured at 23.8 GHz; the large field of view and the insensitivity to non-precipitating clouds is evident.

In Figure 8b, collocation of the data from two sensors is demonstrated. VIIRS and ATMS data are displayed for a west to east transect between South Korea and Japan. The difference in the measurements is readily apparent (VIIRS IR window seeing clouds and a blackbody like earth surface with high spatial resolution versus microwave window seeing through clouds at coarse spatial resolution to a grey body like earth surface with

considerable surface reflection of down welling atmospheric radiation). Colocation in space and time is readily displayed with HYDRA2 for the VIIRS, CrIS, and ATMS sensors on Suomi NPP as well as with MODIS and AIRS sensors on Terra and Aqua and the IASI sensors on MetOp.

5. Summary

As these few examples illustrate, HYDRA2 offers several tools to interrogate multispectral and hyperspectral remote sensing data quantitatively and to explore the correlations between radiance measurements and features in the images. Continued development over the next several years is planned in order to incorporate more multispectral and hyperspectral instrument systems into the HYDRA2 menu. In addition several improvements will be added including (1) improving the user interface, (2) adding the capability to animate sequences in time or wavenumber, (3) introducing a state saving device (ie. a persistence mechanism), (4) enhancing collaboration at remote sites through granule sharing, (5) enabling more high-spectral data analysis (ie principal component analyses), and (6) providing more interaction between scripting and the application.

The HYDRA2 project is an on-going development effort. Planned future developments include features that will enable remote multiple site viewing of and interaction with the same data set; this will enhance use at the Direct Broadcast sites and collaborations at remote sites.

More information and the freeware may be found at: <http://www.ssec.wisc.edu/hydra2/>.

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Appendix 1. Getting and Setting Up HYDRA2

HYDRA2 is freely distributed from this public website:

<http://cimss.ssec.wisc.edu/cspp/>

For Windows Operating Systems (OS) (XP, VISTA 7 and 8) download the ‘exe’ file for latest version using binary ftp mode, and then run it by double-clicking the file icon. The installer will ask where you wish to install the program. Accept the default, C:\Program Files\HYDRA2. Start the program by selecting Start | All Programs | HYDRA2 | runHYDRA. A window named “HYDRA” will appear (Figure A1); it will indicate the version you are using. A window named “runHYDRA” will also appear (this window may be minimized, but do not close it).

For Mac OSX use the ‘dmg’ installer and simply double-click to install into the /Applications folder. To start HYDRA2, double-click the icon in that folder. The icon can also be dragged to the applications docking station after which a single click of the icon will start the application.

For the Linux OS (64bit), the ‘sh’ installer will extract into the directory of choice, or use

the 'tar.gz' and install by entering "gzip -cd hydra_v1.5_linux.tar.gz| tar xvf -" at a command prompt. This will create a sub-directory named "hydra" into which everything required to run will be installed. To run HYDRA, first change directory into the 'hydra' directory, and enter "./runHydra" at the command prompt.

The HYDRA window enables you to load new files and to select regions within the current file. HYDRA is designed to read MODIS Level-1B 1KM files in HDF4 format. Files obtained from the NASA DAAC, or those produced locally by a direct broadcast ground station (including IMAPP), can also be used.

Appendix 2. Summary of HYDRA 3.0 Commands

In all windows

Shift-right click-drag to zoom in image within display

Right click-drag to move image or roam within display

In HYDRA window (see Figure A1)

Under File, select the VIIRS directory (a VIIRS folder) or File(s) (MOD02 or MYD02 for MODIS, AIRS for AIRS, SCRIS for CrIS, SATMS for ATMS) that is to be studied. (1) For VIIRS and MODIS, file selection will result in a listing of spectral bands available, an image of the IR window with coastlines, and a default subset of the granule that will be displayed in a new window upon clicking on display. The subset of the image can be adjusted with a right click and drag. The spectral band can be changed with a left click on another choice. (2) For CrIS, AIRS, and ATMS, a new window opens showing the spectral band brightness temperatures and a spectral window image showing the data coverage. Left click a drag on the green line in the top display to change the spectral band displayed below.

Left click on spectral band desired (default is IR window)

Left click-drag to highlight subset of image for display

Left click on Display at bottom to create a new image in window #1. Once Window#1 is established you can choose to replace the image in Window#1, to overlay a another image in Window#1, or to open a new Window#2 by using the arrows next to the Display command.

Tools/RGB Composite will open new a box where you have to select the R, G, and B spectral bands desired by left clicking on the color and then on the spectral band. When all three have been selected, left click on Create in the RGB Composite window to establish the RGB image. Left click on Display in the main HYDRA window to open a new window wherein the RGB image is displayed.

Tools/Band Math will open a new display where you have to select two, three, or four

spectral bands that you wish to combine with + , - , x , or / operations. Spectral bands are selected by left clicking on the spectral band and then the appropriate box in the Band Math equation. After selecting the desired Band Math click on create and the pseudo image dataset will appear under Combinations in the main HYDRA window. Click on Display to see the Band Math result in a new Window.

In Window and Band Math Display (see Figure A2)

Left click-drag to move cursor within display

Left click on bottom left icon (house) to restore original display

Left click on bottom box (indicating band number) to open range, gamma, reset, and B&W vs color options (see Figure A3)

Range can manually set BTmin (rmin) and BTmax (rmax). Range entries can be typed in to enhance low or high reflectances or BTs or they can be set by right click and sliding the top of the green bars in the reflectance/BT histogram. For the VIIRS DNB try very small values for your initial min to max range

Gamma can be adjusted to stretch the dynamic range. It is a non-linear mapping from color to value. For infrared, $color_value = BT^{**}gamma$. For visible, when $gamma = 0.5$, this is the square root enhancement popular with VIS.

Reset restores the dynamic range to the min and max values in the display.

Color options include inverse gray (BTmax is black, BTmin is white), gray, rainbow (BTmax is red, BTmin is blue), and inverse rainbow. Contrast from white to black (or blue to red) can be adjusted in the range.

When overlays exist in a window, display can be moved from one overlay to another by clicking on the arrow at bottom of window. The check next to the band (or Band Math) identifier controls whether that image is contained in the loop controlled by the arrow at the bottom of the window. An overlay can be removed by clicking on the red circle to the right of the band identifier. (see Figure A4)

When two displays are open, toggle on link button in lower left to link zoom and roam in two displays (default is to have the windows linked)

After engaging Tools/Transect, one can left click-drag to change end point of the transect. Note that Transect can be opened in several windows simultaneously. (see Figure A5)

To engage Tools/Scatter, left click on Tools/Scatter in a first window to establish the x-axis and then left click on Tools/Scatter in a second window to establish the y-axis of scatter plot. The scatter plot will appear in a separate display. Two windows are necessary; Scatter is not properly initiated when using the overlay from one window alone.

In Scatter Display (see Figure A6)

Selecting purple, green, and blue points (with box or curve) in the scatter window will show the associated pixels in the two image windows; conversely selecting pixels in either image window will show the associated points in the scatter window.

Left click on the points box (bottom of scatter window) to create density scatter plot; toggle back and forth between points and density

Left click on stats to see stats for purple, green, and blue selections.

In AIRS, CrIS, or ATMS SDR (Sensor Data Record) Display

Select the file(s) to be displayed (AIRS for AIRS, SCRIS for CrIS, SATMS for ATMS)

Move the green line in the spectrum (left click drag) to change the spectral band displayed below.

When viewing the AIRS/CrIS/ATMS spectrum, zoom using shift- left click–drag. Restore to full spectrum using control-left click.

When viewing AIRS/CrIS/ATMS spectral band image left click drag to move cursor within image (note if VIIRS data over same area is open then cursor will move in both VIIRS and CrIS/ATMS images; same for AIRS and MODIS)

Click on Tools to have the option for Transect, Scatter, and FourChannelCombine. In FourChannelCombine the colored lines have to be moved (left click drag) to the desired wavenumber (GHz). Expanding beyond two spectral bands is initiated by completing the mathematical operator desired in the FourChannelCombine equation.

When viewing AIRS or CrIS profile retrievals (temperature, water vapor, and ozone can be found under the parameter), transect and scatter (under Tools) can be used in the same way as before.

In the AIRS or CrIS Retrvl Display left click and drag on the green line in the vertical profile to change the altitude of the parameter being displayed.

The red cursor in the CrIS Retrvl Display will move in synch with the red cursor in CrIS or VIIRS or ATMS spectral band displays; the blue cursor moves independent of any cursor in the other images.

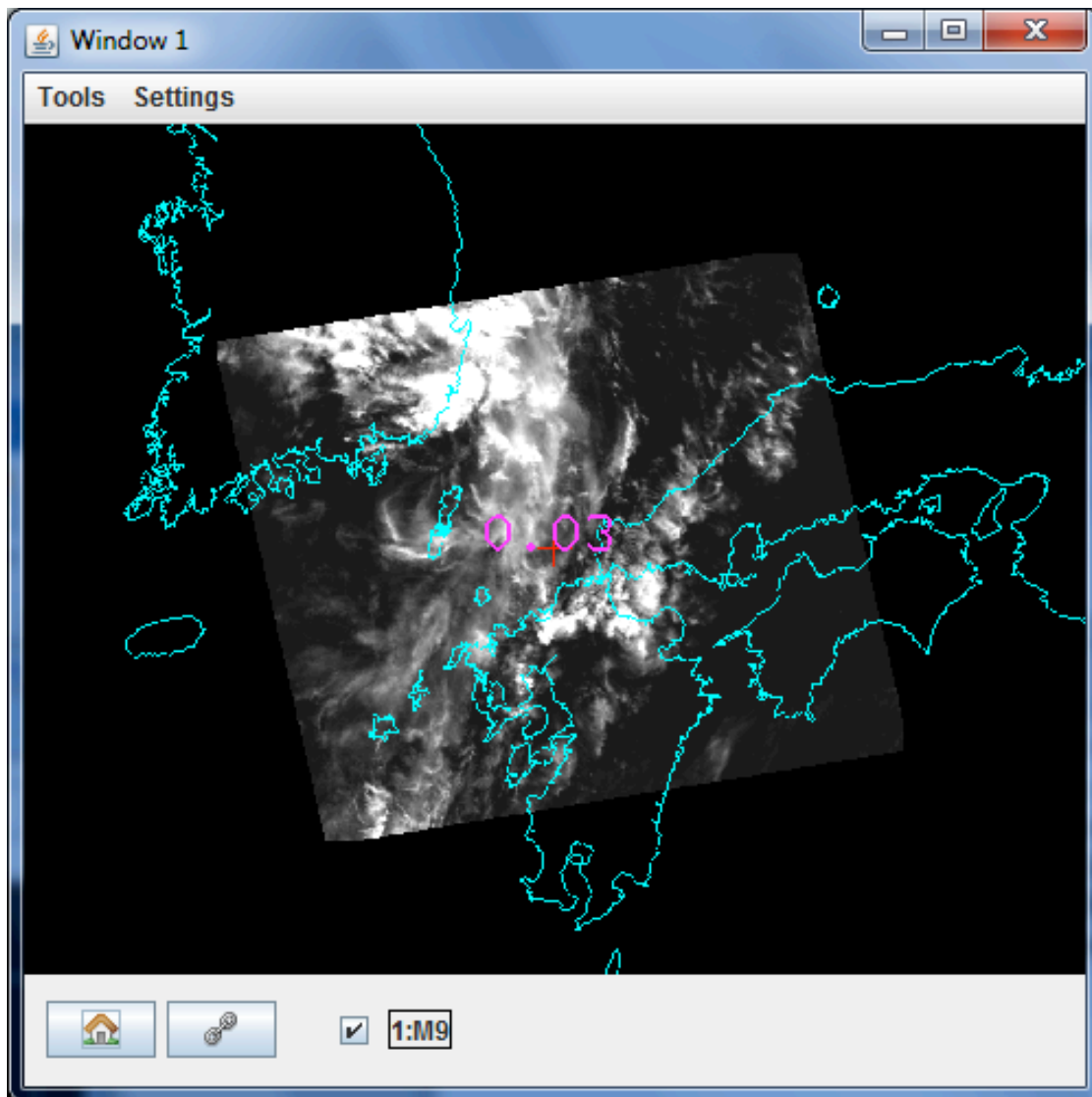


Figure 1a: VIIRS granule of 1.38 μm reflectance measurements from 30 August 2012 over southern Korea and Japan 422 UTC.

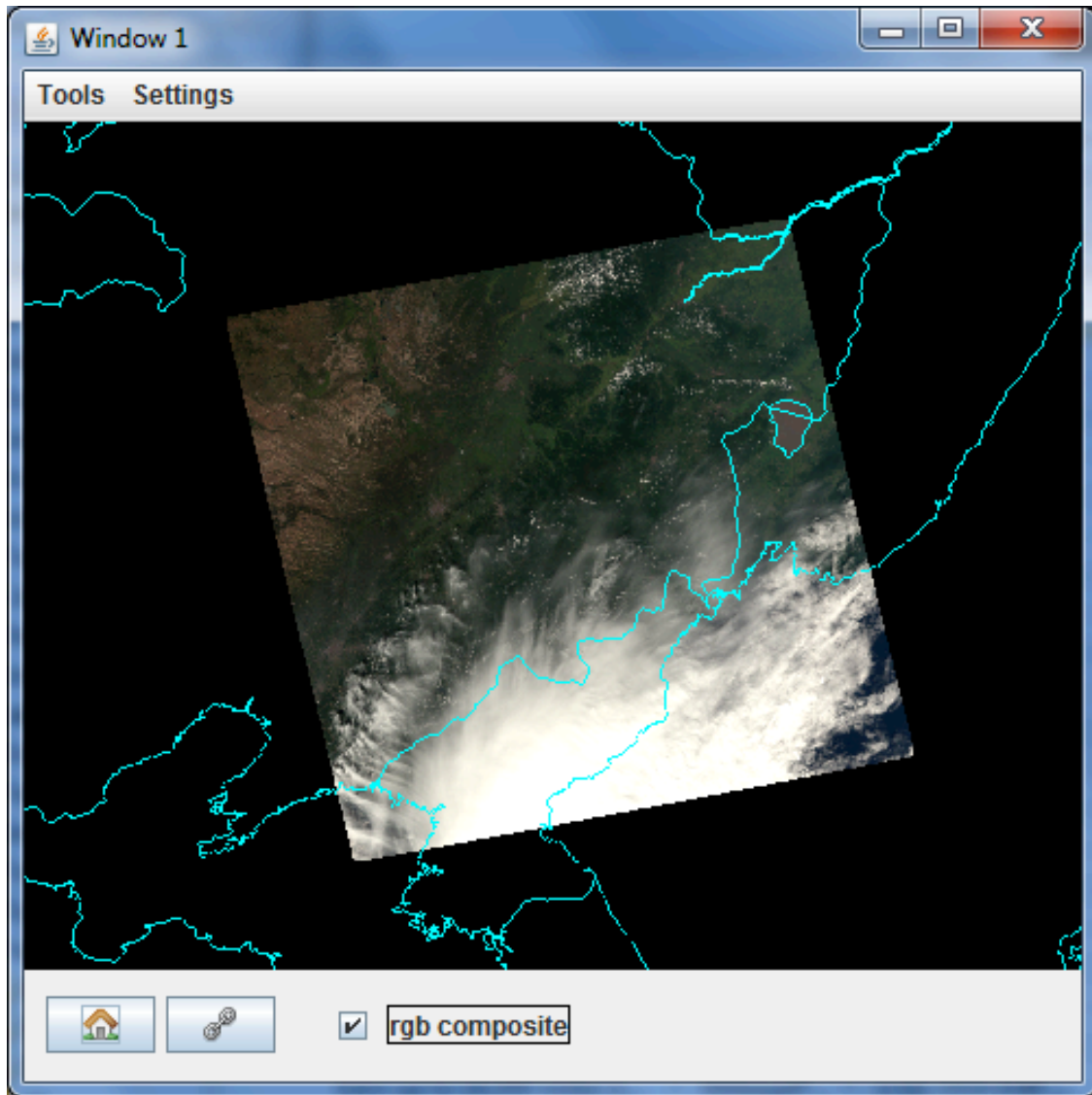


Figure 1b: A pseudo RGB image composed using “RGB Composite” under Tools. Red is VIIRS M15 (10.8 μm), green is M12 (3.7 μm), and blue is M1 (0.41 μm).

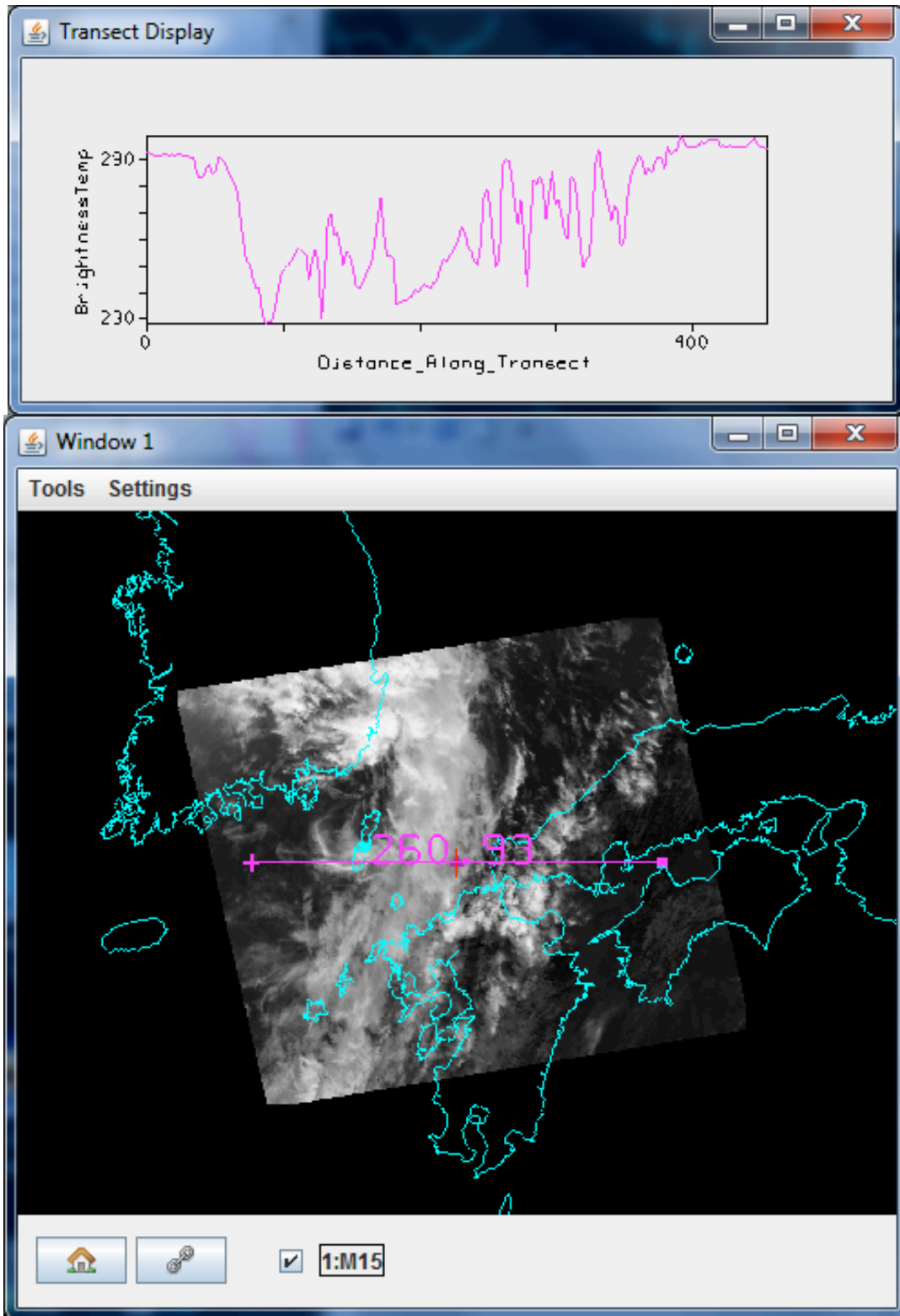


Figure 1c: Infrared window brightness temperatures (top) for the indicated transect in the 10.8 μm M15 image (bottom) proceeding from west to east. Clouds at 230 K and ocean surface at 290 K are evident.

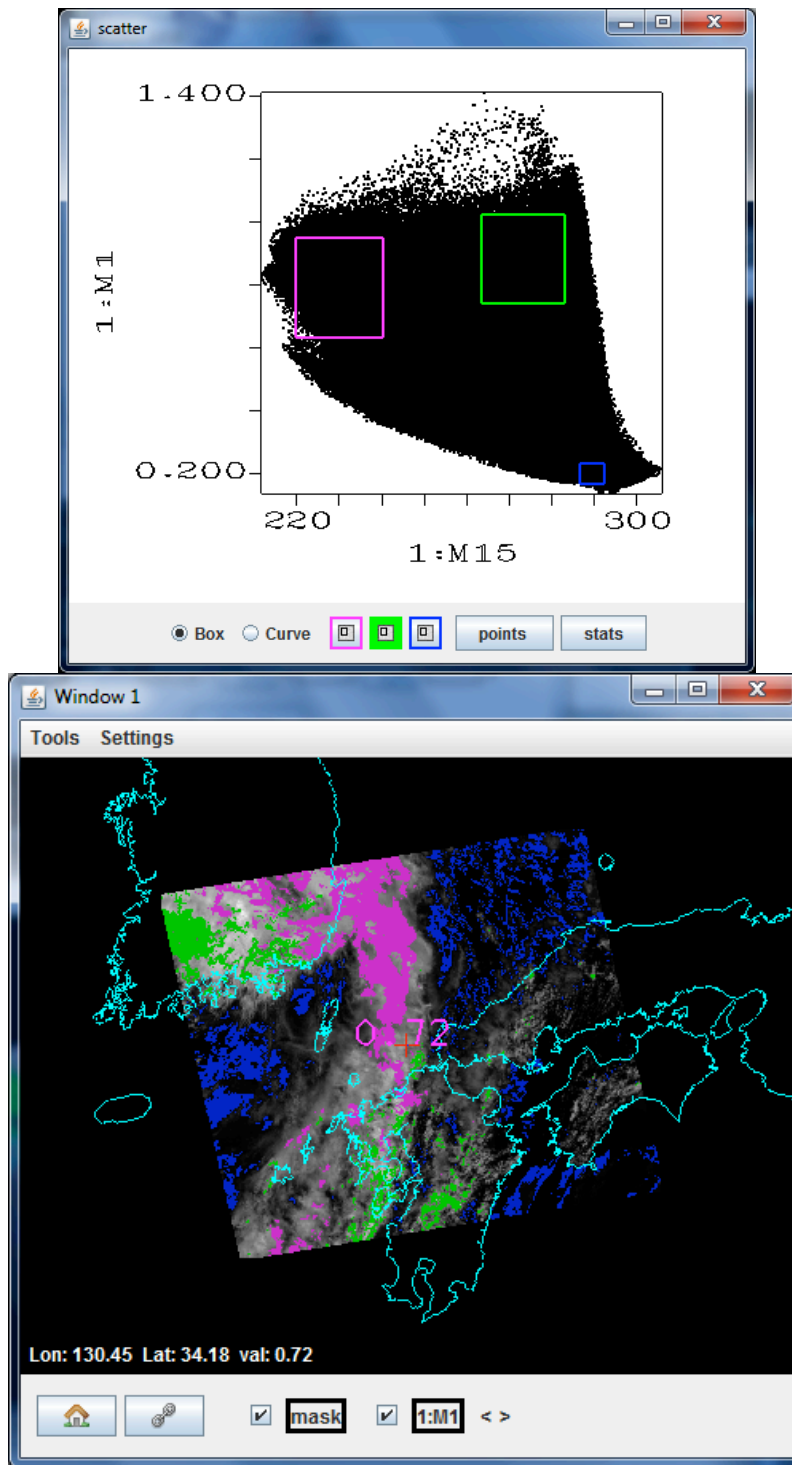


Figure 2: (top) Scatter plot of visible $0.41 \mu\text{m}$ reflectances (y-axis) against infrared window $10.8 \mu\text{m}$ brightness temperatures (x-axis). Pixels in the scatter plot are highlighted in different colors and their locations are marked in the visible $0.41 \mu\text{m}$ reflectance image (bottom). Purple highlights cold and reflecting, green warm and reflecting, and blue warm and non-reflecting. The color mask can be clicked on and off with the check mark.

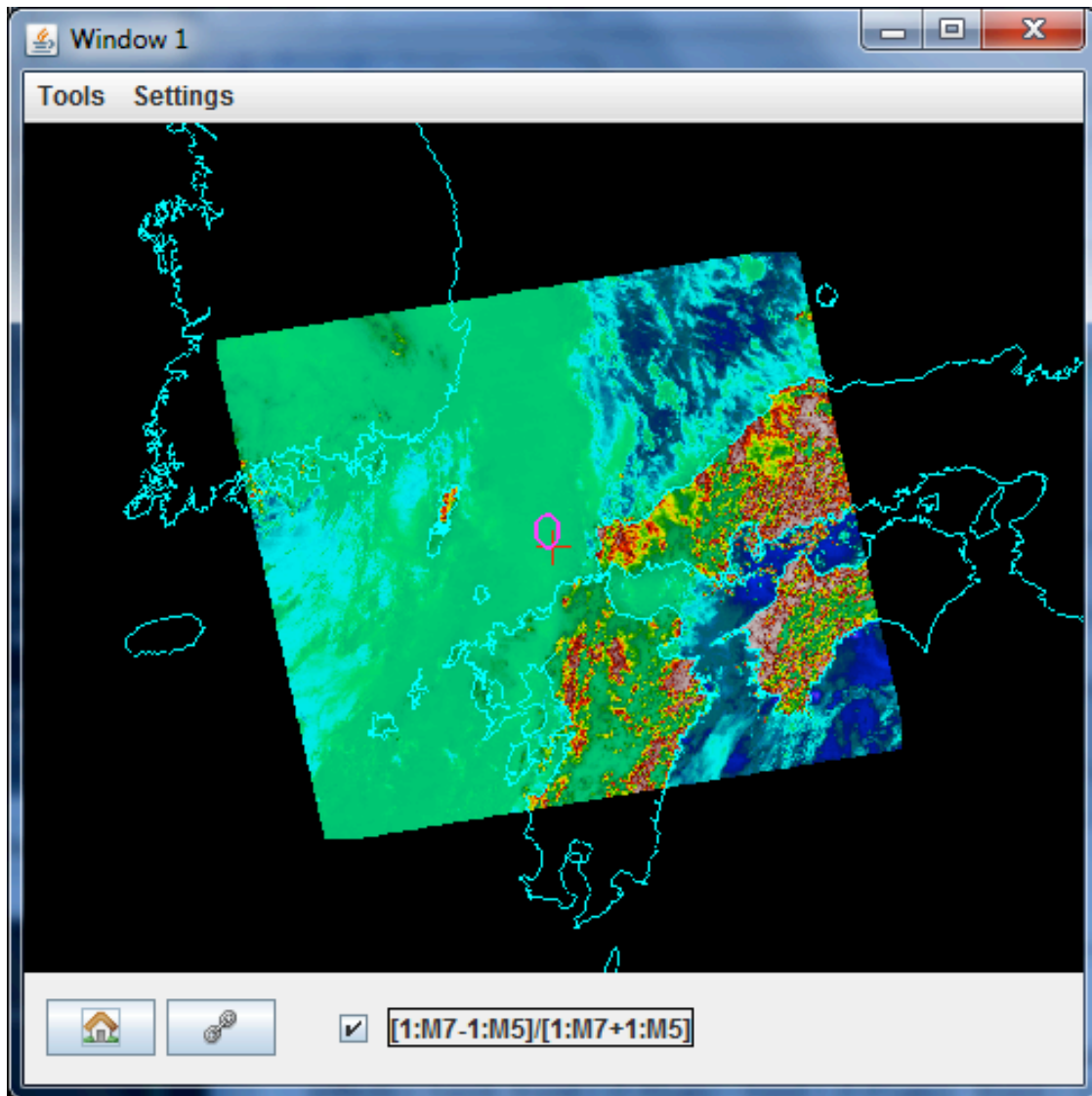


Figure 3: A pseudo image of normalized vegetation index constructed with VIIRS reflective bands [band M7 (0.87 μm) – band M5 (0.67 μm)] / [band M7 (0.87 μm) + band M5 (0.67 μm)]. Clouds obscure the land mass of South Korea but the vegetation (red areas) in Japan under clear skies is evident.

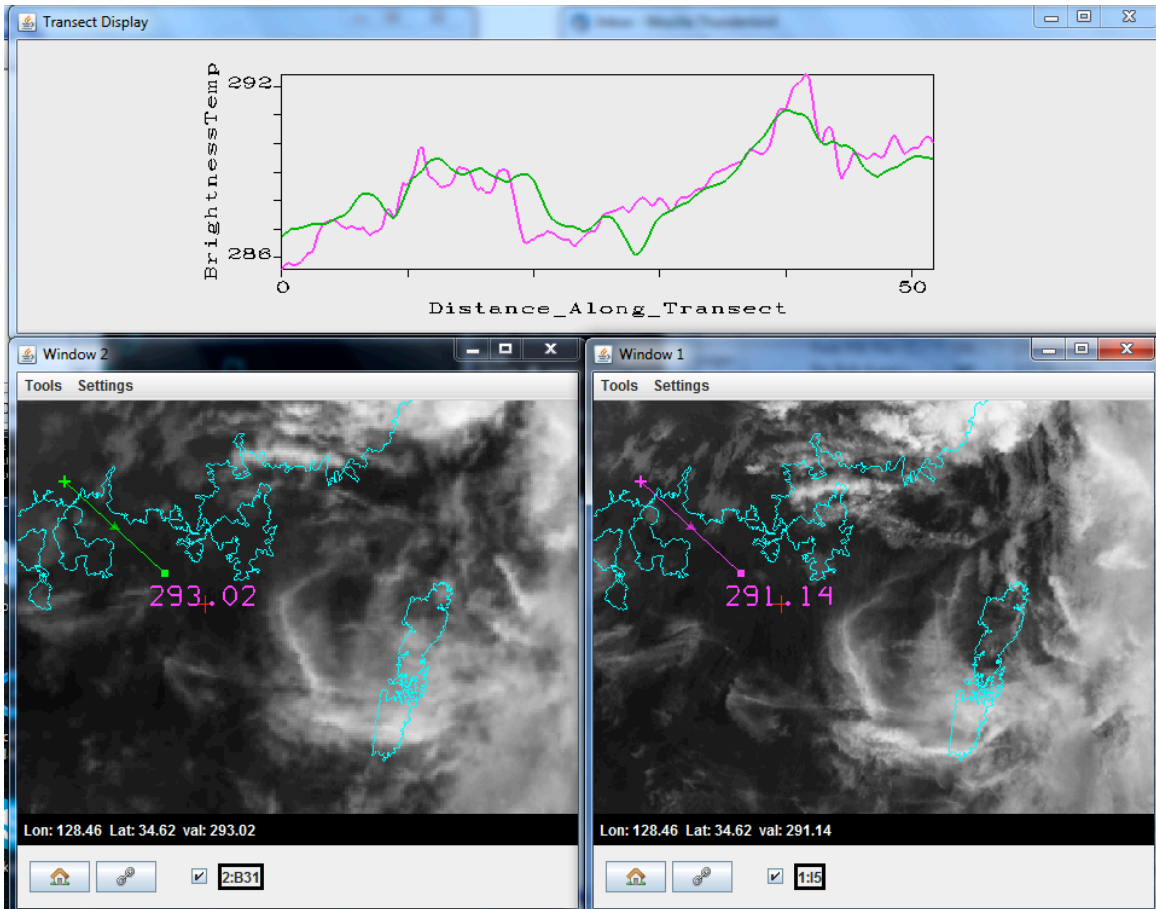


Figure 4: Comparison of 30 August 2012 VIIRS infrared window I5 at 380 m resolution (bottom right) from 422 UTC and corresponding MODIS IRW Band 31 at 1 km resolution from 440 UTC (bottom left) along with a transect over clear skies (top). The higher spatial resolution of the VIIRS reveals more details over land and water across the coastline.

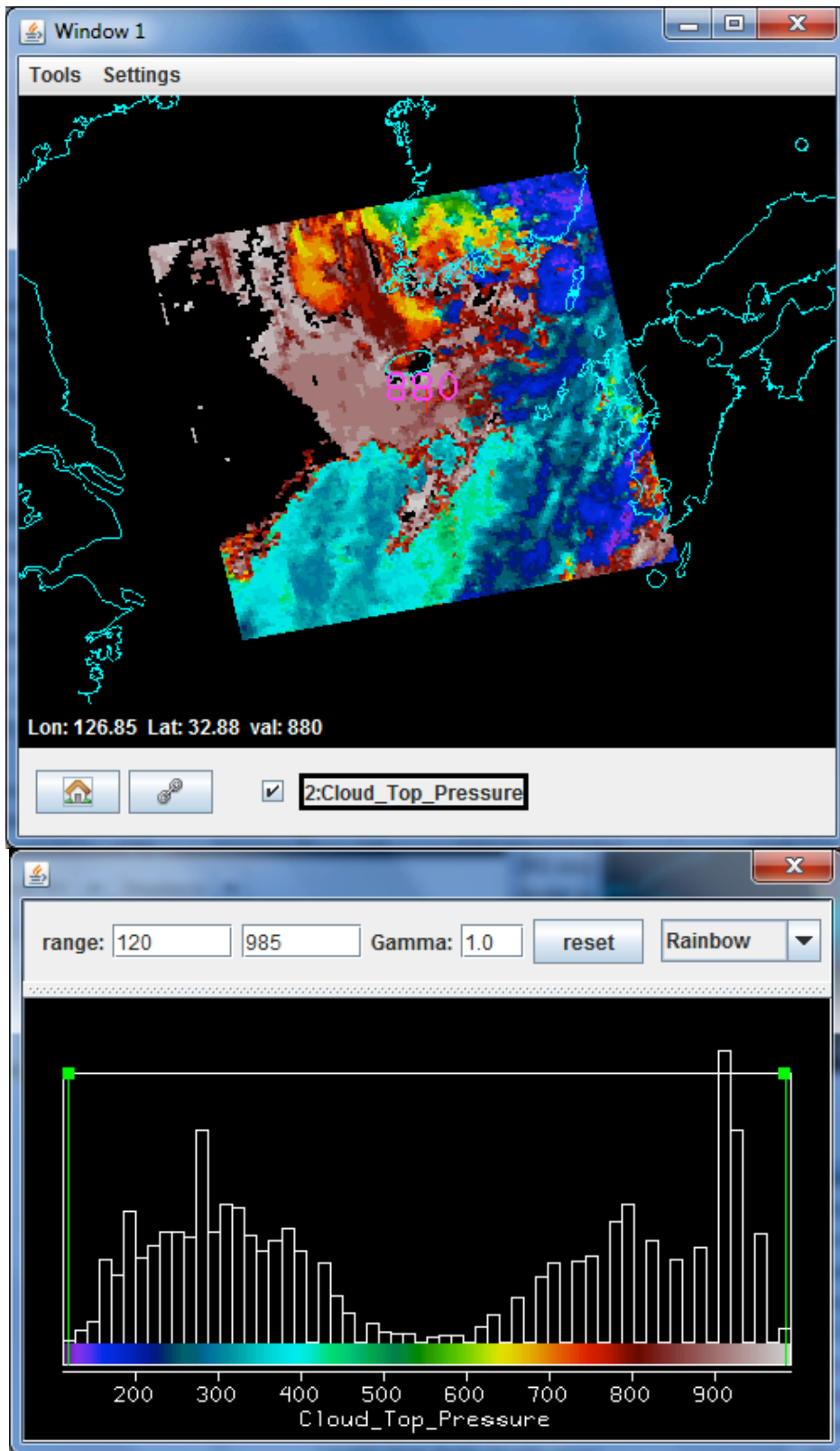


Figure 5: Derived product display of MYD06 cloud top pressures in hPa.

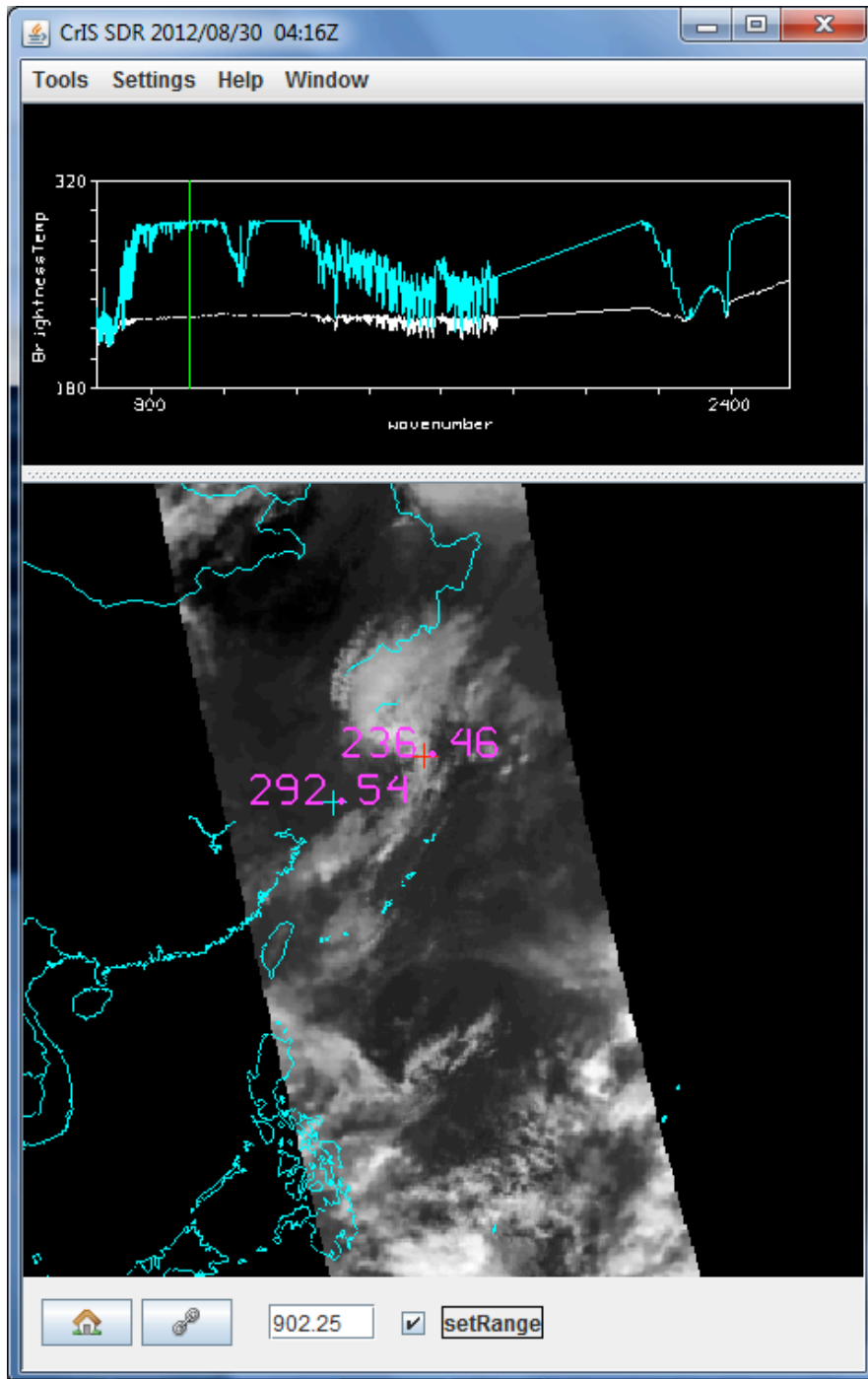


Figure 6a: HYDRA2 display of CrIS data over Asia-Oceania on 30 August 2012 showing spectra (top) and long wave (902 cm⁻¹) infrared window image (bottom). Brightness temperature spectra from 650 to 2550 cm⁻¹ are measured by CrIS over the pixel in the Sea of Japan (marked by the turquoise cross and shown in the turquoise spectra) and over the nearby pixel in the high clouds (marked by the red cross and shown in the white spectra). Straight lines in the spectra cover the spectral gaps in the CrIS measurements. Sea of Japan brightness temperatures in the infrared window regions are near 290 K while the cloud top temperatures are about 225 K.

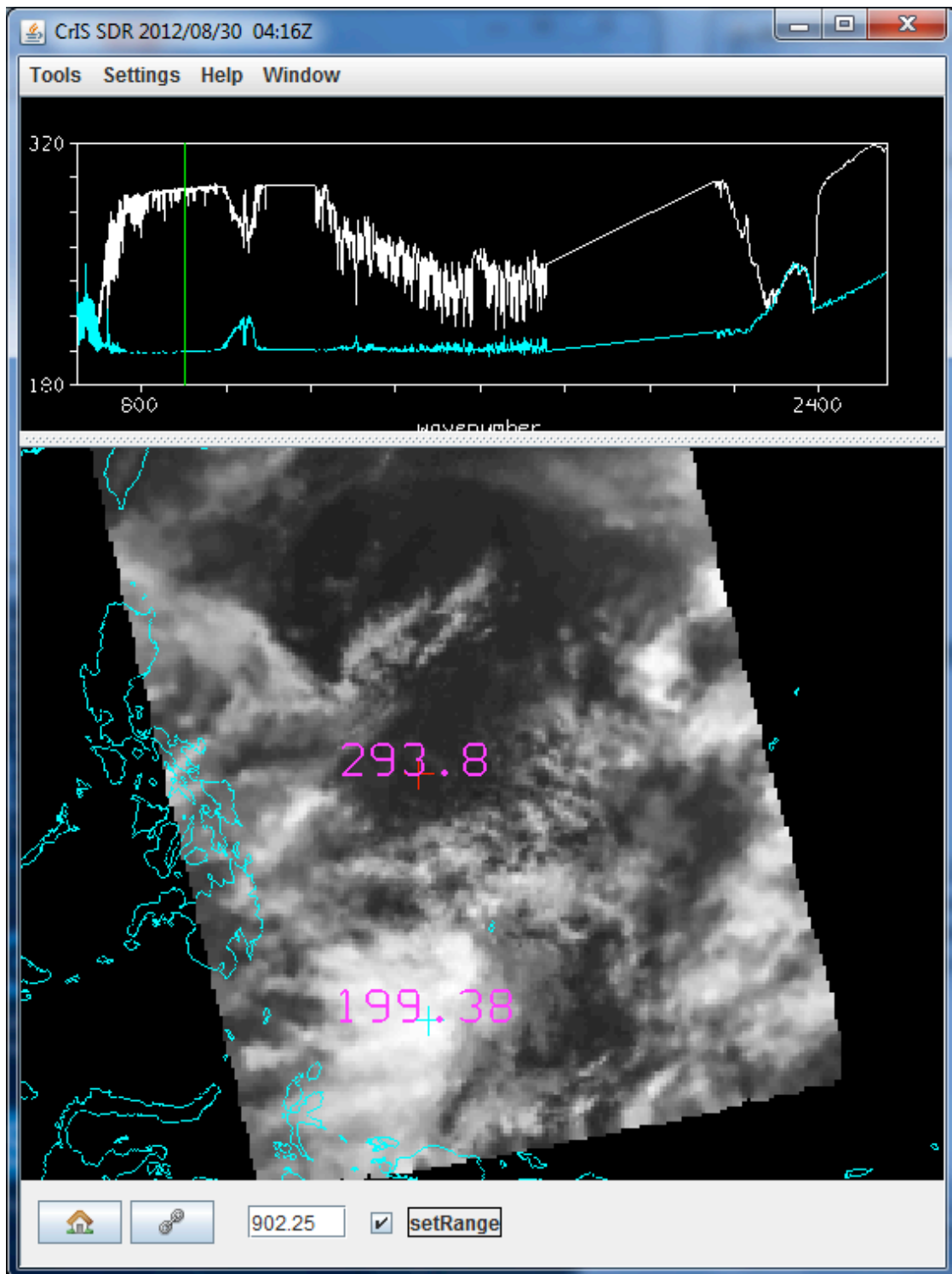


Figure 6b: Zoom in on the tropical clouds east of the Philippines. Note the spectra in the ozone absorption region near 1050 cm^{-1} observed over the cloudy pixel (marked by the turquoise dot). Cloud temperatures get warmer by about 10 K in the spectral region that is more opaque to ozone indicating that the cloud top is likely in the stratosphere.

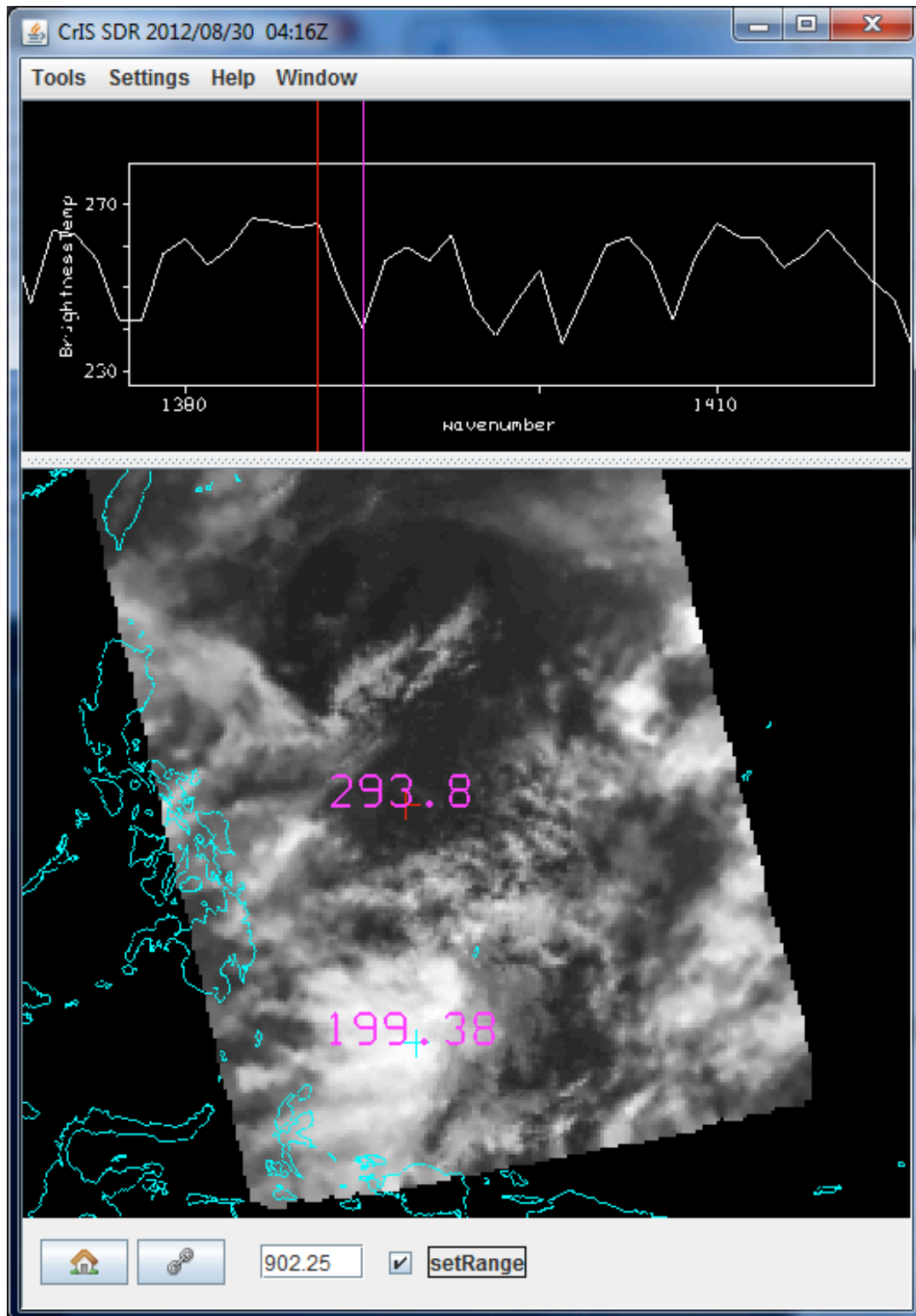


Figure 7a: (top) CrIS measured spectrum between 1380 and 1410 east of the Philippines (marked by red cross) and (bottom) the infrared window image from 909.25 cm⁻¹ showing locations of warmest and coldest brightness temperatures.

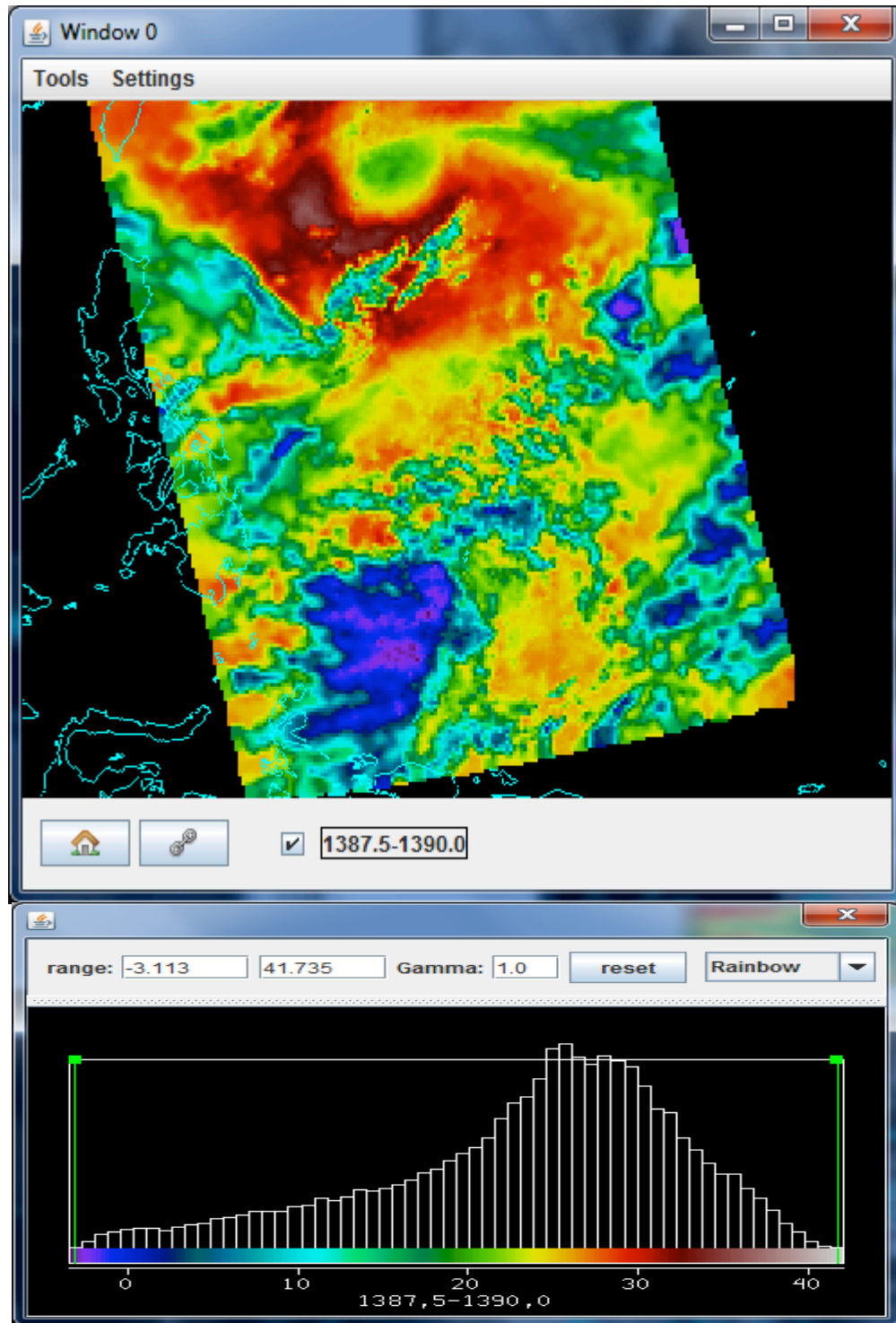


Figure 7b: (top) Band Math display of brightness temperature differences between 1387.5 cm⁻¹ (off the water vapor rotational absorption line) minus 1390.0 cm⁻¹ (on the water vapor rotational absorption line). (bottom) Color bar indicating the associated brightness temperature differences. Differences of 30 K (red) are seen in clear regions and differences less than 1 K (blue) in opaque high cloudy regions, indicating the spectral and spatial sensitivity of the CrIS measurements.

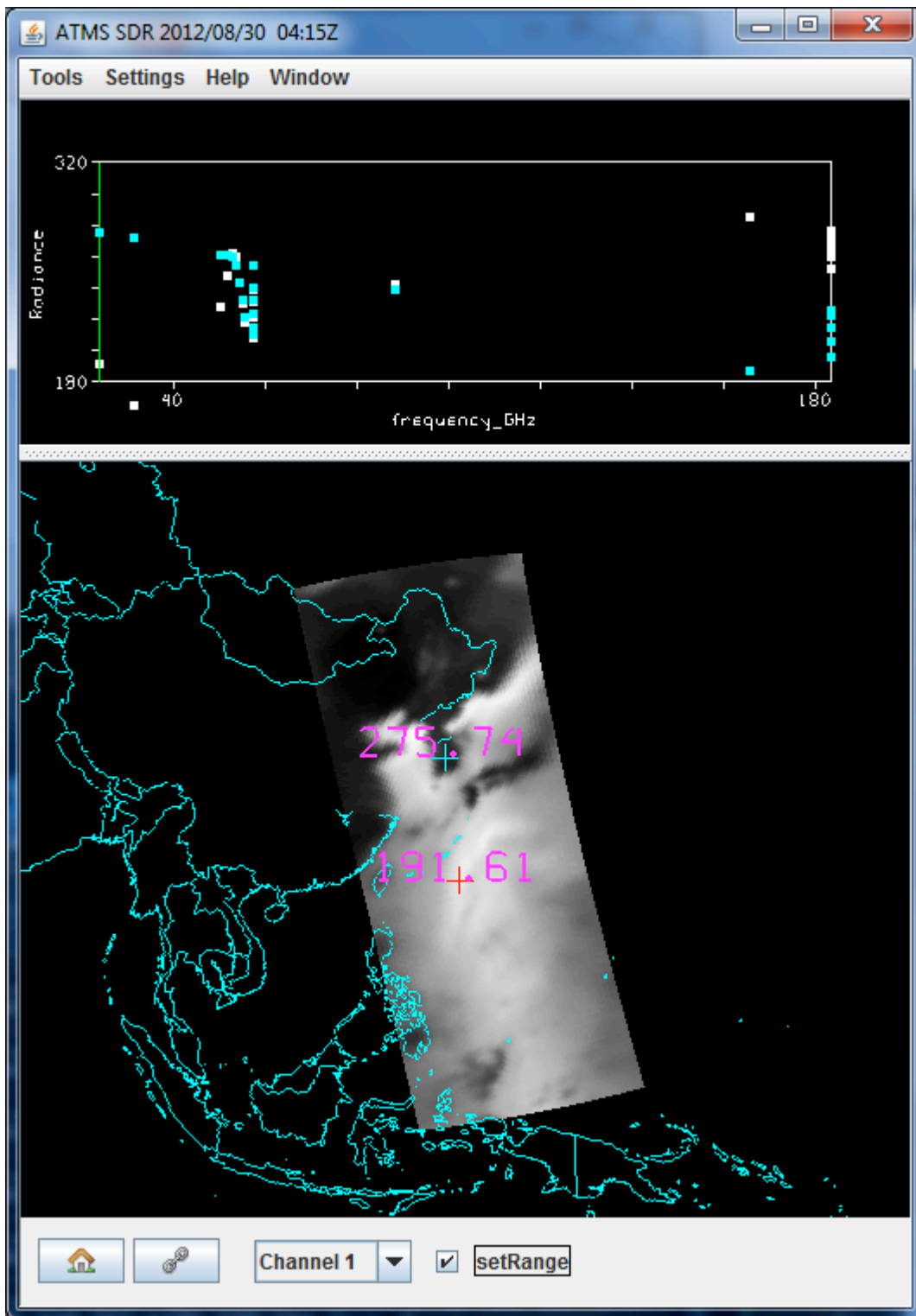


Figure 8a: (Top) ATMS measured spectra from 23.8 to 183 GHz just off the coast of China (turquoise cross) and over the Pacific Ocean (white cross). (Bottom) Brightness temperatures measured in the microwave window at 23.8 GHz.

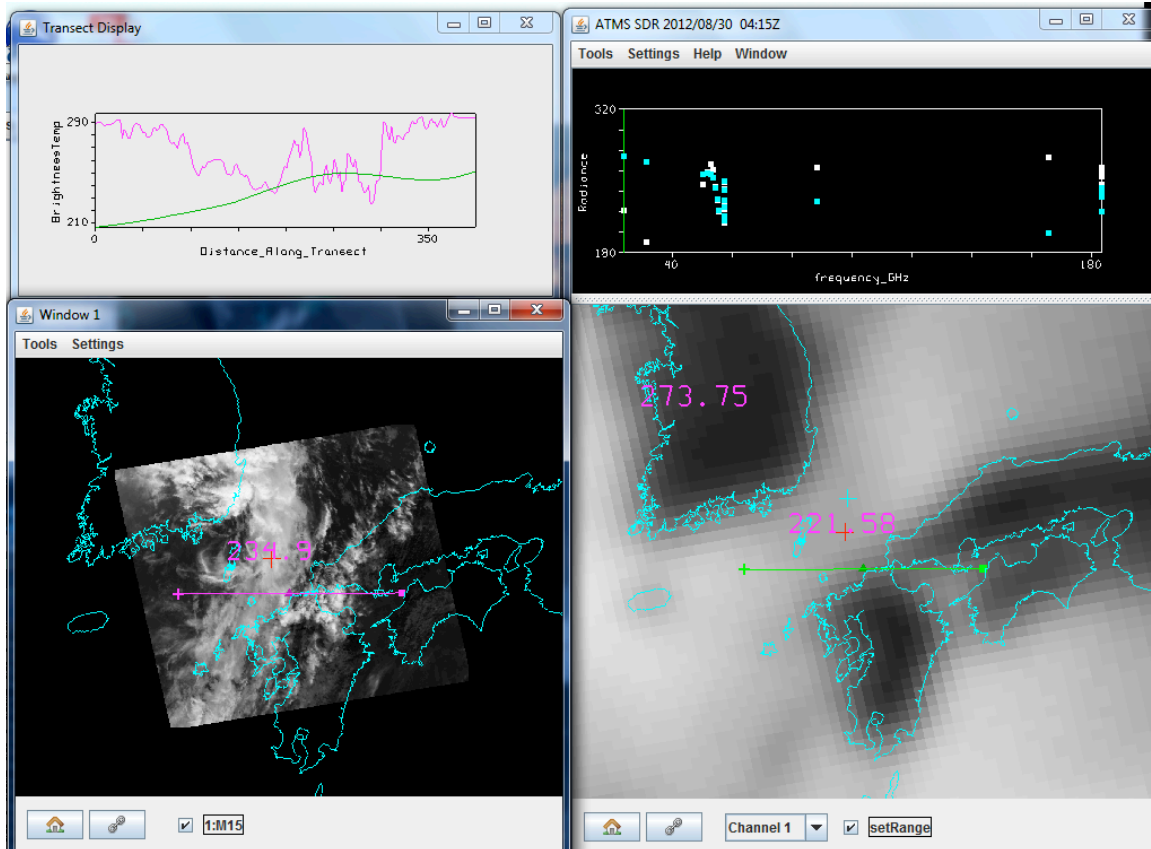


Figure 8b: (Top left) Transect display comparing VIIRS IR window with ATMS microwave window brightness temperatures. (Top right) ATMS measured spectra from 23.8 to 183 GHz for two cursor locations. (Bottom left) VIIRS brightness temperatures measured in the infrared window at 10.8 μm (M15) with the transect location superimposed. (Bottom right) Co-located ATMS brightness temperatures measured in the microwave window at 23.8 GHz with the transect location superimposed.

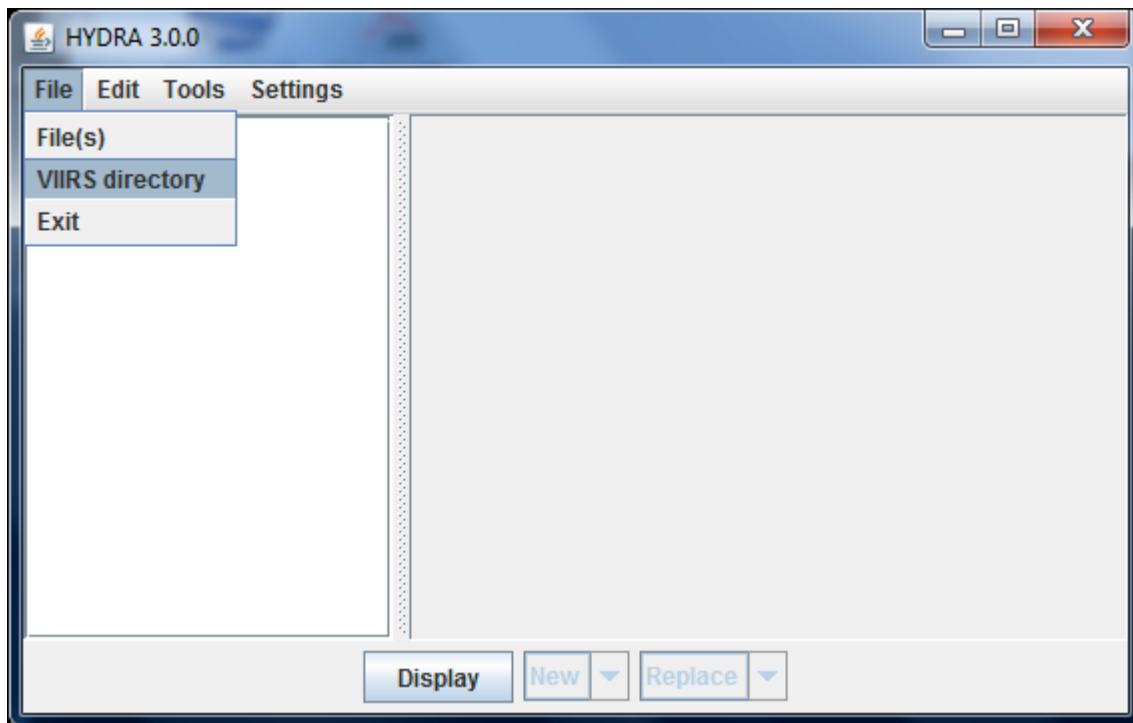


Figure A1: The HYDRA window before data set selection.

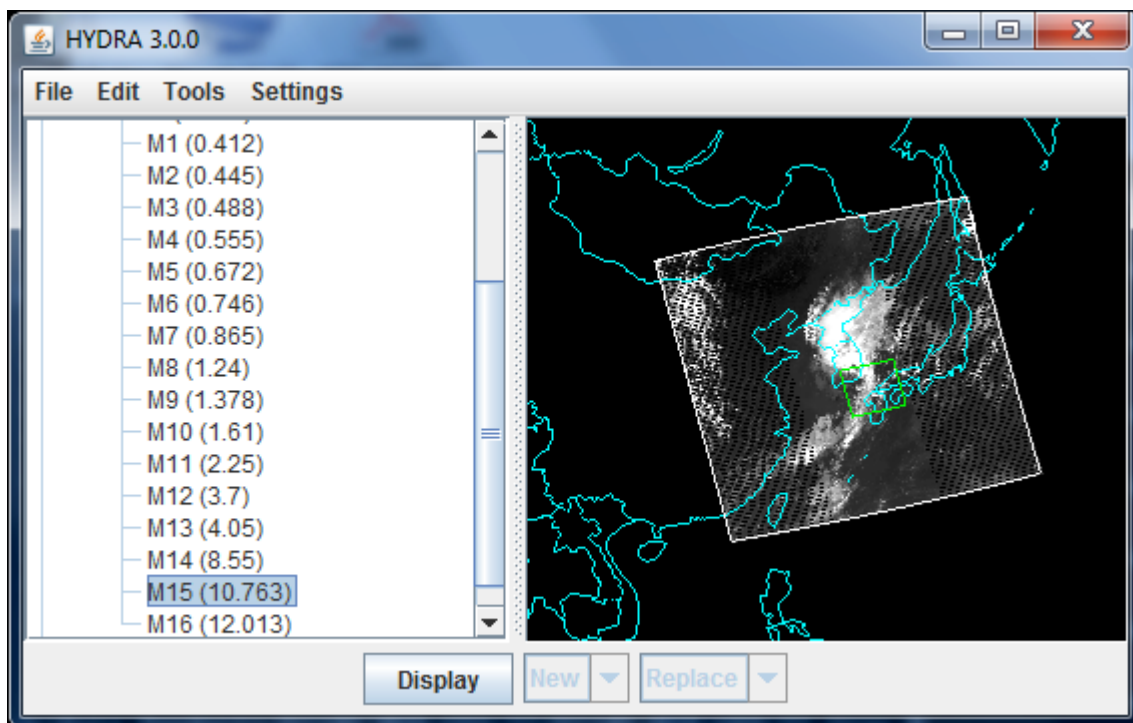


Figure A2: HYDRA window after selection of VIIRS data from 422 UTC on 30 August 2012 over Korea.

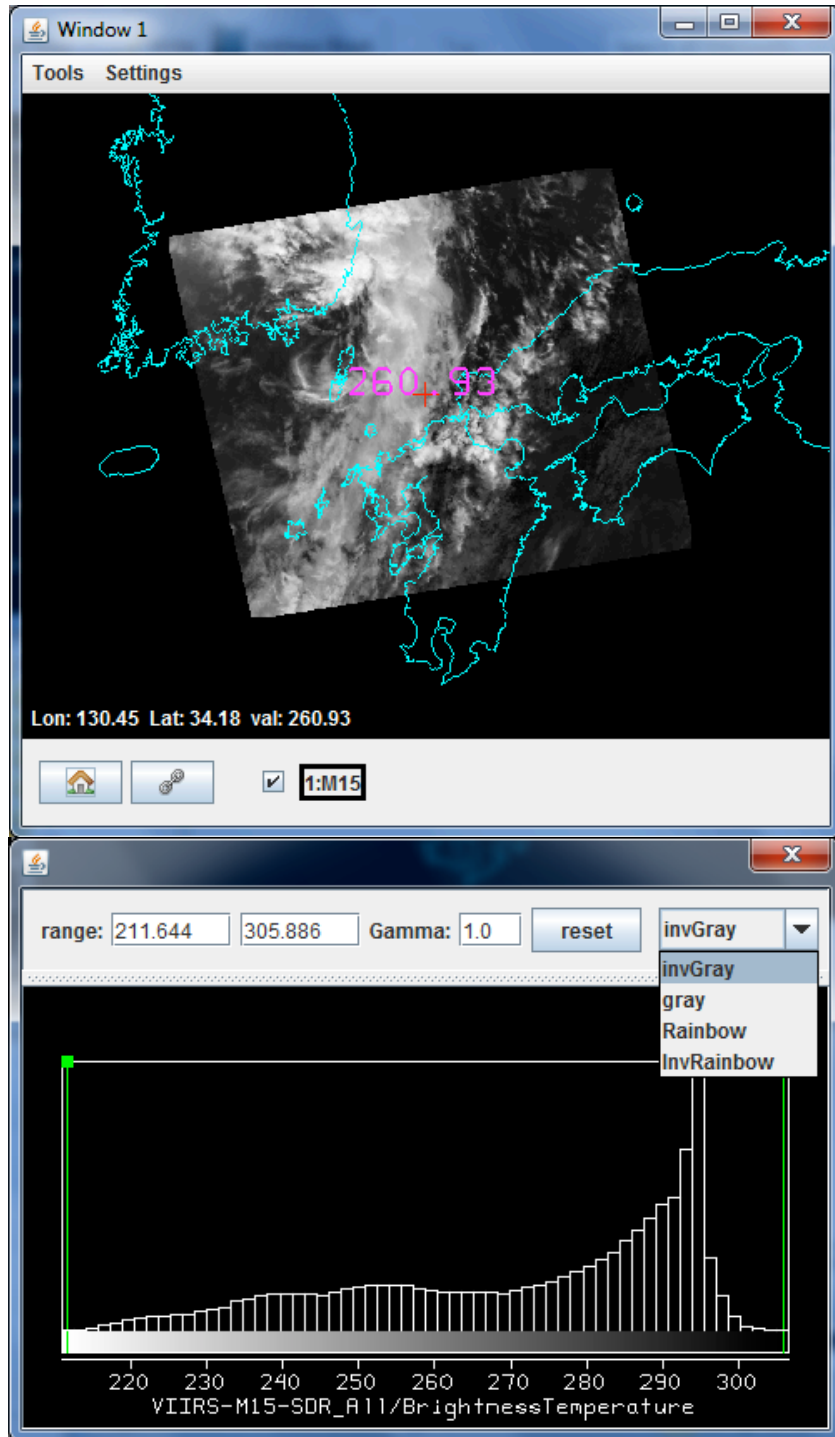


Figure A3: Image enhancement options opened by clicking on the box at the bottom of the window indicating the spectral band. Range entries can be typed in to enhance low or high reflectances or BTs or they can be set by right click drag on the top of the green bars in the reflectance/BT histogram. Reset restores the dynamic range to the min and max values in the display. Color options include inverse gray (BTmax is black, BTmin is white), gray, rainbow (BTmax is red, BTmin is blue), and inverse rainbow.

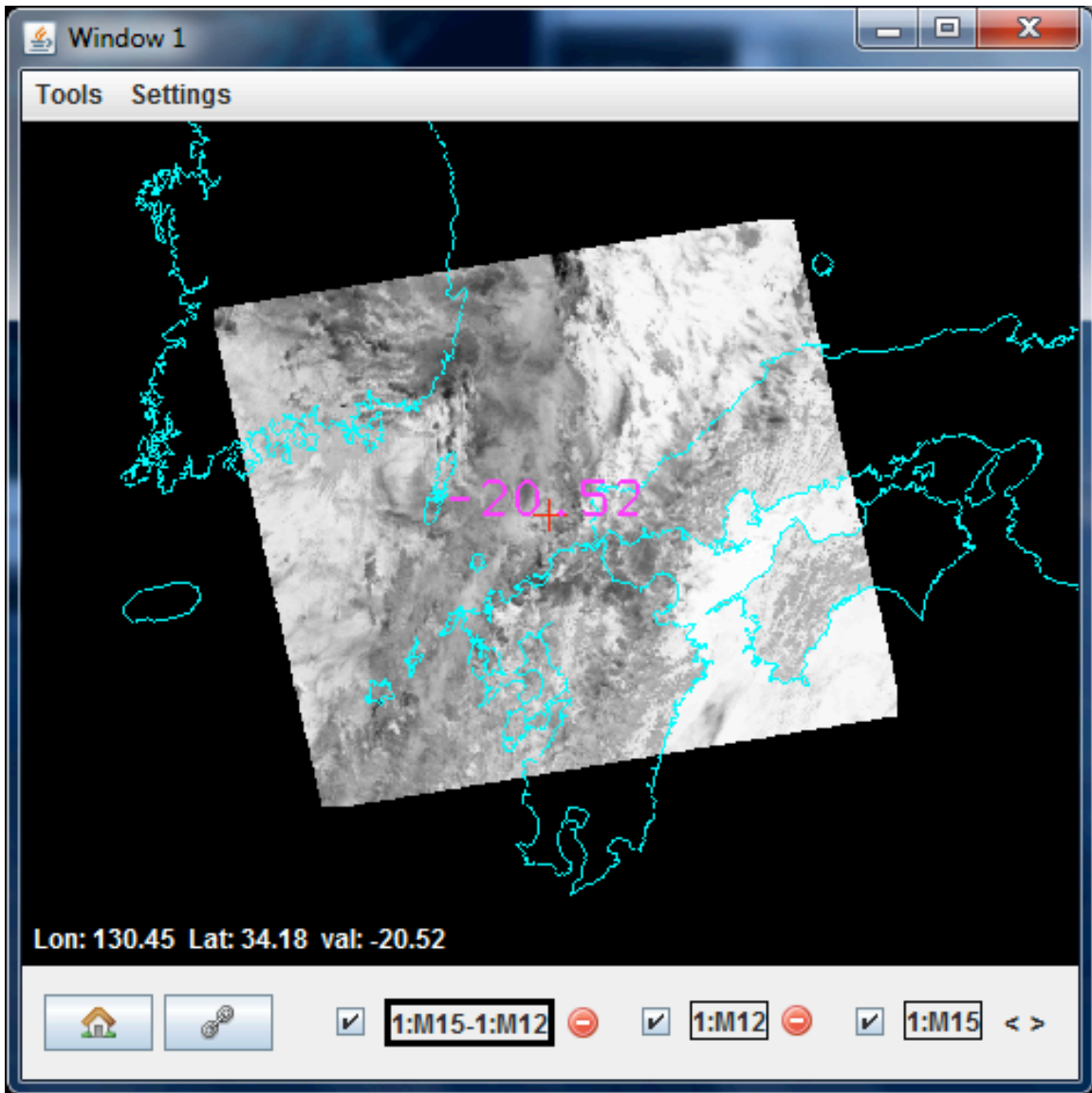


Figure A4: Window with overlay of three VIIRS brightness temperature images (BT(M15) at 10.8 μm minus BT(M12) at 3.7 μm , BT(M12) at 3.7 μm , and BT(M15) at 10.8 μm). The bold outline indicates which of the overlays is on display. When overlays exist in a window, the display can be moved from one overlay to another by clicking on the arrow at bottom right of the window. The check next to the band (or Band Math) identifier controls whether that image is contained in the loop controlled by the arrow at the bottom of the window. An overlay can be removed from the window by clicking on the red circle to the right of the band identifier.

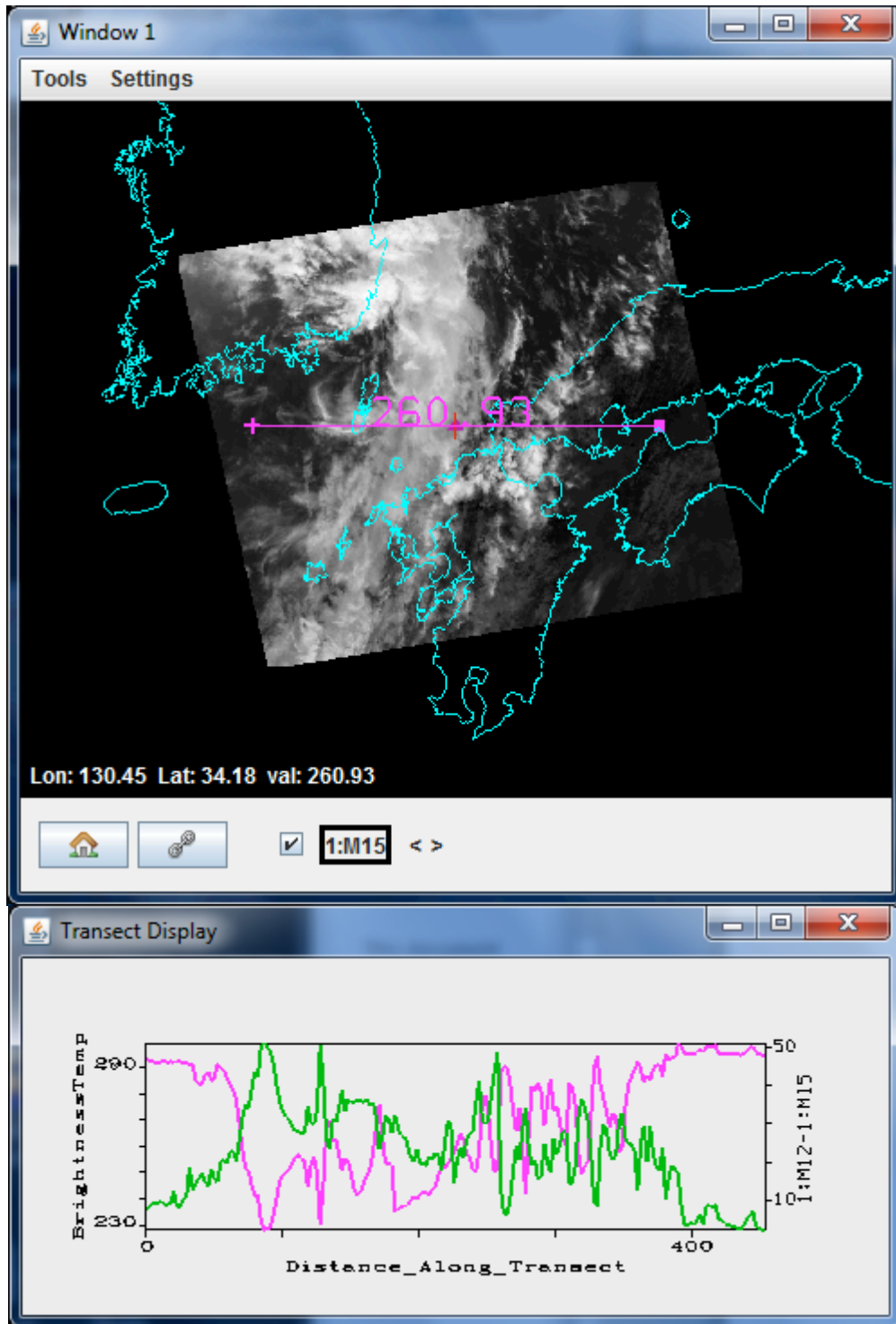


Figure A5: Transect Display of BT(M15) shown in the purple plot and [BT(M12)-BT(M15)] shown in the green plot for M12 at 3.7 μm and M15 at 10.8 μm . The reflected solar contributions often make BT(M12) greater than BT(M15).

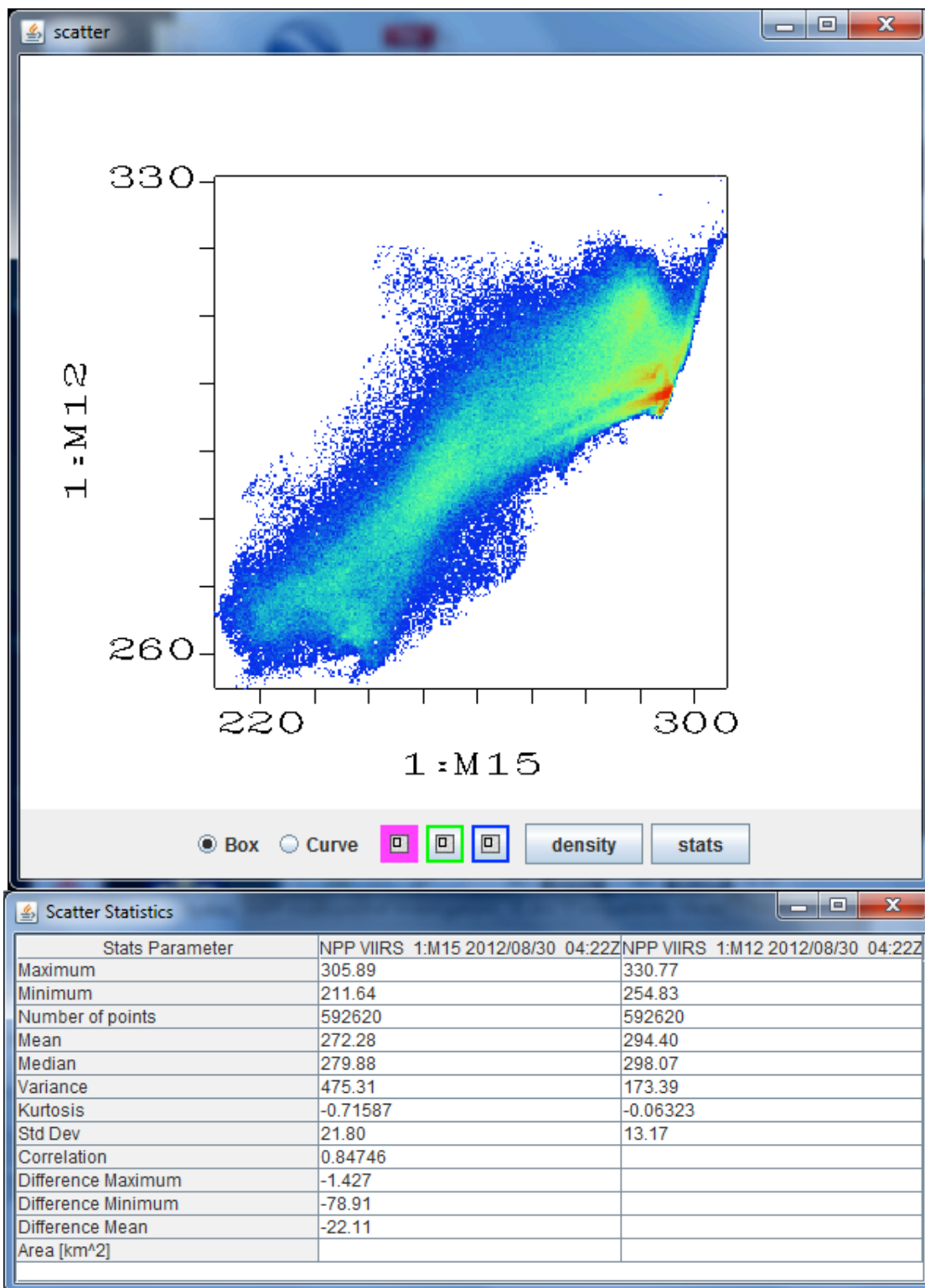


Figure A6: (Top) Scatter window (in density mode) showing BT(M15 or 10.8 μm) on x-axis versus BT(M12 or 3.7 μm) on y-axis. Red points show highest occurrence and blue points show least. (Bottom) Scatter statistics for the pixels shown in the scatter plot.