Satellite Thermal Infrared surveying on geothermal features in Northern Taiwan

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Overview

- This research applied and integrated Thermal Infrared (TIR) Remote Sensing technology with existing geophysical methods for the geothermal exploration in Ilan Plain of northeastern Taiwan and volcanic monitoring in Tatun Volcanic Group (TVG) of northern Taiwan, respectively.
- Results suggest that TIR Remote Sensing is a valuable tool for mapping and quantifying surface features of geothermal and volcanic area with less time-consuming and high cost-efficiency.

Outline

- Introduction to Thermal Infrared (TIR) remote sensing and Geothermal Energy in Taiwan
- Geothermal Anomaly Mapping Using Landsat ETM+ data in Ilan Plain
- Exploring and monitoring geothermal and volcanic activity using Satellite Thermal Infrared data in Tatun Volcanic Group (TVG)
- Conclusion Remarks

USGS
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Crustal Geophysics and Geochemistry Science Center

Geophysical and Remote Sensing Surveys in Support of Mineral Resources Research

Remote Methods for Characterizing Mineral Resources

Remote sensing and geophysics are both tools for data collection by instrumentation not in direct contact with the subject being studied. Remote sensing uses satellite imagery to look at variations in the earth's surface, while geophysics employs quantitative physical methods to study subsurface phenomena. The integration of geophysics and remote sensing with geologic mapping can be applied to a wide variety of investigations, such as mineral and energy resource assessments, environmental characterizations, groundwater studies, and human health and ecosystems.

Geophysical and Remote Sensing Surveys in Support of Resources Research (USGS)

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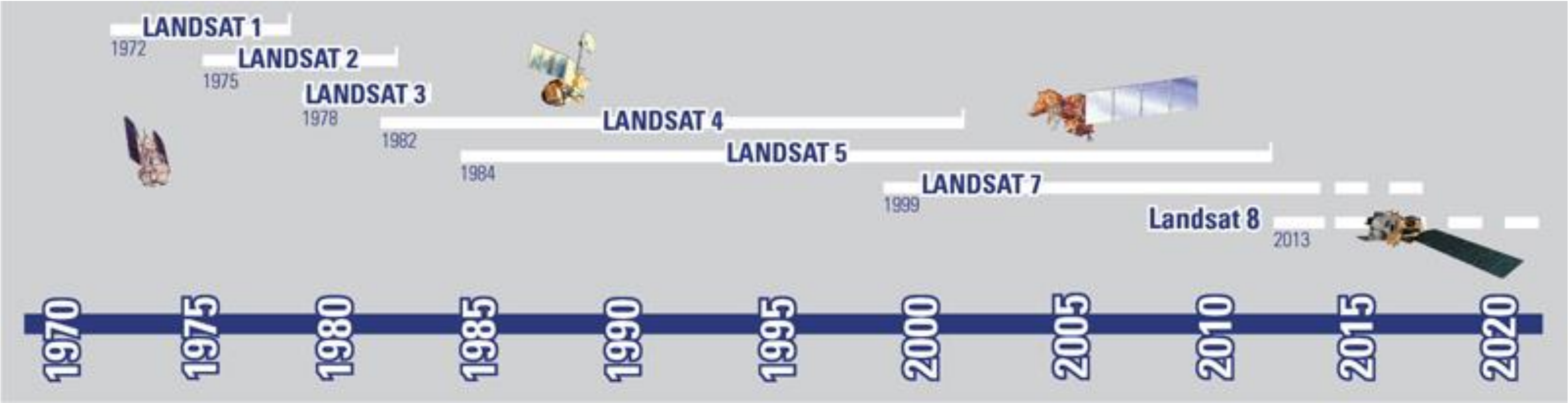
Satellite Remote Sensing …

Source: The 36th International Symposium on Remote Sensing of Environment

Landsat program:
Landsat 7 (1999.4~) & Landsat 8 (2013.2~)

Landsat Missions Timeline (U.S. Geological Survey)

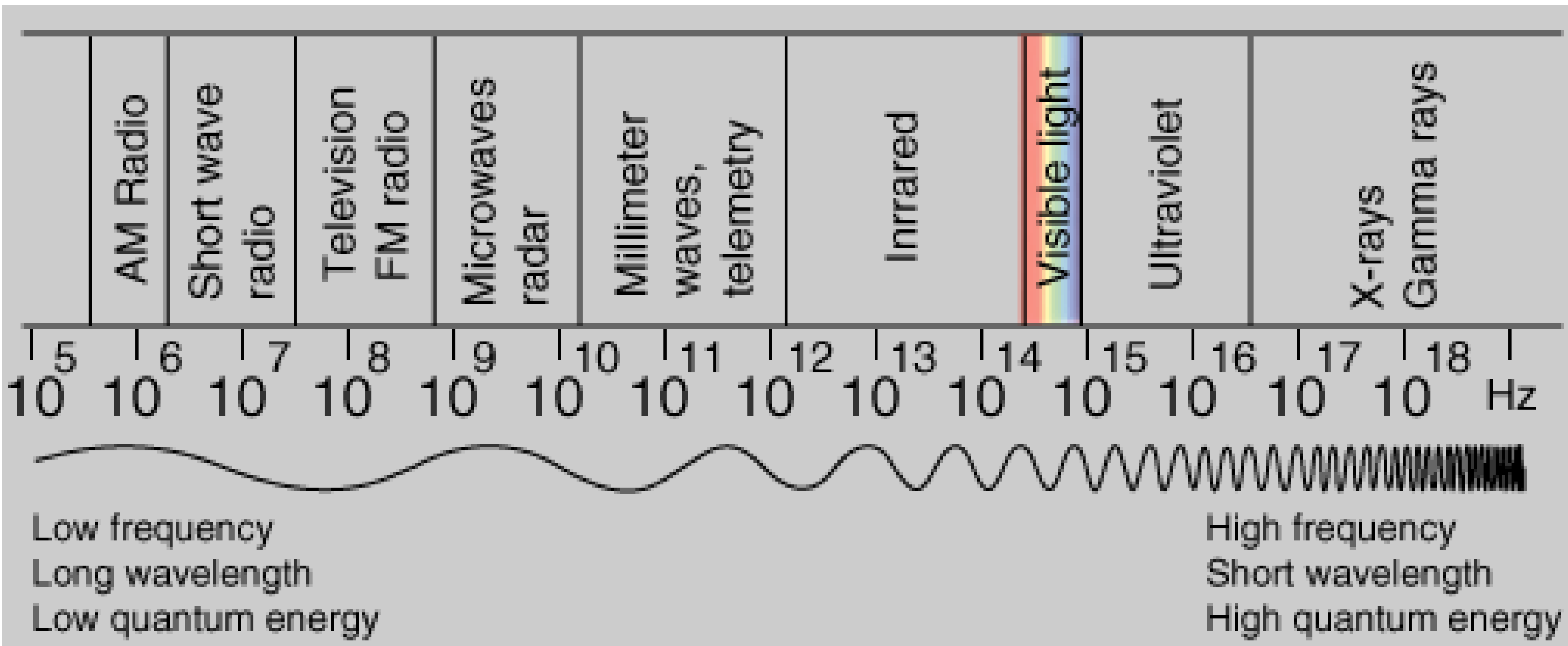


Satellite	Launch	Decommissioned	Sensors
Landsat 1	July 23, 1972	January 6, 1978	MSS/RBV
Landsat 2	January 22, 1975	July 27, 1983	MSS/RBV
Landsat 3	March 5, 1978	September 7, 1983	MSS/RBV
Landsat 4	July 16, 1982	June 15, 2001	MSS/TM
Landsat 5	March 1, 1984	2013	MSS/TM
Landsat 6	October 5, 1993	Did not achieve orbit	ETM
Landsat 7	April 15, 1999	Operational	ETM+
Landsat 8	February 11, 2013	Operational	OLI/TIRS

L7 bands compared to L8 bands. Table courtesy of B. Markham (July 2013)

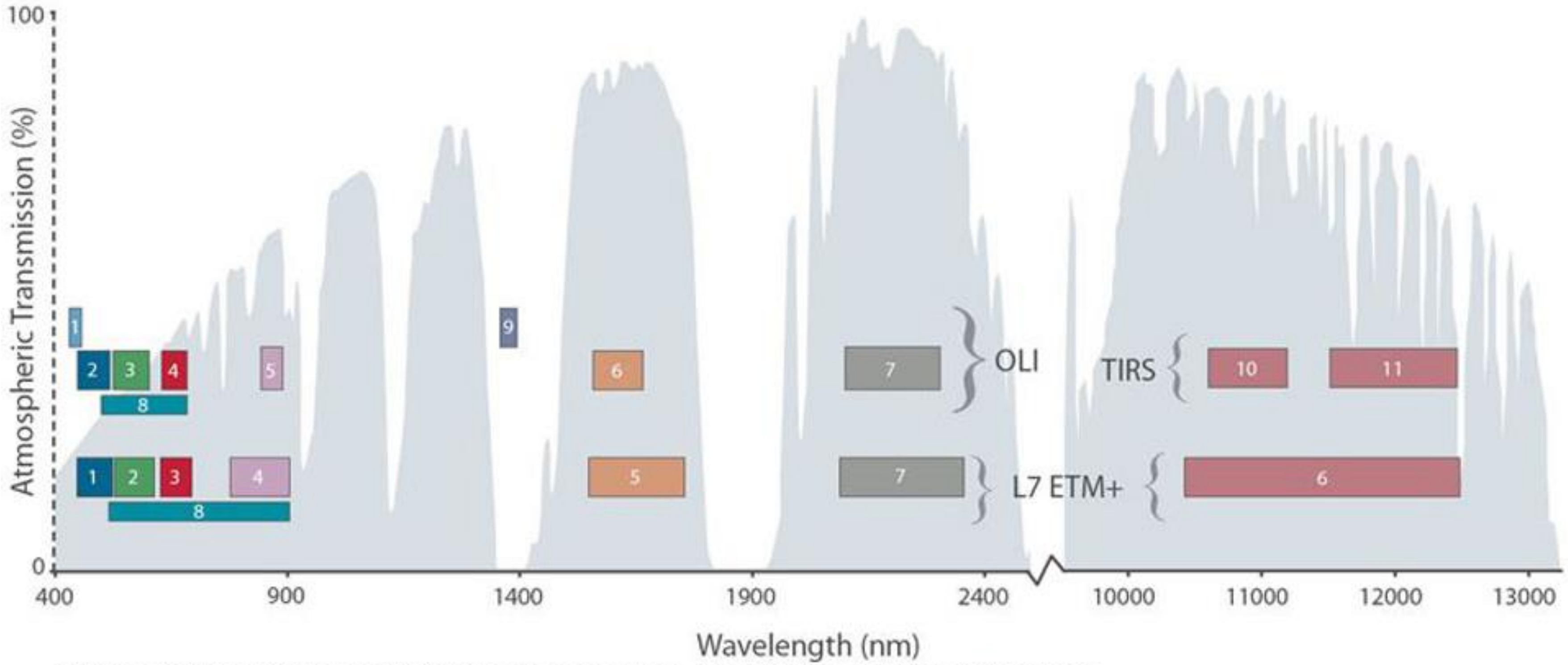
Landsat-7 ETM+ Bands (µm)			Landsat-8 OLI and *TIRS* Bands (µm)		
			30 m Coastal/Aerosol	0.435 - 0.451	Band 1
Band 1	30 m Blue	0.441 - 0.514	30 m Blue	0.452 - 0.512	Band 2
Band 2	30 m Green	0.519 - 0.601	30 m Green	0.533 - 0.590	Band 3
Band 3	30 m Red	0.631 - 0.692	30 m Red	0.636 - 0.673	Band 4
Band 4	30 m NIR	0.772 - 0.898	30 m NIR	0.851 - 0.879	Band 5
Band 5	30 m SWIR-1	1.547 - 1.749	30 m SWIR-1	1.566 - 1.651	Band 6
Band 6	60 m TIR	10.31 - 12.36	*100 m TIR-1*	*10.60 – 11.19*	Band 10
			100 m TIR-2	*11.50 – 12.51*	Band 11
Band 7	30 m SWIR-2	2.064 - 2.345	30 m SWIR-2	2.107 - 2.294	Band 7
Band 8	15 m Pan	0.515 - 0.896	15 m Pan	0.503 - 0.676	Band 8
			30 m Cirrus	1.363 - 1.384	Band 9

The Electromagnetic Spectrum



Source: http://web.eng.fiu.edu/~mathmatters/m2ed/HeatTransferConvectionAndRadiation/chapter3.html

Band designations for the Landsat 7 & 8



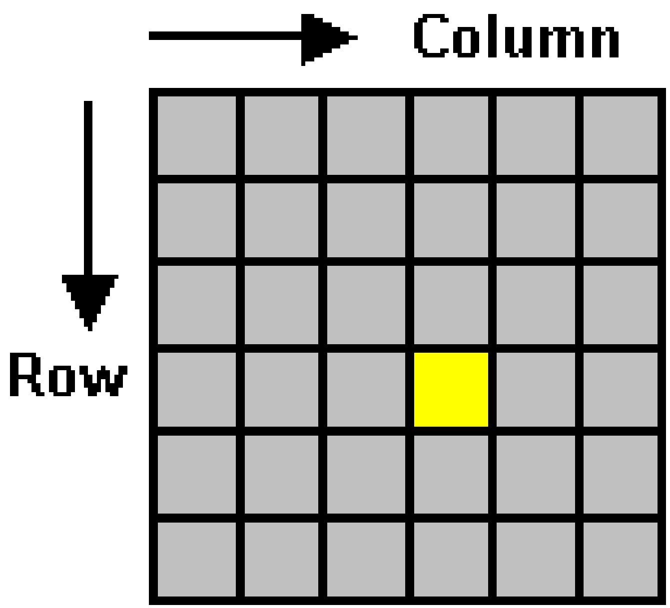
Bandpass wavelengths for Landsat 8 OLI and TIRS sensor, compared to Landsat 7 ETM+ sensor

Note: atmospheric transmission values for this graphic were calculated using MODTRAN for a summertime mid-latitude hazy atmosphere (circa 5 km visibility).

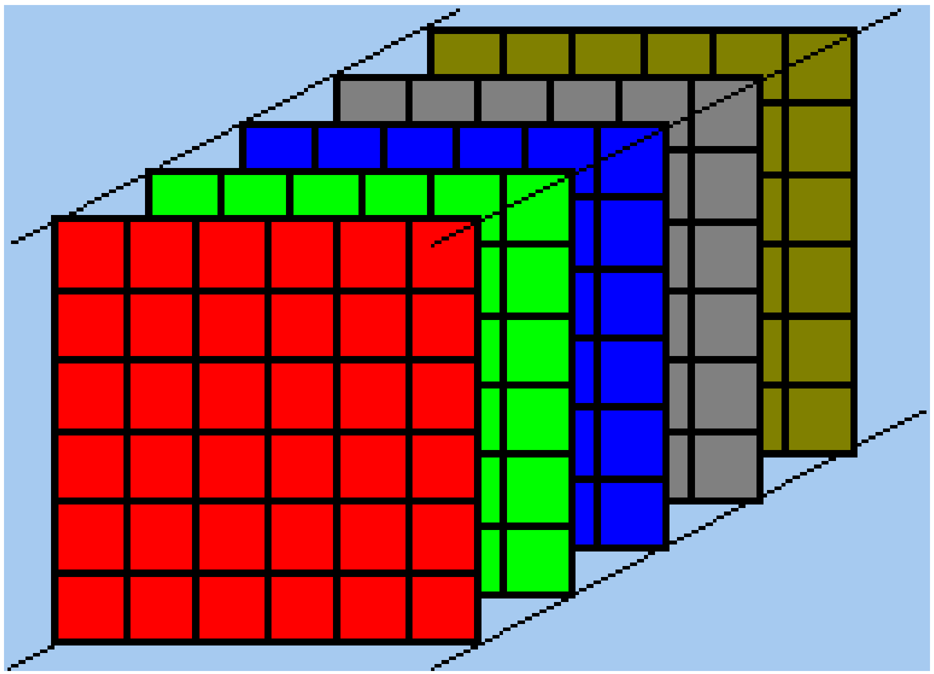
Source: USGS

Digital image & Multilayer image

(Source: http://www.crisp.nus.edu.sg/~research/tutorial/image.htm)



A digital image is a two-dimensional array of pixels. Each pixel has an intensity value (represented by a digital number) and a location address (referenced by its row and column numbers).



An illustration of a multilayer image consisting of five component layers.

Thermal Energy in Day-to-Day Life
(http://www.hunting-night-vision.com/blog/thermal-vision-vs-infrared-night-vision)

Contour map of silica heat flow in Taiwan

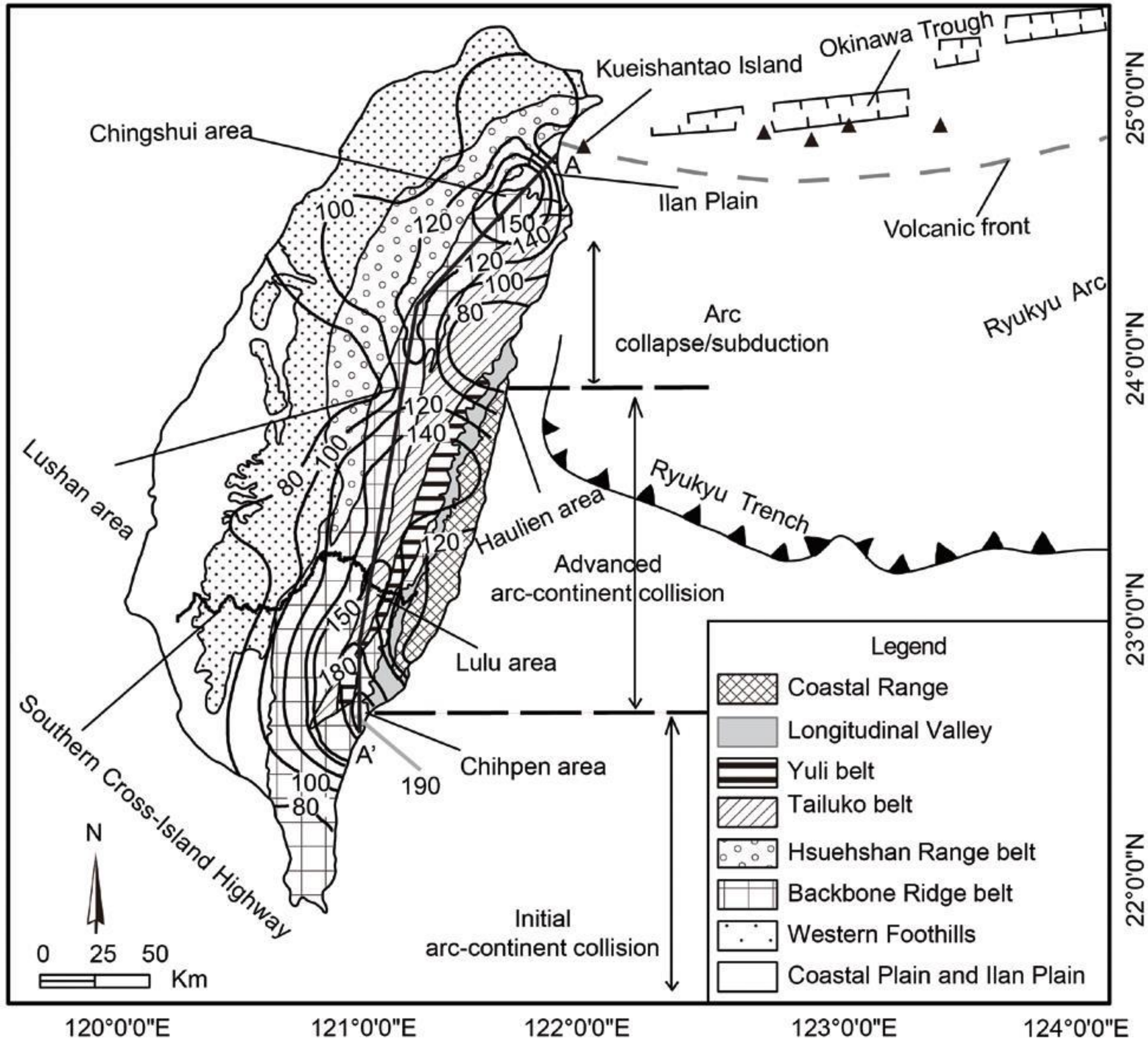
- Four hot potential geothermal sites:

(1) Tatun Volcanic Group (TVG) of northern Taiwan;

(2) Ilan Plain of northeastern Taiwan;

(3) Lushan area of central Taiwan; and

(4) Huatung area of eastern Taiwan

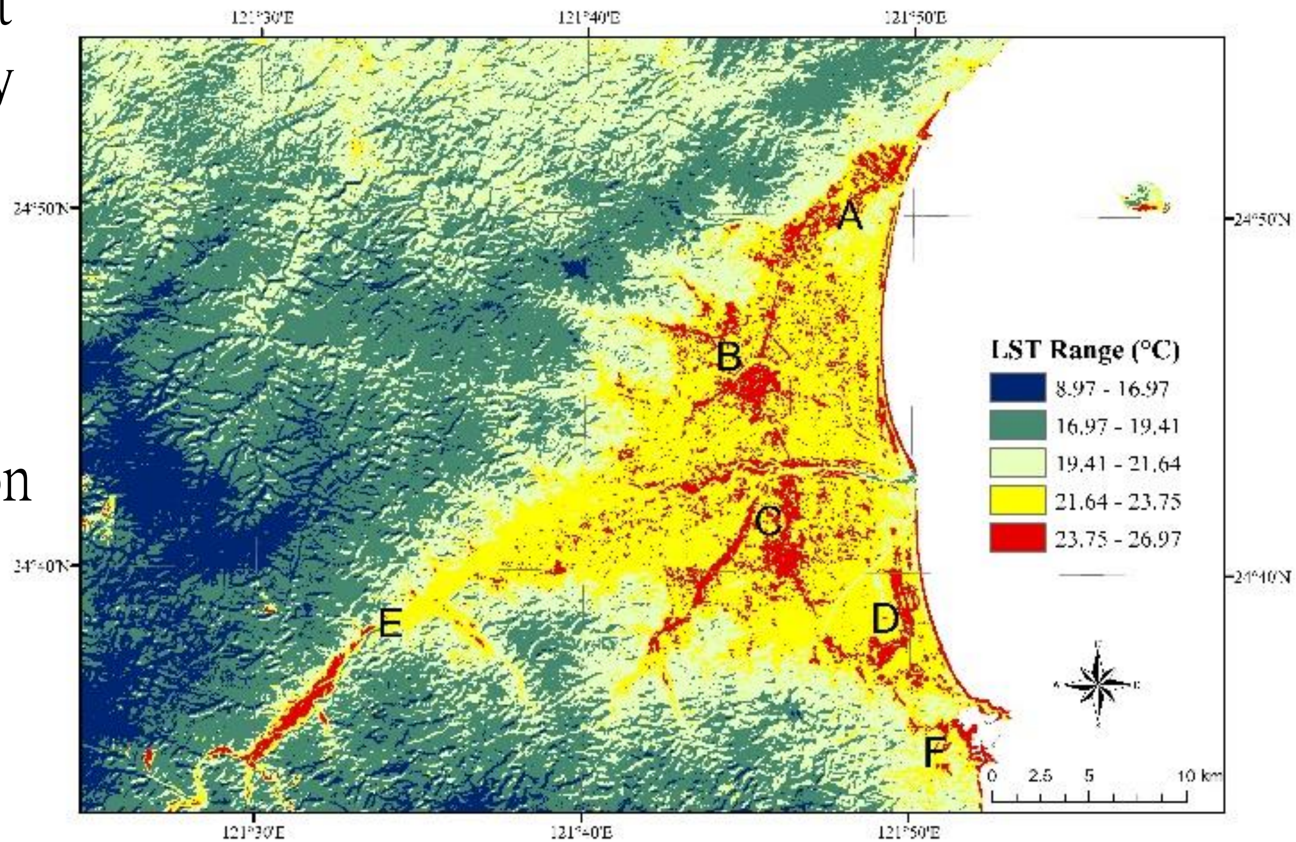


Liu, C.-M.; Song, S.-R.; Kuo, C.-H. Silica geothermometry applications in the taiwan orogenic belt. *Terrestrial, Atmospheric & Oceanic Sciences* **2015**, *26*.

TIR Remote Sensing Applications in Geothermal Resources

- Thermal infrared (TIR) images have been used to detect geothermal activity for over half a century.
- In 1961, U.S. Geological Survey (USGS) initiated on Yellowstone National Park

Pattern of Land Surface Temperature (LST) distribution of Landsat 7 ETM+ in Ilan Plain on December 3, 2001.



Abbreviation and Terminology

- Tatun Volcanic Group (TVG)
- Thermal Infrared (TIR), emissivity
- Landsat 7/ETM+
- Terra, Aqua/MODIS
- The Land Surface Temperature (LST) is the radiative skin temperature of ground.
- Hilbert-Huang Transform (HHT)

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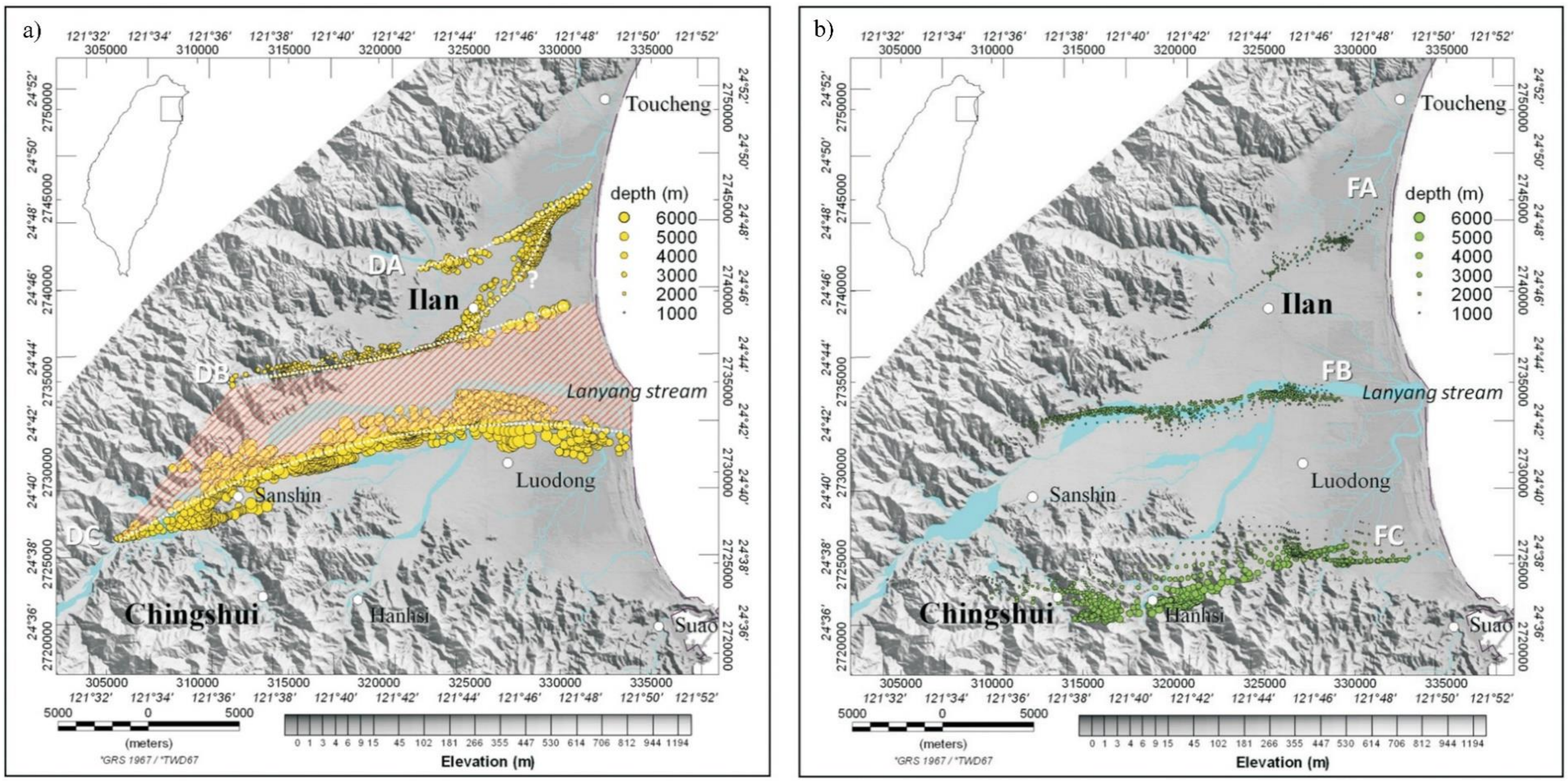
Geomagnetic, gravity, and magnetotelluric (MT) survey in the Ilan Plain

The surface projection of the fault and dyke solutions in the Ilan Plain. a) Three groups of dykes (DA, DB and DC). b)Three groups of faults (FA, FB and FC). The shaded area between DB and DC could be related to the WE high magnetic anomaly area associated with igneous intrusive rock.



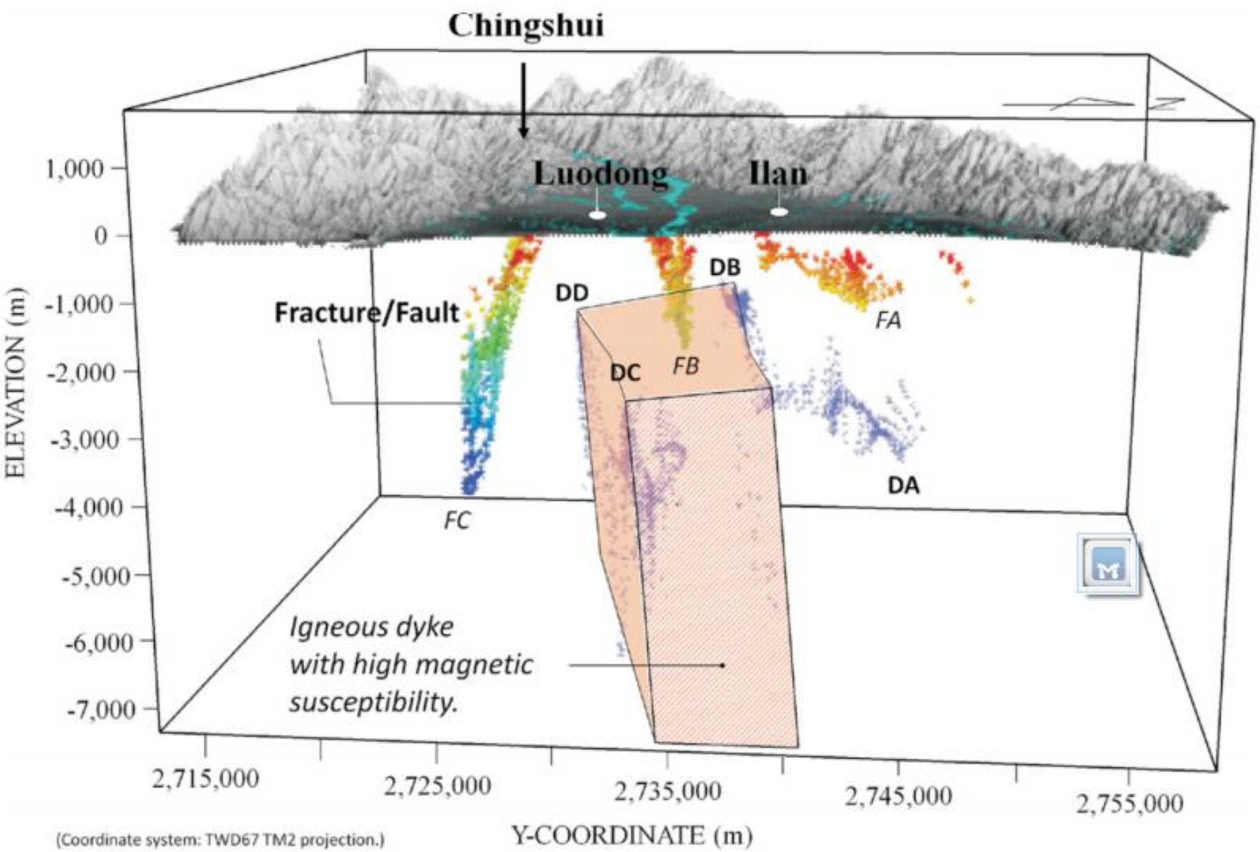
Tong, L.-T.; Ouyang, S.; Guo, T.-R.; Lee, C.-R.; Hu, K.-H.; Lee, C.-L.; Wang, C.-J. Insight into the geothermal structure in chingshui, ilan, taiwan. Terrestrial, Atmospheric and Oceanic Sciences 2008, 19, 413.

Geomagnetic, gravity, and magnetotelluric (MT) survey in the Ilan Plain

- Surveys: geomagnetic survey in 1978 (dataset of 425 stations); gravity survey in 1976 (data of 636 stations); MT survey in 2006 (33 broadband data points)
- Results: 1) shallow magma chamber and intrusive igneous rock causes the high heat flow and geothermal gradient; 2) Geothermal fluid circulated within the fracture zone in the deep was heated by the hot rock in the Chingshui geothermal field.

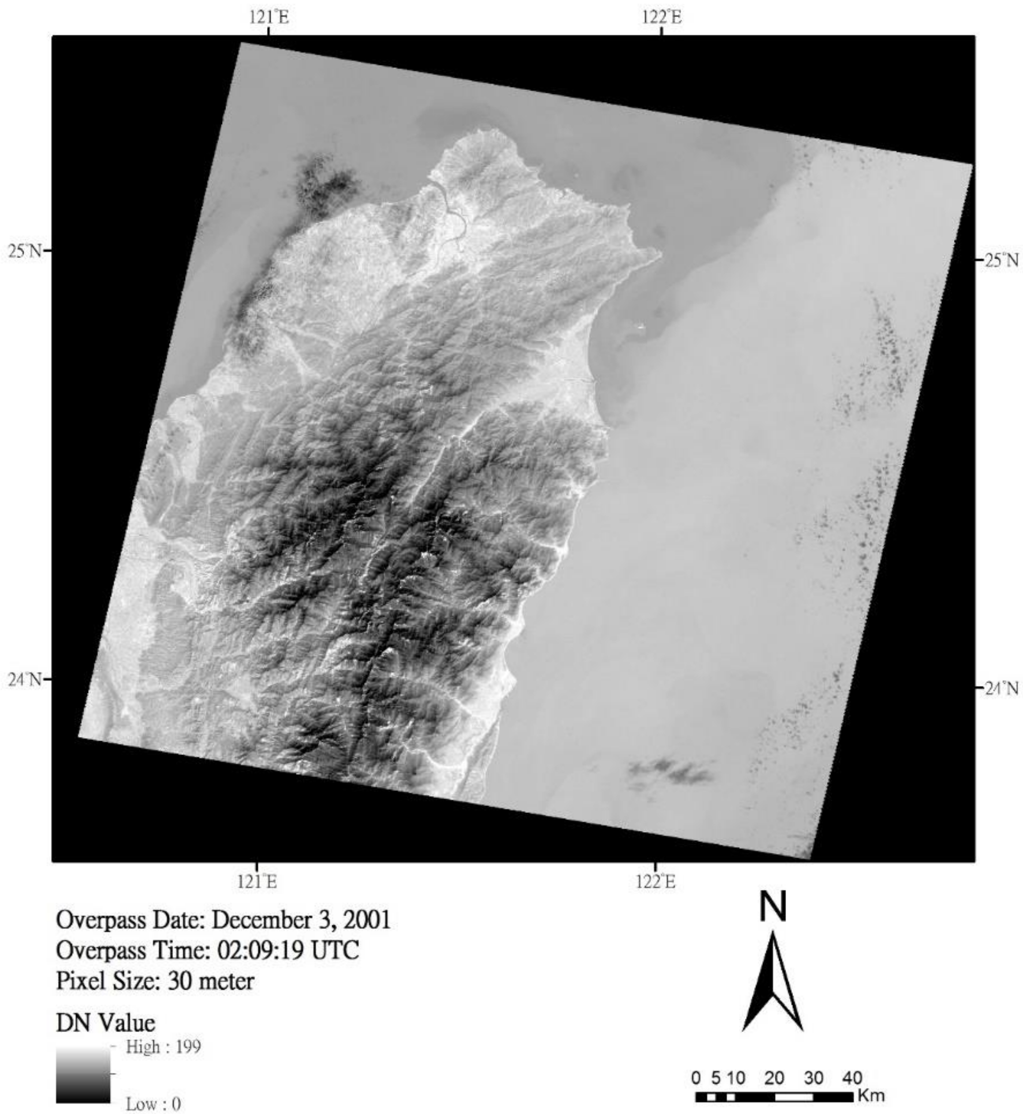
Geomagnetic, gravity, and magnetotelluric (MT) survey in the Ilan Plain

A 3-D view of fault and dyke solutions beneath the Ilan plain

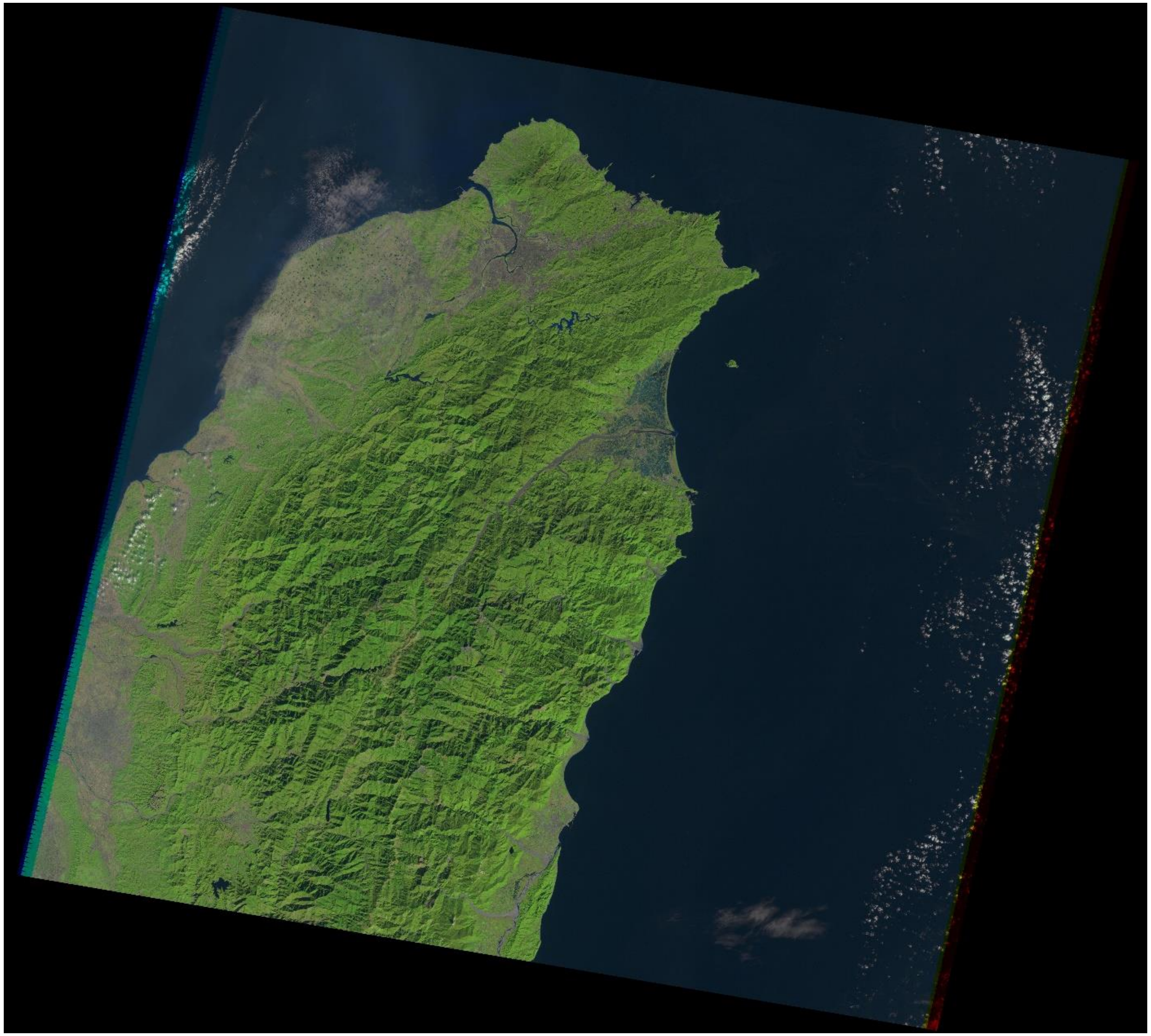


Tong, L.-T.; Ouyang, S.; Guo, T.-R.; Lee, C.-R.; Hu, K.-H.; Lee, C.-L.; Wang, C.-J. Insight into the geothermal structure in chingshui, ilan, taiwan. Terrestrial, Atmospheric and Oceanic Sciences 2008, 19, 413.

Landsat 7 ETM+ thermal infrared image acquired on December 3, 2001.



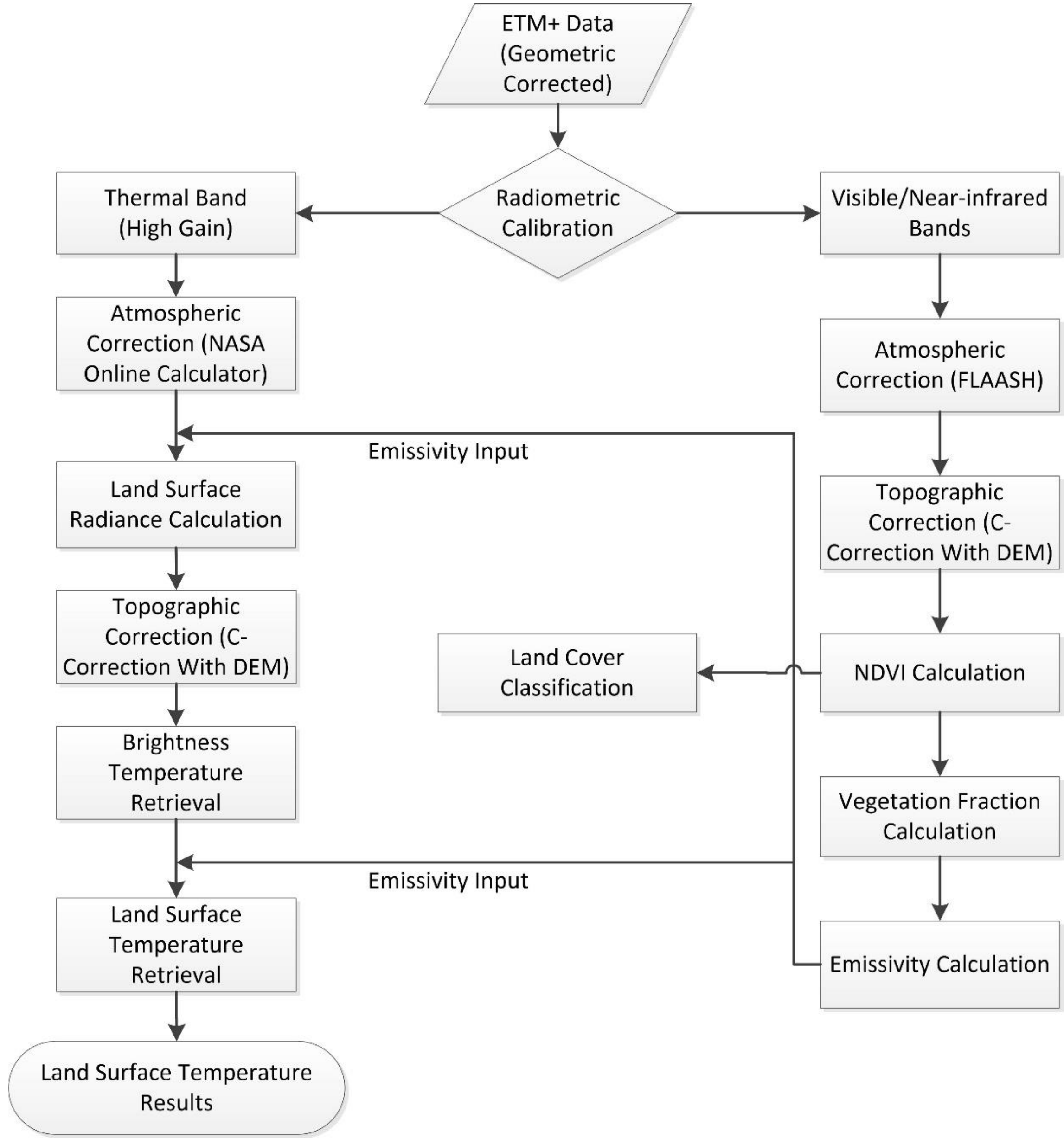
Landsat 7 Scene (Dec. 3, 2001)

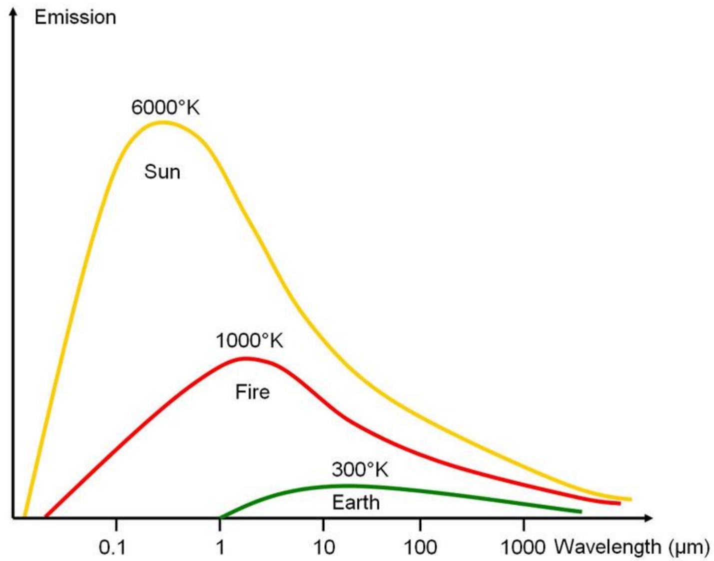


Flow chart of LST retrieval

Main steps of data processing:

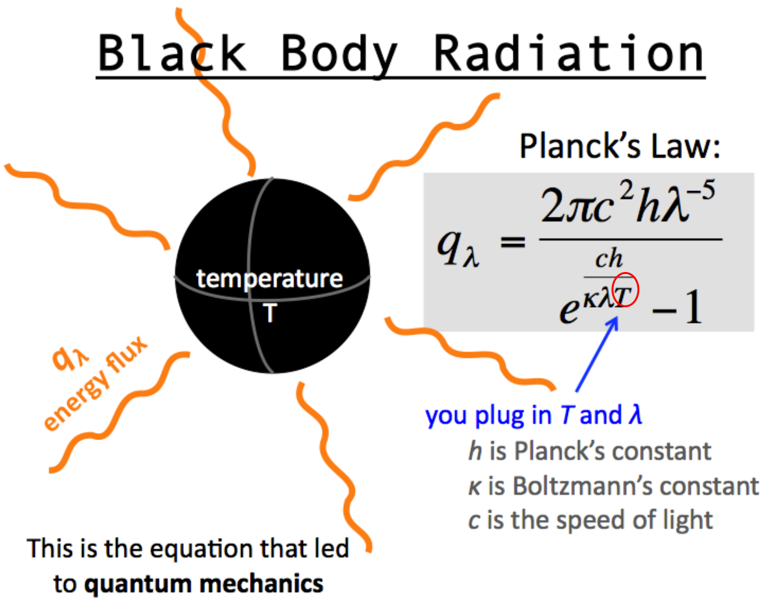
- radiometric calibration,
- atmospheric correction,
- topographic correction and
- emissivity calculation.





Planck's law: Emission as a function of wavelengths of objects having different absolute temperatures.

Source: ESA Eduspace with modifications



$$T = \frac{T_B}{1 + (\lambda T_B / \alpha) \ln \varepsilon}.$$

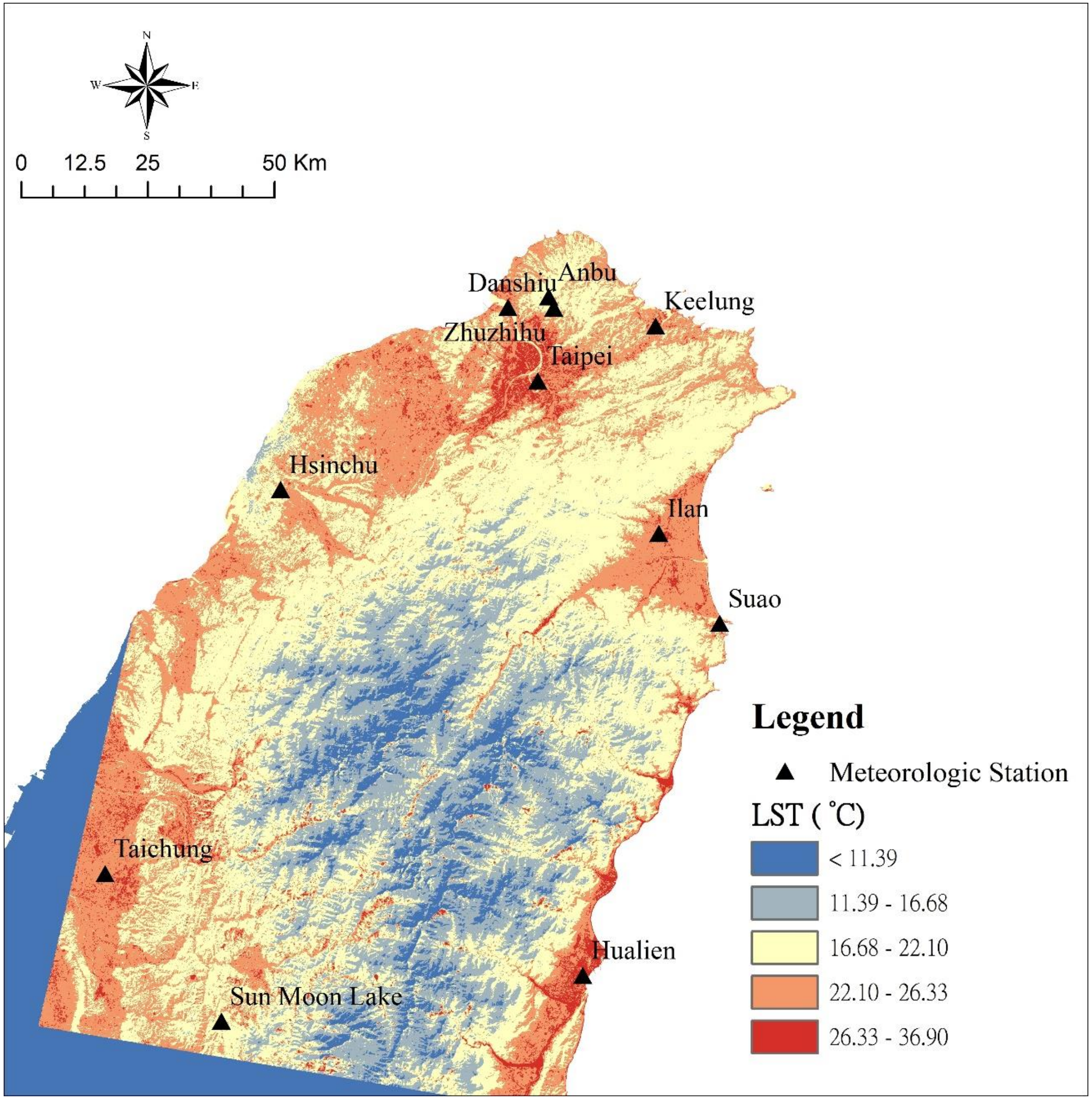
$$\alpha = hc/K \ (1.438 \times 10^{-2} \ \mathrm{mK}),$$

Source: Artis, D.A.; Carnahan, W.H. Survey of **emissivity** variability in thermography of urban areas. Remote Sensing of Environment 1982, 12, 313-329.

Source: https://audioboom.com/boos/158229-the-stefan-boltzmann-law

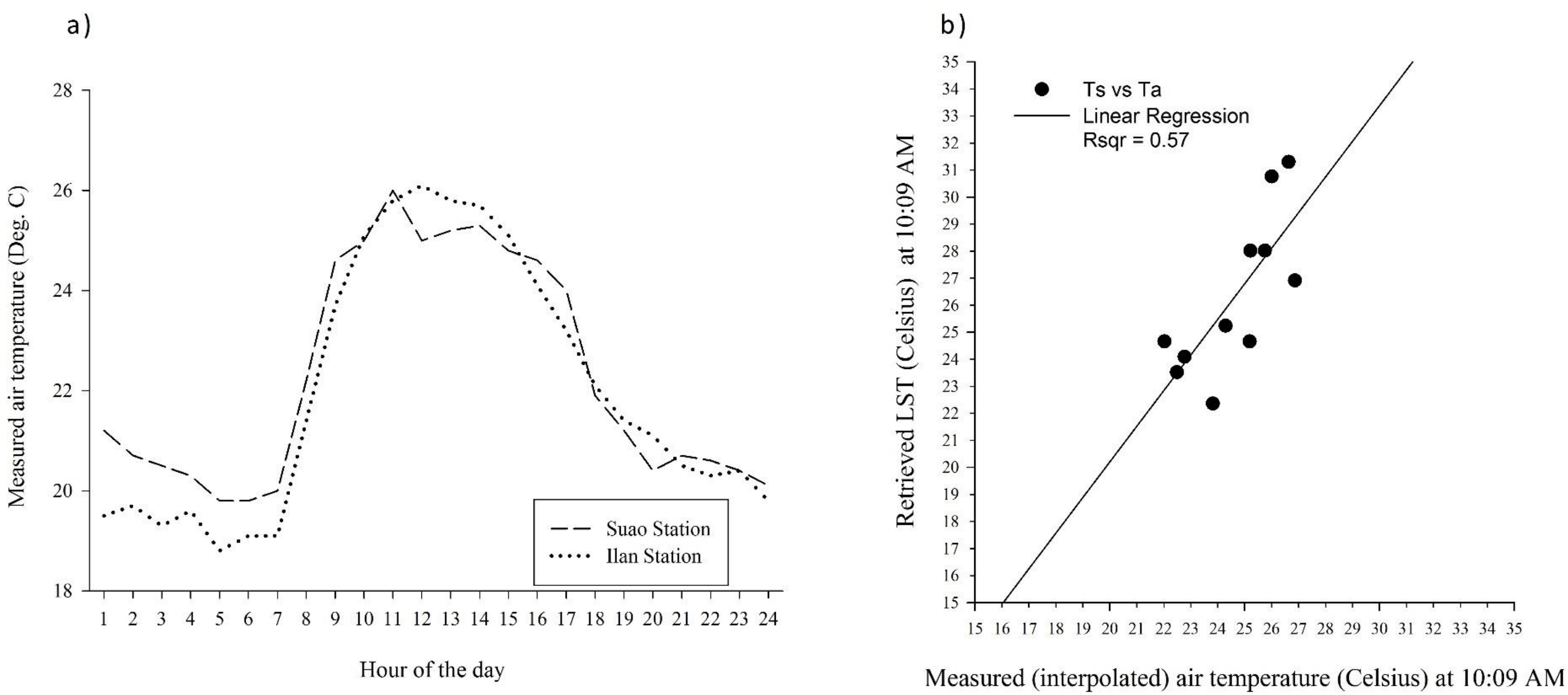
Validation of satellite derived LST

- Ground-truth validation from meteorological temperature data
- Geographical location of meteorological stations and the corresponding LST retrieval (Scene-specific).



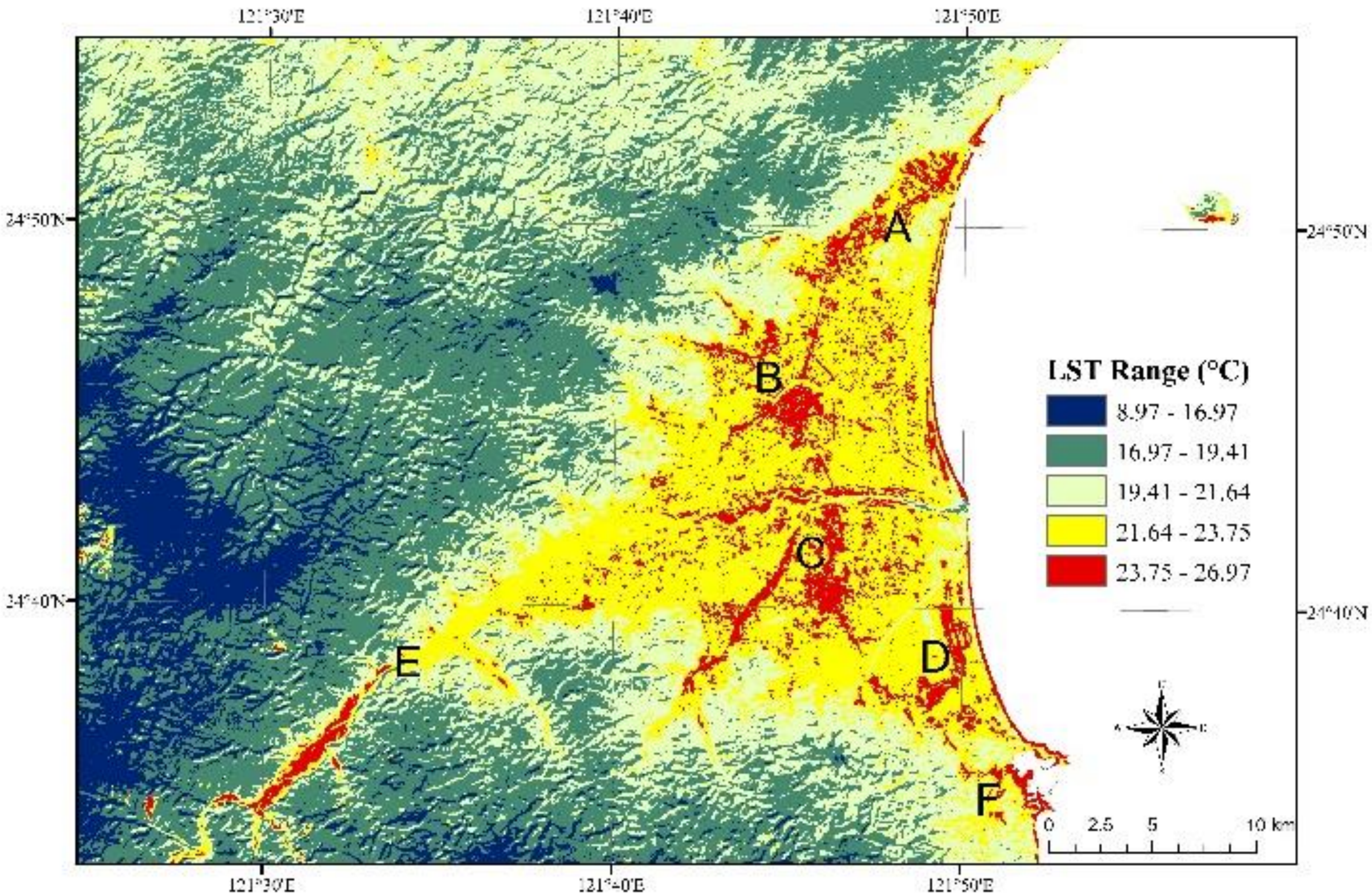
Validation of satellite derived LST

Major discrepancies might be caused by differences in the scales of resolution between the satellite and ground-based CWB meteorological stations (i.e. the scale mismatch).



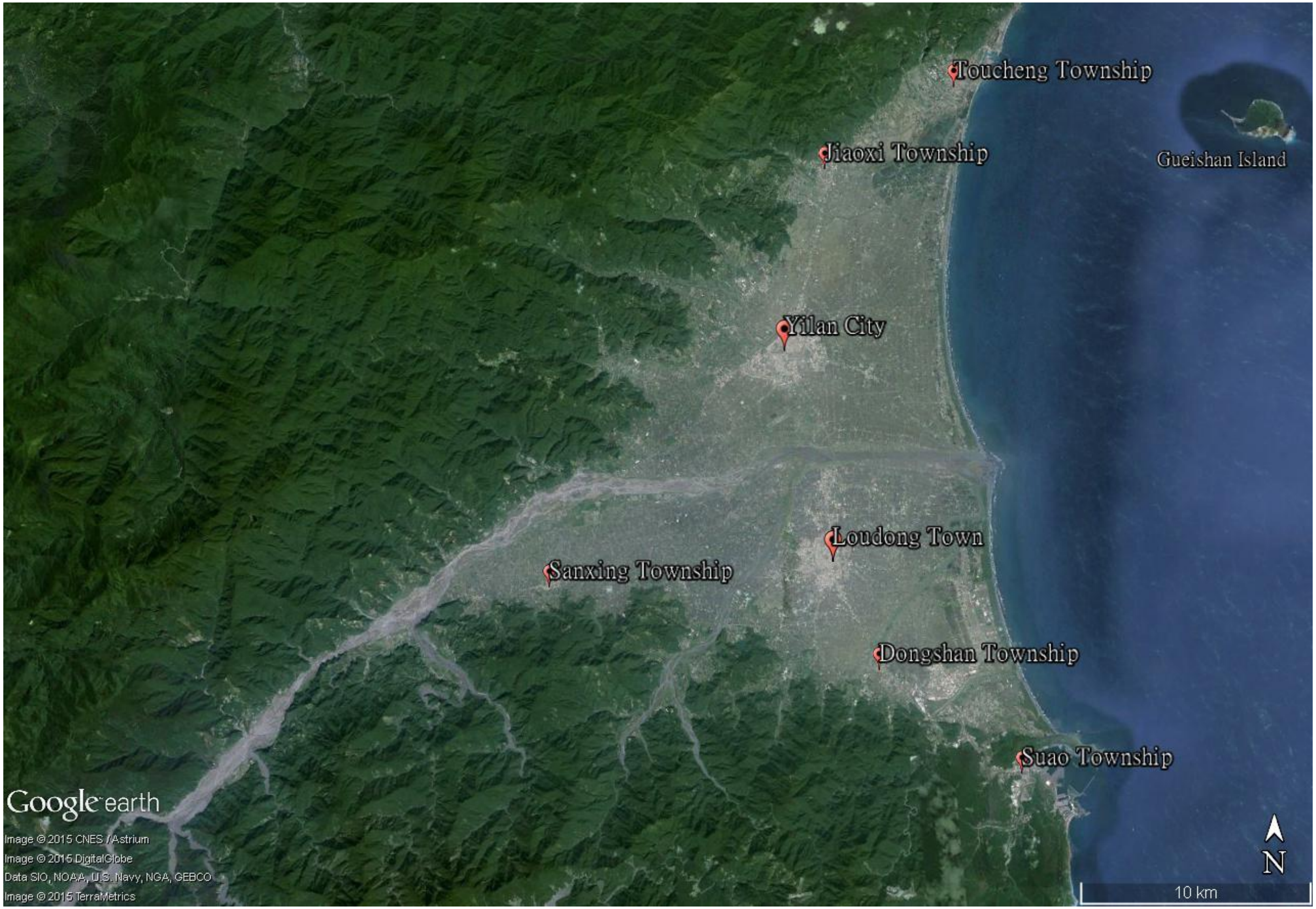
- a) CWB hourly measured air temperature variation for 2 sites in Ilan Plain on December 3, 2001. b) Scatter plot of the measured air temperature and retrieved LST with fitted linear curves.

The retrieved LST distribution of Ilan Plain

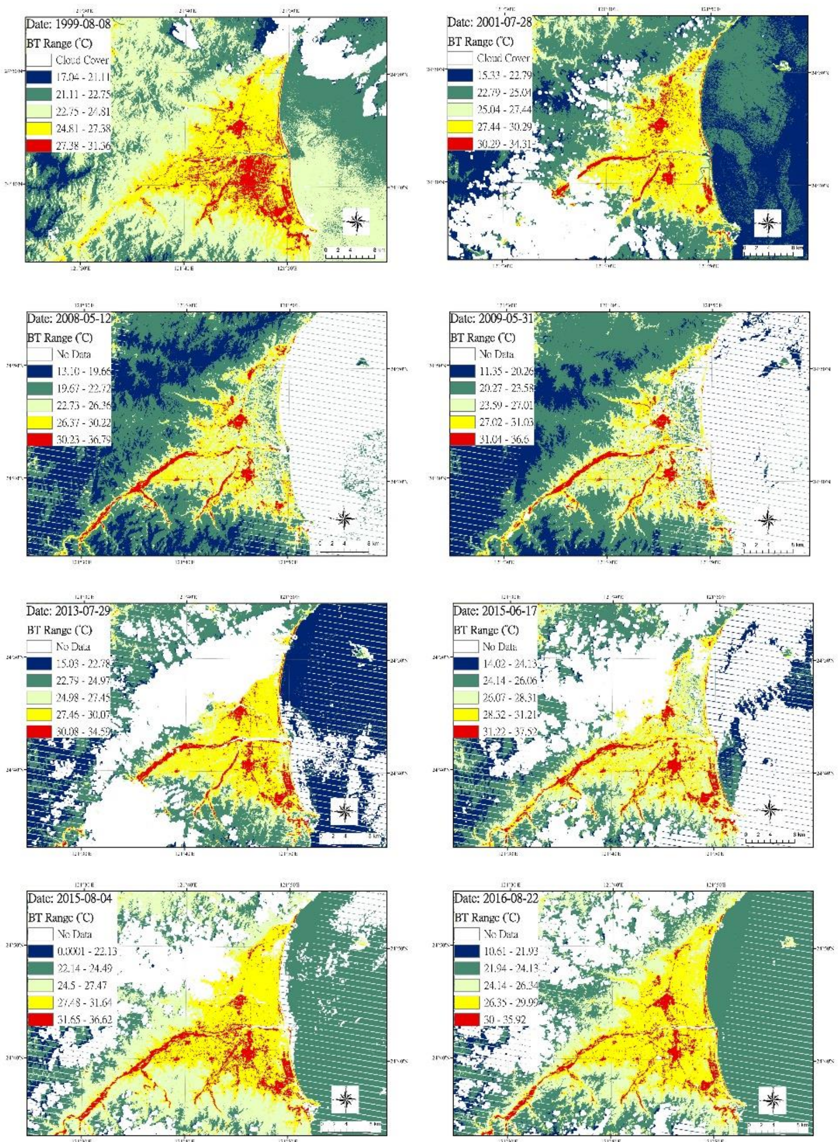


- Pattern of LST distribution in Ilan Plain from Landsat 7 ETM+ on December 3, 2001. Major thermal anomalous areas are indicated by A, B, C, D, E and F.

Ilan Plain (around 330 km^2)

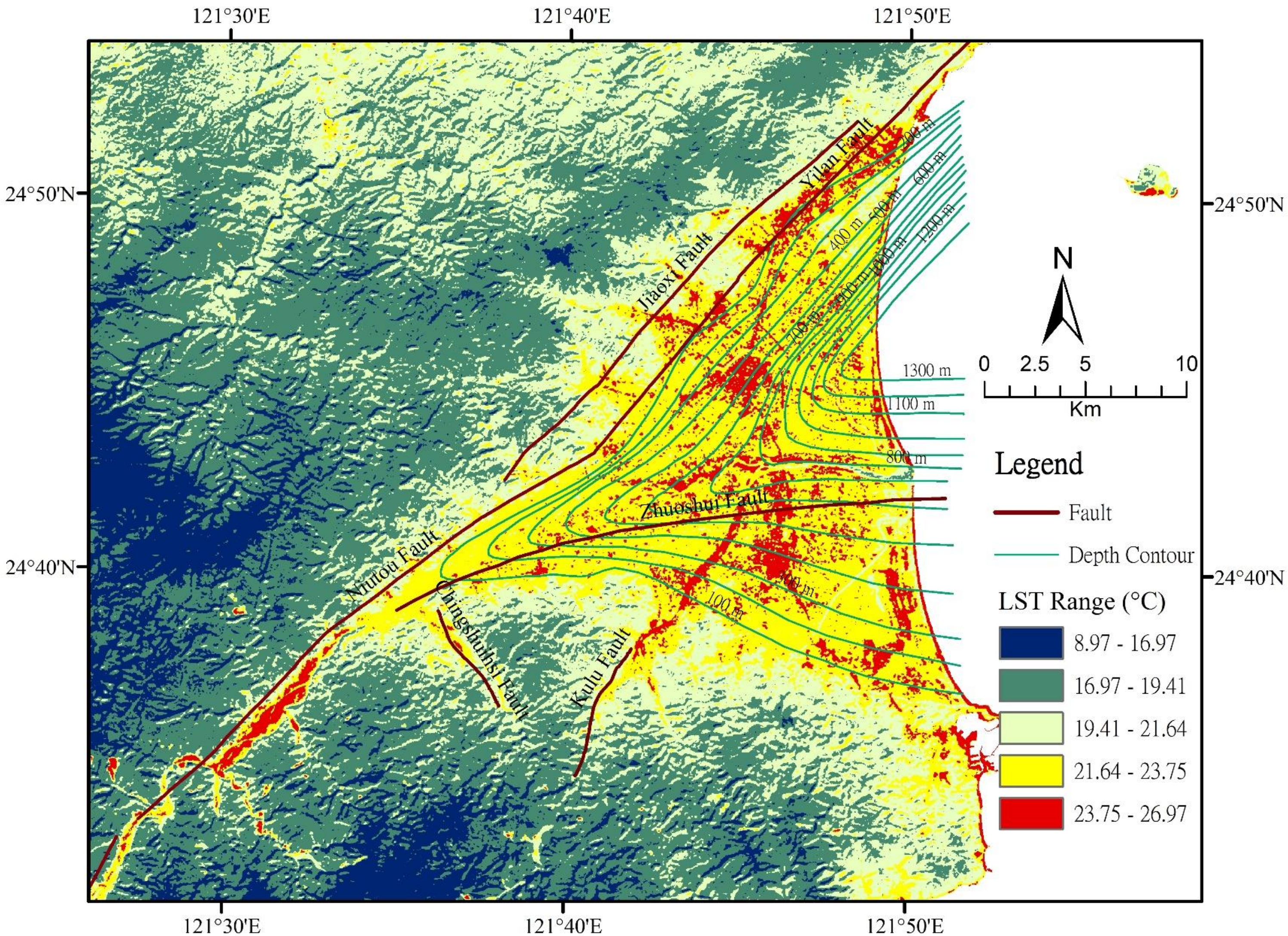


Multi-temporal Brightness Temperature imagery for the verification of the LST anomaly results



- Pattern of Brightness Temperature distribution in Ilan plain from Landsat 7 ETM+ on 8 August 1999, 28 July 2001, 12 May 2008, 31 May 2009, 29 July 2013, 17 June 2015, 4 August 2015, and 22 August 2016, respectively. Blank areas (white color) indicate "No Data" caused by either cloud coverage or image gaps. Thermal anomalous areas are illustrated by red color in the imagery.

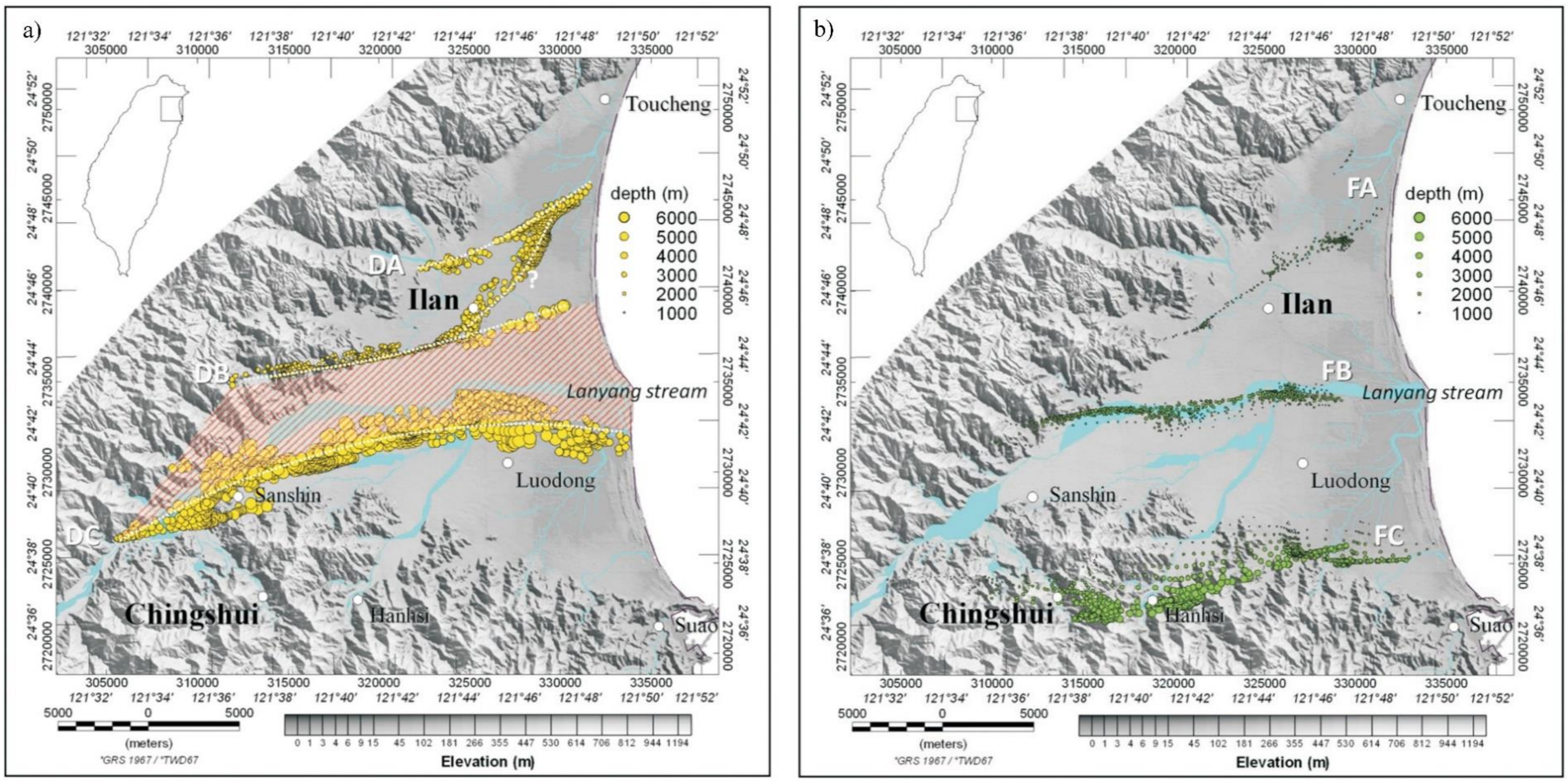
LST overlaps with faults



LST compared with fault structure (dark umber bold line) and basement depth contour (blue line) in Ilan Plain.

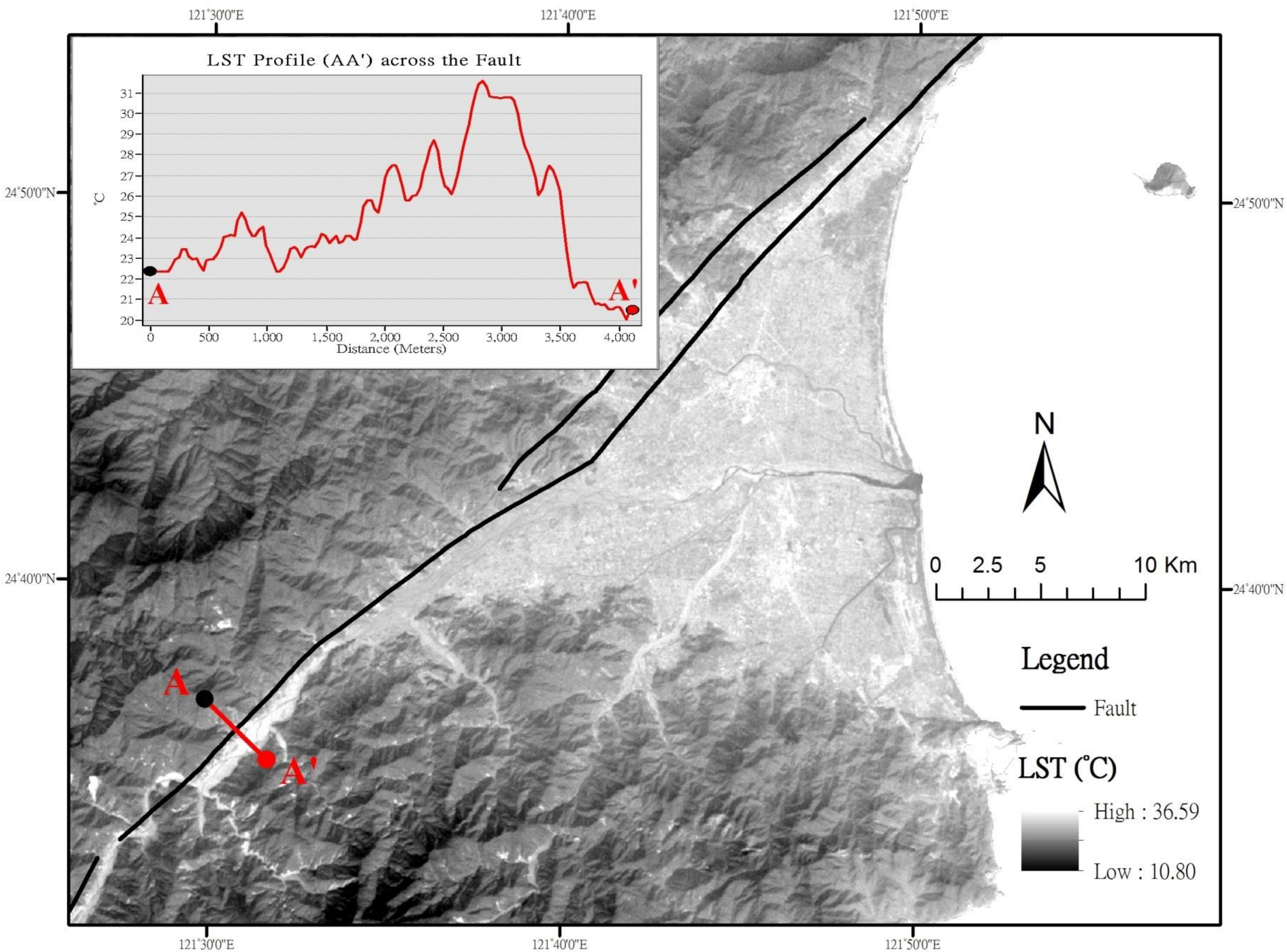
Geomagnetic, gravity, and magnetotelluric (MT) survey in the Ilan Plain

- The surface projection of the fault and dyke solutions in the Ilan Plain. a) Three groups of dykes (DA, DB and DC) were noticed. b)Three groups of faults (FA, FB and FC) were observed. The solid yellow and green circles indicate the depth of fault and dyke solutions beneath the Ilan plain, respectively

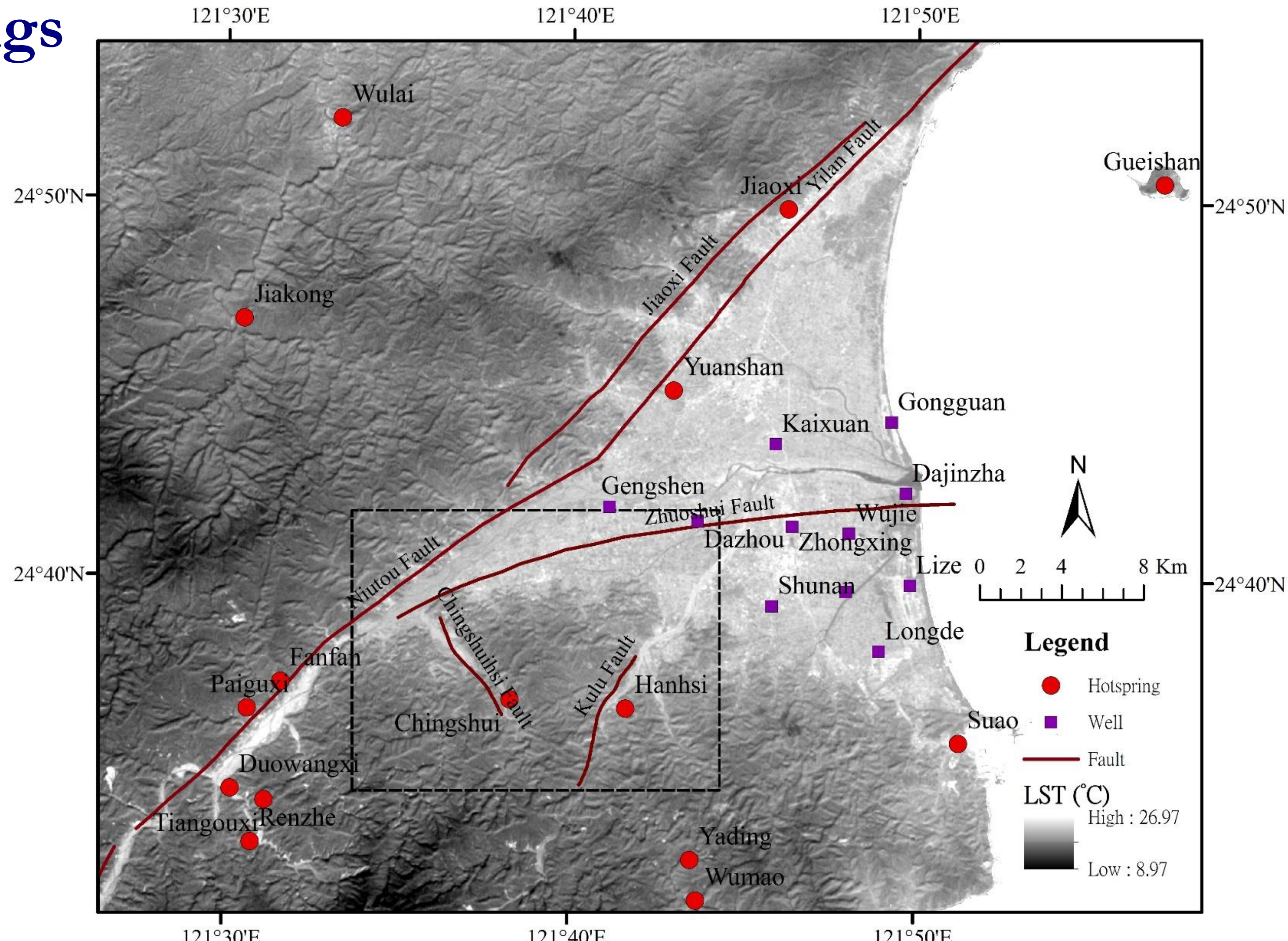


Tong, L.-T.; Ouyang, S.; Guo, T.-R.; Lee, C.-R.; Hu, K.-H.; Lee, C.-L.; Wang, C.-J. Insight into the geothermal structure in chingshui, ilan, taiwan. Terrestrial, Atmospheric and Oceanic Sciences 2008, 19, 413.

LST Profile (AA') across the Fault

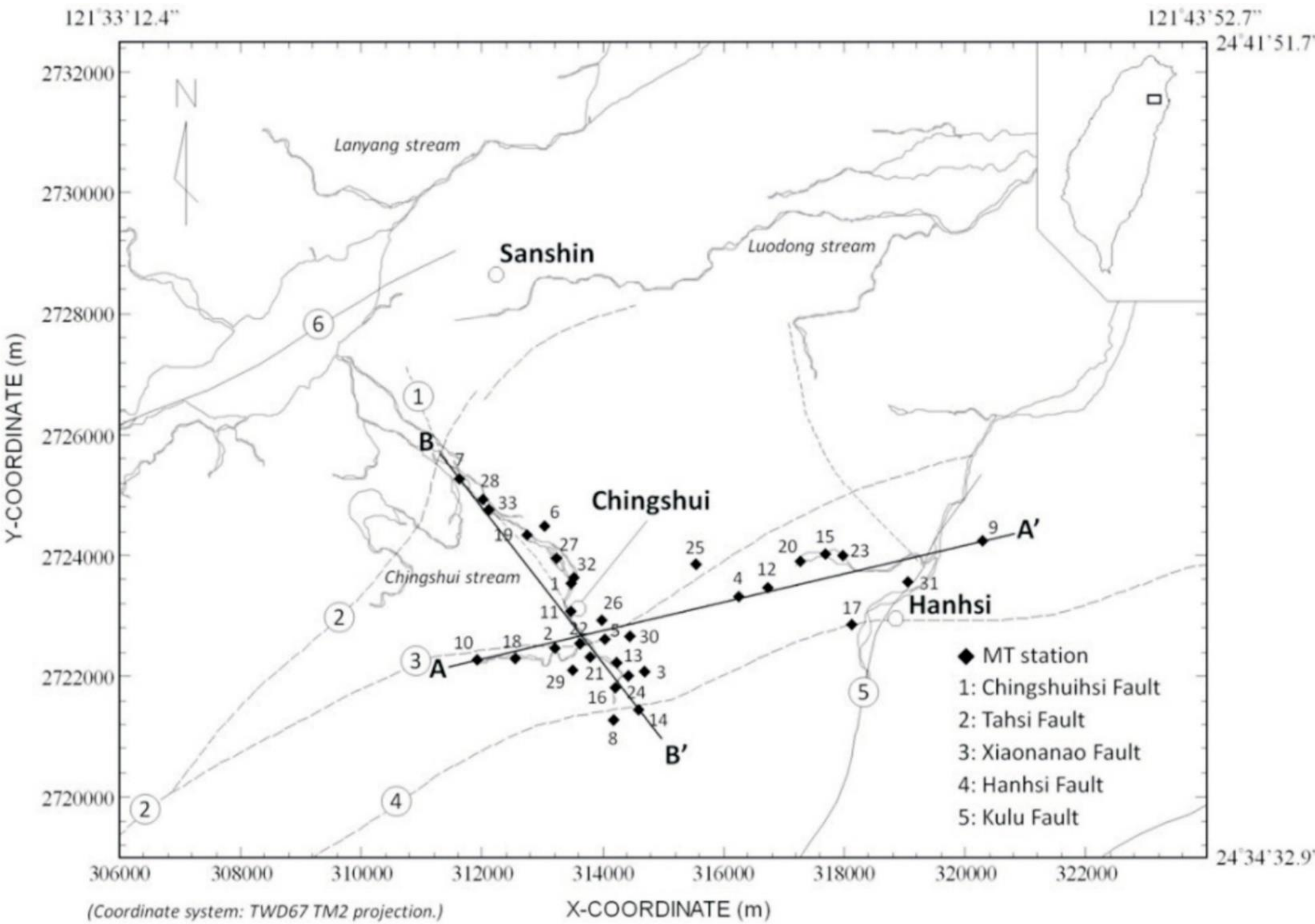


LST overlaps with geothermal drillings and hot springs



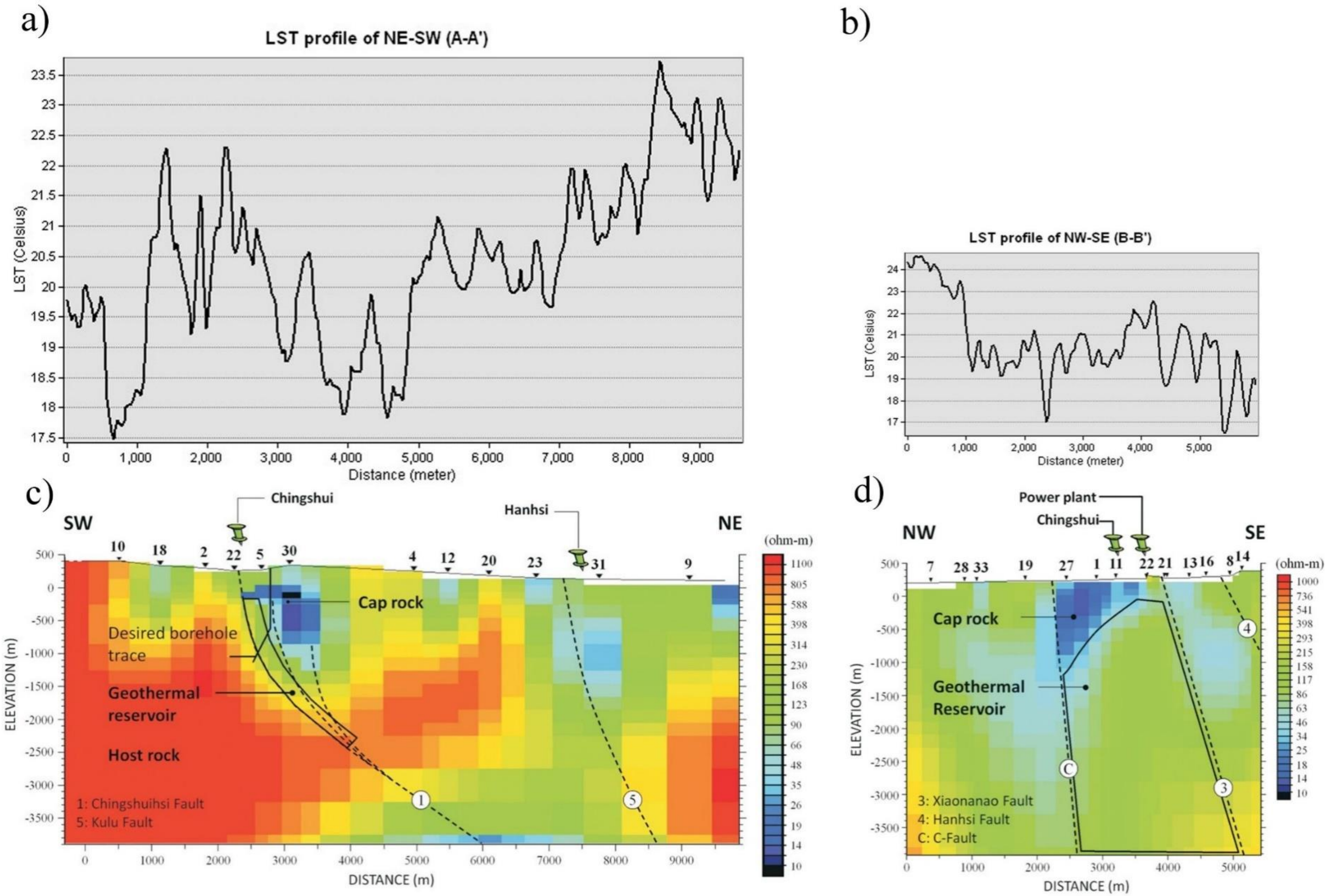
- Geothermal drillings and hot springs in Ilan area. Purple squares in the plain indicate geothermal drillings and red circles annotate hot springs. The dashed box shows the Chingshui geothermal area.

Magnetotelluric (MT) survey- Profile A and profile B



- MT stations in the Chingshui geothermal area. Most stations are confined in the valley because of the hilly topography. Profile A (A-A' NE-SW) and profile B (B-B' NW-SE) are constructed for further analysis.

LST profiles compared with MT resistivity section



- LST profiles compared with MT resistivity section of profile A and profile B from Tong, et al., 2008. The low-resistivity zones identified in the resistivity sections (c, d) are echoed in the LST profiles (a, b).

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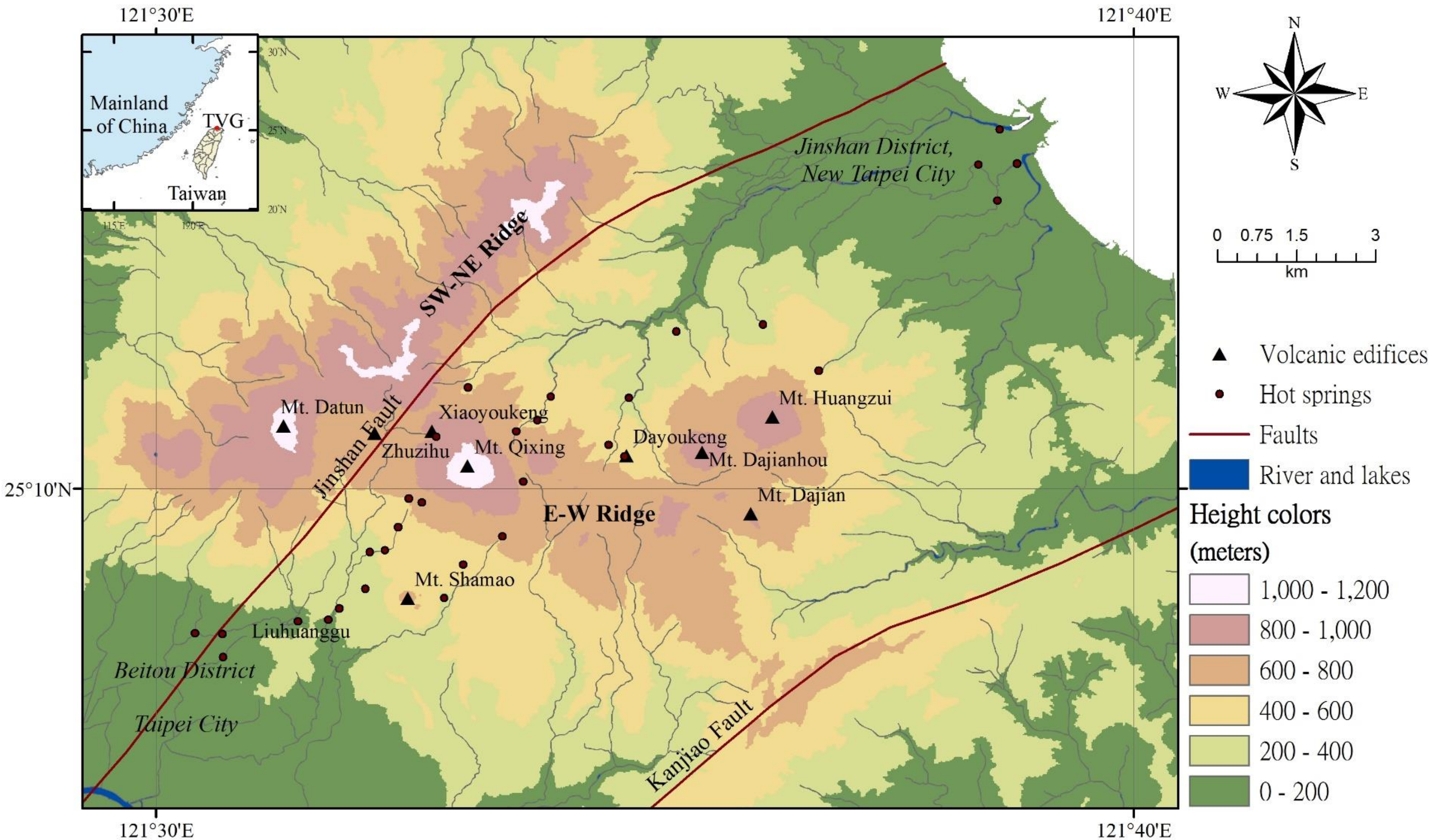
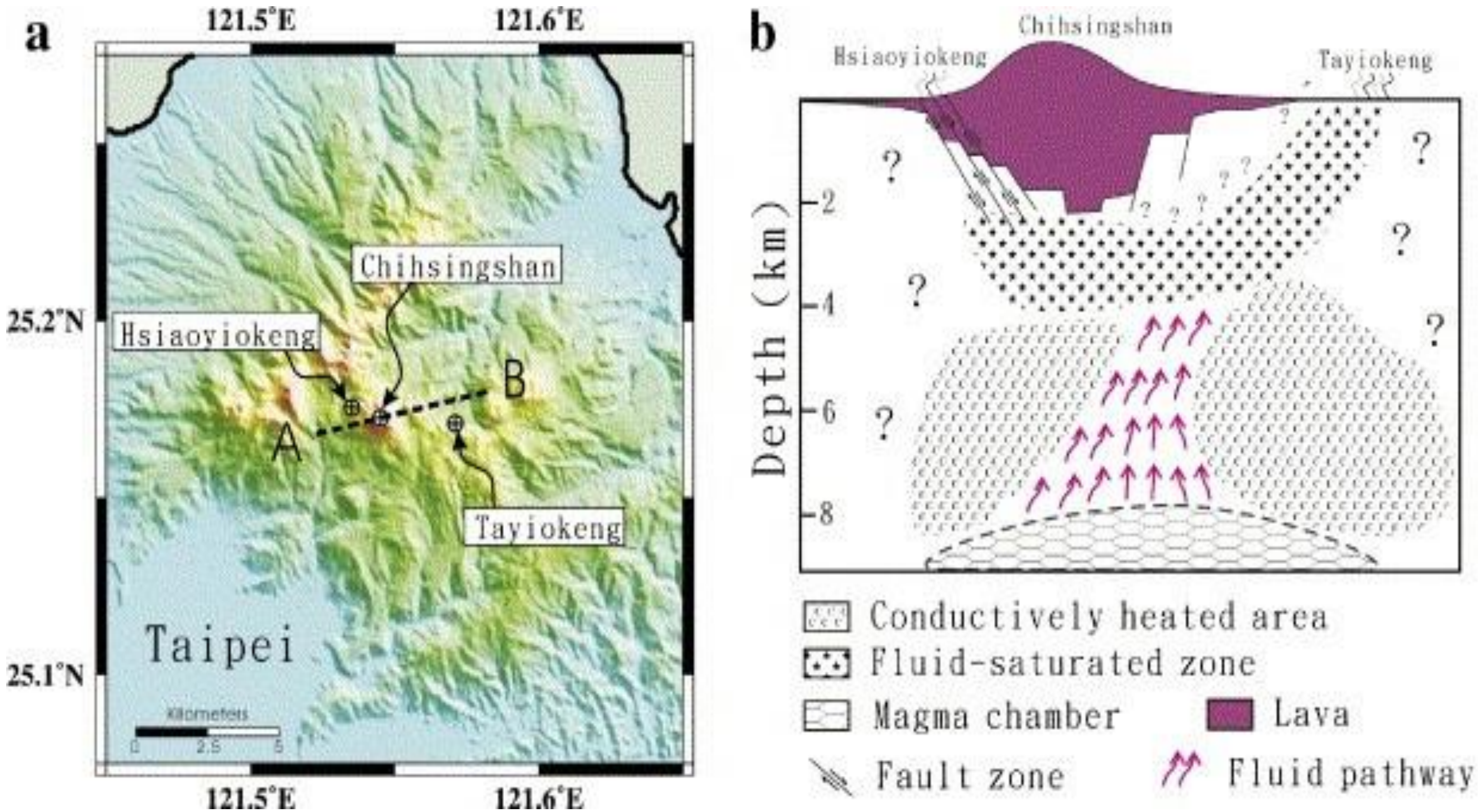
- Conclusion Remarks

Geography and DEM map of Tatun Volcanic Group (TVG)



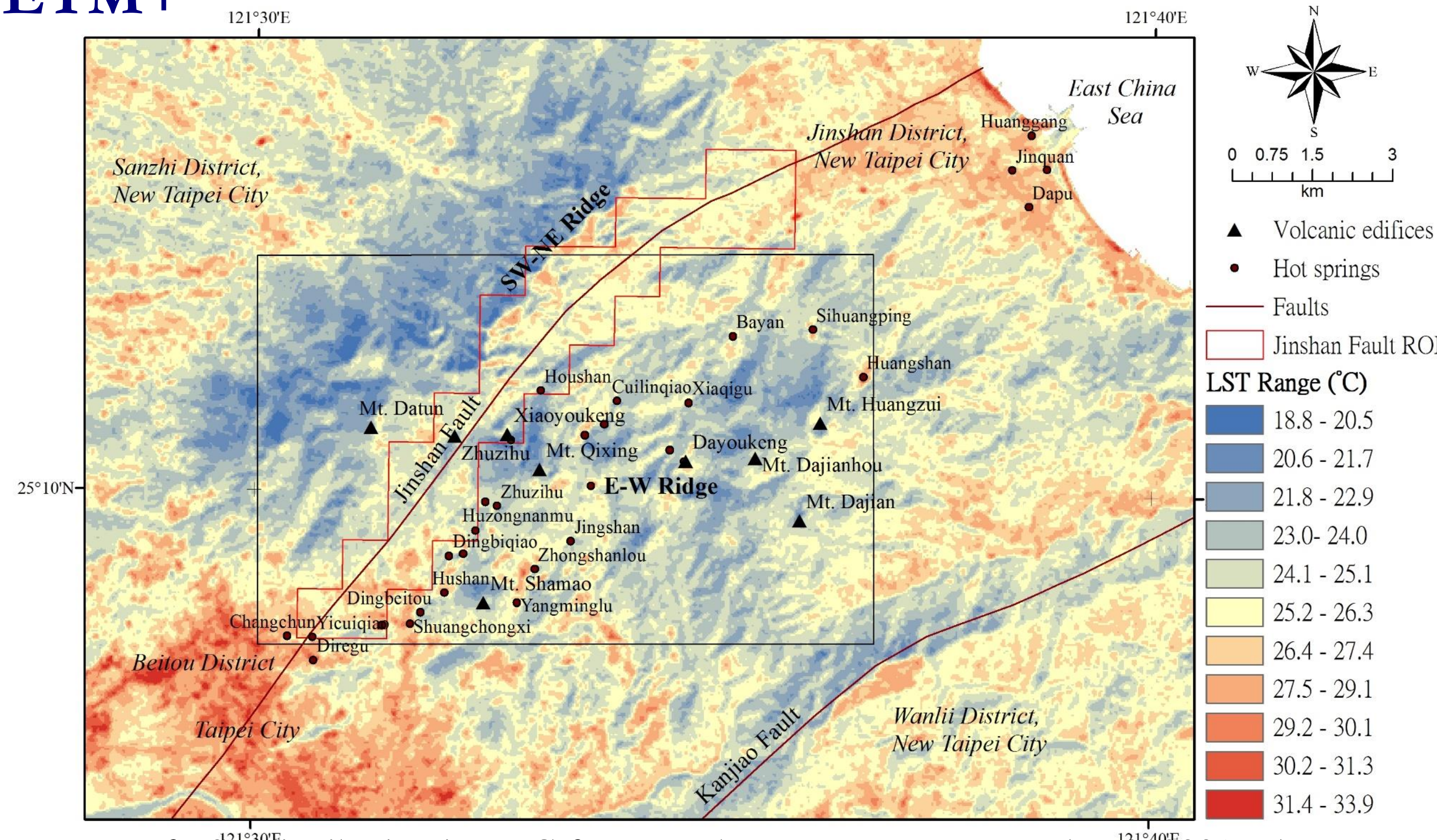
- Location and DEM map of Tatun Volcanic Group (TVG), Northern Taiwan. Main volcanic ridges, volcanoes, and hot springs are indicated.

A possible modal of the volcano–hydrothermal system beneath TVG



- (a) The approximate orientation of the cross-section AB in TVG area. (b) The possible profile of the volcano – hydrothermal system beneath the TVG (Konstantinou et al., 2007).

Pattern of LST distribution in TVG from Landsat 7 ETM+

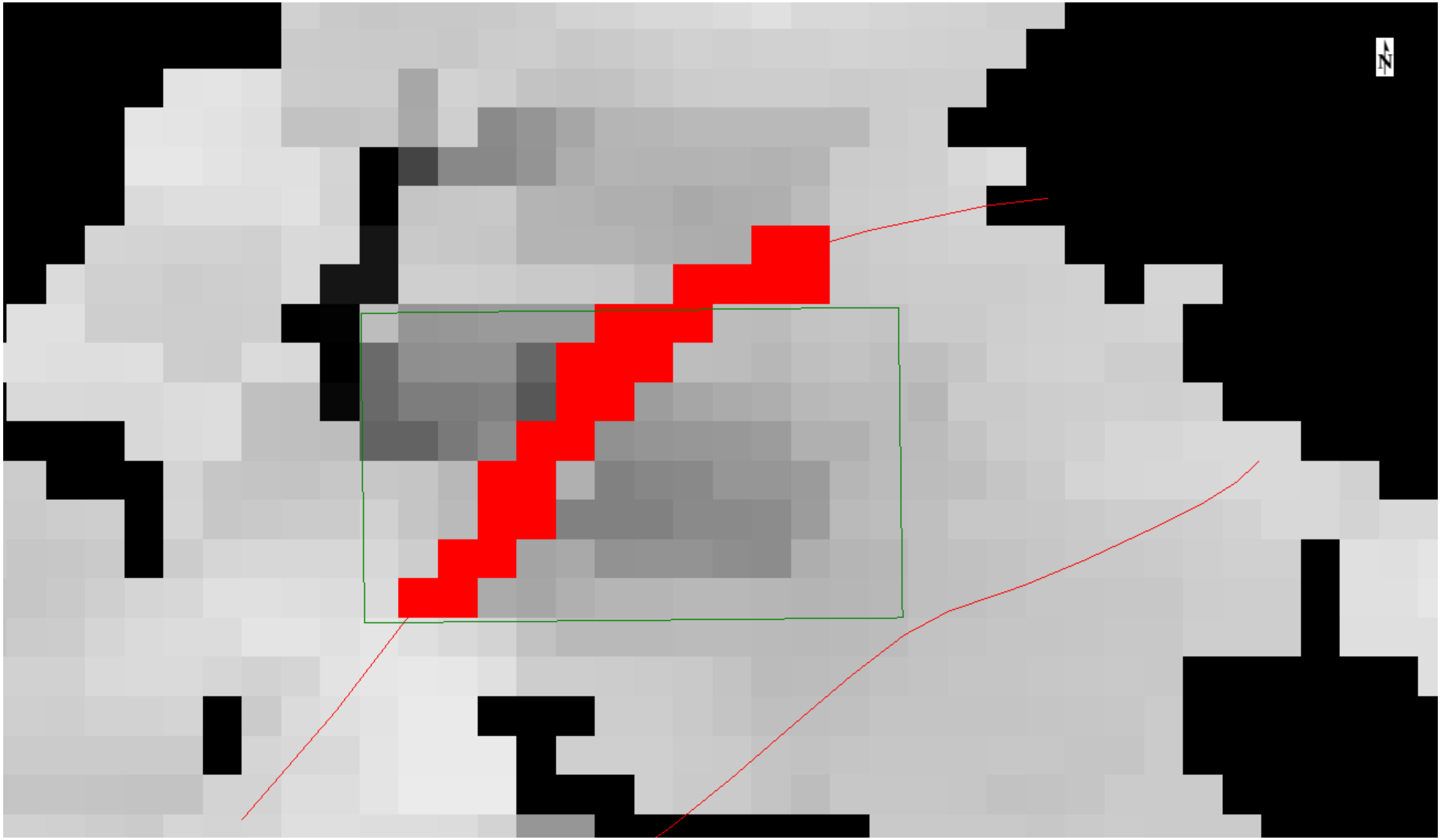


- Pattern of LST distribution in TVG from Landsat 7 ETM+ on December 3, 2001. The square shows the area of RHF. Specified polygonal region of interest (ROI) of Jinshan fault for the MODIS data analysis is displayed.

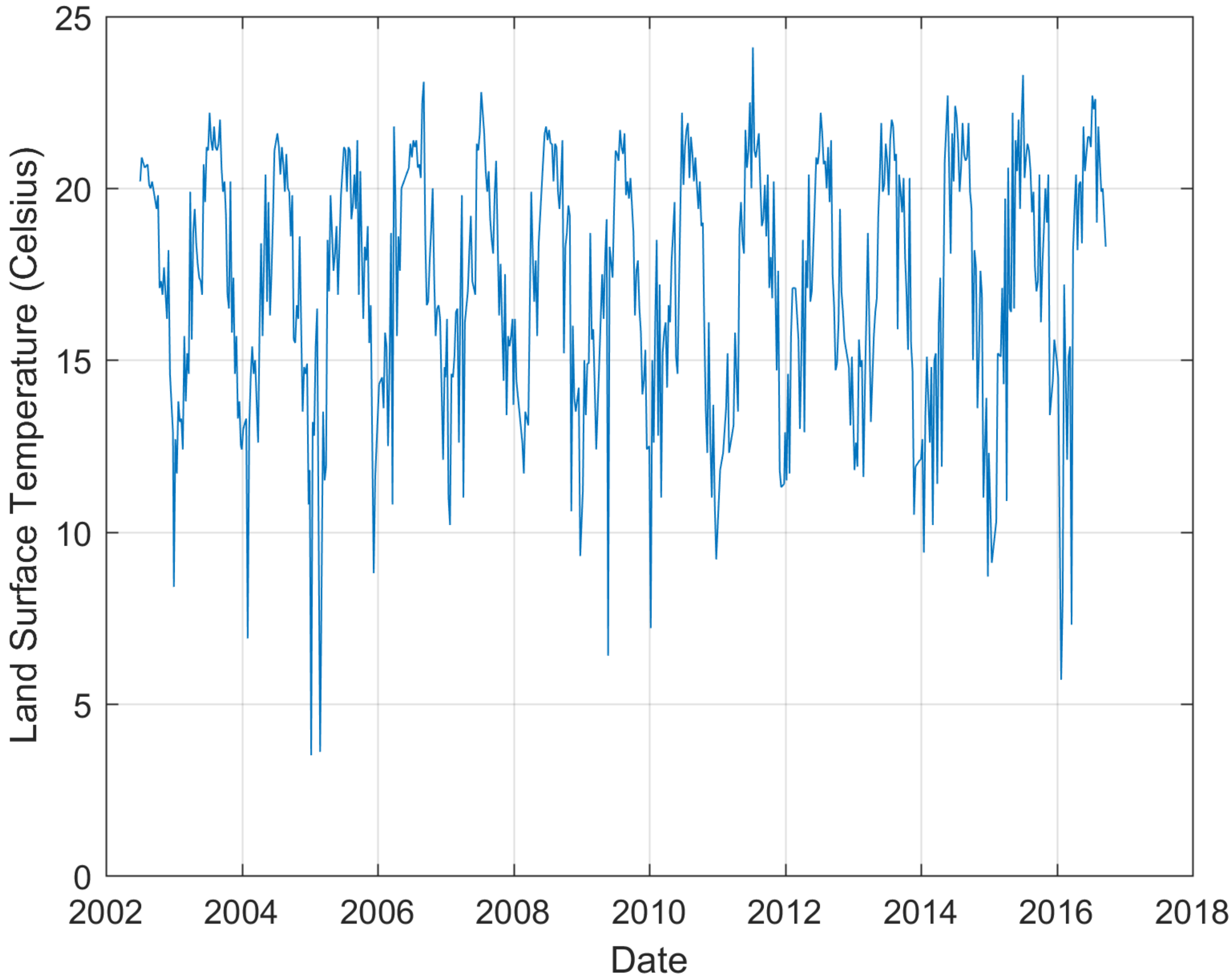
Landsat vs. MODIS LST data

	Landsat	MODIS
Spatial resolution	60m	1000m
Temporal resolution	16 days	1 day
Cloud contamination	Yes	Yes
LST products	No	8-day average LST (Accuracy better than 1K)

MODIS LST Imagery



LST from MODIS at Jinshan fault of TVG



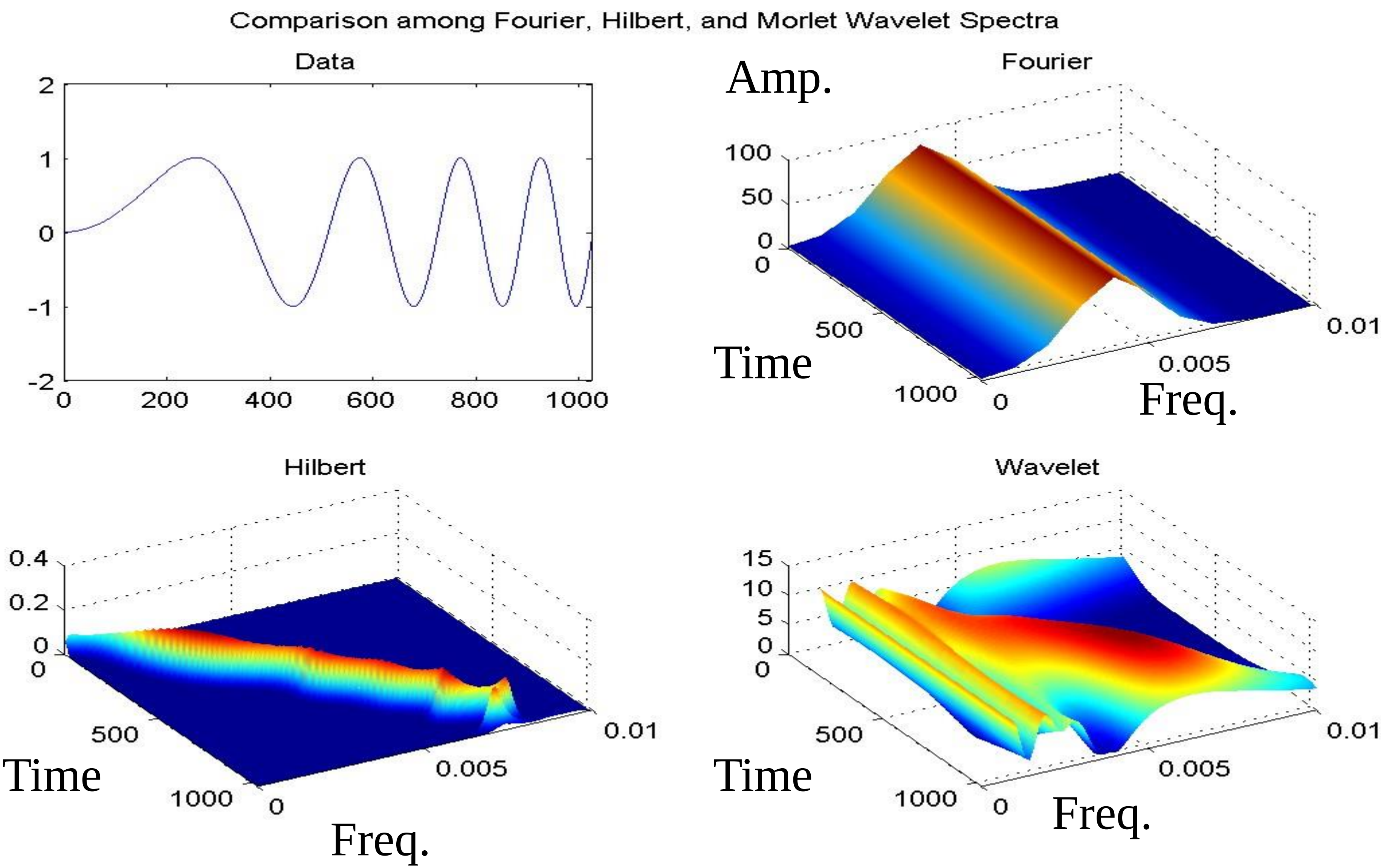
- Illustration of the LST from MODIS at Jinshan fault of TVG from 2002 to 2016.

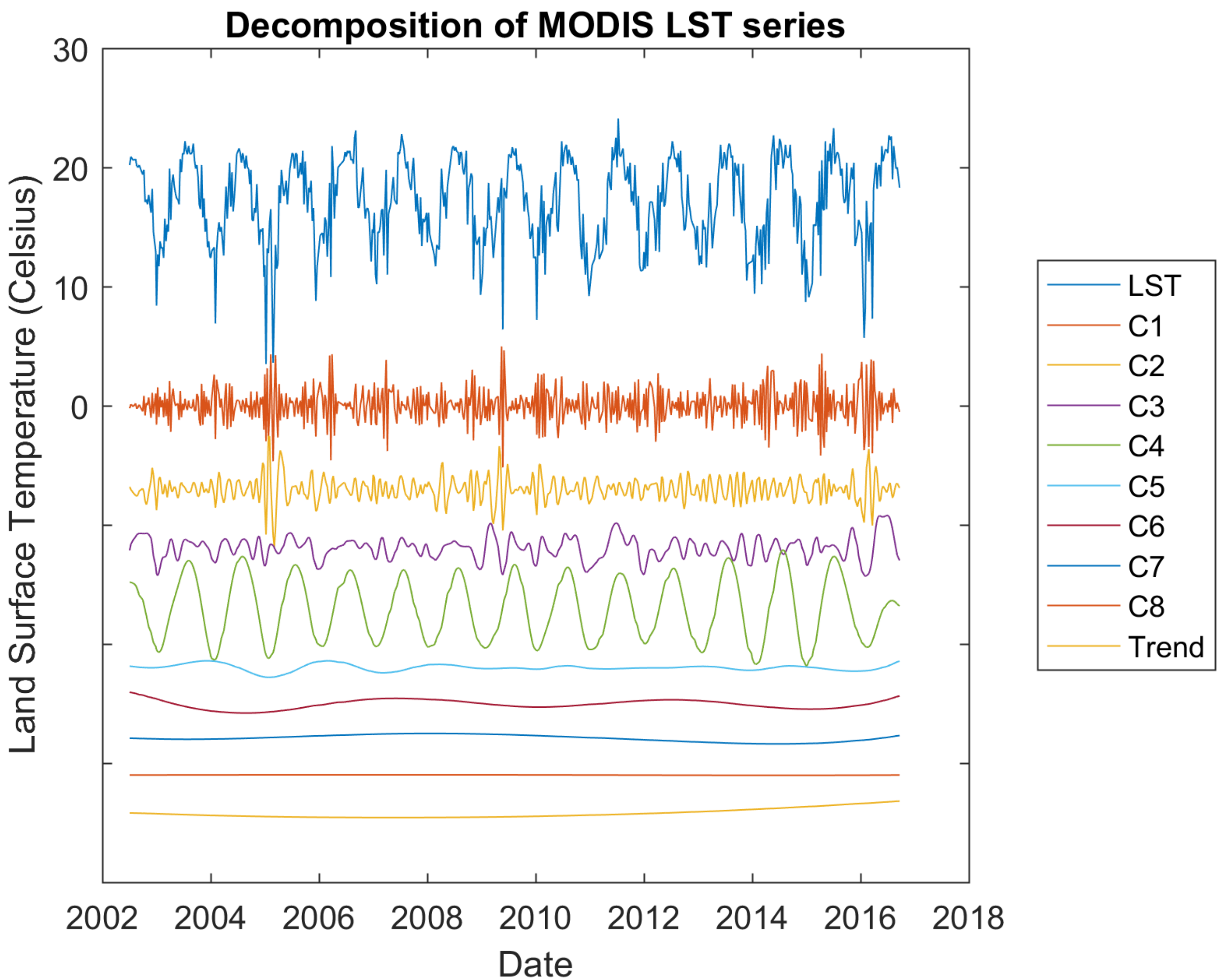
Hilbert-Huang Transform (HHT)

The purpose of HHT is to decompose MODIS LST time series into multiple components in the time domain, and each component is related to a specific physical process. The key part of HHT is EMD with which any complicated data set can be decomposed into multiple intrinsic mode functions (IMFs). Each IMF represents a narrow band frequency – amplitude modulation that is often related to a specific physical process.

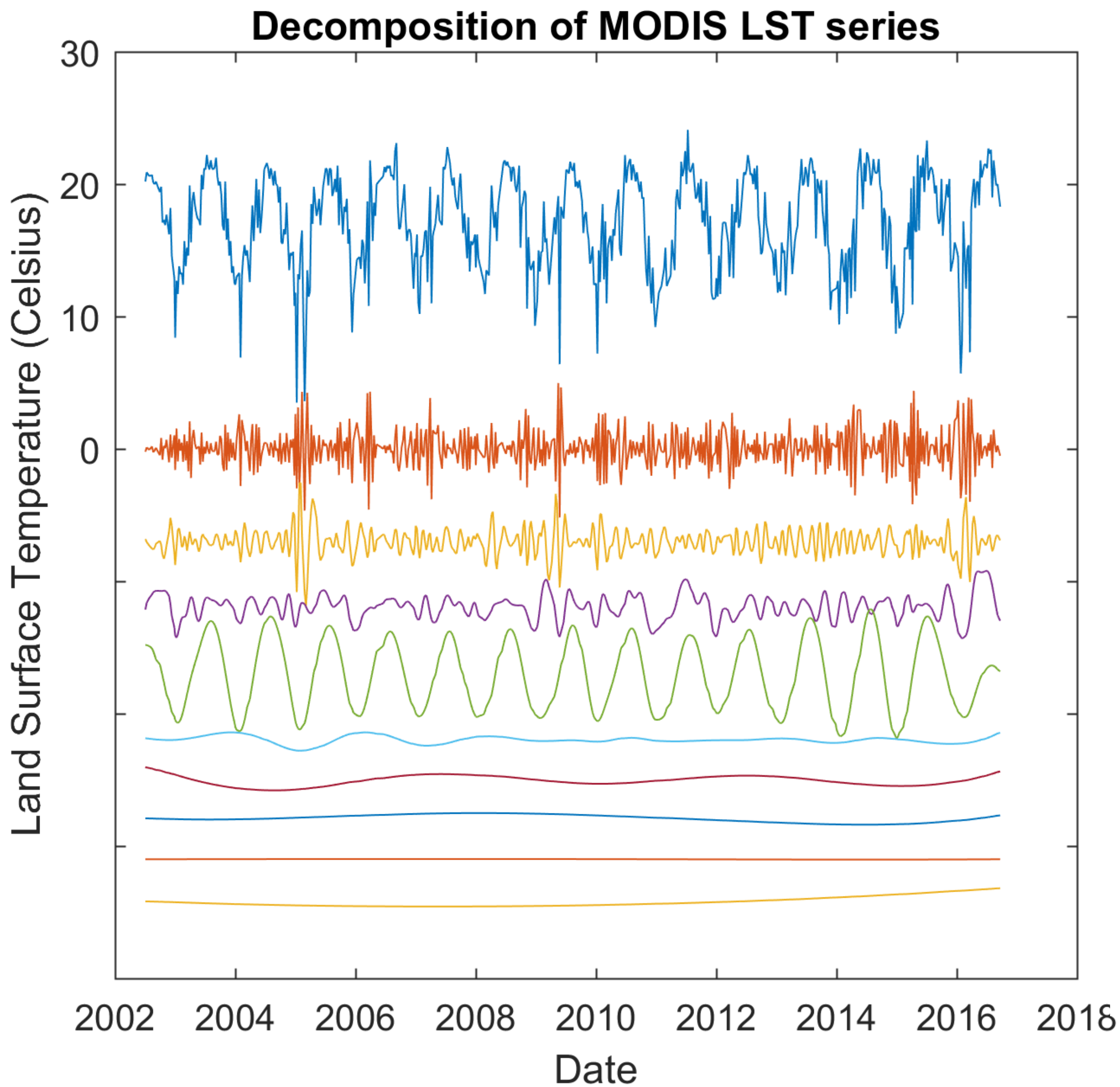
Huang, N. E., and Z. Wu (2008), A review on Hilbert-Huang transform: Method and its applications to geophysical studies, Rev. Geophys., 46, RG2006, doi:10.1029/2007RG000228.

Comparisons: Fourier, Hilbert & Wavelet





- EEMD decomposition of the MODIS LST dataset from 2002 to 2016. The top plot is the MODIS LST data, C1-C8 are the decomposed components, and the bottom plot is the trend.



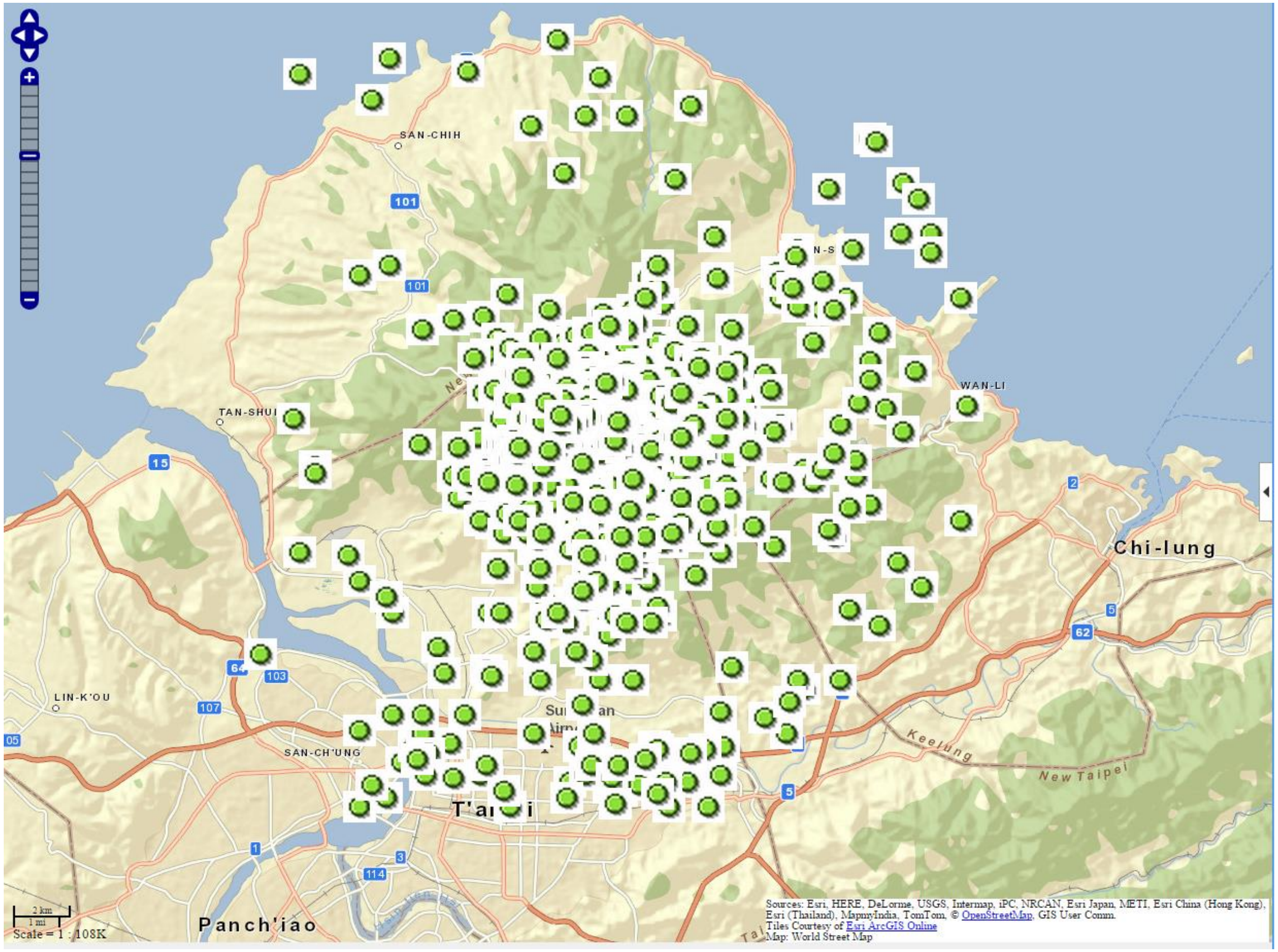
Dominant Frequency

(average period)

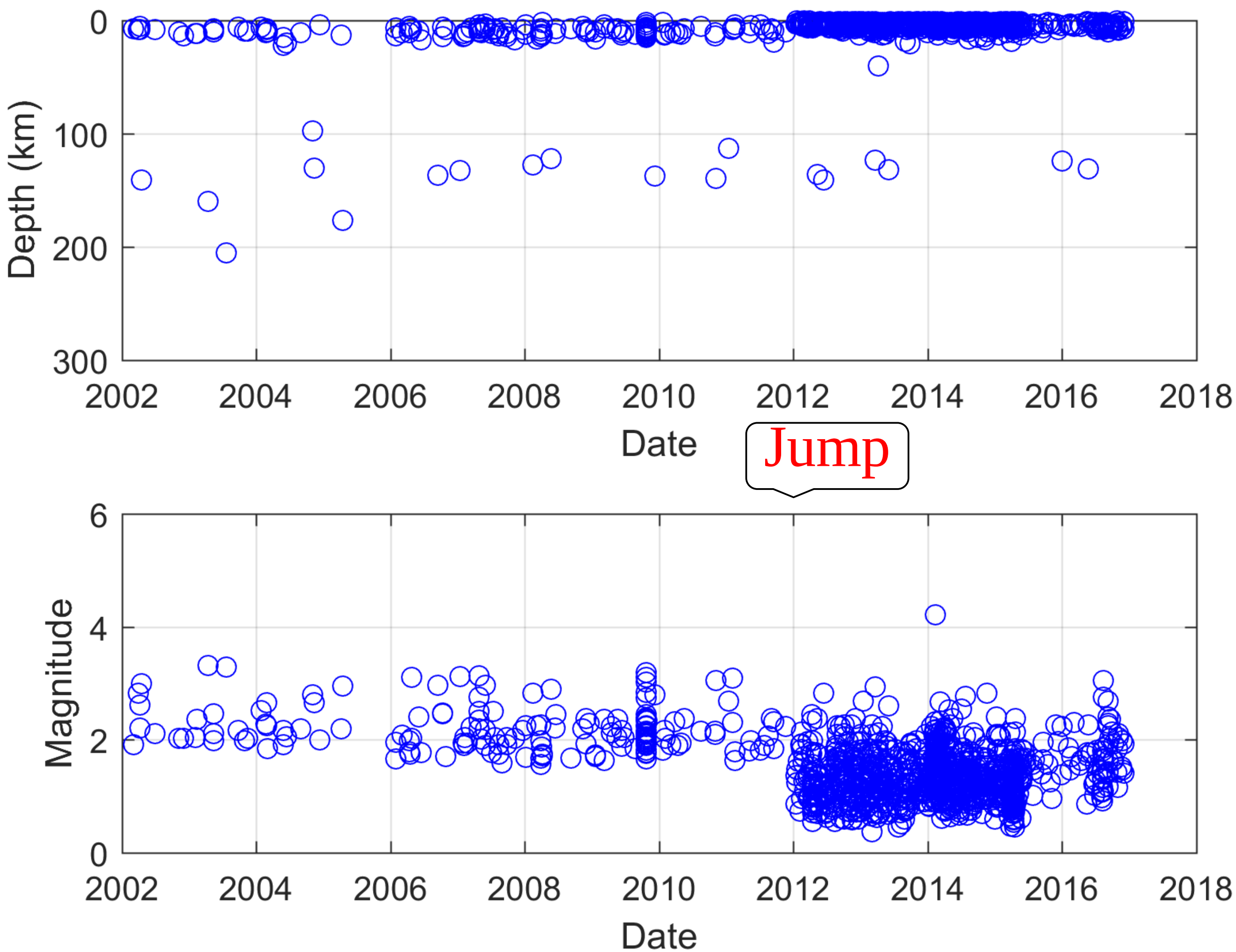
370 days (one year)

C1: 23 days (a month)
C2: 75 days (two months)
C3: 121 days (one third year)
C4: 370 days (one year)
C5: 740 days (quasi-biannual)
C6: 1728 days (half a decade)
C7: 5081 days (one and half decade)
C8: ~ Infinity (few decades and longer)
Trend

Map showing earthquake catalog with epicenters distributed within 15 km centered at Mt. Qixing. The solid green circles indicate the earthquake epicenters.



Earthquake catalog in TVG (2002-2016)

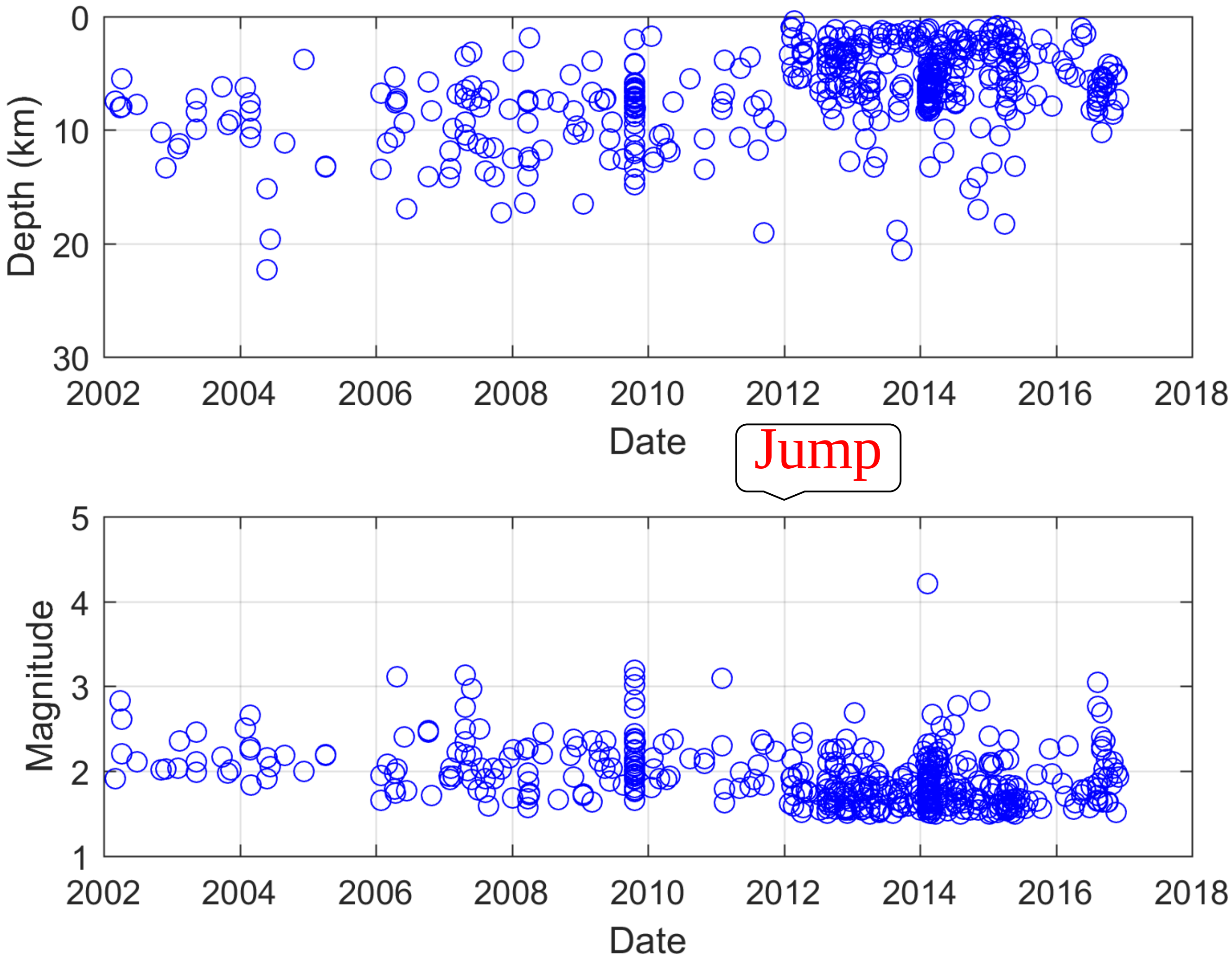


Earthquakes with epicenter distributed within 15 km centered at Mt. Qixing were selected

CWB updated all 16-bit (resolution) seismographs to 24-bit in 2012.

- Magnitude-depth plot (top) and magnitude-time plot (bottom) in TVG from Central Weather Bureau (CWB) earthquake catalog.

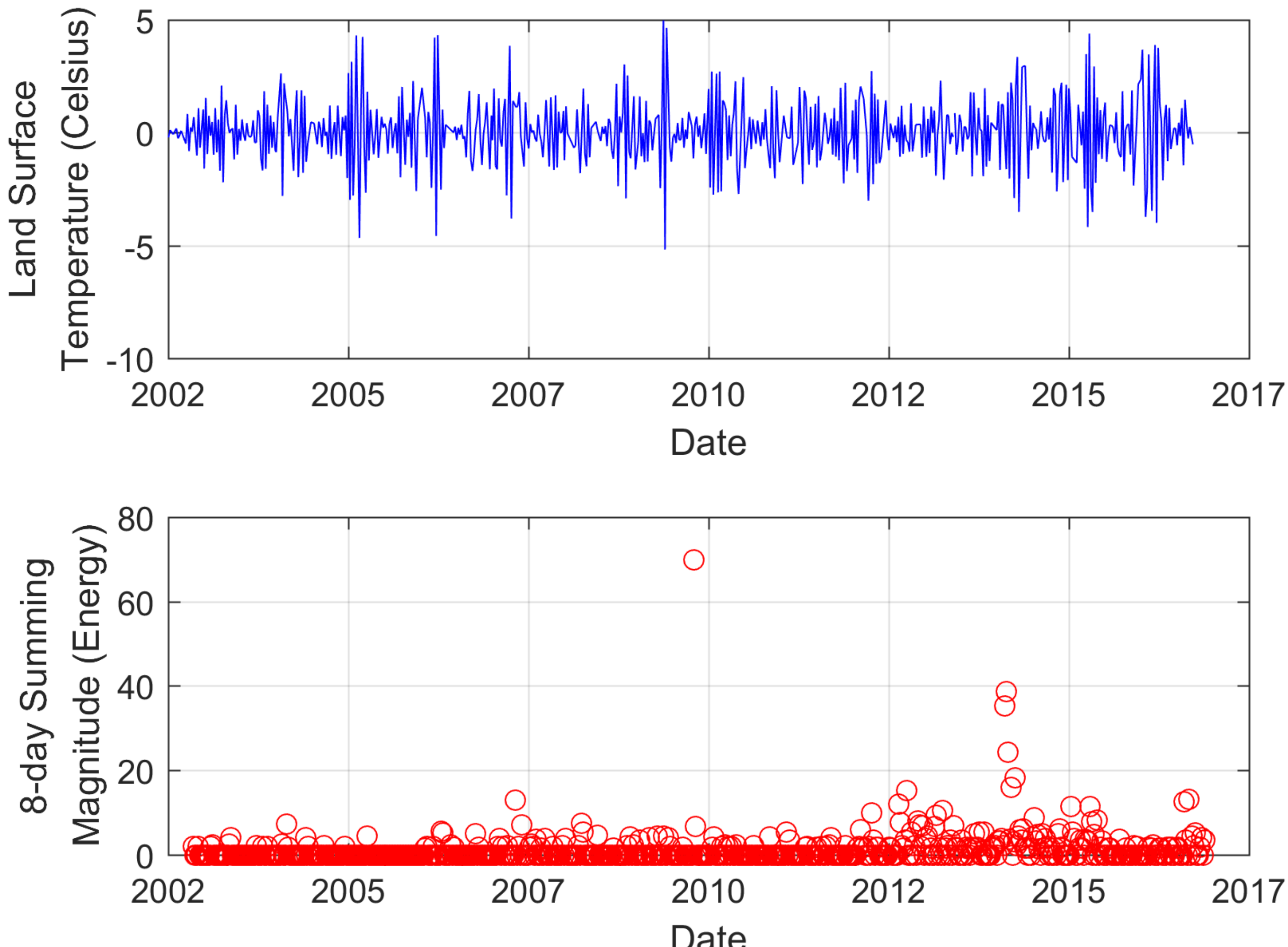
Earthquake catalog in TVG (2002-2016)



Most of the magnitude are smaller than 4. Earthquakes with magnitude less than 1.5 or depth more than 30 km are omitted in this figure and discarded for further analysis.

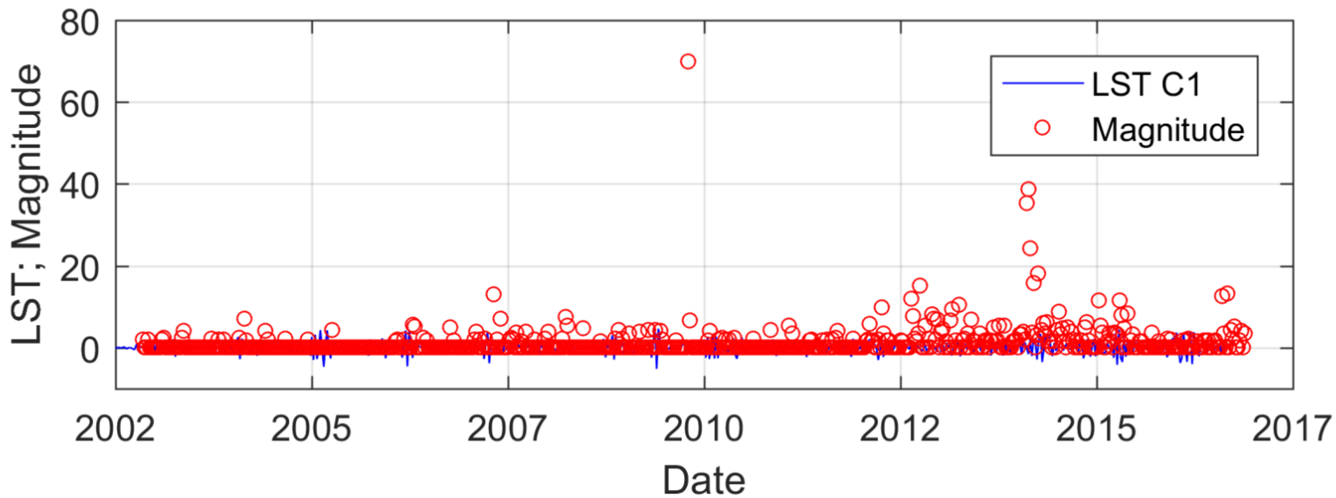
- Magnitude-depth plot (top) and magnitude-time plot (bottom) in TVG from Central Weather Bureau (CWB) earthquake catalog.

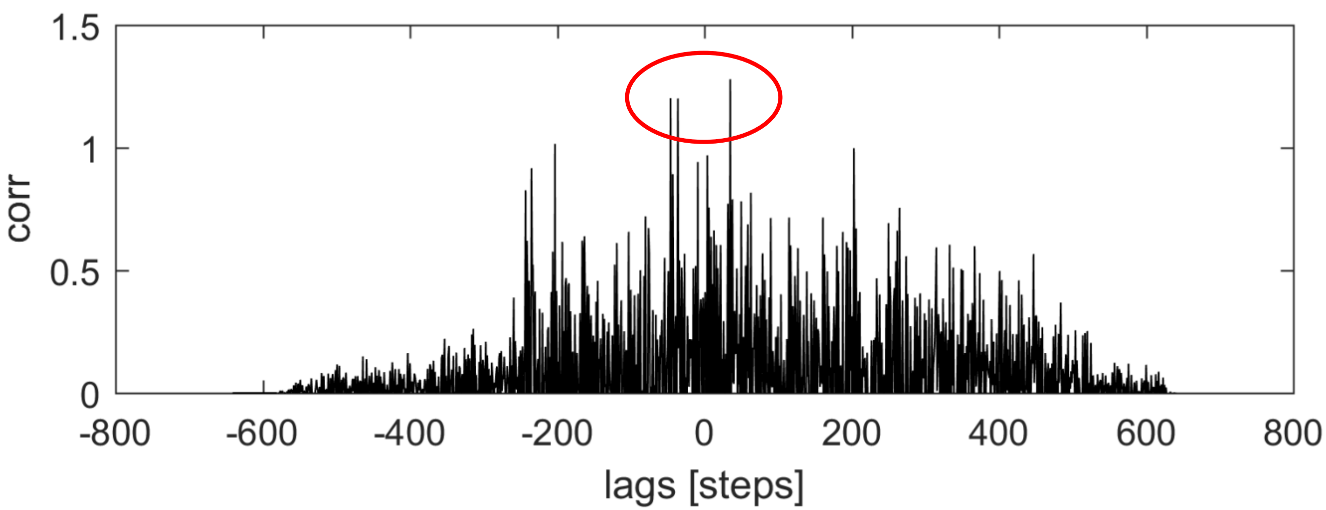
Comparison between C1 and earthquakes magnitude



- Comparison between the first EEMD component C1 and earthquake 8-day summing magnitude series.

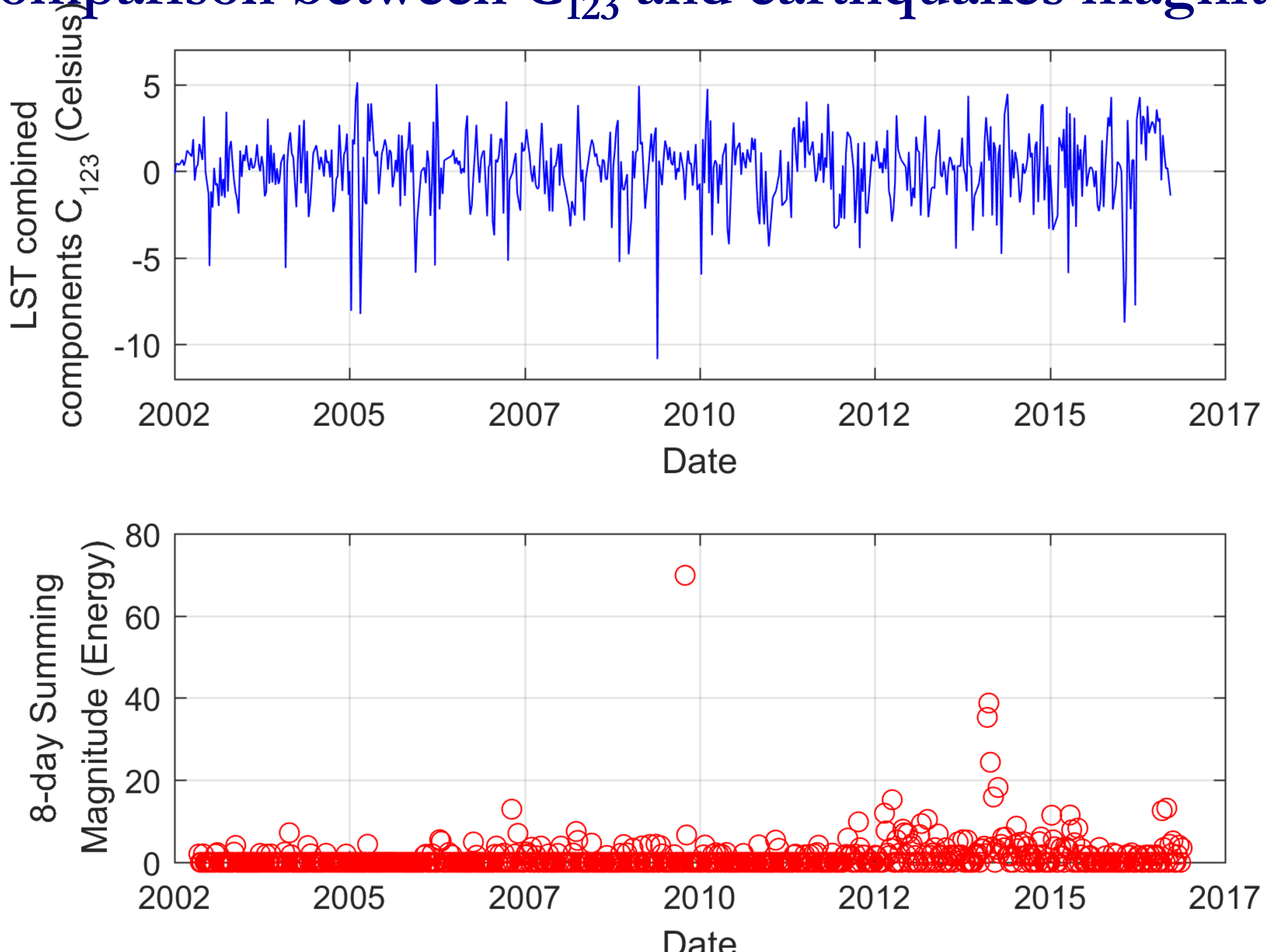
Cross correlation of C1 and earthquakes magnitude





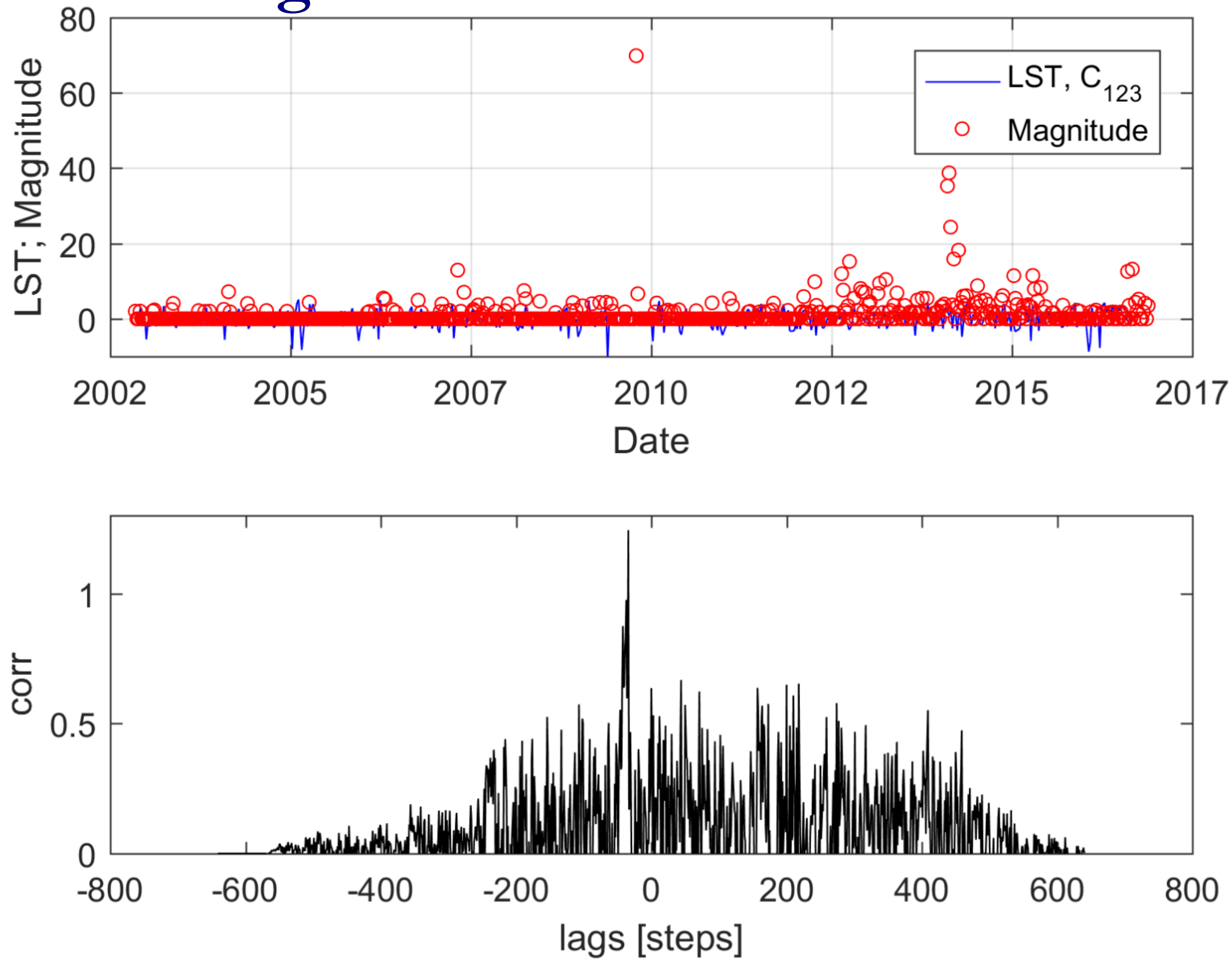
- Cross correlation of the first EEMD component C1 and earthquake 8-day summing magnitude series. The time delay of the peak value is 35 days.

Comparison between C_{123} and earthquakes magnitude

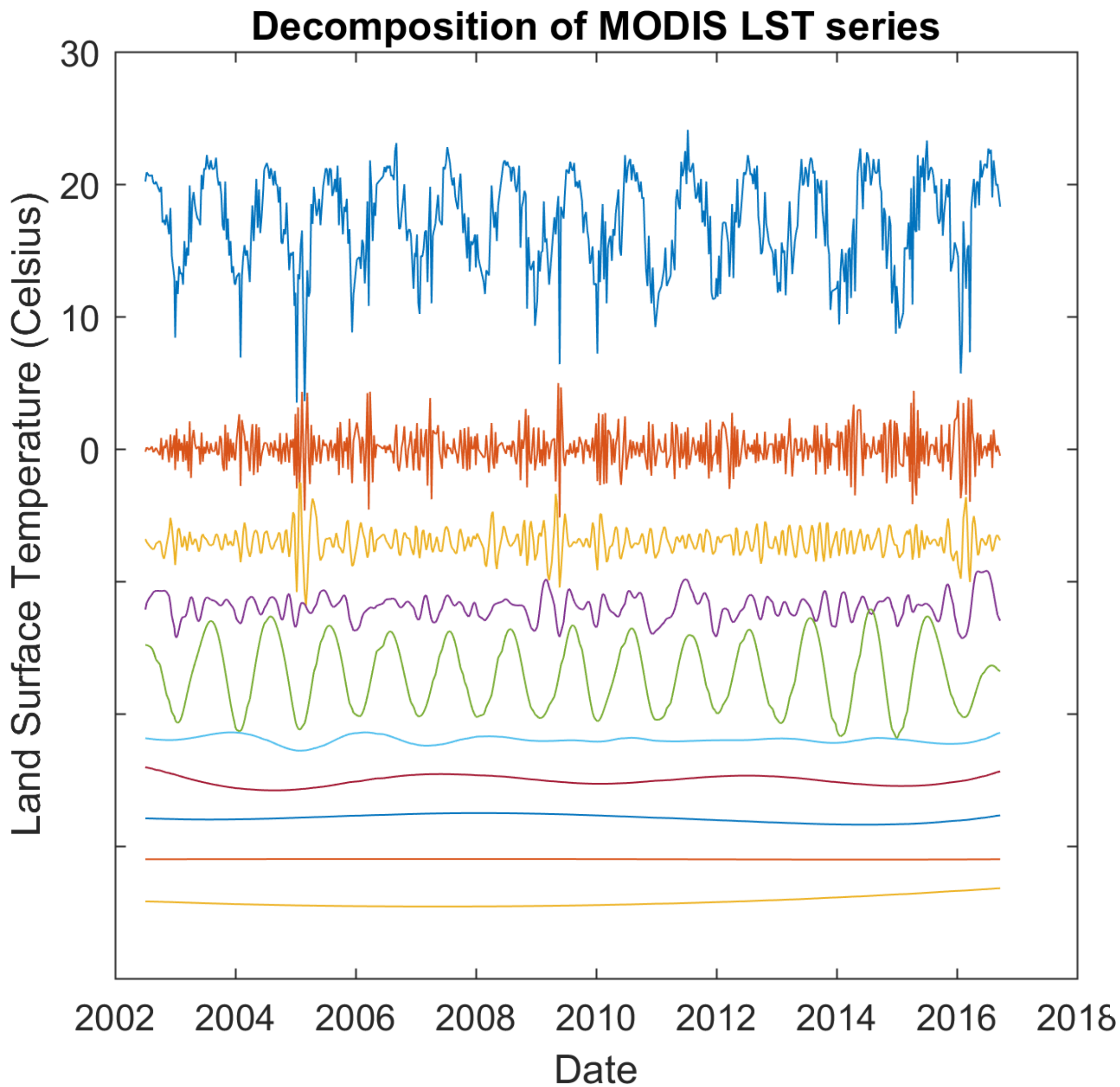


- Comparison between the first EEMD component C1 + C2 + C3 and earthquake 8-day summing magnitude series.

Cross correlation of C_{123} （C1 + C2 + C3） and earthquakes magnitude



- Cross correlation of the combined short period EEMD components C_{123} and earthquake 8-day summing magnitude series. The peak in the correlogram indicates the similarity and time delay of the peak value is -34 days. It means delay LST by -34 days to match with earthquake occurrences.



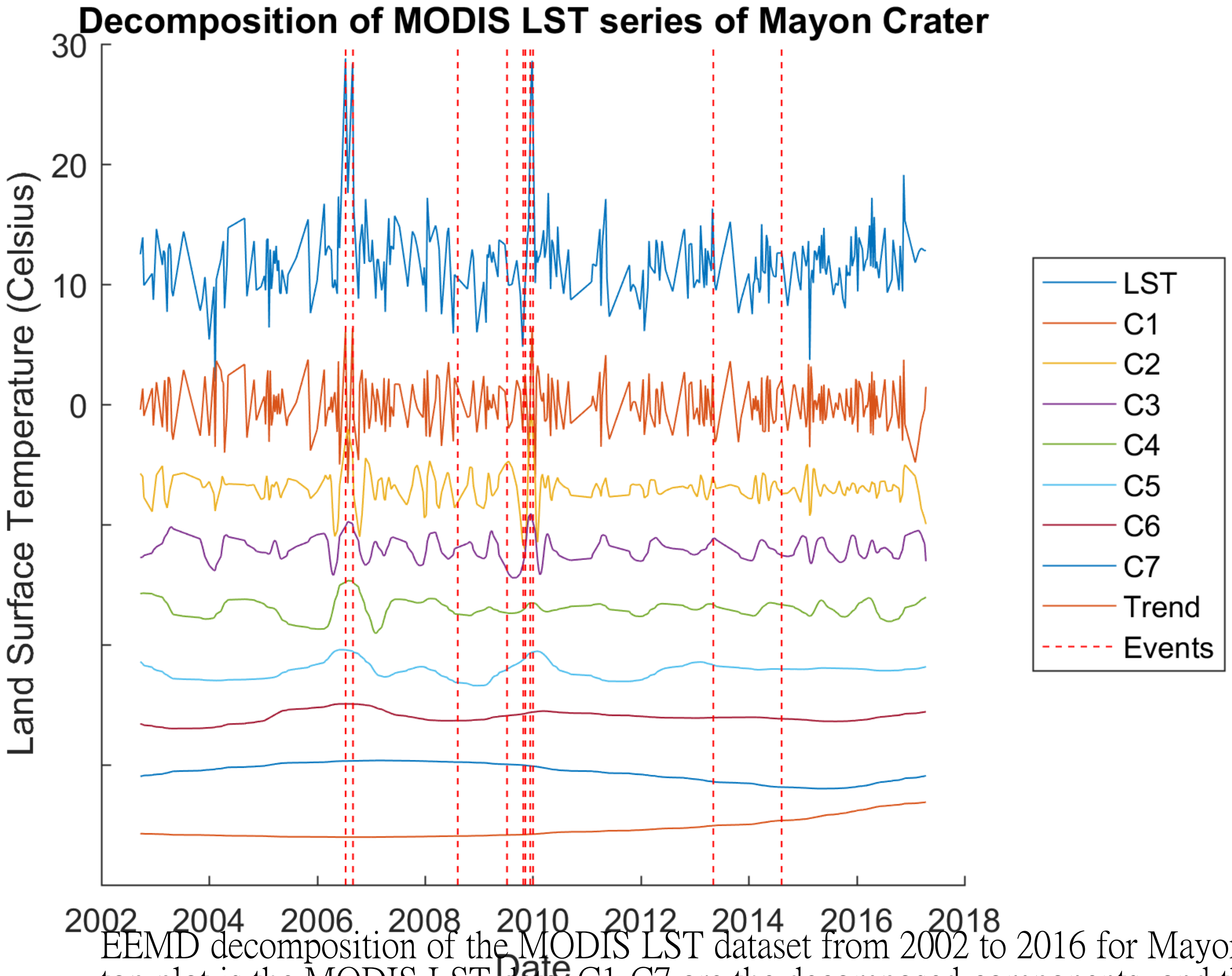
Dominant Frequency

(average period)

370 days (one year)

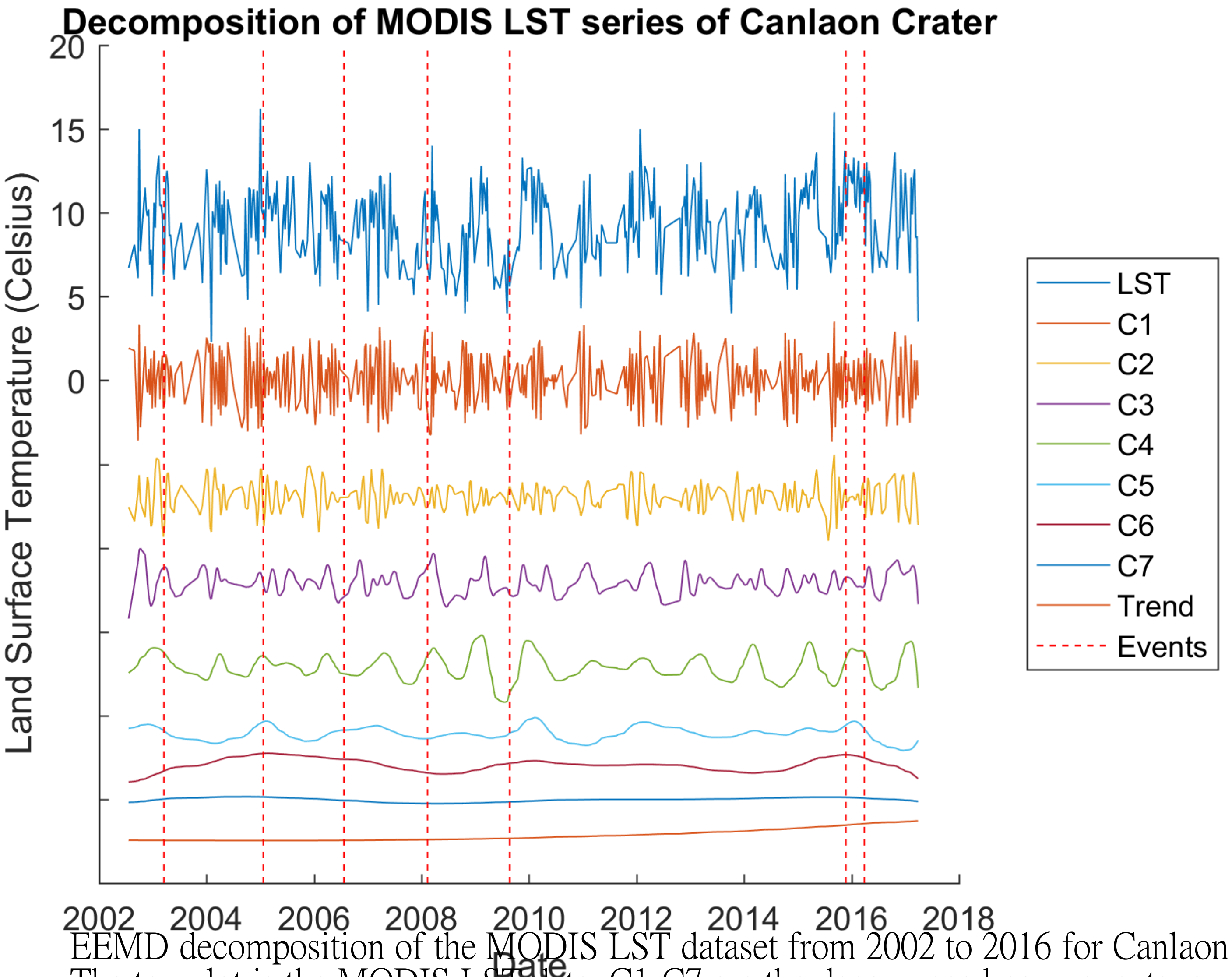
C1: 23 days (a month)
C2: 75 days (two months)
C3: 121 days (one third year)
C4: 370 days (one year)
C5: 740 days (quasi-biannual)
C6: 1728 days (half a decade)
C7: 5081 days (one and half decade)
C8: ~ Infinity (few decades and longer)
Trend

HHT comparison analysis with active volcanoes in Philippines and Indonesia



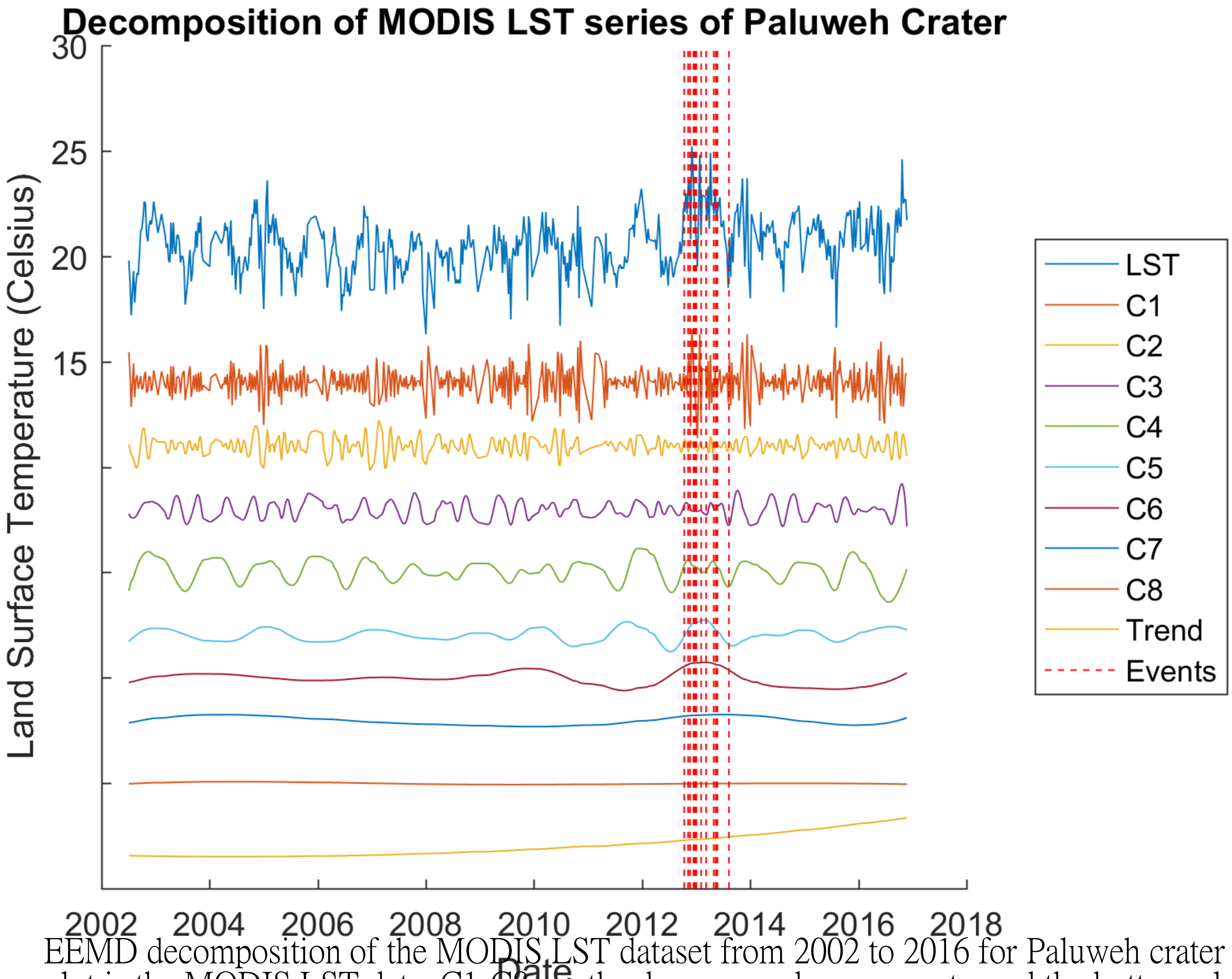
EEMD decomposition of the MODIS LST dataset from 2002 to 2016 for Mayon crater of Philippines. The top plot is the MODIS LST data, C1-C7 are the decomposed components, and the bottom plot is the trend. Vertical dashed red lines indicate the recorded eruptions and volcanic earthquake events.

HHT comparison analysis with active volcanoes in Philippines and Indonesia



EEMD decomposition of the MODIS LST dataset from 2002 to 2016 for Canlaon crater of Philippines. The top plot is the MODIS LST data, C1-C7 are the decomposed components, and the bottom plot is the trend. Vertical dashed red lines indicate the recorded eruptions and volcanic earthquake events.

HHT comparison analysis with active volcanoes in Philippines and Indonesia



EEMD decomposition of the MODIS LST dataset from 2002 to 2016 for Paluweh crater of Indonesia. The top plot is the MODIS LST data, C1-C8 are the decomposed components, and the bottom plot is the trend. Vertical dashed red lines indicate the recorded eruptions and volcanic earthquake events.

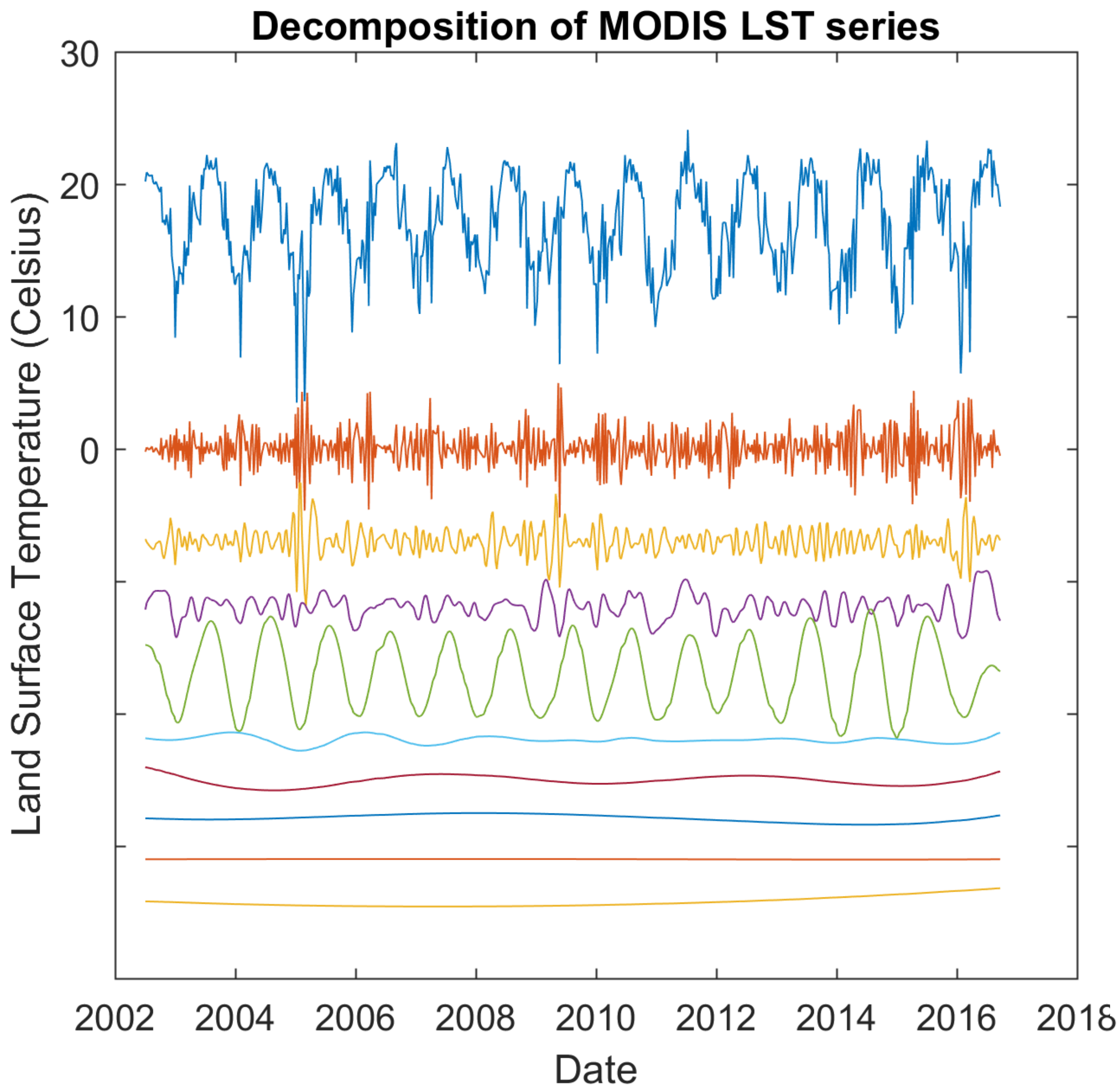
Summary of HHT comparison

- Short period components (one to two month) C1 and C2 are responsive to the volcano eruptions.

- LST appears an increasing tendency while the eruption occurs in Mayon volcano and Paluweh volcano. However, the match between the eruptions and high LST is not consistent in all cases.

  Reason: Data deficiency, scale mismatch, etc.

- LST decomposition C4 (Component 4 with annual period) from currently active volcanoes tend to loss the regularity if eruption occurs. It implies that the deviation of C4 from regular annual cycle can be an indicator of the level of restless of active volcanoes. ➔ regular C4 annual cycle of TVG's LST time series indicates indicates the TVG's current status is quite calm and resting and with no sign of eruption for decades in future.



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Trend

Outline

- Introduction to Geothermal Energy in Taiwan and Thermal Infrared (TIR) remote sensing
- Geothermal Anomaly Mapping Using Landsat ETM+ data in Ilan Plain
- Exploring and monitoring geothermal and volcanic activity using Satellite Thermal Infrared data in Tatun Volcanic Group (TVG)
- Conclusion Remarks

Closing

- LST thermal anomalies have close spatial correlation to faults, thermal springs, and high heat flow area such as fumaroles .
- Integration of thermal infrared data with geological and geophysical data is applicable to the geothermal exploration and volcanic study in Taiwan.

Work in the Field

- “**Geothermal Anomaly Mapping Using Landsat ETM+ data in Ilan Plain, Northeastern Taiwan**” - [Pure and Applied Geophysics 2017, doi: 10.1007/s00024-017-1690-z]

- “**Exploring and monitoring geothermal and volcanic activity using Satellite Thermal Infrared data in TVG, Taiwan**” - [Terr. Atmos. Ocean. Sci., 29, 1-18, doi: 10.3319/TAO.2018.01.22.01]

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THANK YOU FOR LISTENING

ANY QUESTIONS?
COMMENTS?