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# A comprehensive observational database of deformation at global volcanoes for machine learning applications

Lin Shen, Andrew Hooper, Milan Lazecký, Matthew Gaddes, Camila Novoa Lizama,  
Susanna Ebmeier, Scott Watson, Yasser Maghsoudi, Richard Rigby

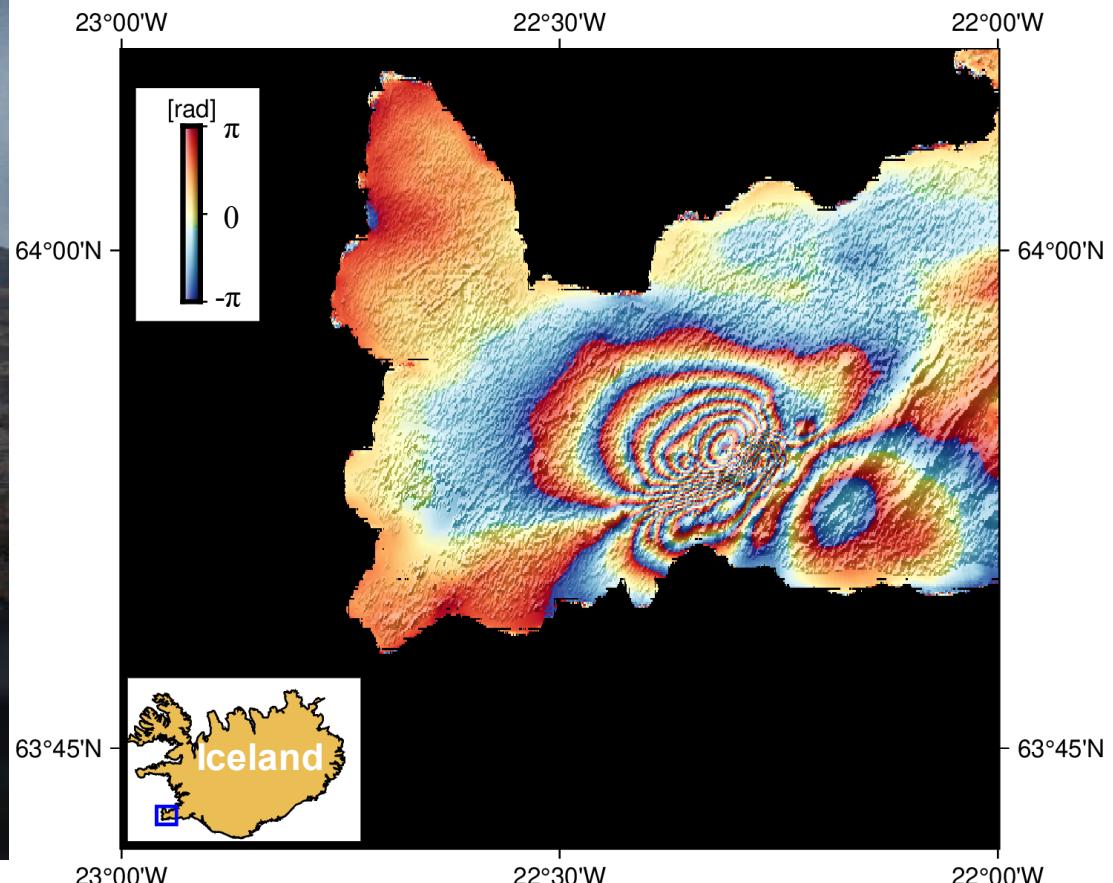
COMET, School of Earth and Environment, University of Leeds

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# Satellite measurements of deformation using InSAR include a high proportion of inter- and pre-eruptive signals



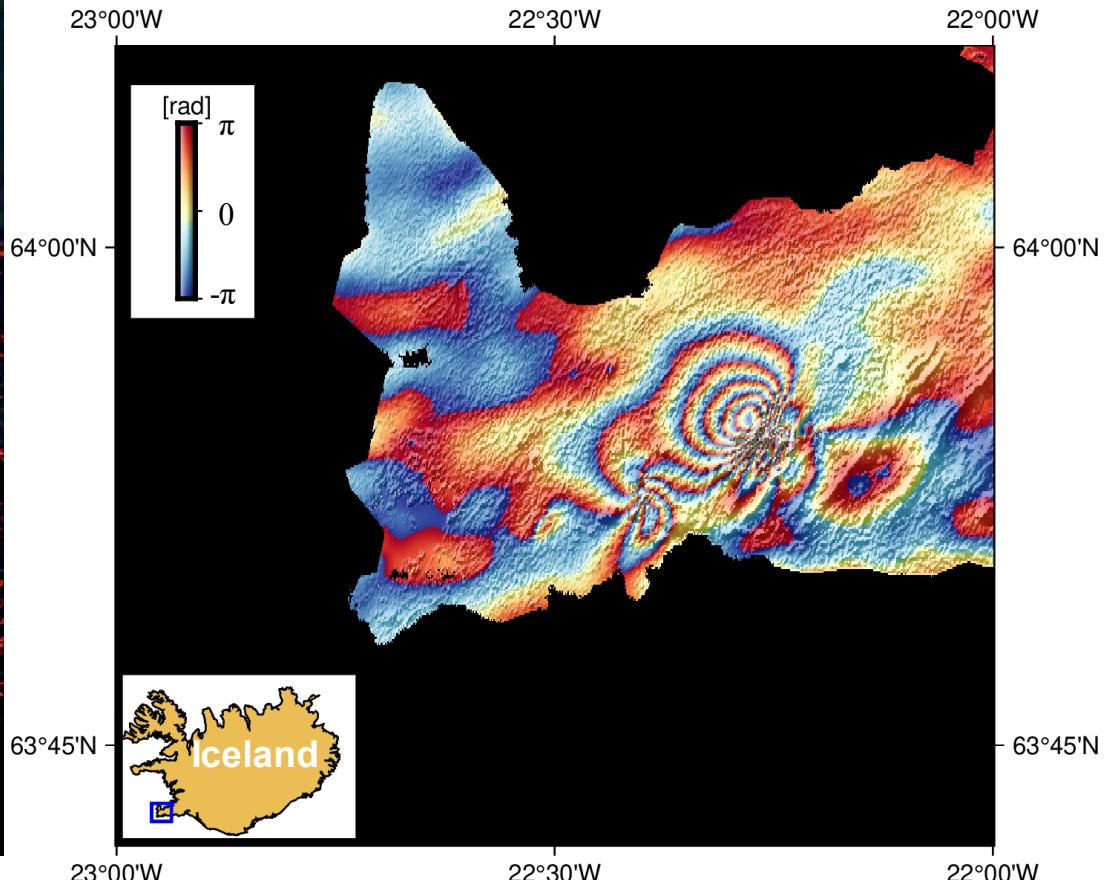
**Sentinel-1 interferogram, Reykjanes  
03 Mar 2021 to 15 Mar 2021**



# Satellite measurements of deformation using InSAR include a high proportion of inter- and pre-eruptive signals



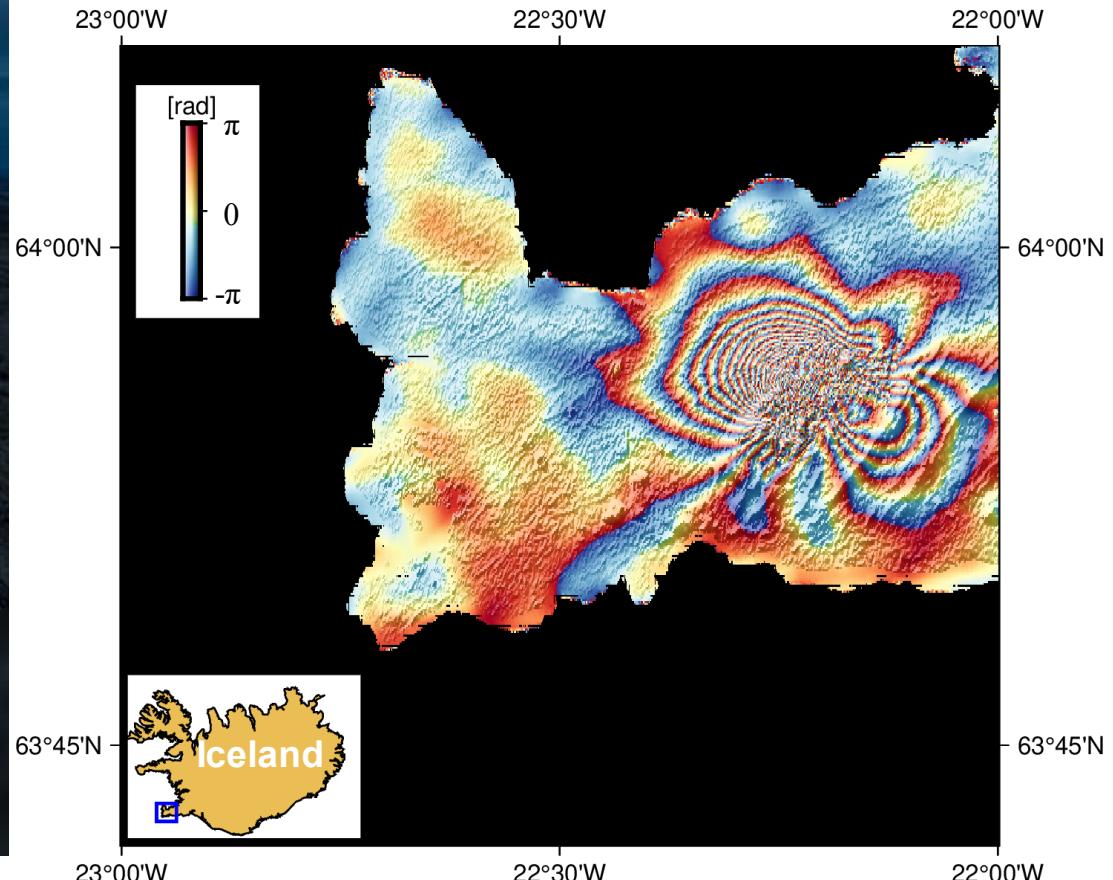
**Sentinel-1 interferogram, Reykjanes  
20 Jul 2022 to 1 Aug 2022**



# Satellite measurements of deformation using InSAR include a high proportion of inter- and pre-eruptive signals



**Sentinel-1 interferogram, Reykjanes  
03 Jul 2023 to 15 Jul 2023**

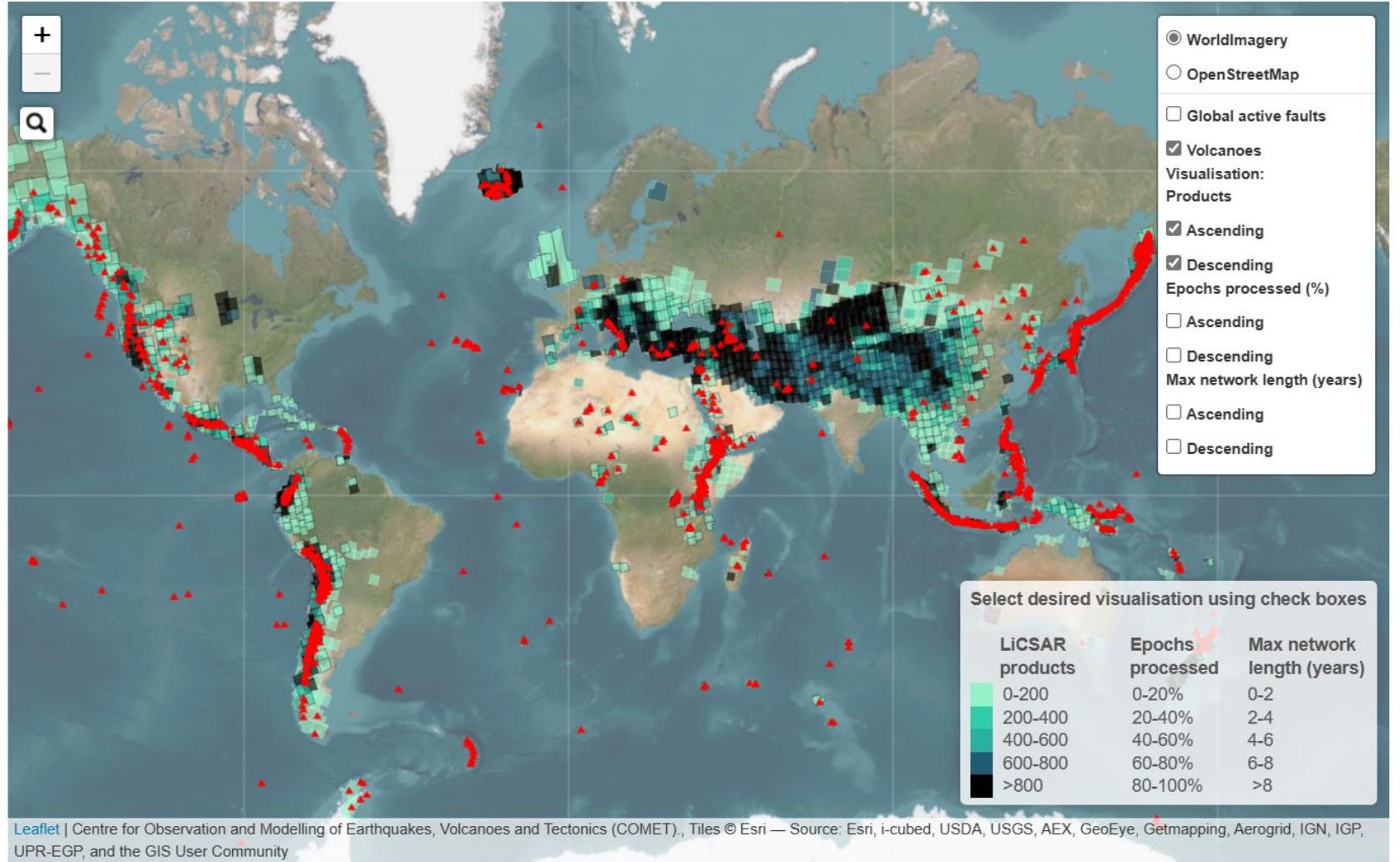


# Towards volcano deformation monitoring using InSAR



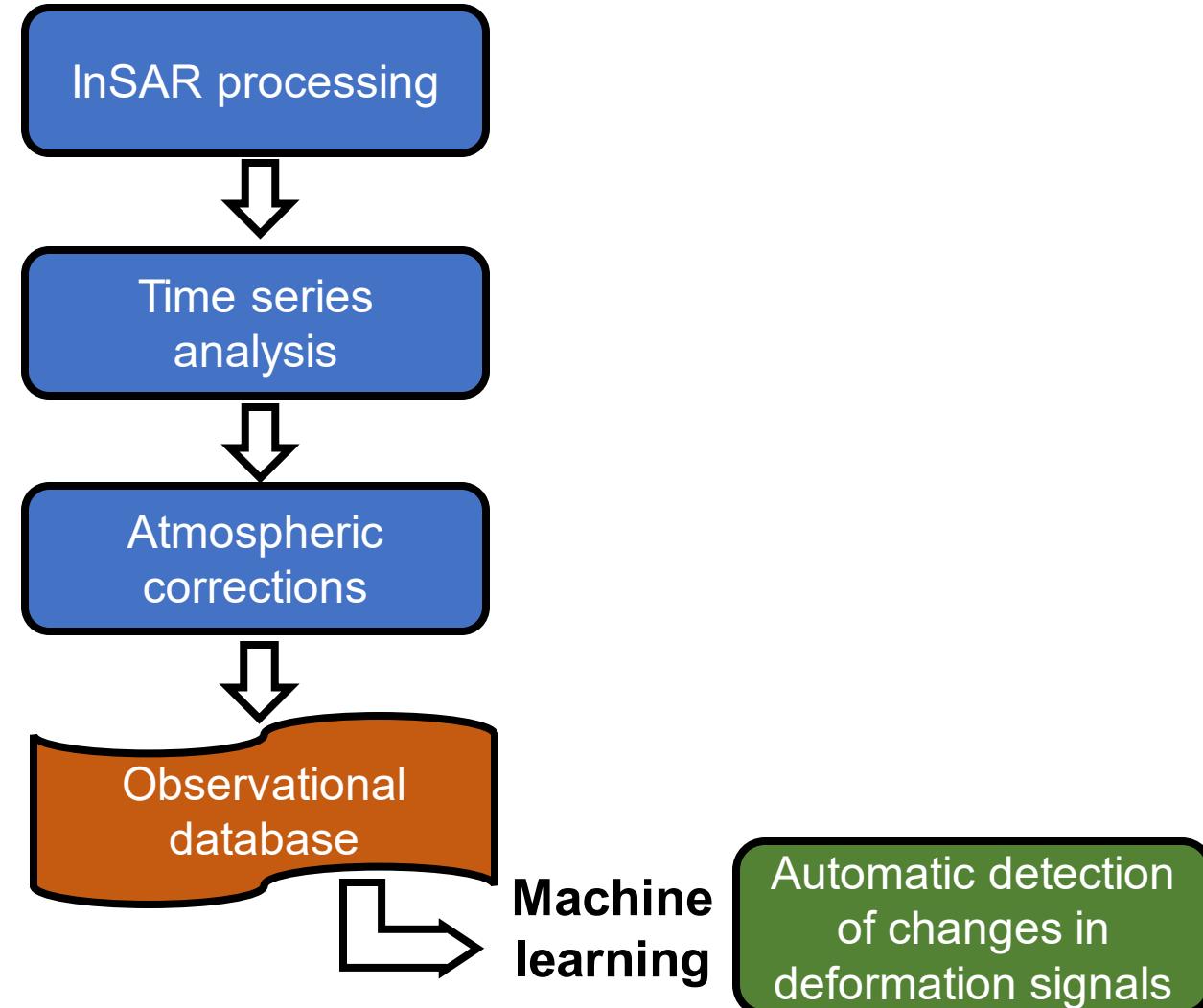
COMET- LiCS Sentinel-1 InSAR Portal

- ❖ Data collected systematically every 6 or 12 days, and available within hours
- ❖ Allow the generation of interferograms over all active volcanoes as soon as Sentinel-1 SLC data is delivered from ESA

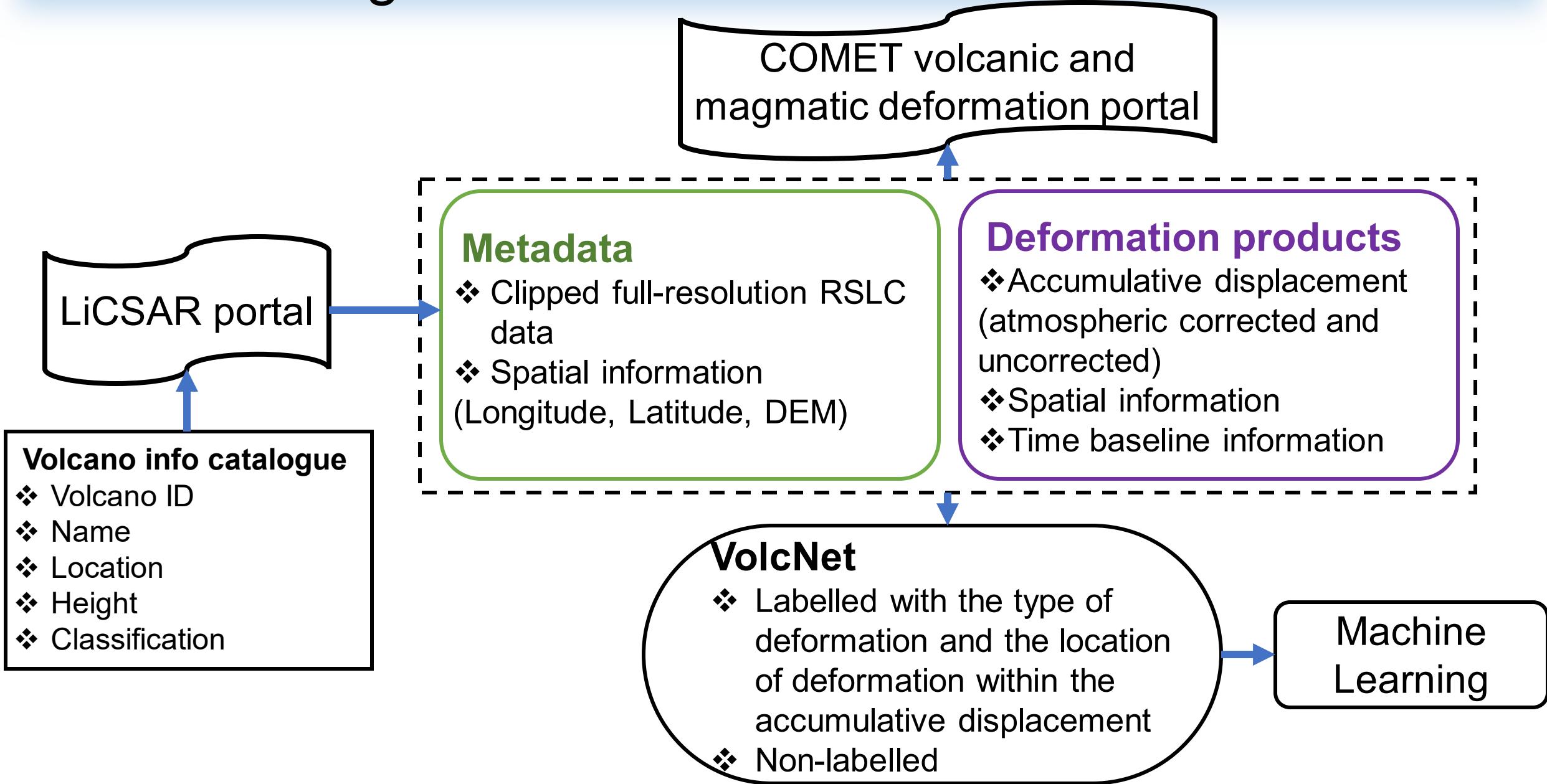


# An automatic processor to derive high-resolution displacement time series over global subaerial volcanoes

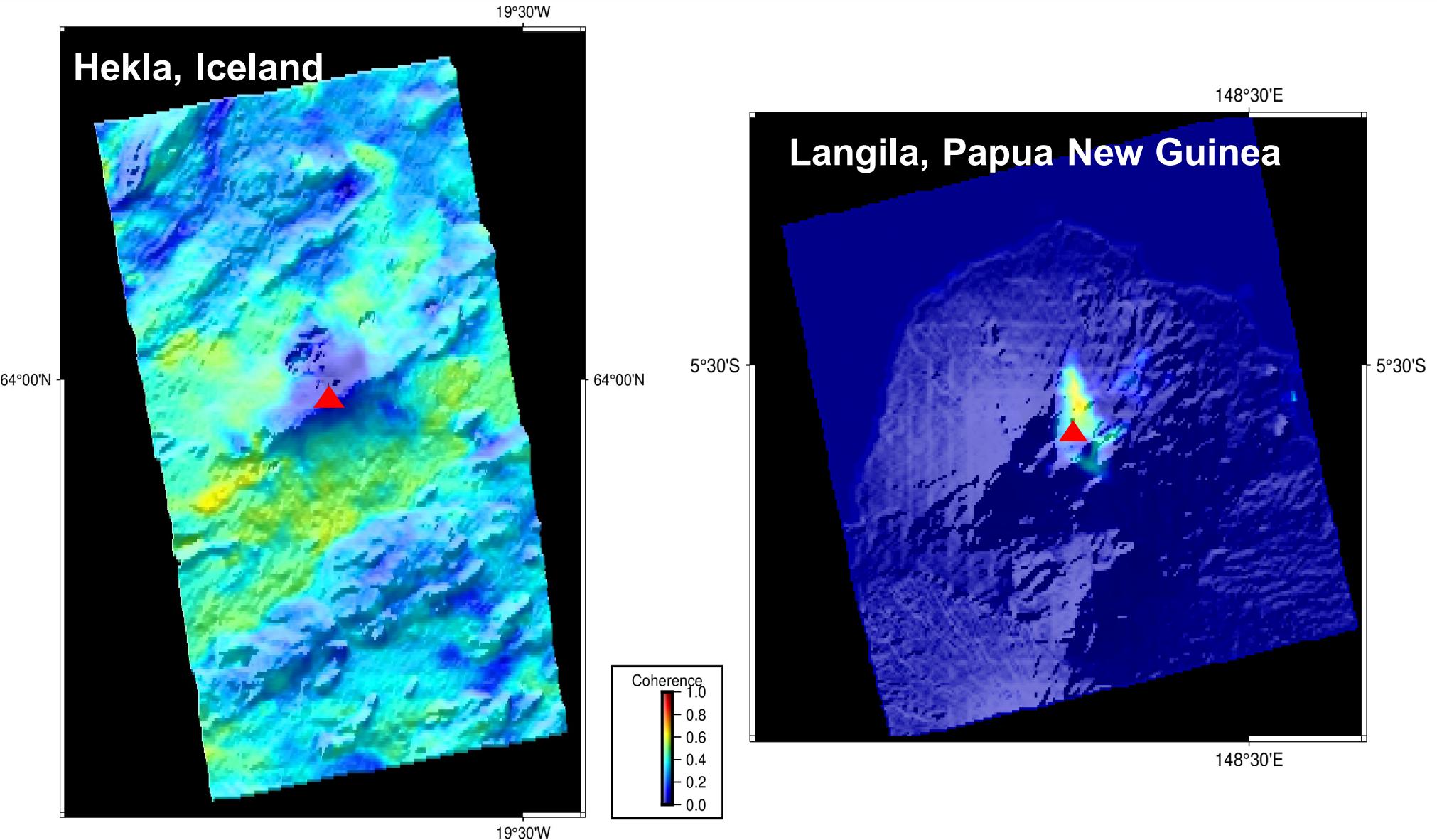
- ❑ Interferograms with inter-, co- and pre-eruptive signals over all subaerial volcanoes, including some volcanoes have not been systematically analysed at all
- ❑ Improved algorithms to address major limits on the effectiveness of InSAR
- ❑ Displacement time series in high resolution of 30 m
- ❑ A minimum data storage requirements by only cropping the area around each volcano



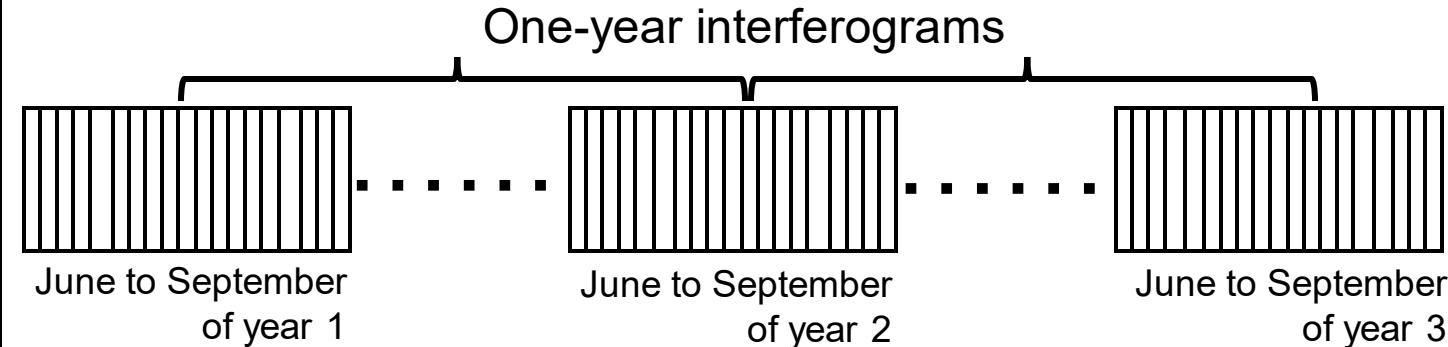
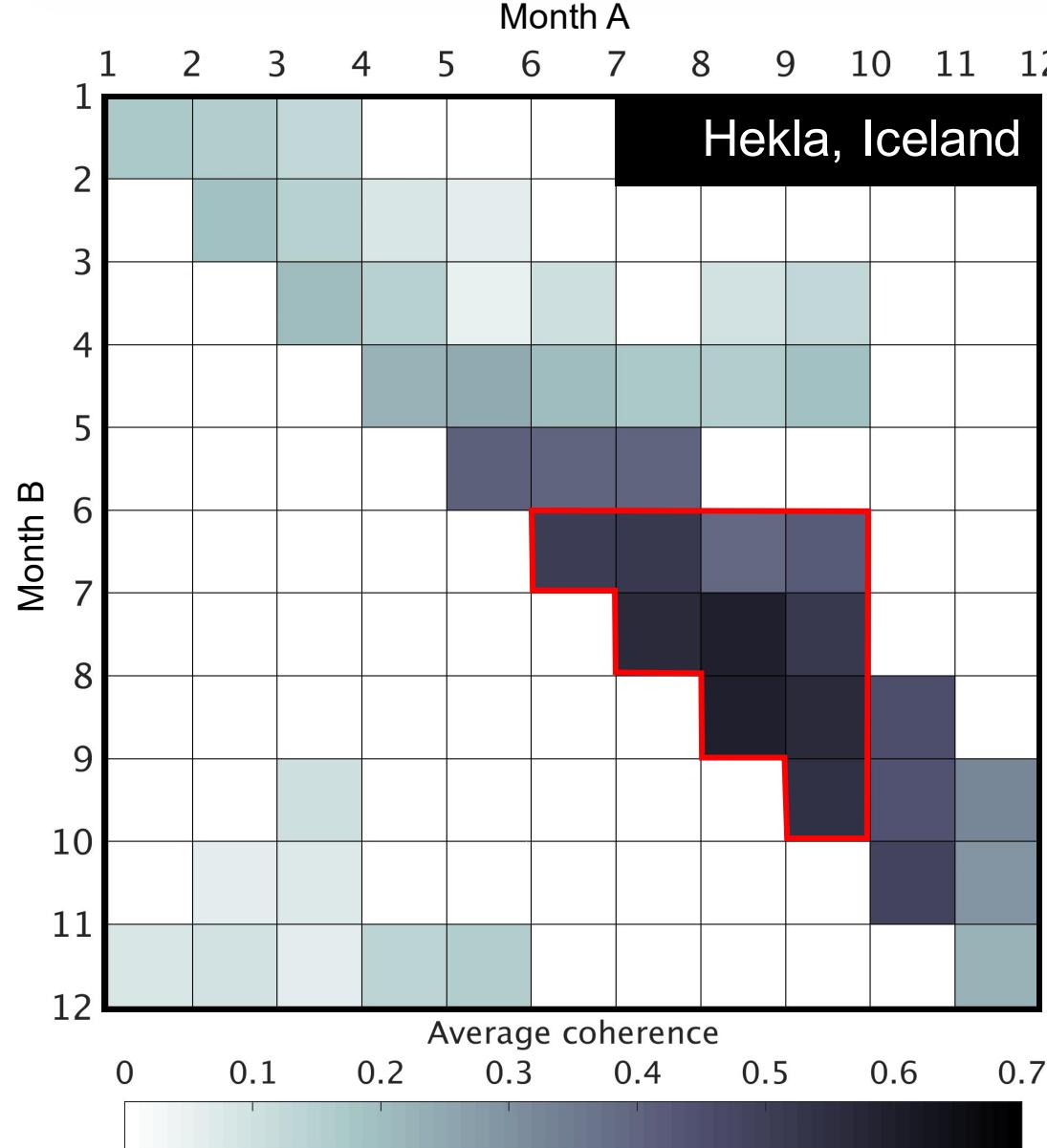
# Database design



# Decorrelated signals in areas of glacial coverage, winter snow and heavy vegetation

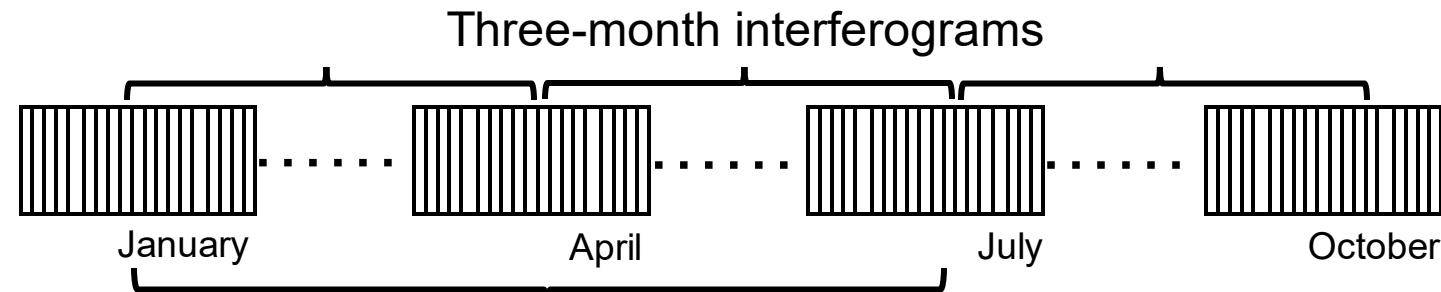
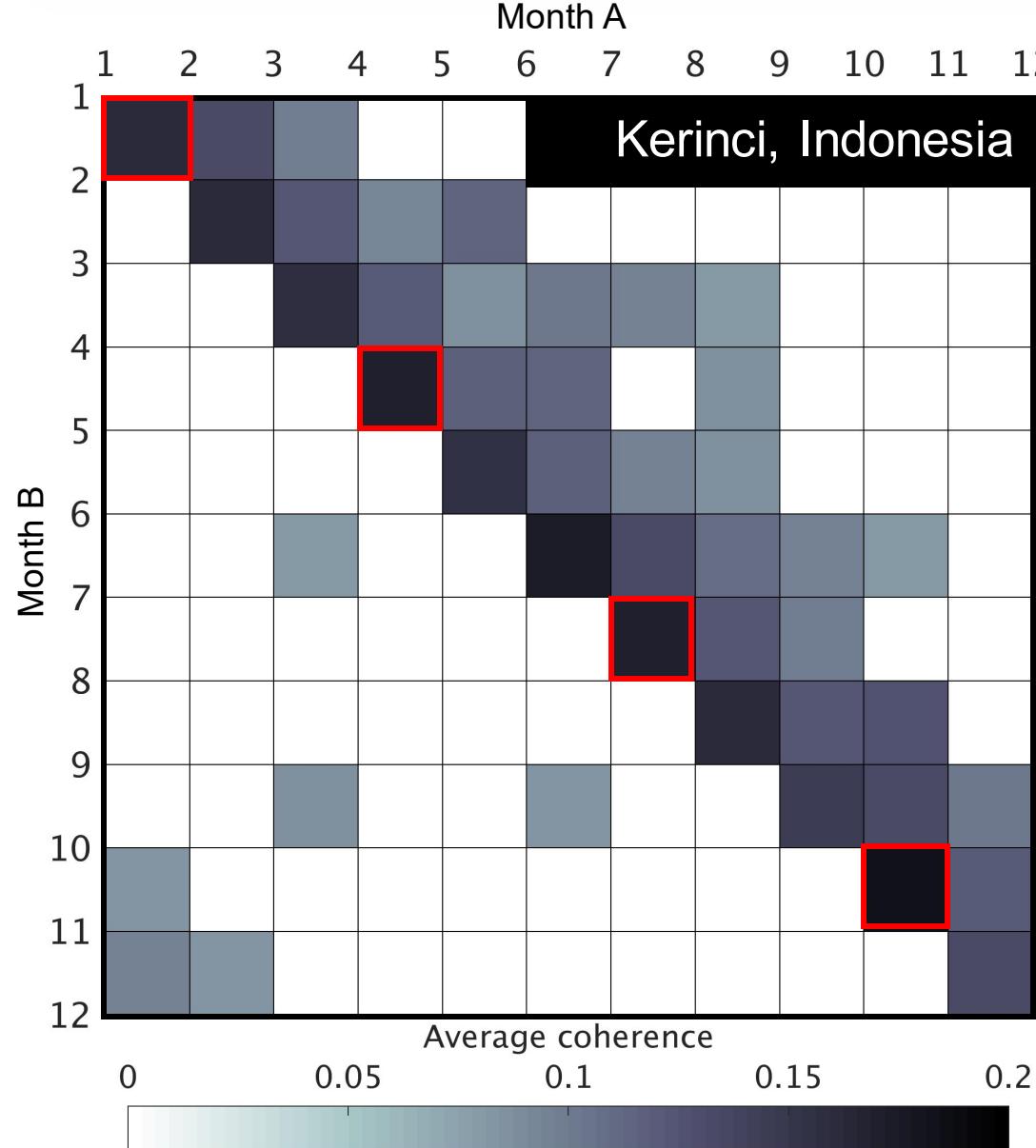


# A coherence analysis for building highly redundant small baseline network of interferograms



- Short-temporal baseline interferograms
- One-year interferograms

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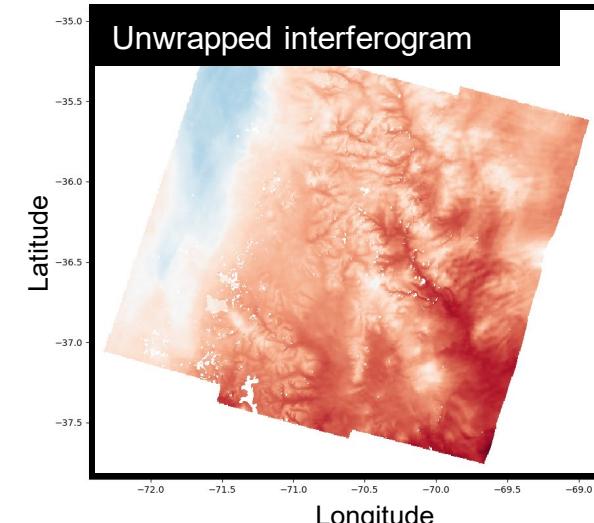
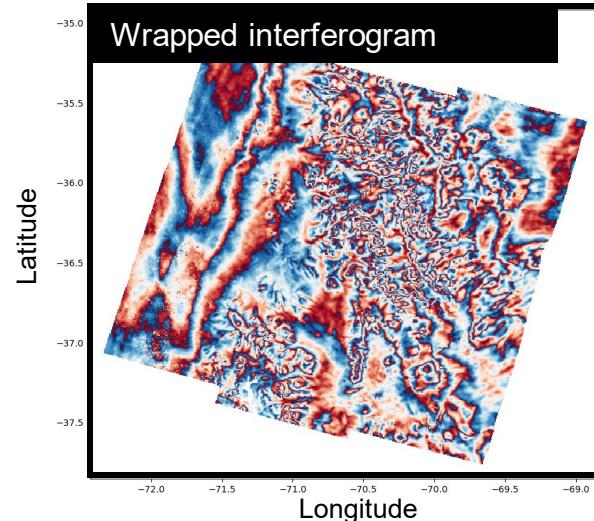


Six-month interferograms

- Short-temporal baseline interferograms
- Three-month interferograms
- Six-month interferograms

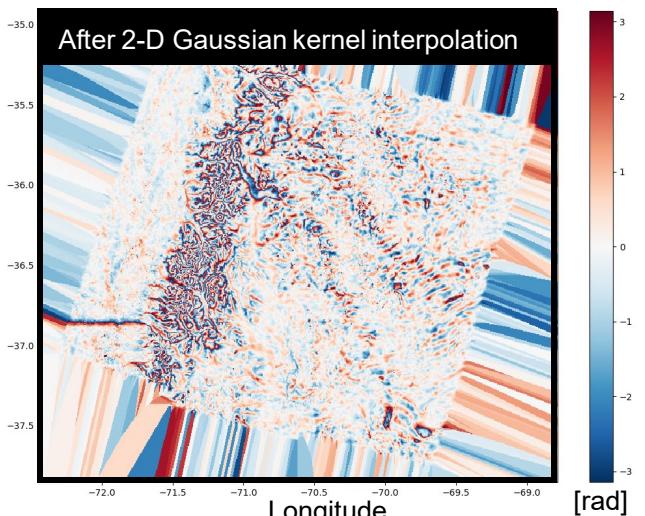
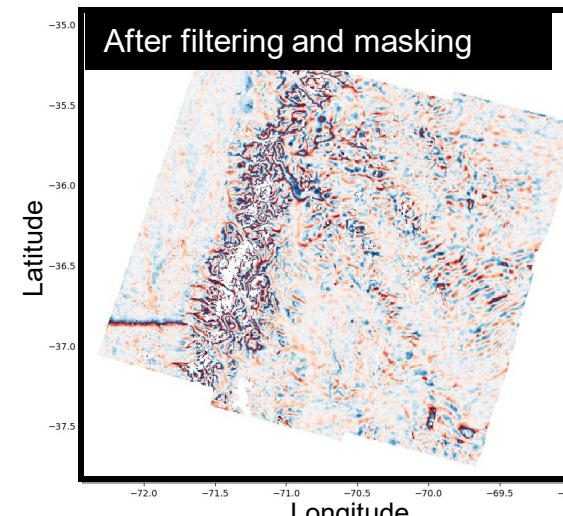
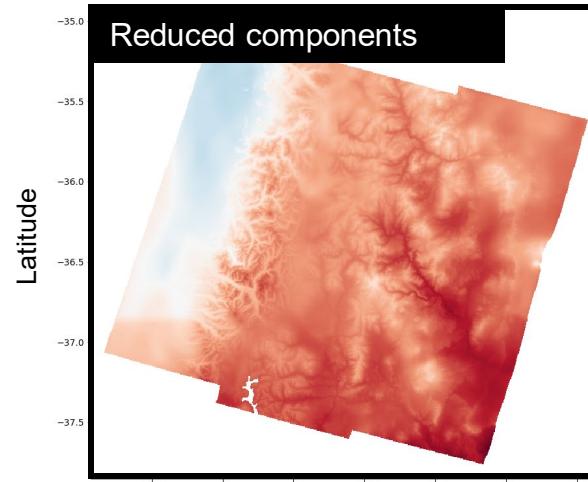
# An improved phase unwrapping algorithm

20191208 - 2020101, Nevados de Chillán



Unwrapping results

A. Reducing phase gradients before unwrapping

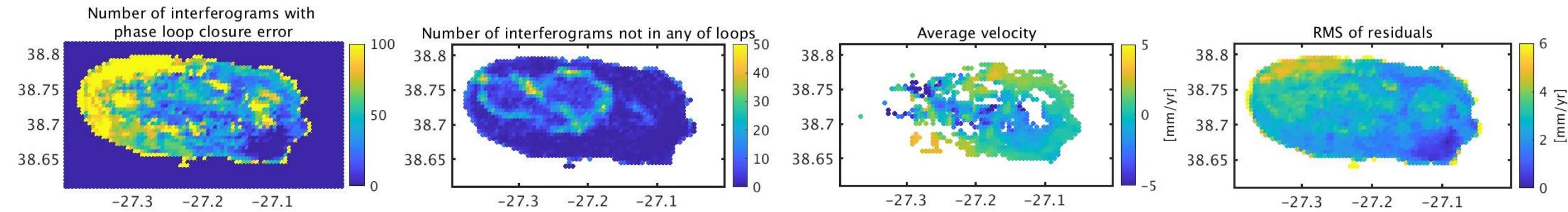


B. Spatial gaussian filtering, masking and interpolation

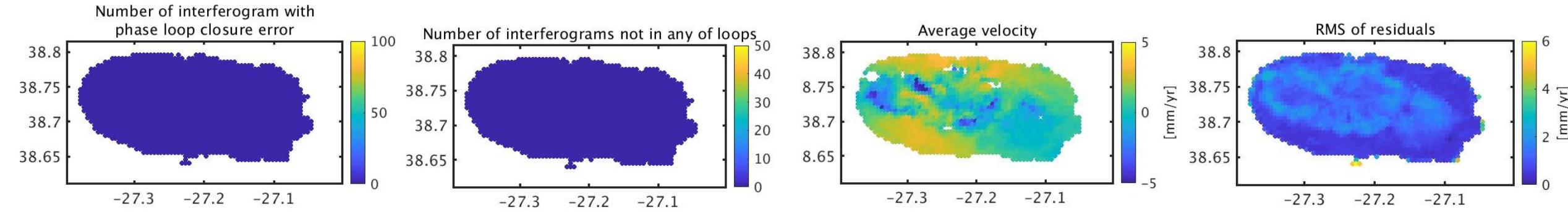
# A novel algorithm for phase loop closure error check

- ❖ Identify individual pixels that fail each phase loop closure error check
- ❖ Exclude non-redundant interferograms not in any of loops for each pixel

Without pixel-wise phase loop closure error check



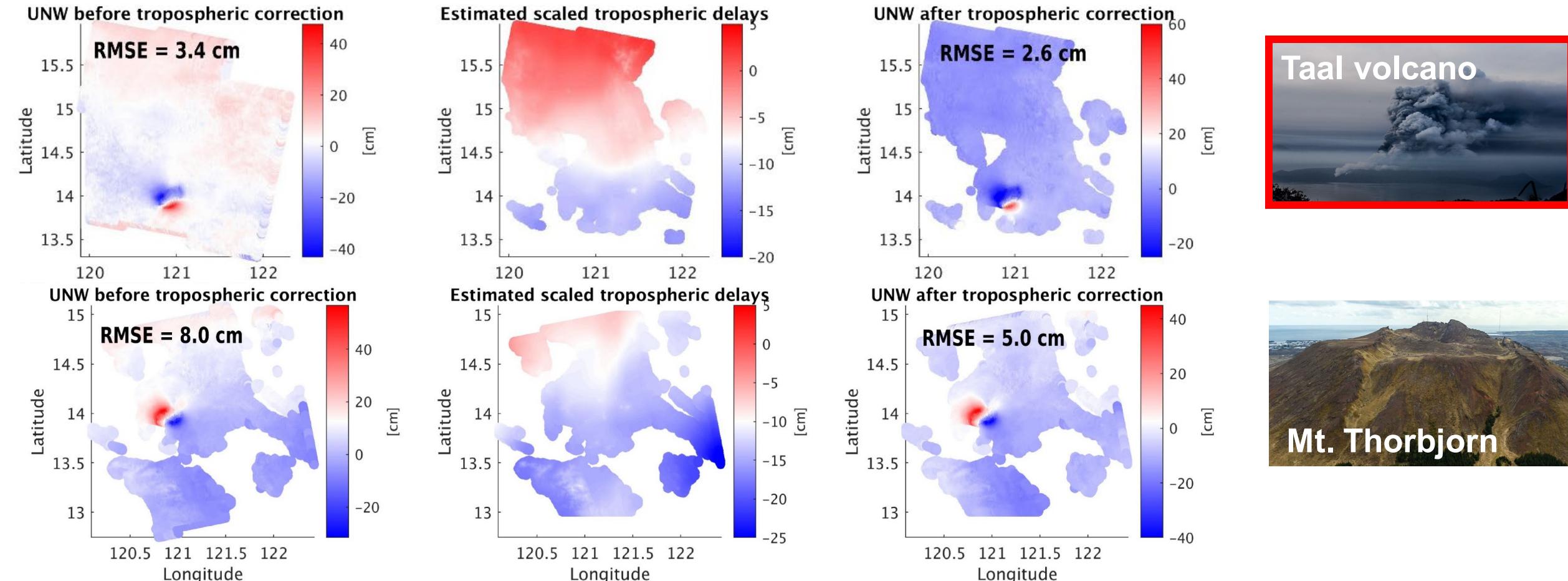
VS.



With pixel-wise phase loop closure error check

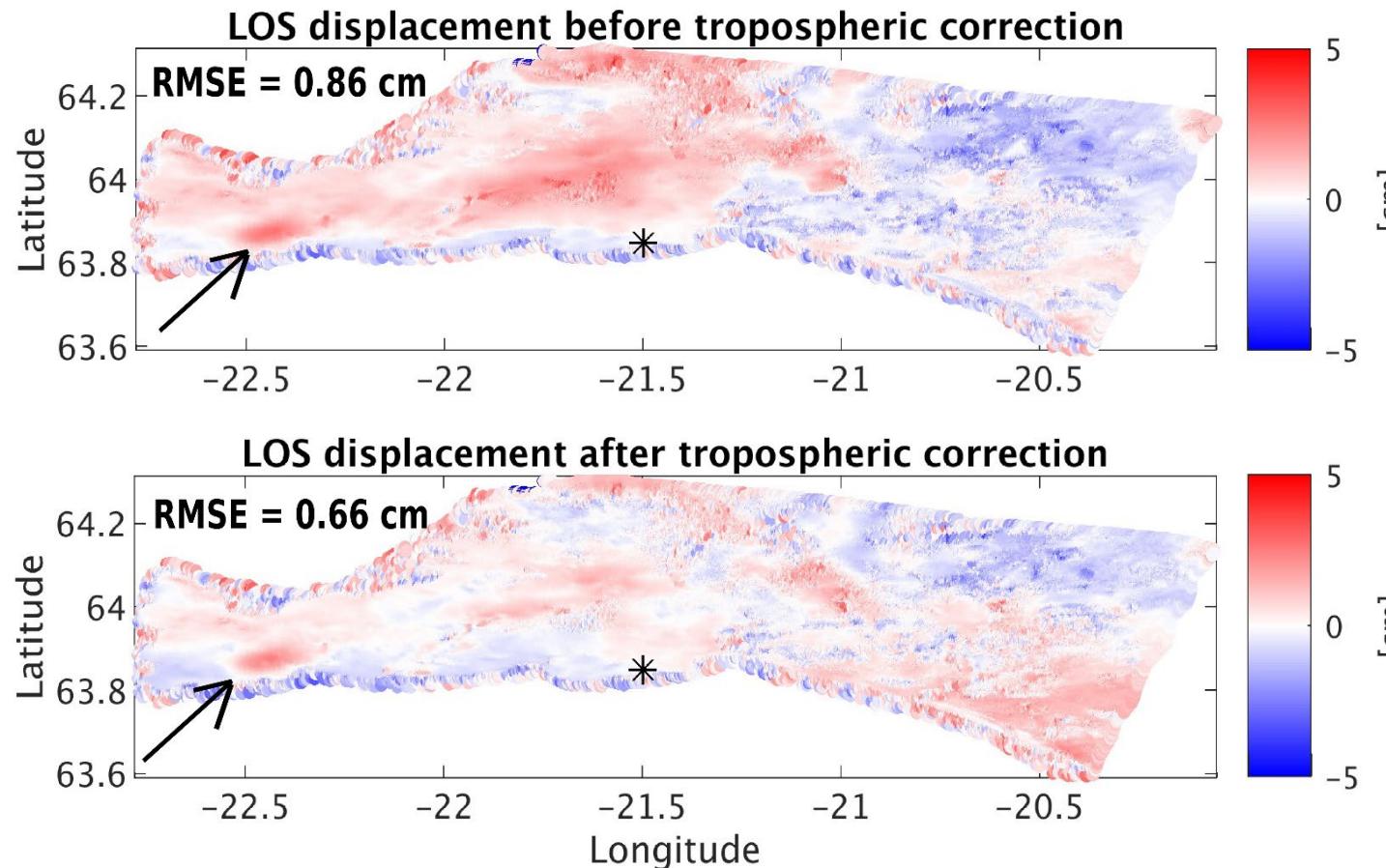
# Tropospheric correction with a spatially varying scaling method - co-eruptive signals

- ❖ Use high-resolution ECMWF data to define the form of the relationship between tropospheric delay and height [Shen et al., 2019]
- ❖ Use interferometric phase to refine the interpolation of weather model data in time and space

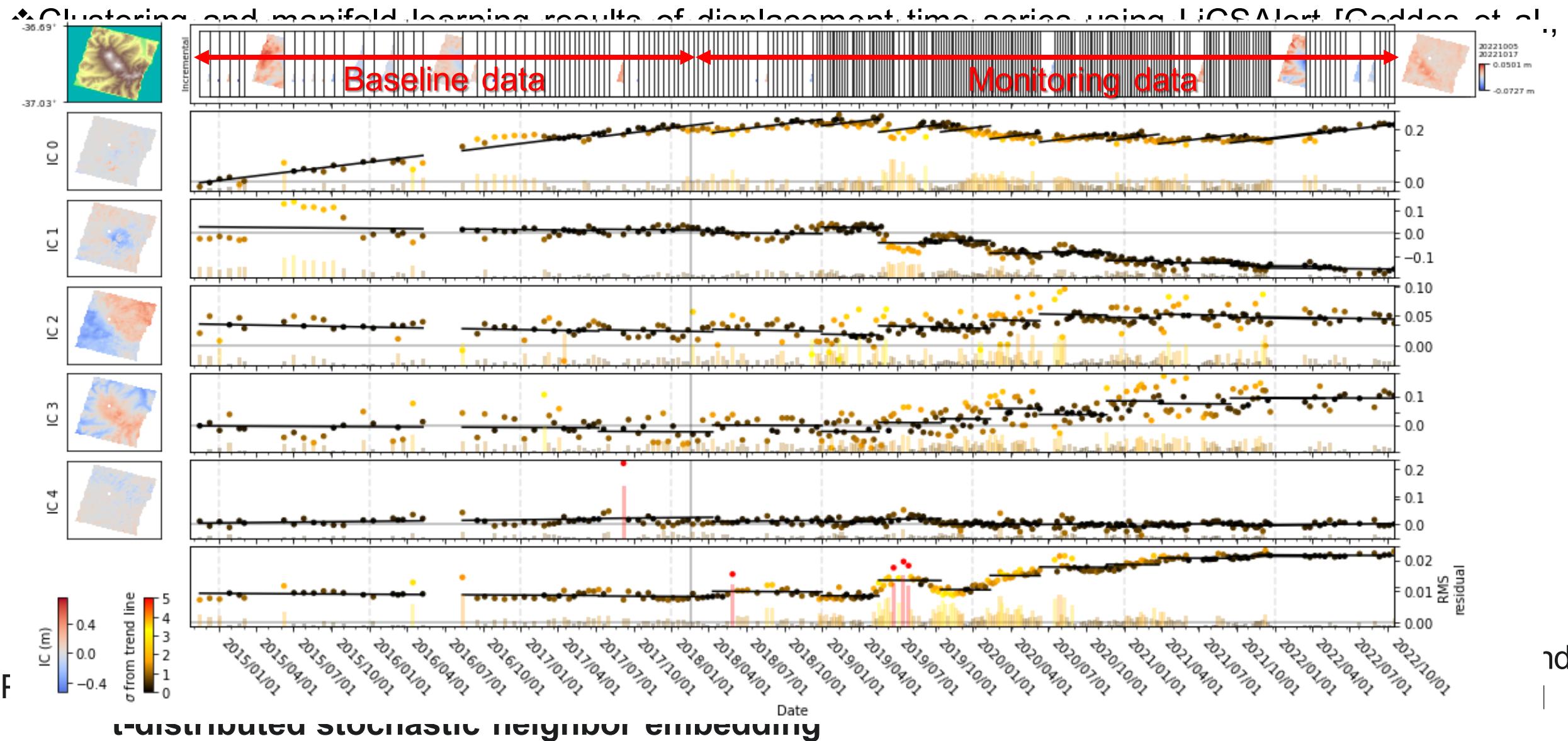


# Tropospheric correction with a spatially varying scaling method - inter-eruptive signals

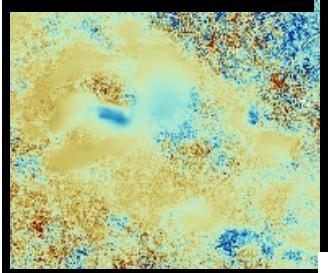
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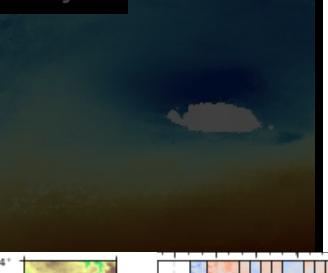
# Automatic detection of changes in deformation signals using independent component analysis



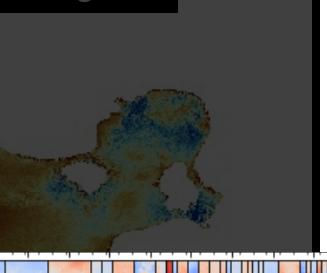
Ceboruco



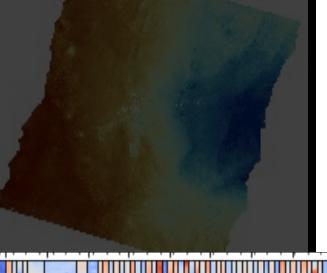
Askja



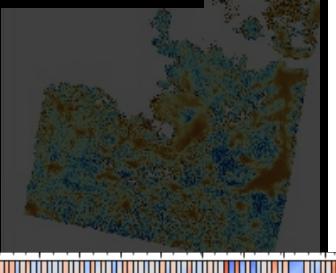
Adagdak



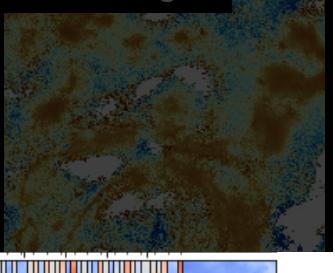
San Pedro-Pellado



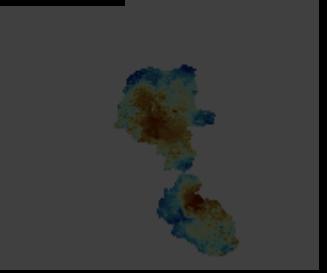
Sinabung



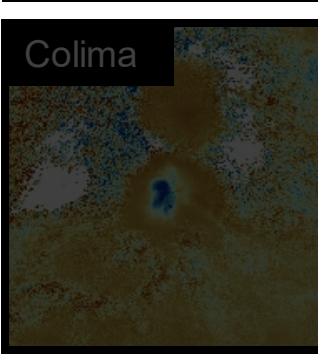
Acatenango



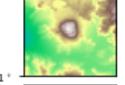
Lipari



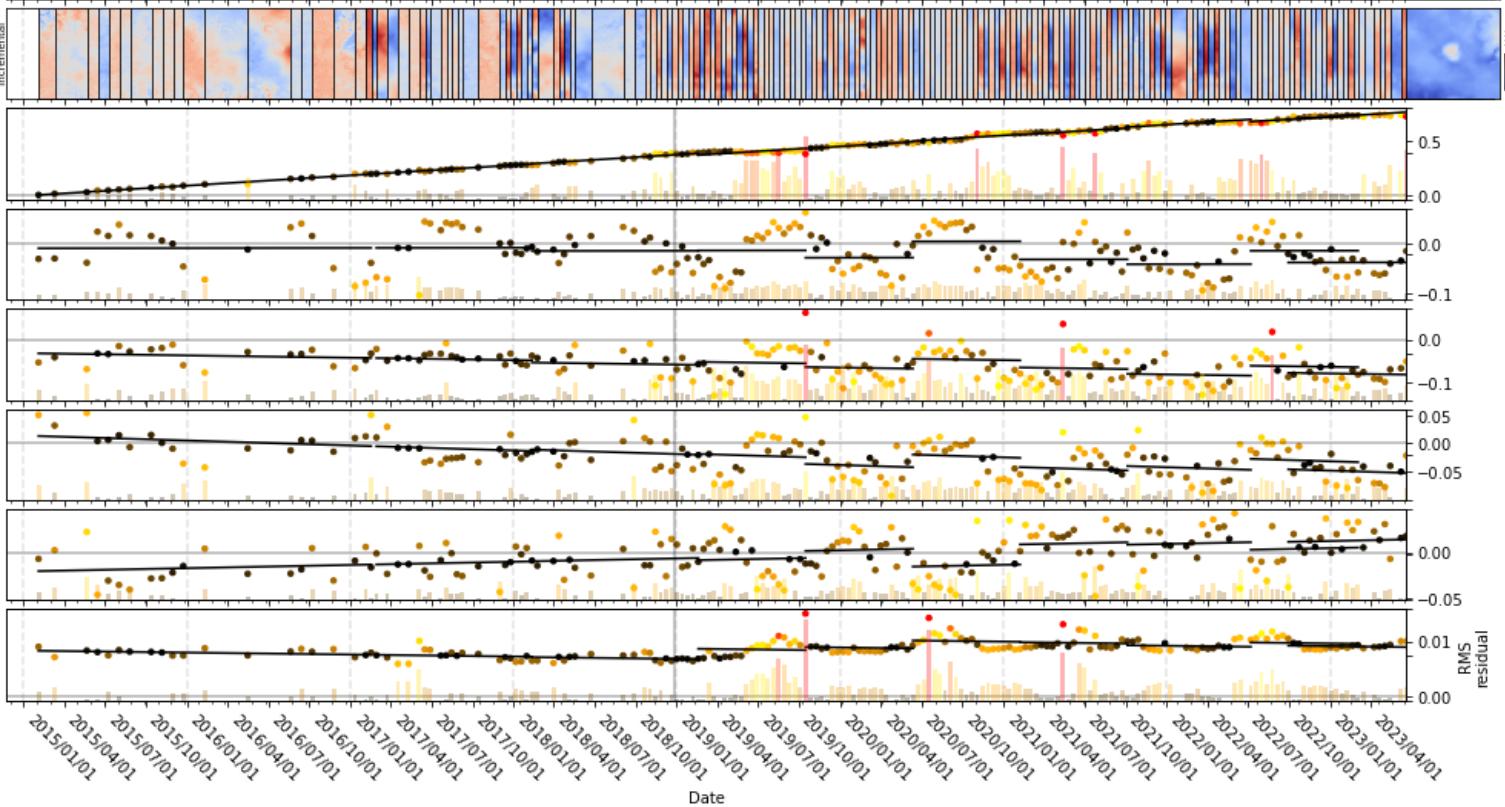
Colima



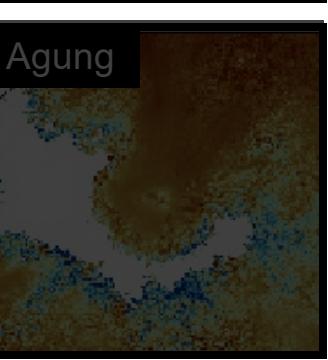
21.24°



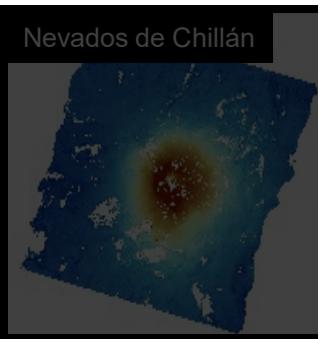
Incremental



Agung



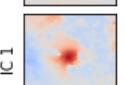
Nevados de Chillán



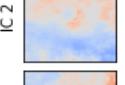
21.01°



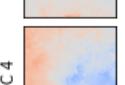
IC 0



IC 1



IC 2



IC 3



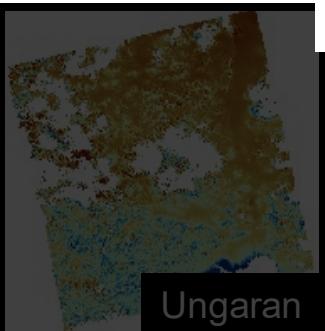
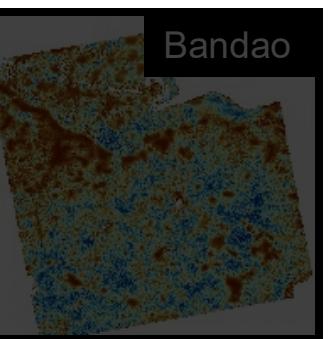
IC 4



RMS residual



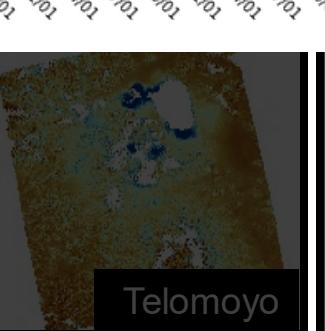
Bandao



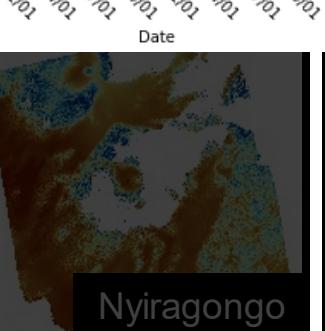
Ungaran



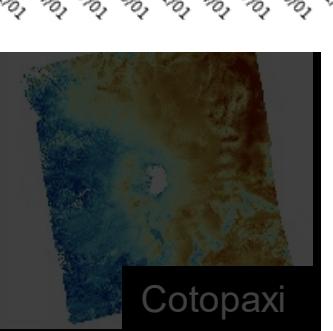
Chichinautzin



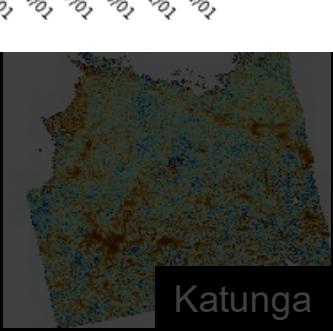
Telomoyo



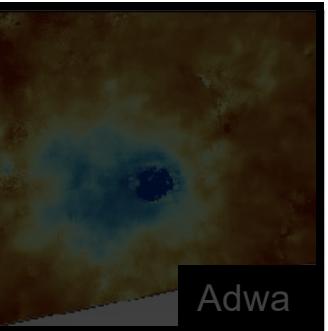
Nyiragongo



Cotopaxi

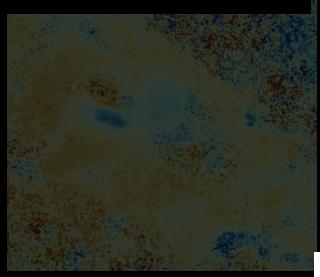


Katunga

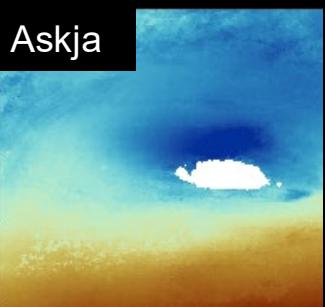


Adwa

Ceboruco



Askja



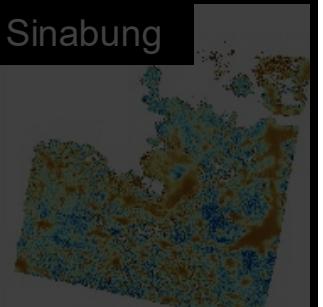
Adagdak



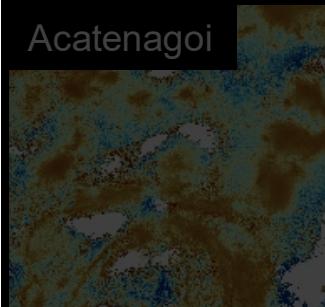
San Pedro-Pellado



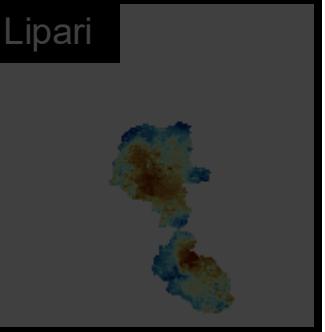
Sinabung



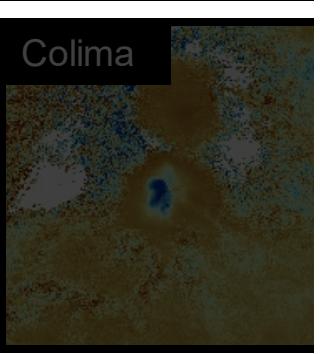
Acatenango



Lipari



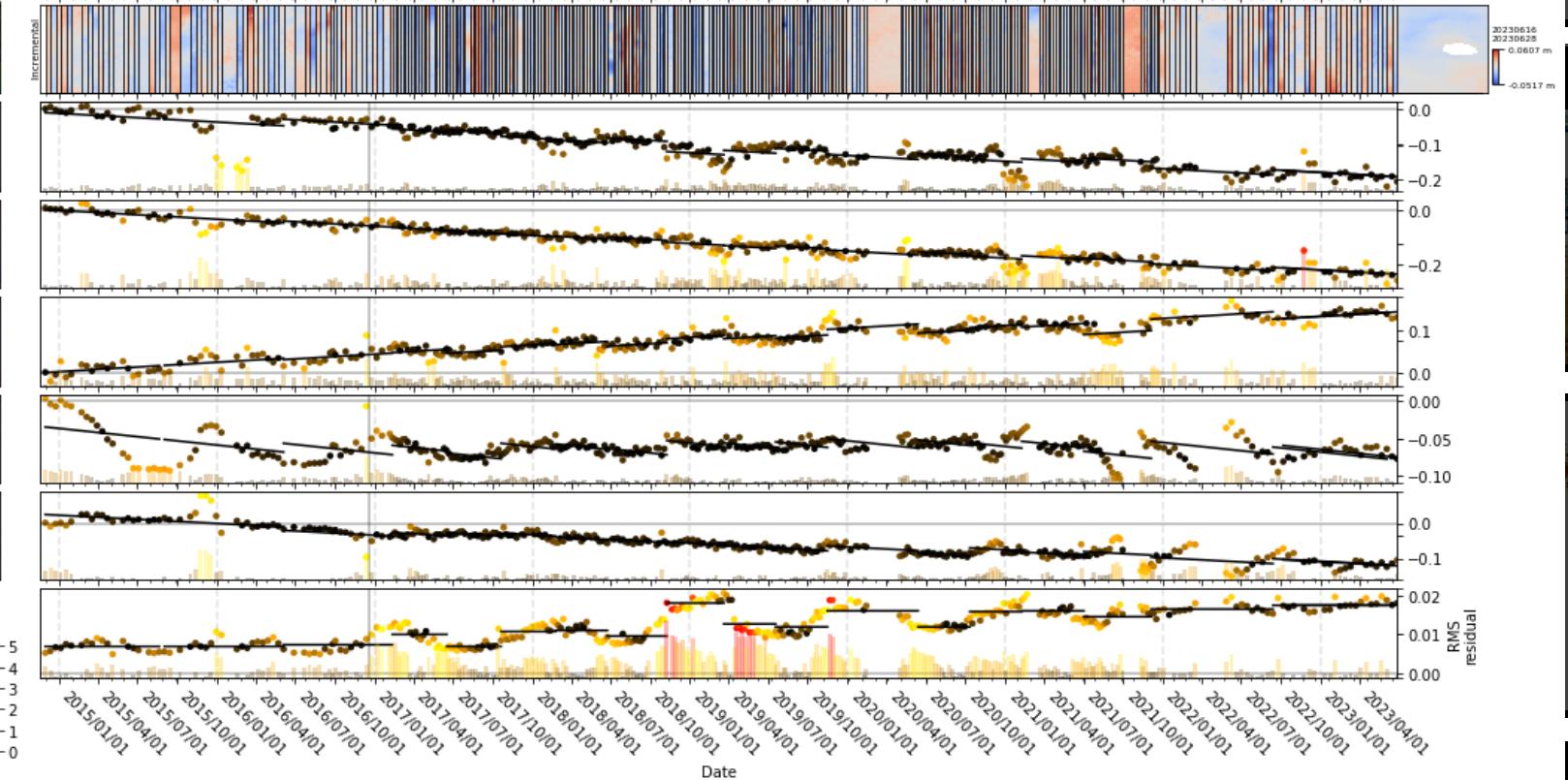
Colima



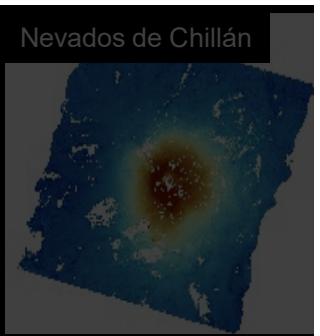
65.15°

Incremental

64.92°



Nevados de Chillán



IC 3

IC 4

σ from trend line

5

4

3

2

1

0

-0.3

-0.6

-0.3

0

0

IC (m)

σ from trend line

5

4

3

2

1

0

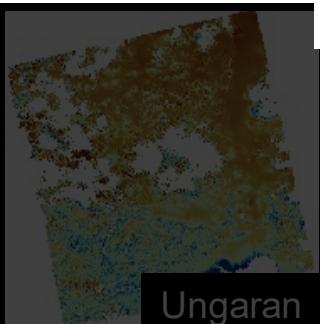
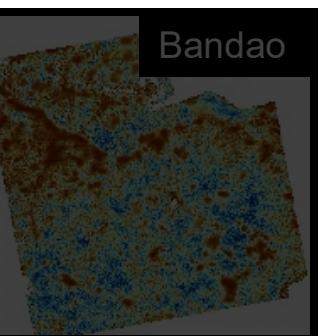
-0.3

-0.6

Date

2015/01/01 2015/04/01 2015/07/01 2015/10/01 2016/01/01 2016/04/01 2016/07/01 2016/10/01 2017/01/01 2017/04/01 2017/07/01 2017/10/01 2018/01/01 2018/04/01 2018/07/01 2018/10/01 2019/01/01 2019/04/01 2019/07/01 2019/10/01 2020/01/01 2020/04/01 2020/07/01 2020/10/01 2021/01/01 2021/04/01 2021/07/01 2022/01/01 2022/04/01 2022/07/01 2023/01/01 2023/04/01

Bandao



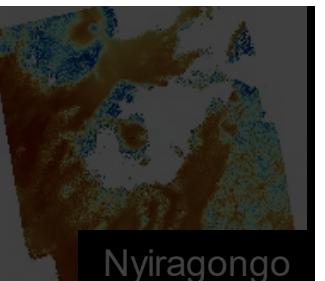
Ungaran



Chichinautzin



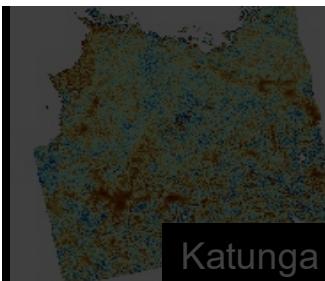
Telomoyo



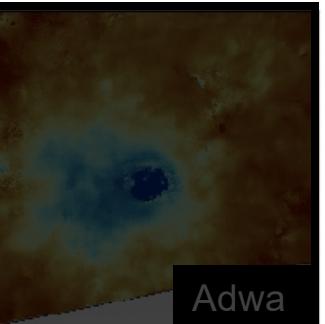
Nyiragongo



Cotopaxi

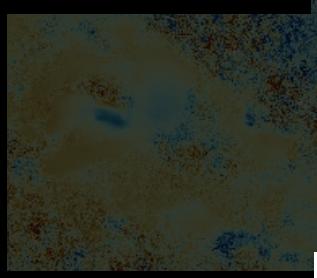


Katunga

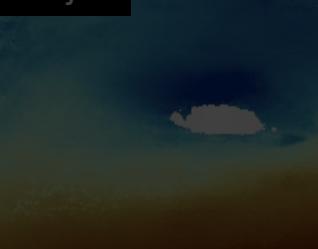


Adwa

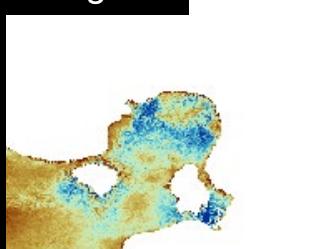
Ceboruco



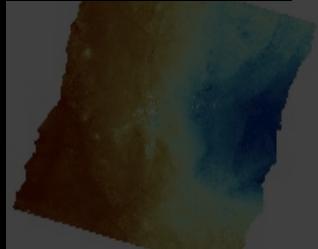
Askja



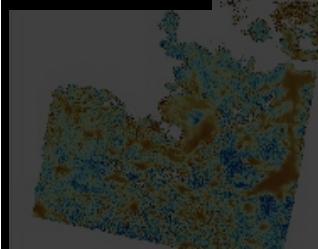
Adagdak



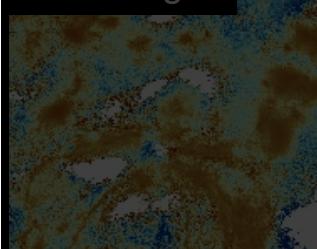
San Pedro-Pellado



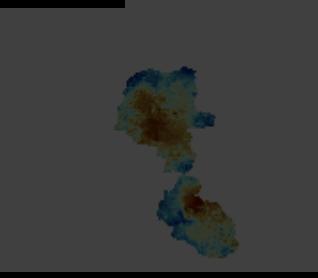
Sinabung



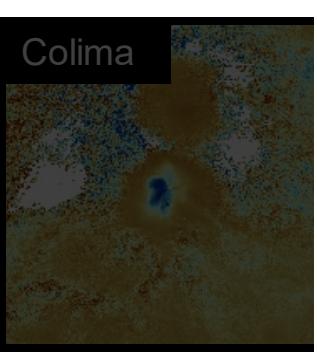
Acatenagoi



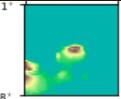
Lipari



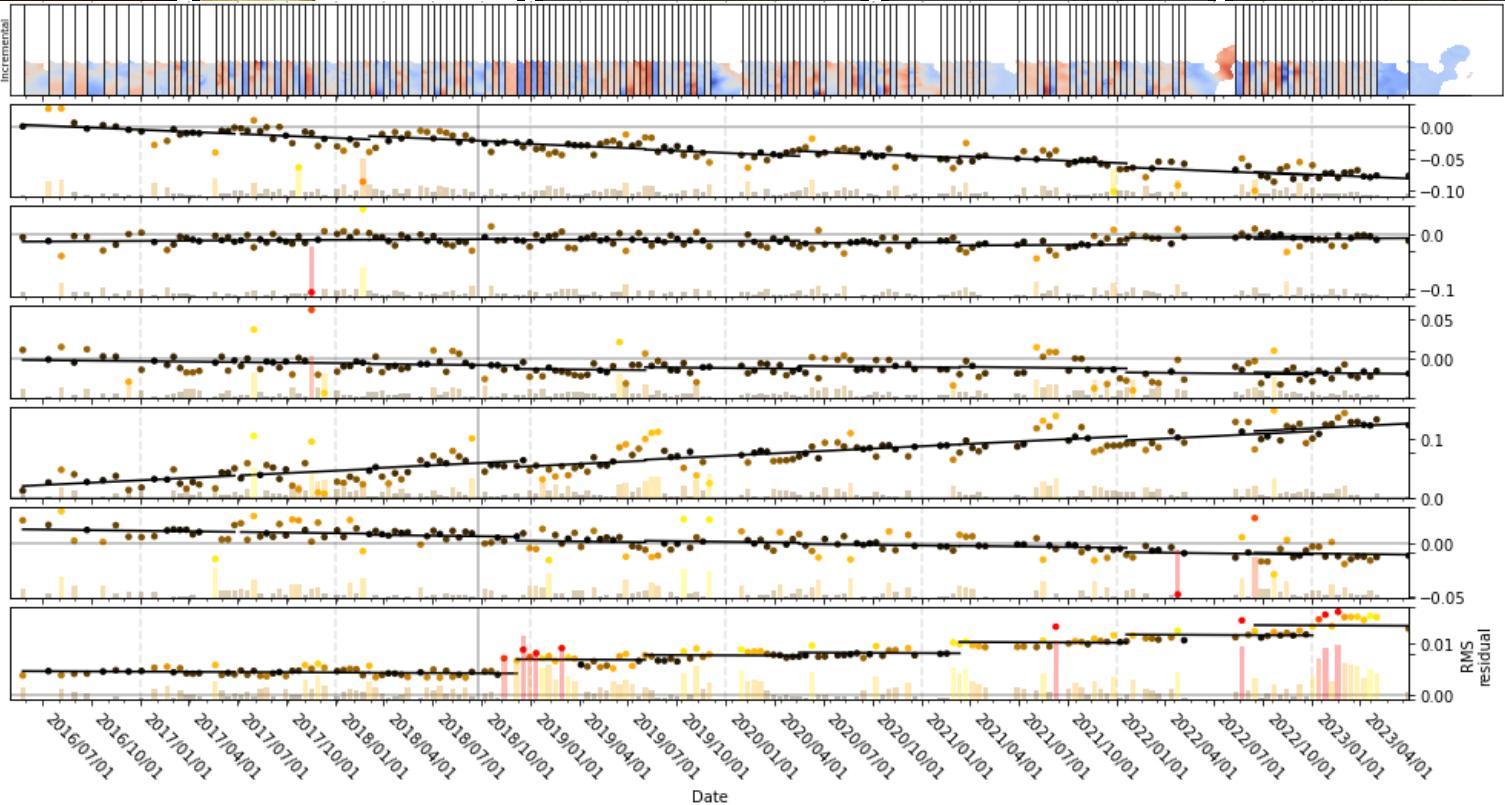
Colima



51.88°



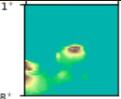
Incremental



Nevados de Chillán



52.1°



Date

2015/07/01

2016/01/01

2016/07/01

2017/01/01

2017/04/01

2018/01/01

2018/04/01

2018/07/01

2019/01/01

2019/04/01

2019/07/01

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2020/07/01

2021/01/01

2021/04/01

2022/01/01

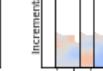
2022/04/01

2022/07/01

2023/01/01

2023/04/01

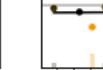
IC 0



IC 1



IC 2



IC 3

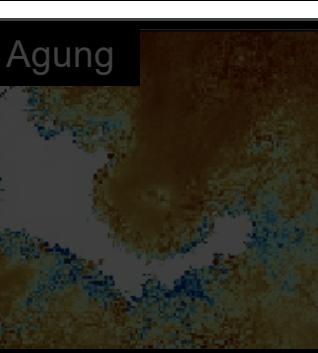


IC 4

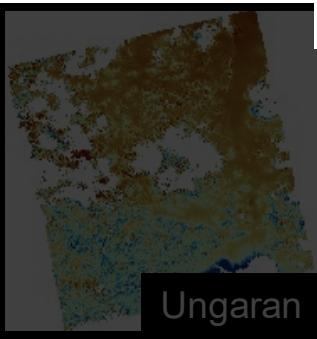
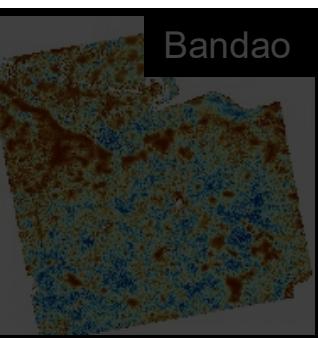


RMS residual

Agung



Bandao



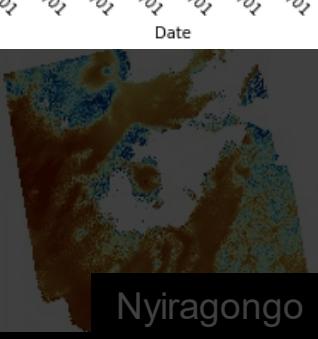
Ungaran



Chichinautzin



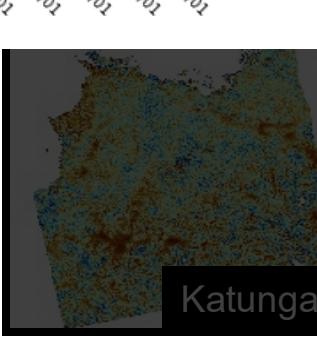
Telomoyo



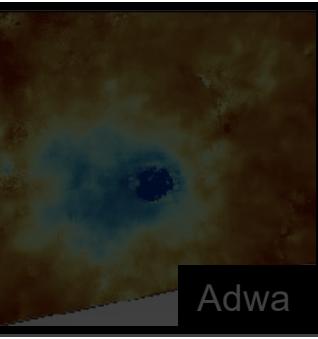
Nyiragongo



Cotopaxi

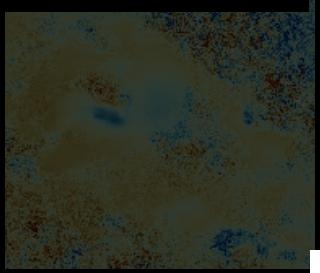


Katunga



Adwa

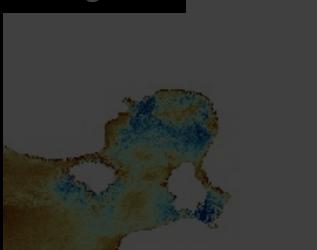
Ceboruco



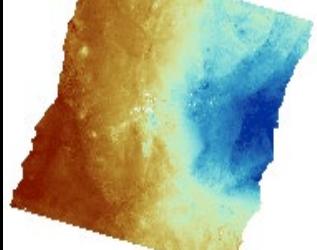
Askja



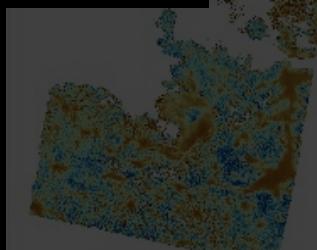
Adagdak



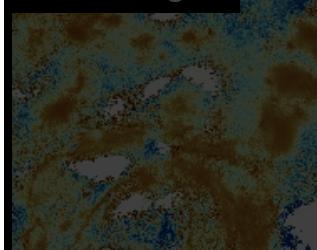
San Pedro-Pellado



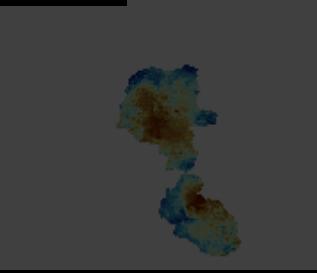
Sinabung



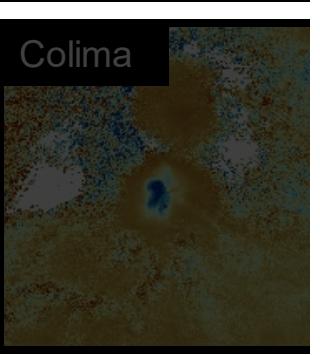
Acatenango



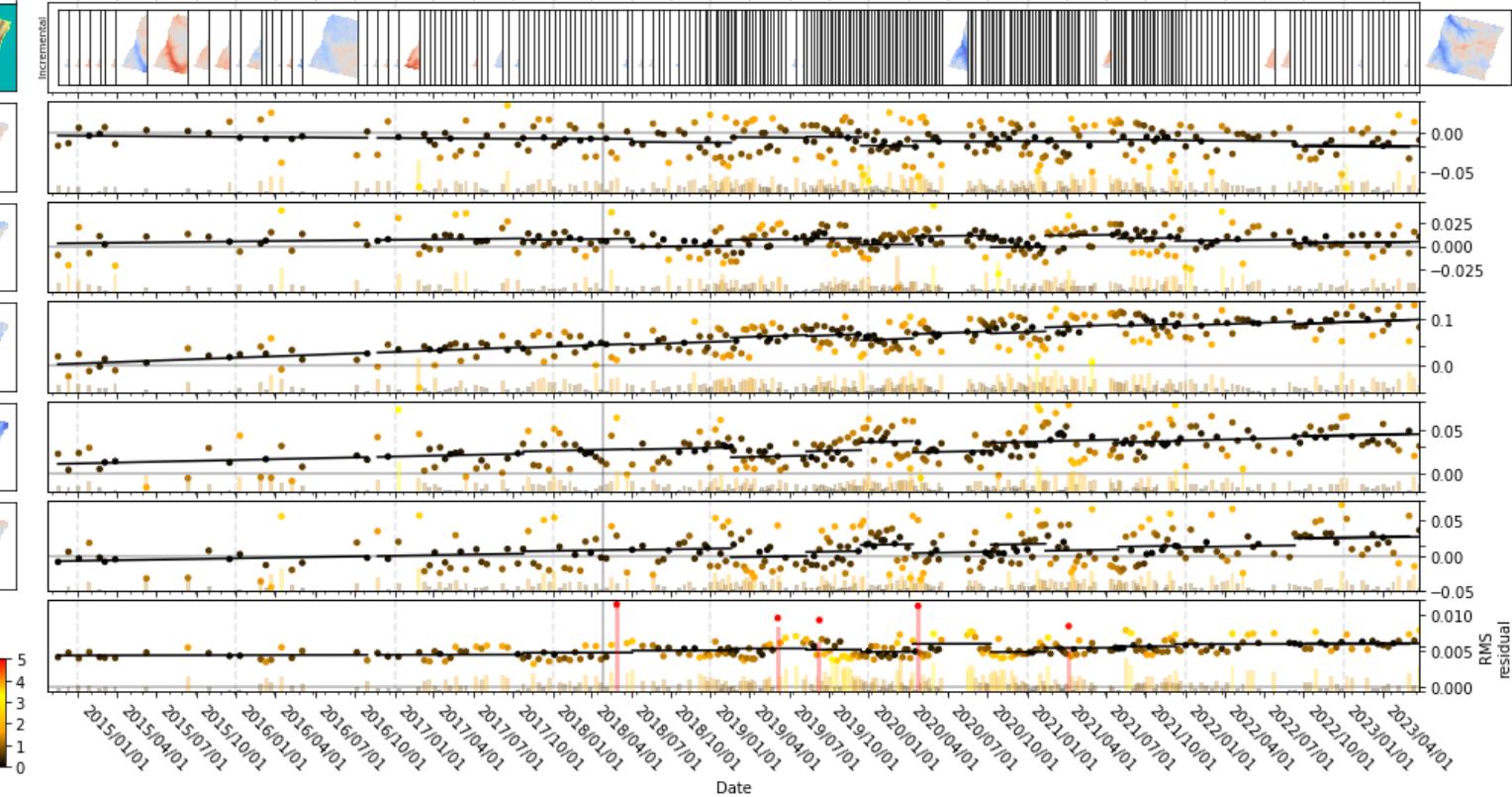
Lipari



Colima



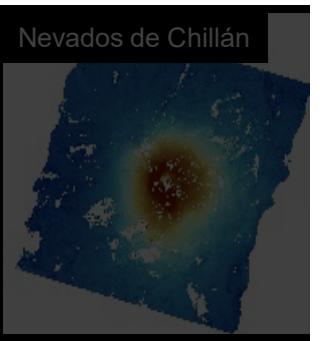
Incremental



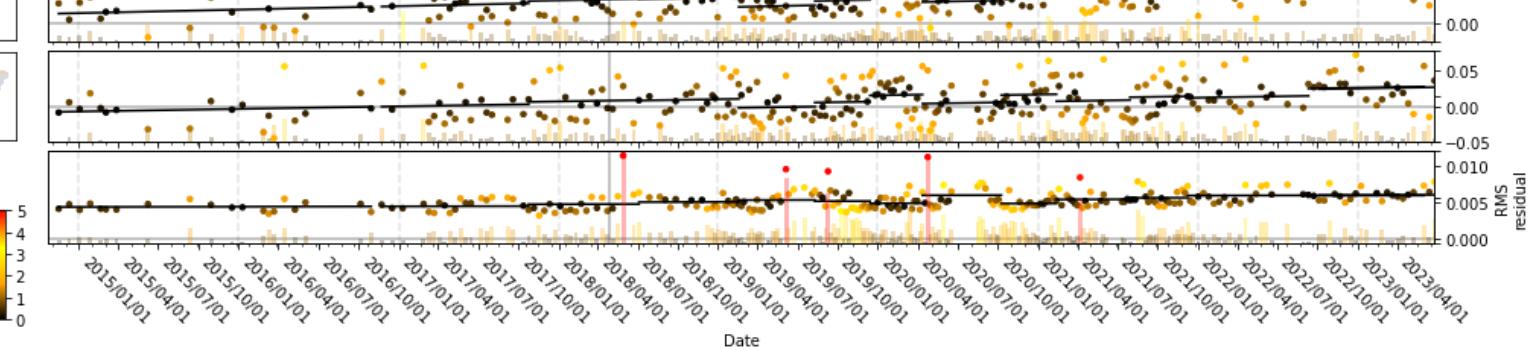
Agung



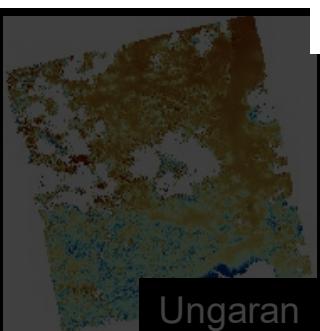
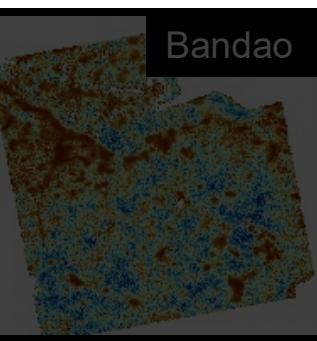
Nevados de Chillán



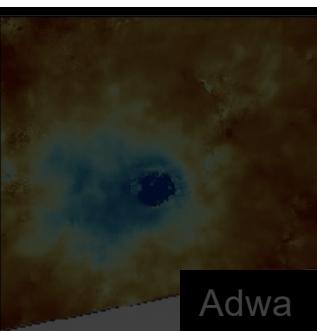
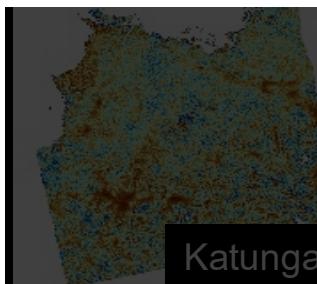
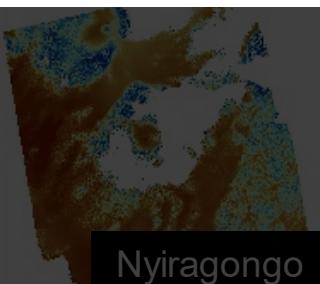
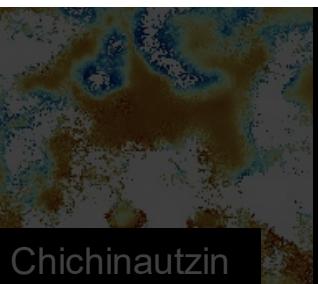
IC 0



Bandao

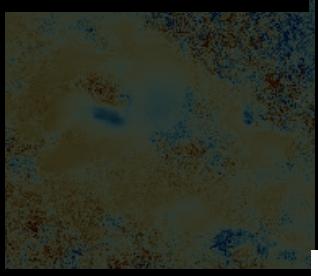


Ungaran

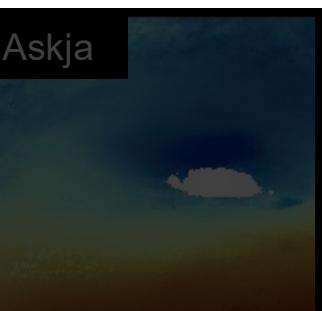


Adwa

Ceboruco



Askja



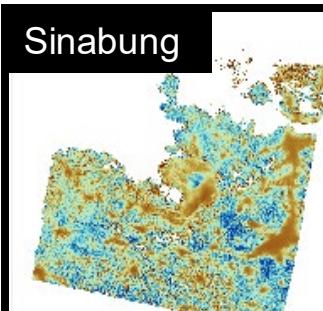
Adagdak



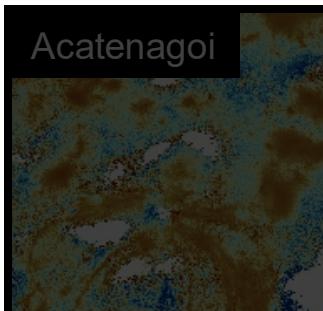
San Pedro-Pellado



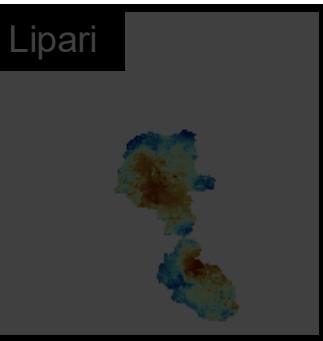
Sinabung



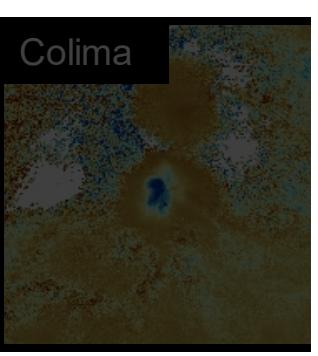
Acatenagoi



Lipari



Colima



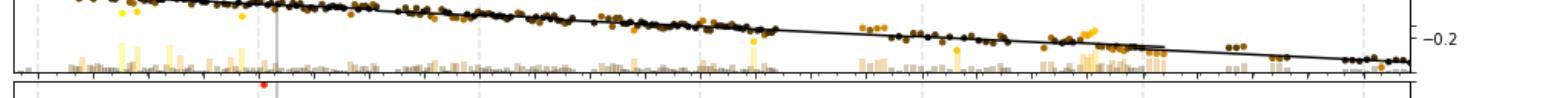
3.33°

Incremental

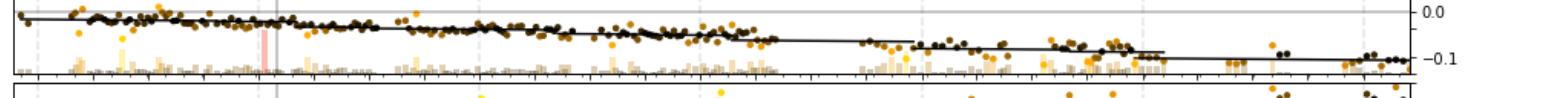


3.01°

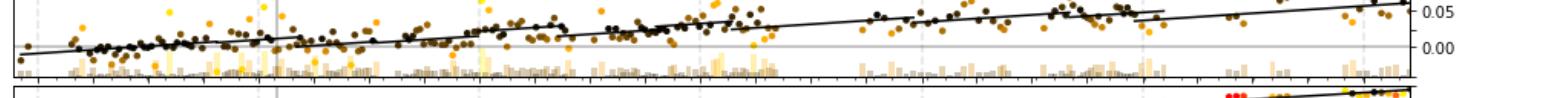
IC 0



IC 1



IC 2



IC 3



IC 4



IC (m)

σ from trend line

5

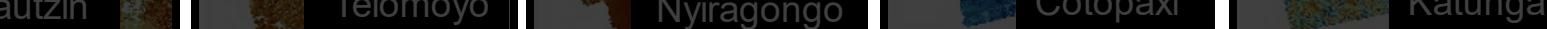
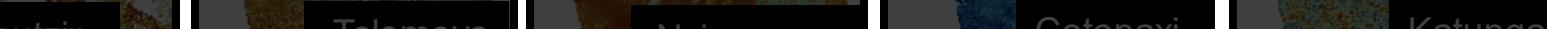
4

3

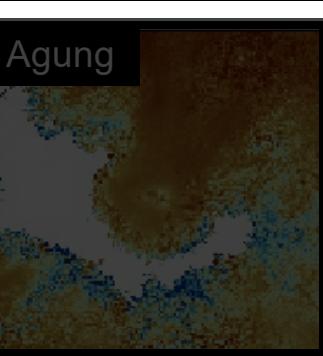
2

1

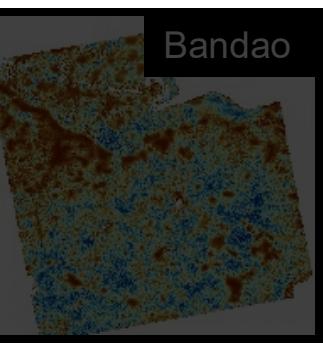
0



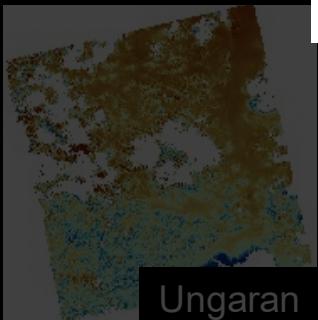
Agung



Bandao



Ungaran



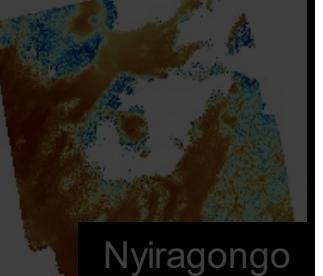
Chichinautzin



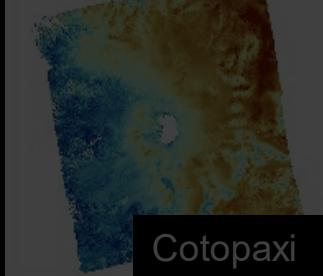
Telomoyo



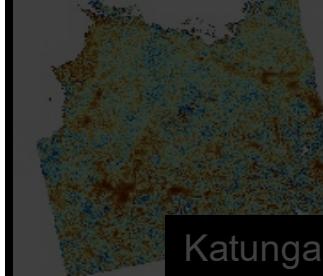
Nyiragongo



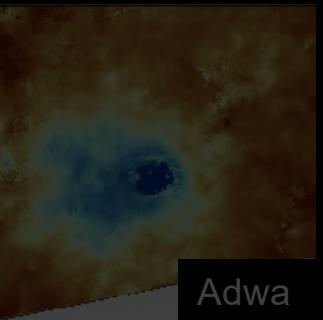
Cotopaxi



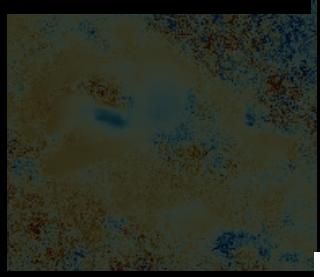
Katunga



Adwa



Ceboruco



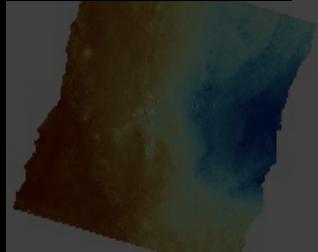
Askja



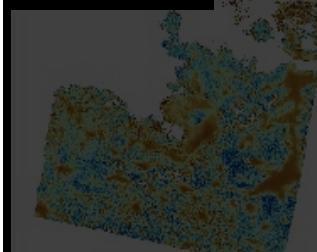
Adagdak



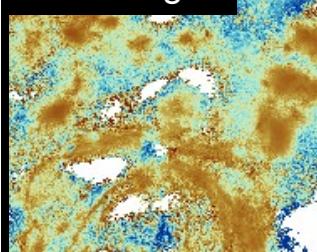
San Pedro-Pellado



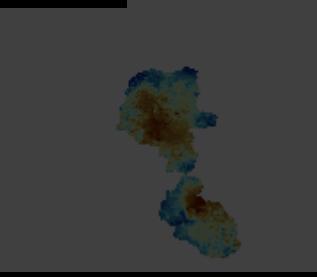
Sinabung



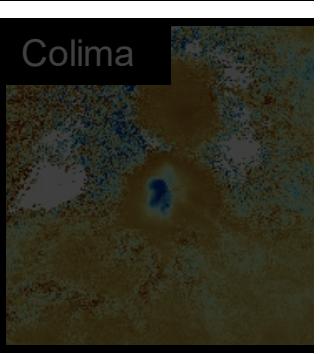
Acatenagoi



Lipari

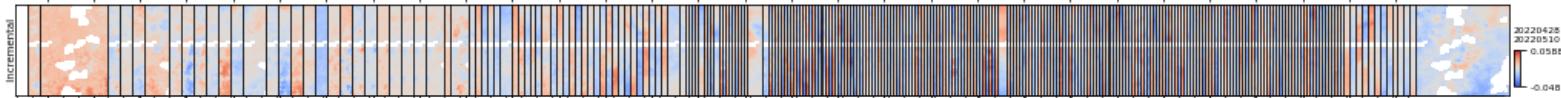


Colima



14.61°

Incremental



14.39 °

IC 0

IC 1

IC 2

IC 3

IC 4

 $\sigma$  from trend line

5

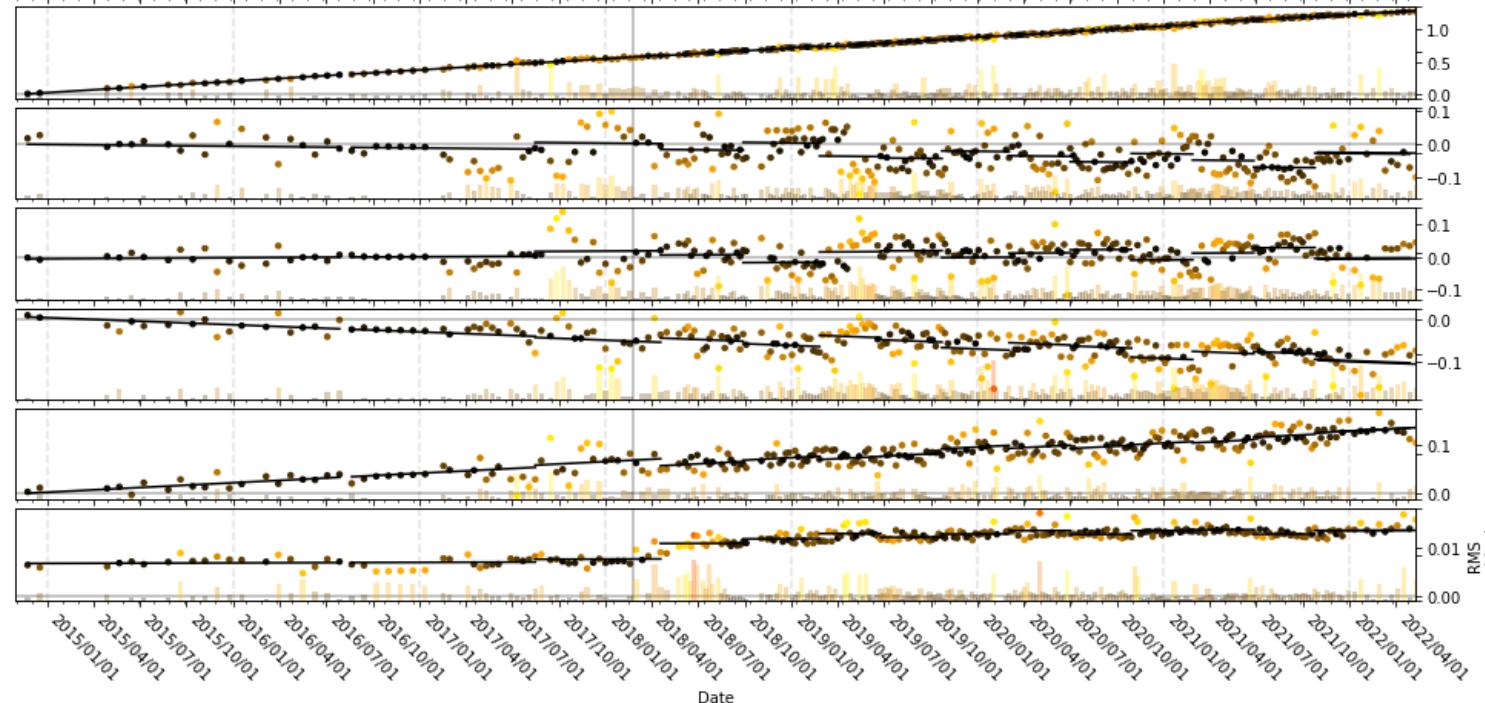
4

3

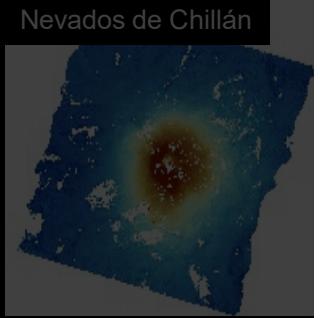
2

1

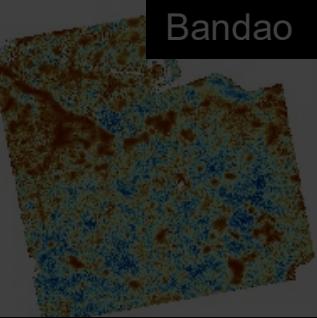
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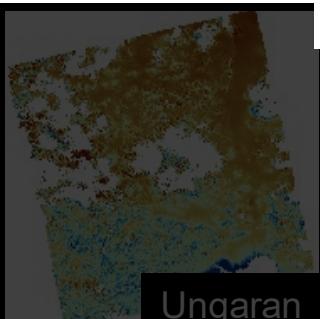
Nevados de Chillán



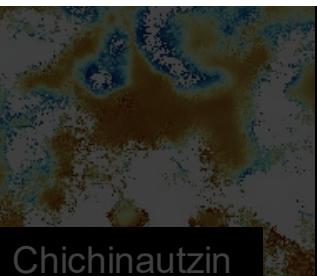
Agung



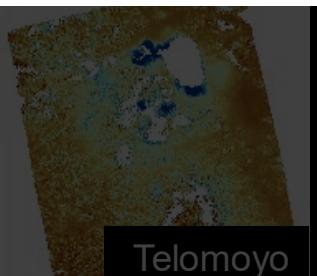
Ungaran



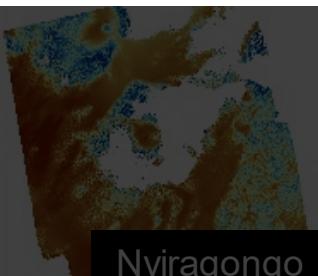
Chichinautzin



Telomoyo



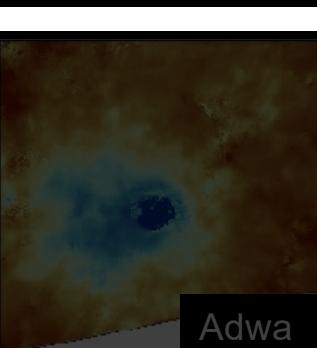
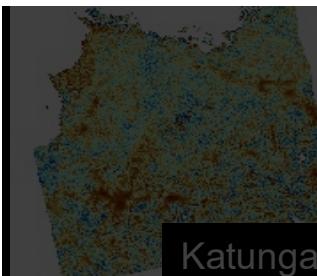
Nyiragongo



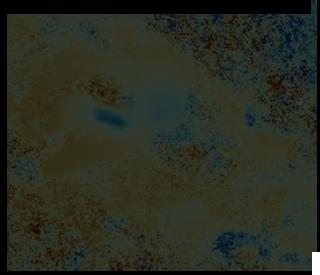
Cotopaxi



Katunga



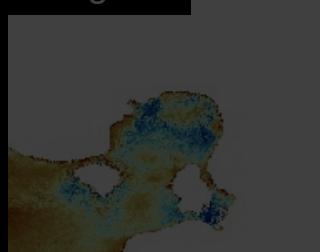
Ceboruco



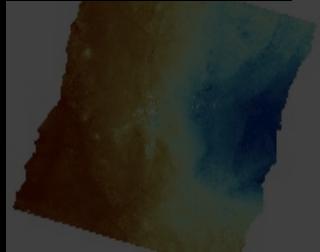
Askja



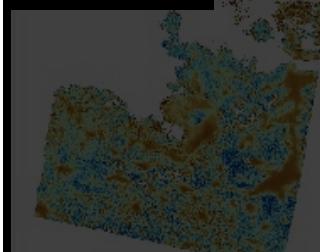
Adagdak



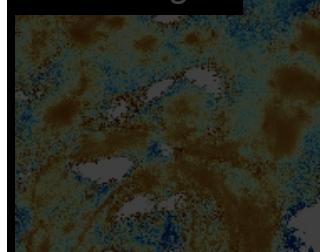
San Pedro-Pellado



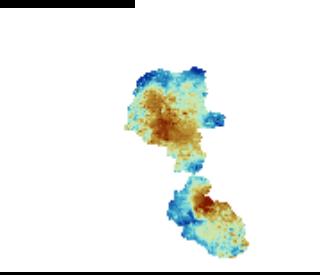
Sinabung



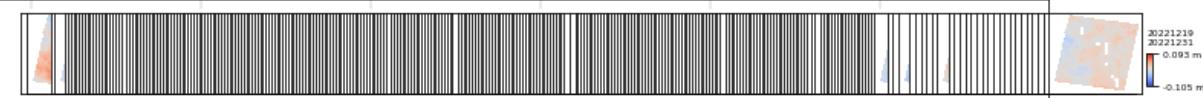
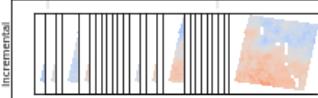
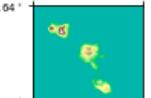
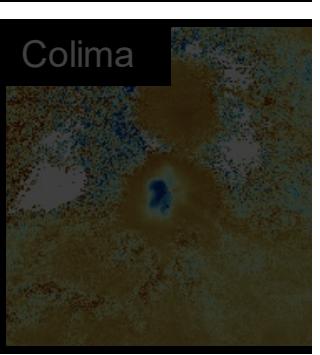
Acatenagoi



Lipari



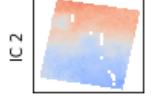
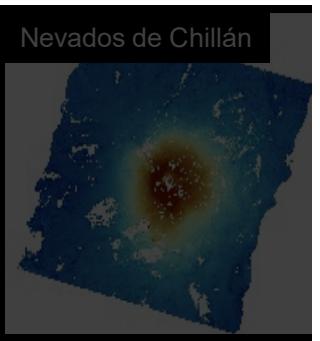
Colima



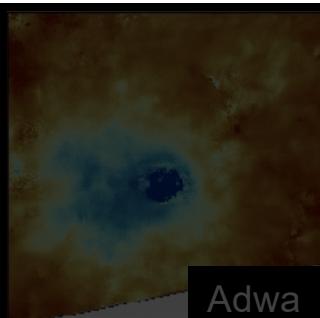
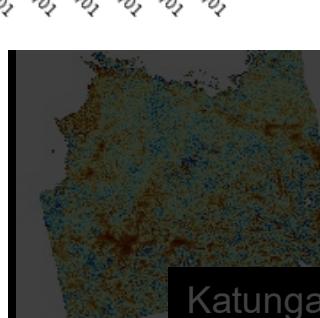
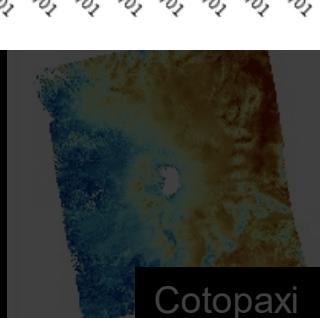
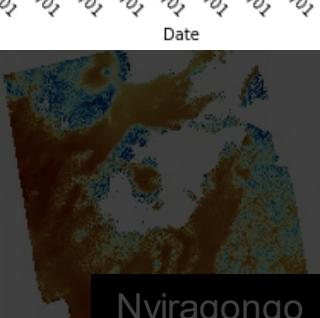
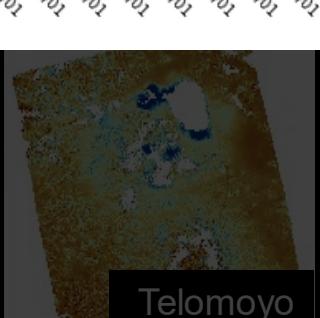
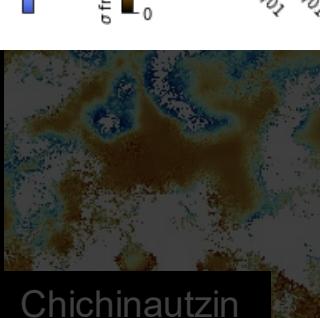
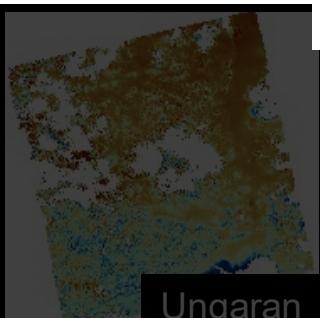
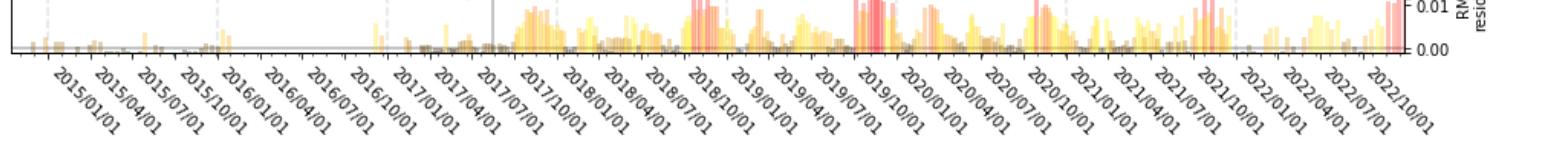
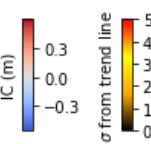
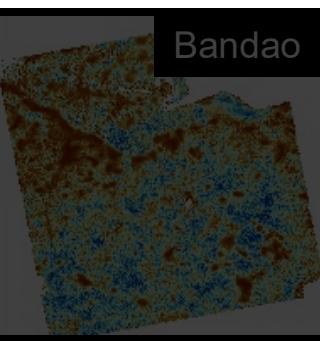
Agung



Nevados de Chillán



Bandao



Ungaran

Chichinautzin

Telomoyo

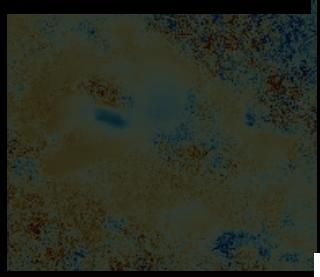
Nyiragongo

Cotopaxi

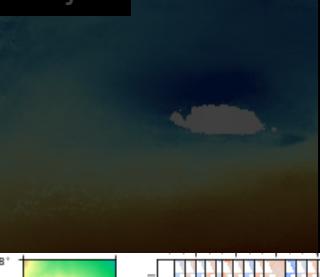
Katunga

Adwa

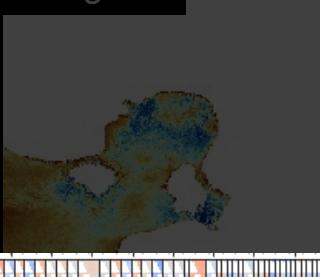
Ceboruco



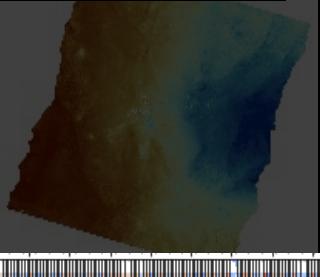
Askja



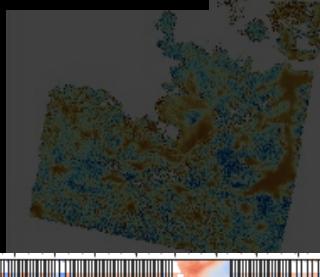
Adagdak



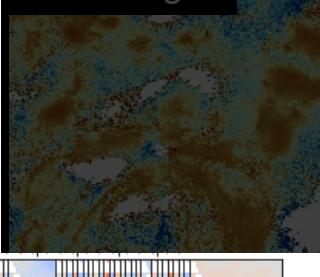
San Pedro-Pellado



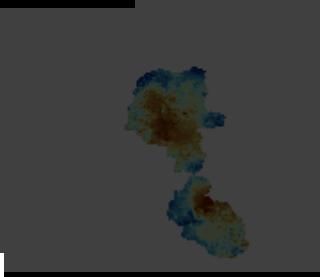
Sinabung



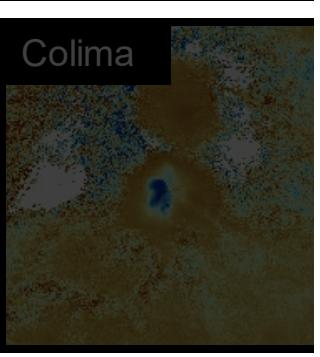
Acatenango



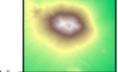
Lipari



Colima



-8.28°



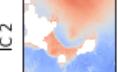
IC 0



IC 1



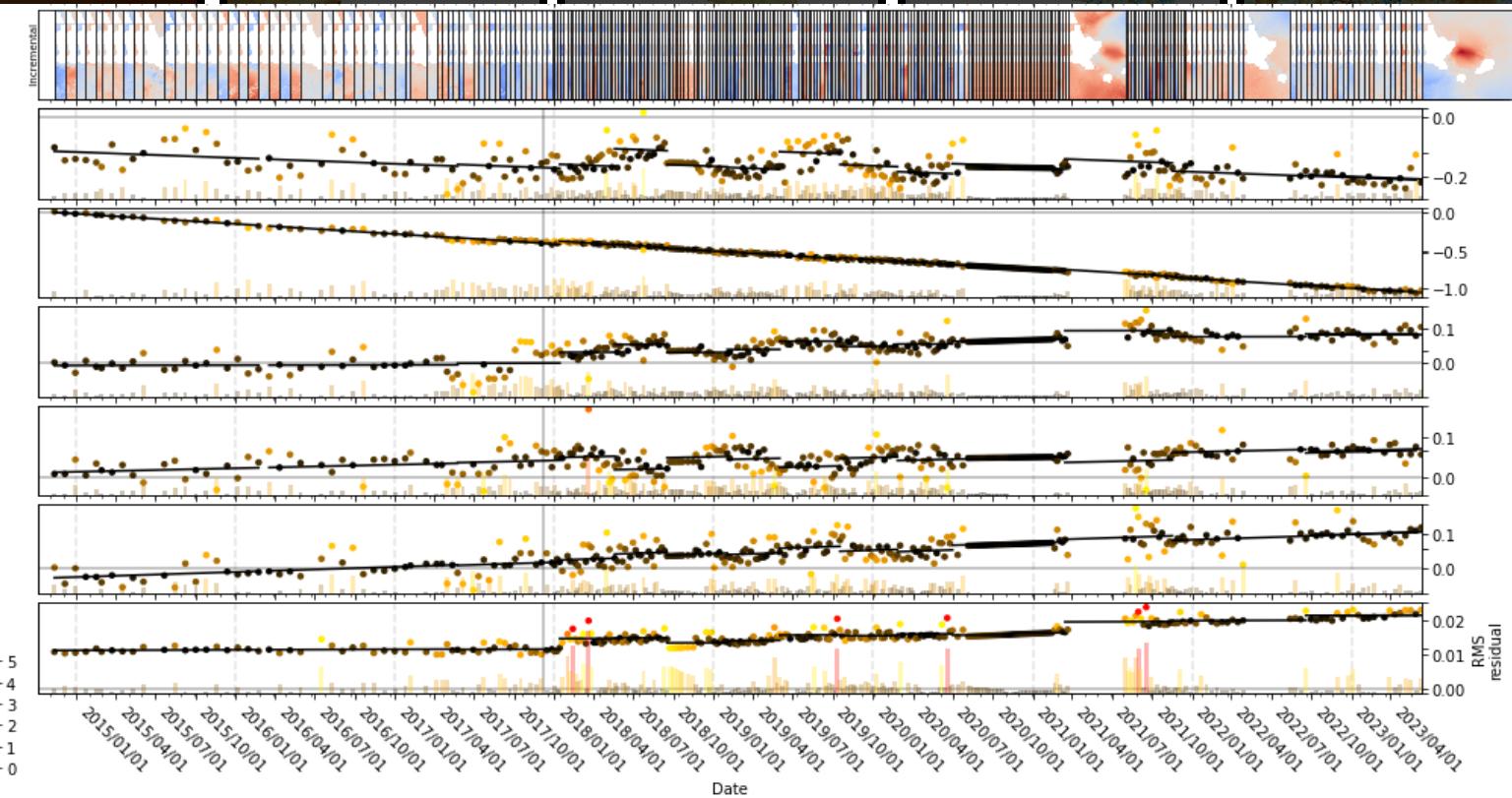
IC 2



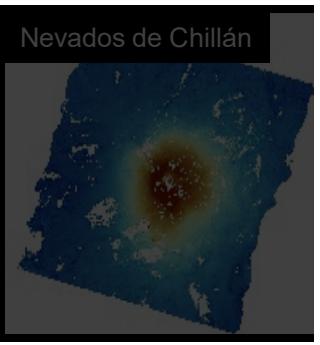
IC 3



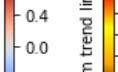
IC 4



Nevados de Chillán



IC (m)

 $\sigma$  from trend line

5



4



3



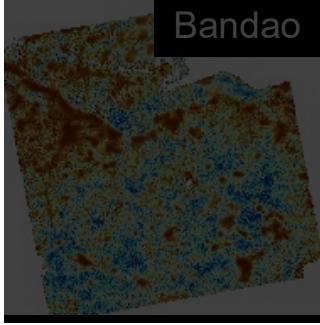
2



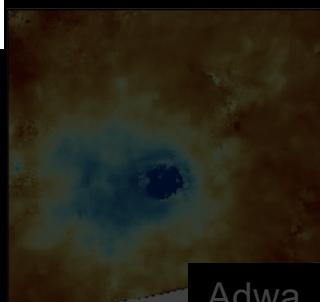
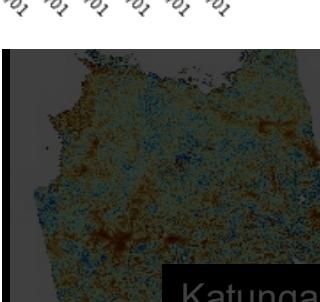
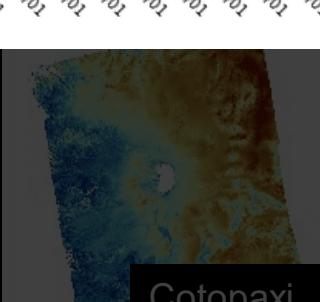
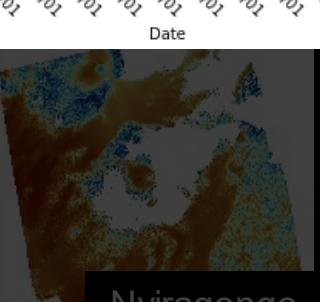
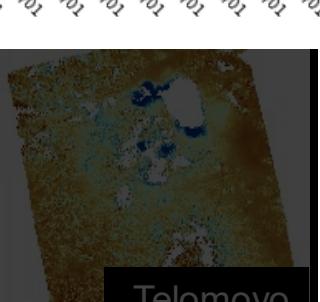
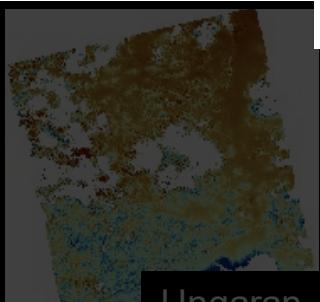
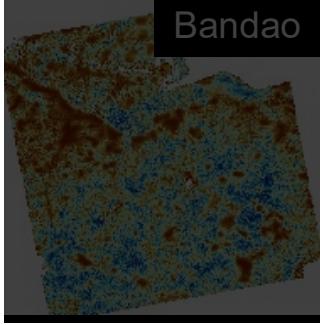
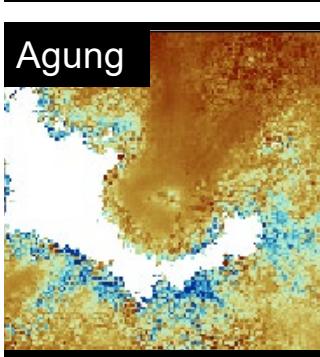
1



0



Agung



Ungaran

Chichinautzin

Telomoyo

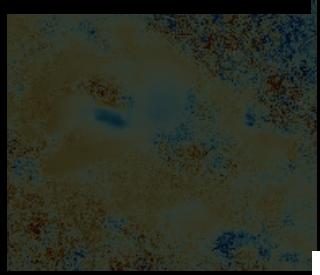
Nyiragongo

Cotopaxi

Katunga

Adwa

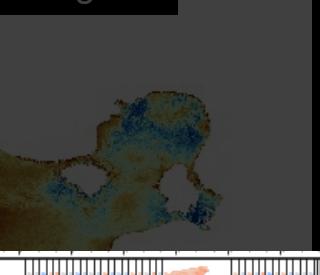
Ceboruco



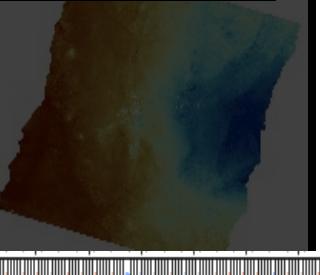
Askja



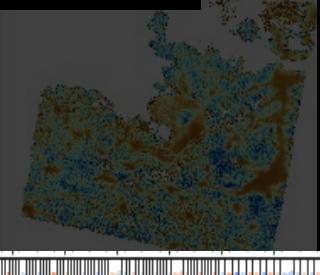
Adagdak



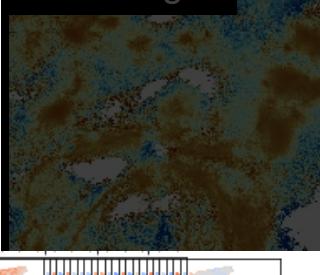
San Pedro-Pellado



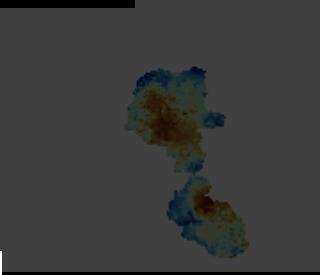
Sinabung



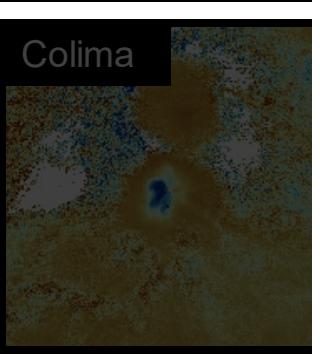
Acatenagoi



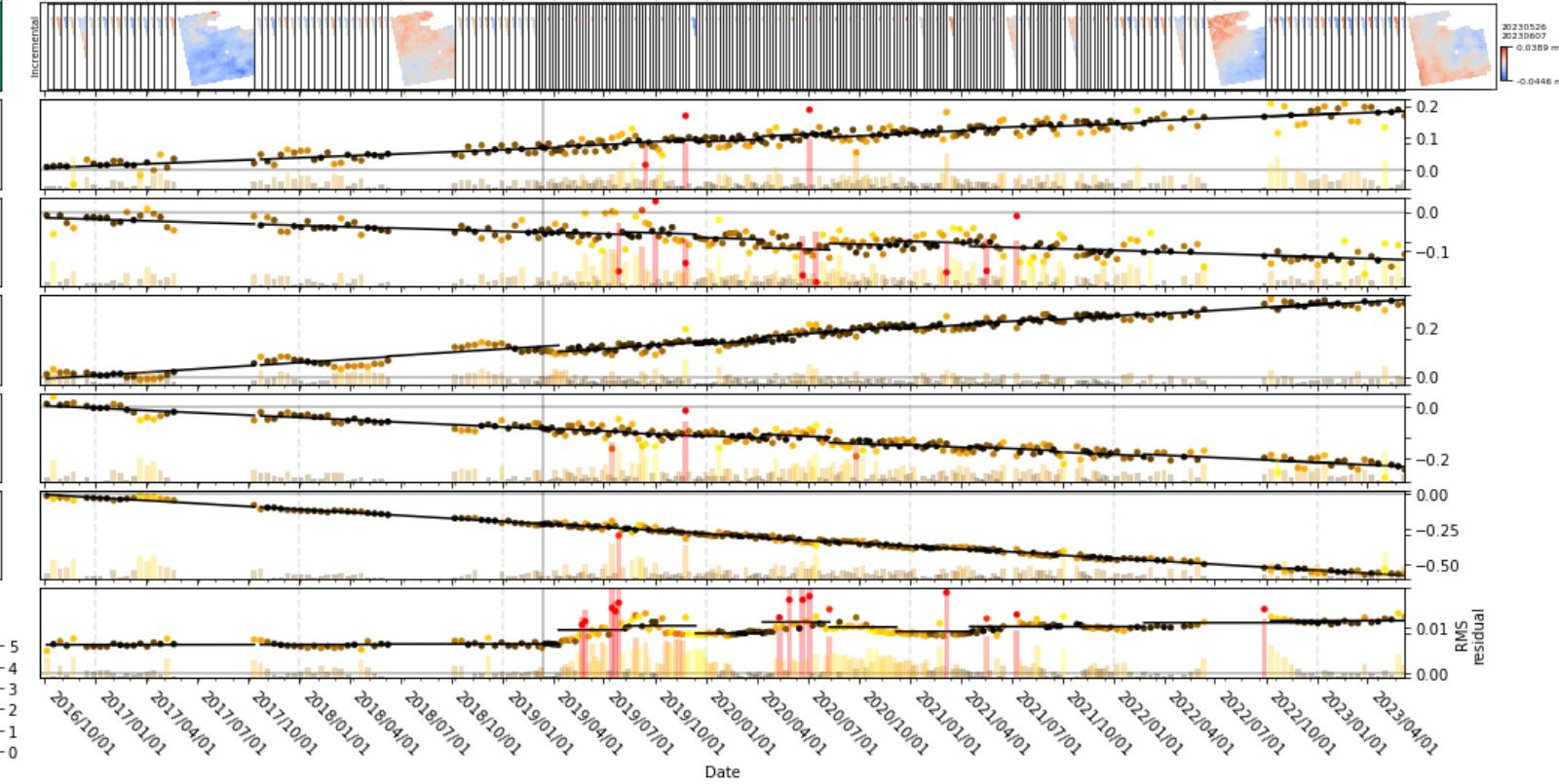
Lipari



Colima



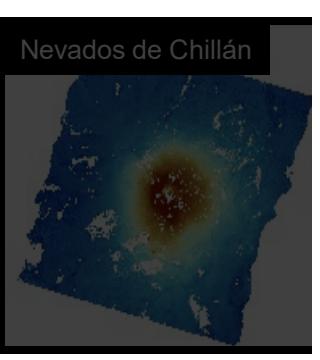
20.93 °



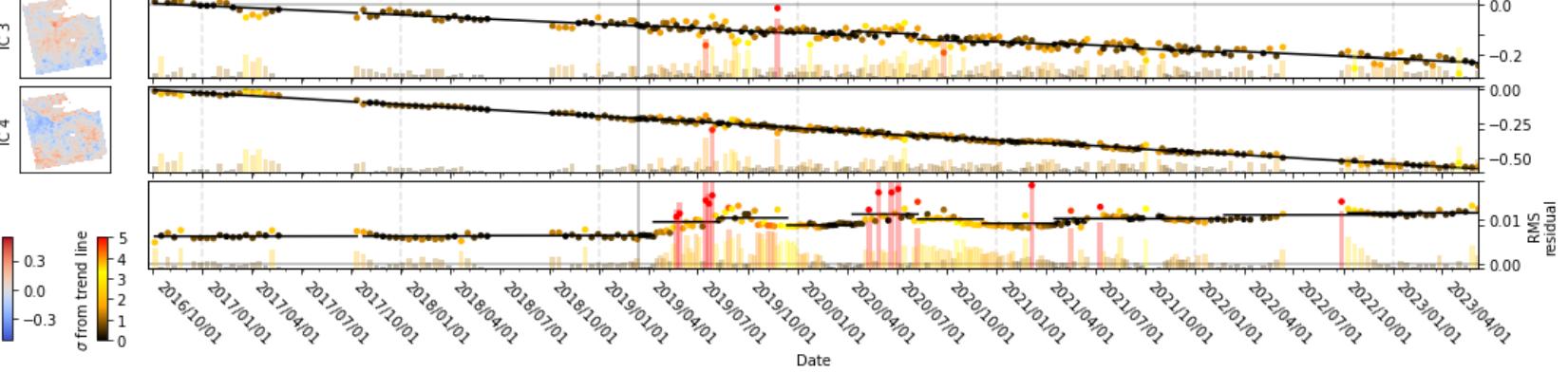
Agung



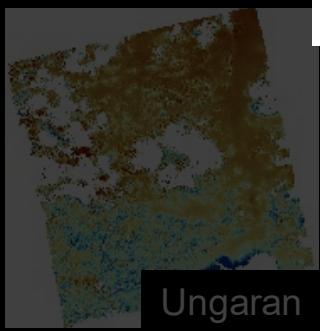
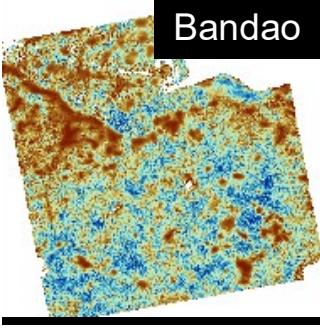
Nevados de Chillán



20.63 °



Bandao



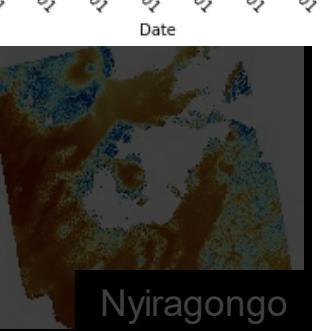
Ungaran



Chichinautzin



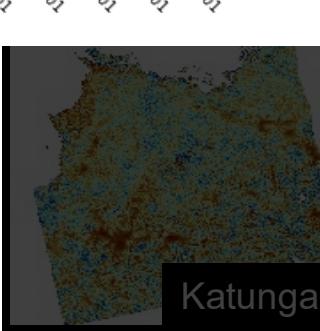
Telomoyo



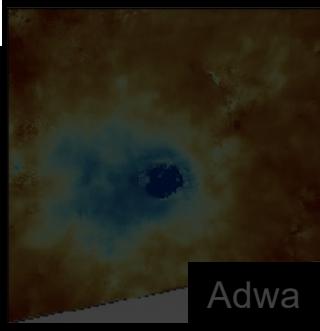
Nyiragongo



Cotopaxi

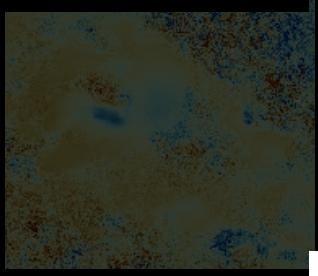


Katunga

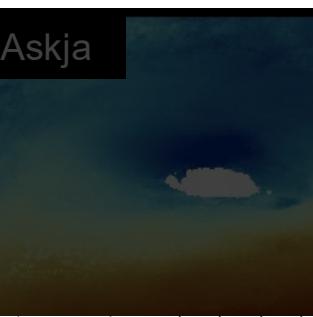


Adwa

Ceboruco



Askja



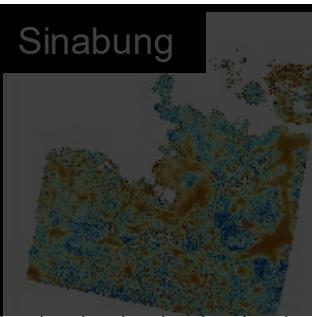
Adagdak



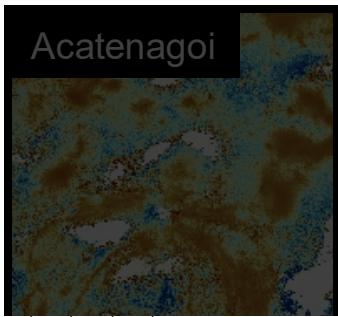
San Pedro-Pellado



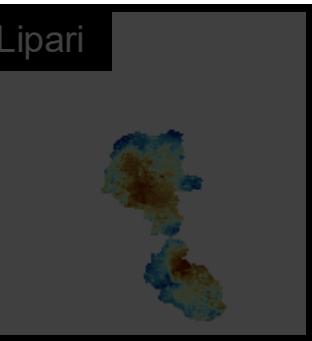
Sinabung



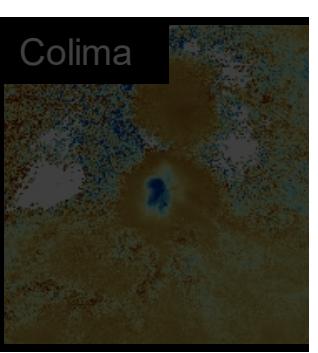
Acatenagoi



Lipari

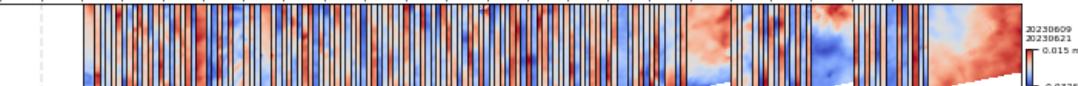
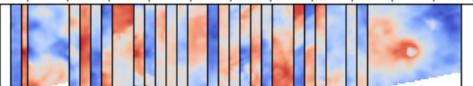


Colima



9.96°

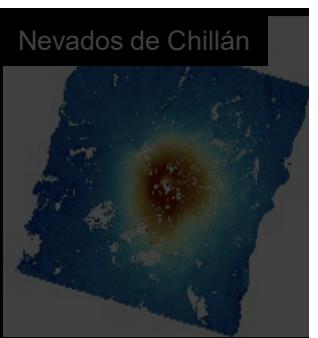
Incremental



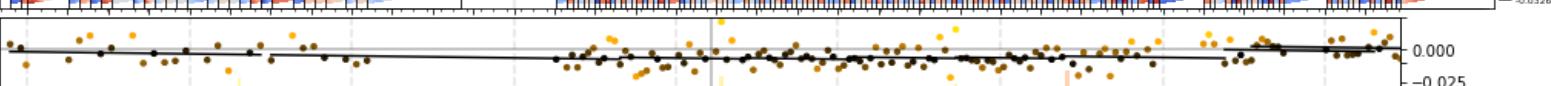
Agung



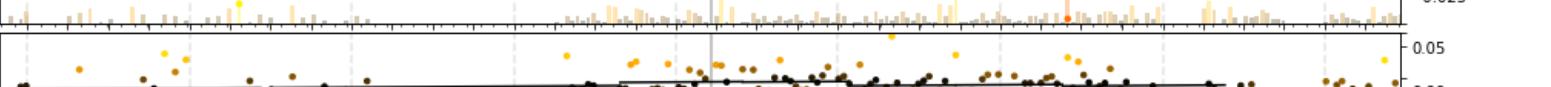
Nevados de Chillán



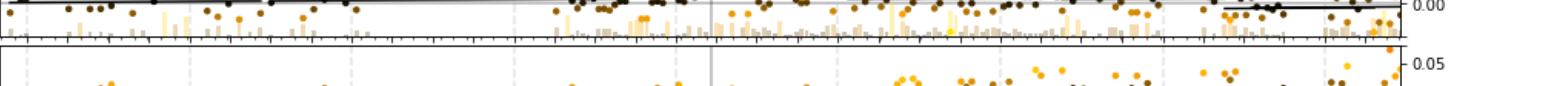
IC 0



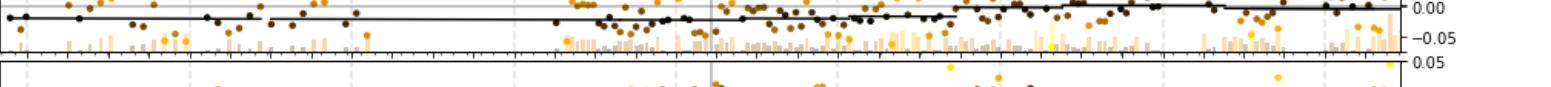
IC 1



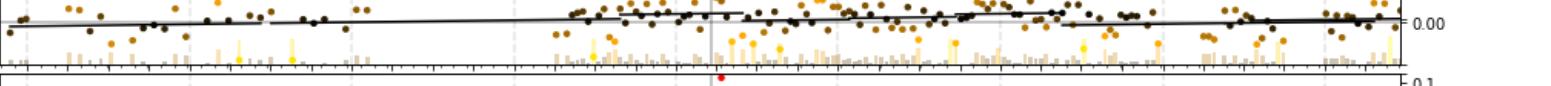
IC 2



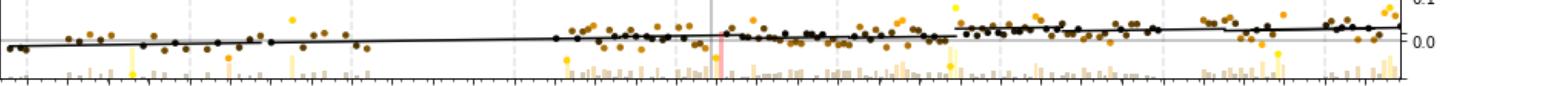
IC 3



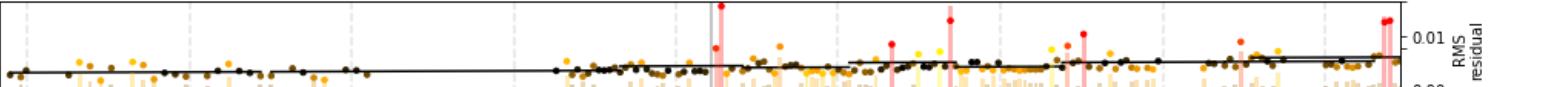
IC 4



σ from trend line



0



0.3



0.6



0.9



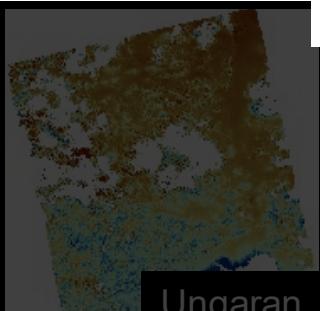
1.2



1.5



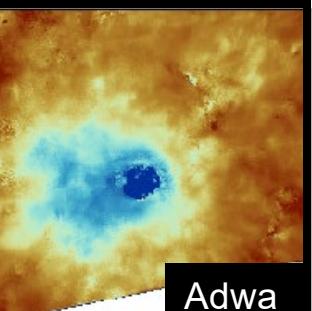
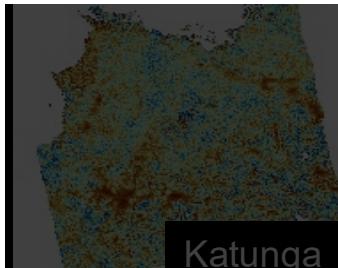
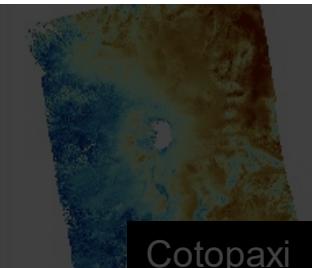
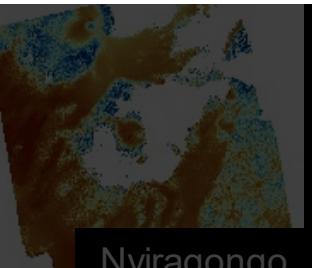
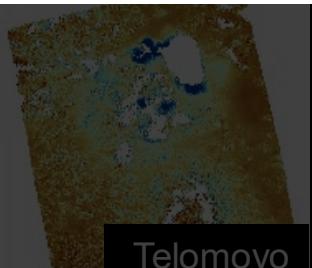
Date



Chichinautzin

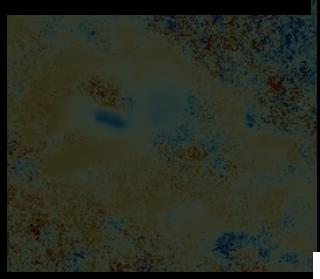


Telomoyo

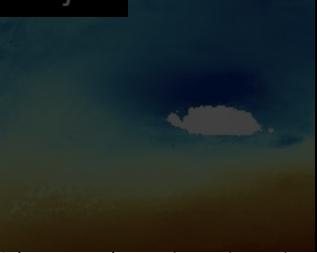


Adwa

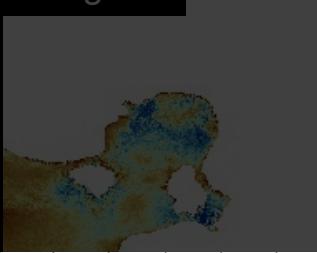
Ceboruco



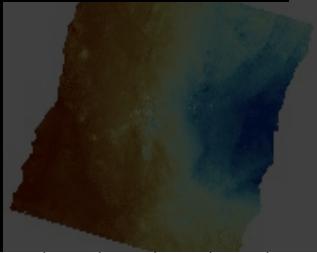
Askja



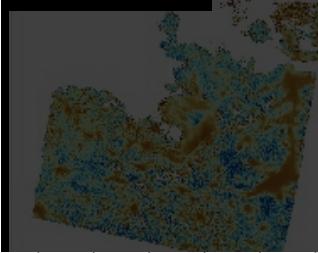
Adagdak



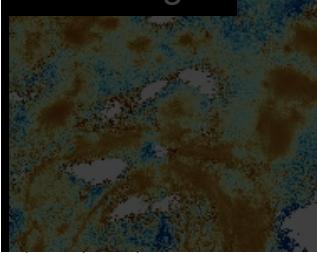
San Pedro-Pellado



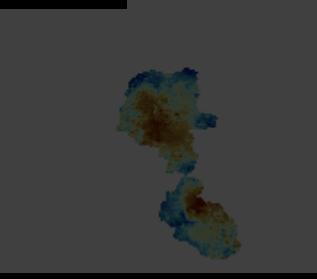
Sinabung



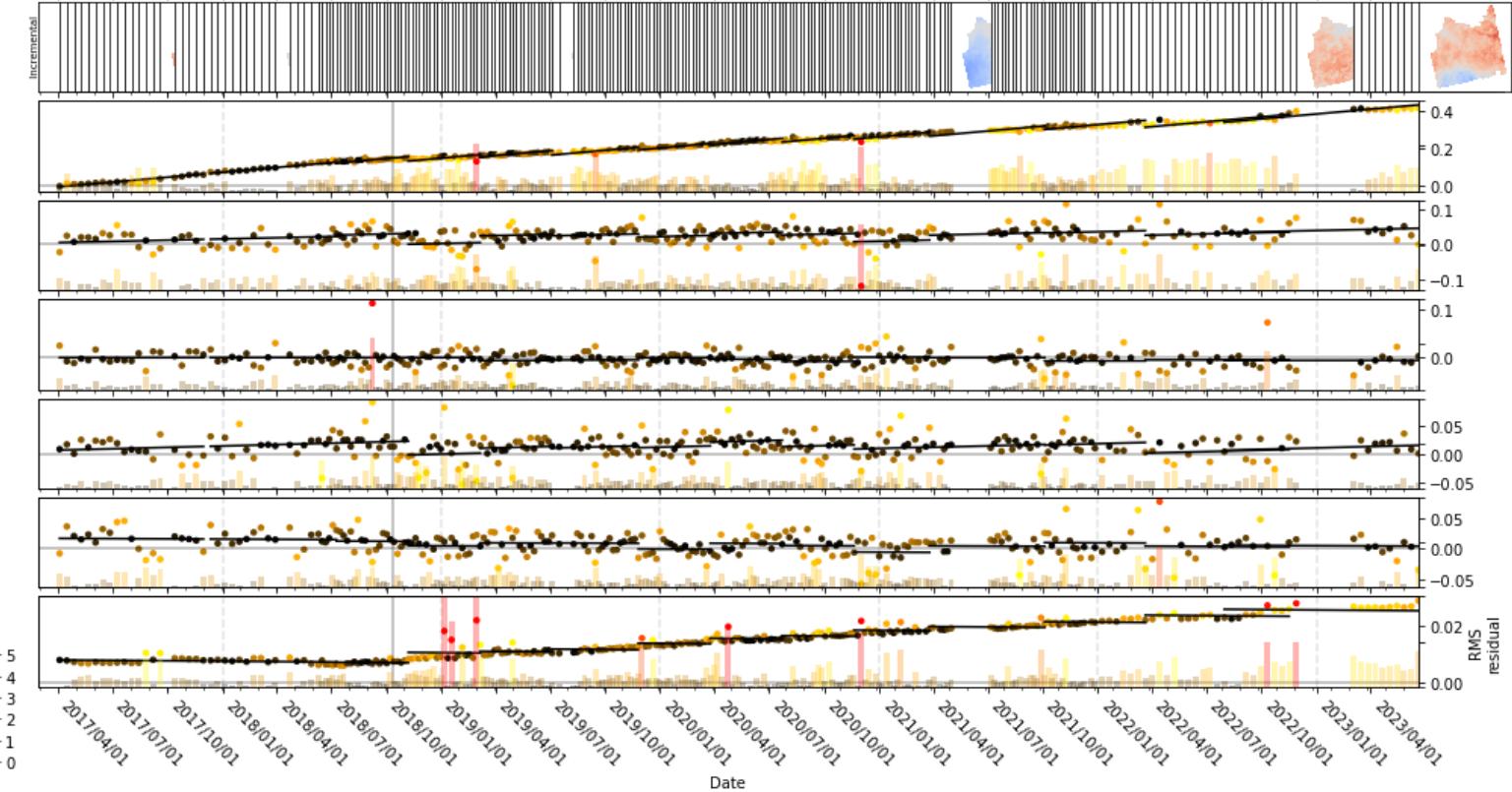
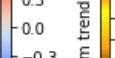
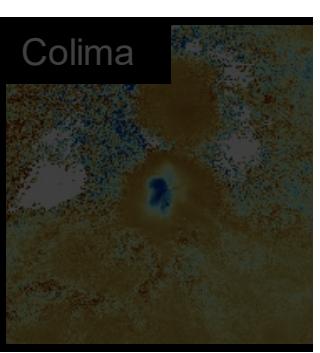
Acatenagoi



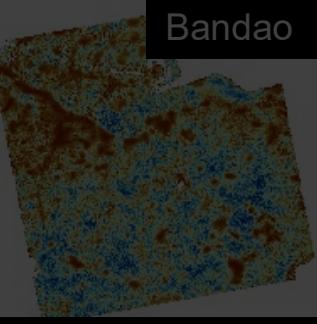
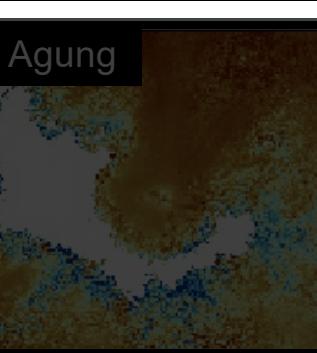
Lipari



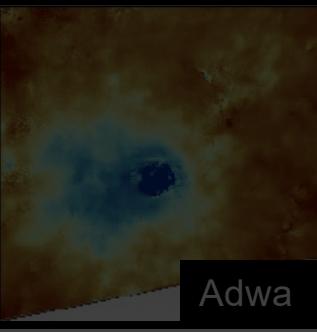
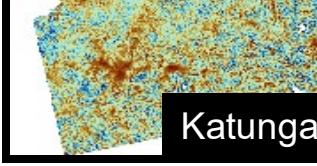
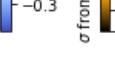
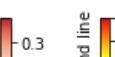
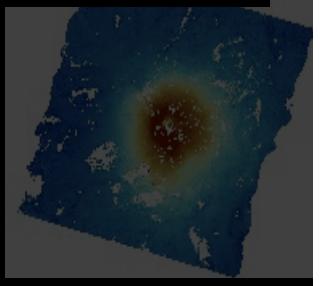
Colima



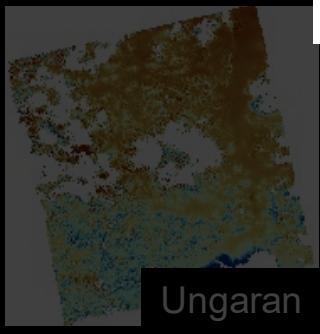
Agung



Nevados de Chillán



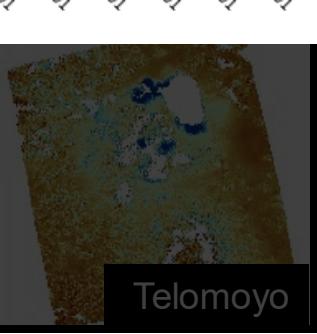
Adwa



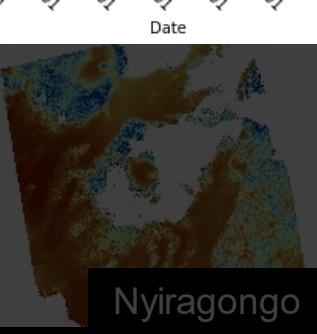
Chichinautzin



Telomoyo



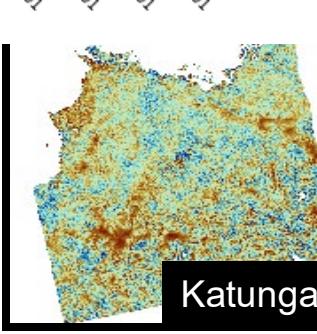
Nyiragongo



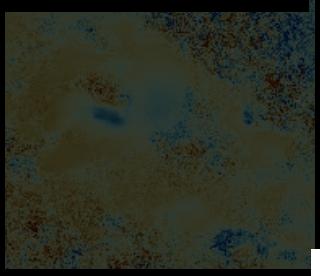
Cotopaxi



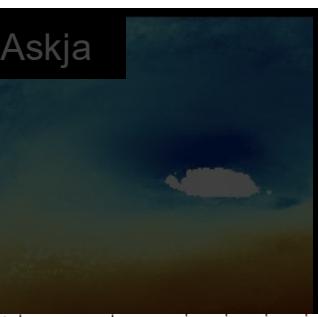
Katunga



Ceboruco



Askja



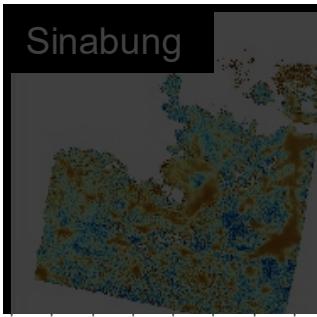
Adagdak



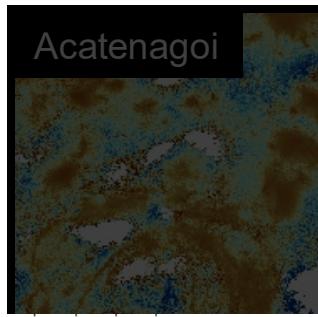
San Pedro-Pellado



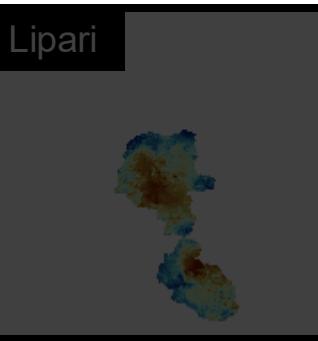
Sinabung



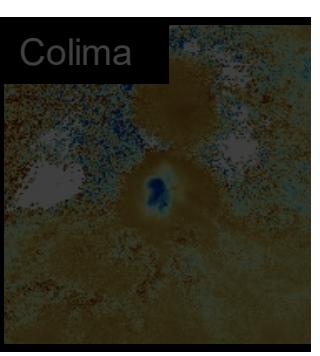
Acatenagoi



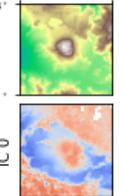
Lipari



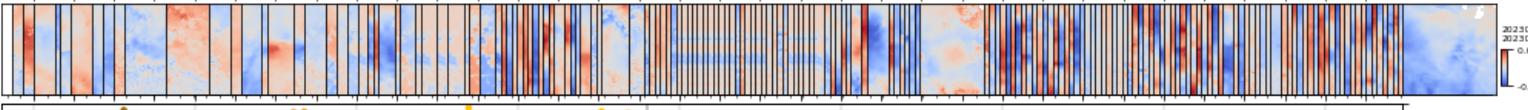
Colima



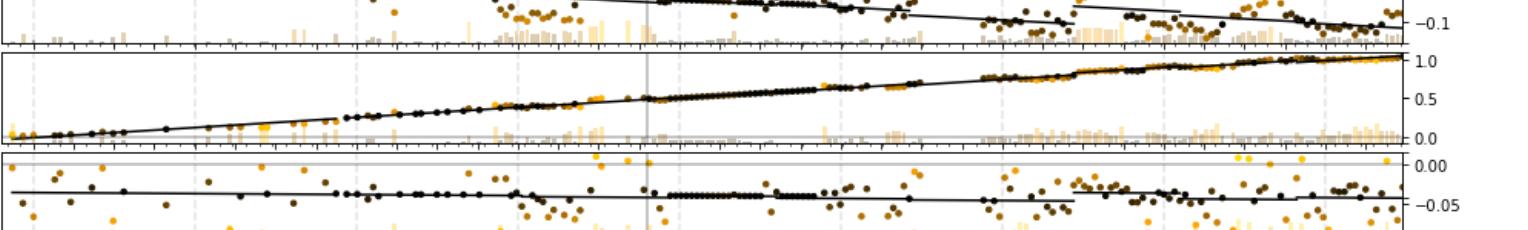
21.01°



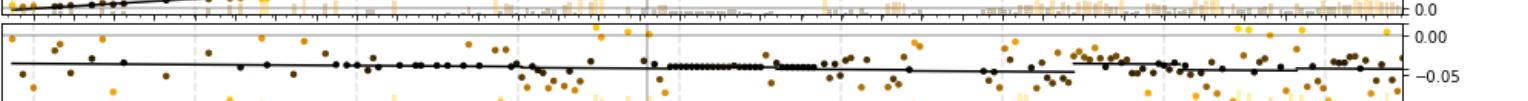
Incremental



IC 0



IC 1



IC 2



IC 3



IC 4

 $\sigma$  from trend line

5

4

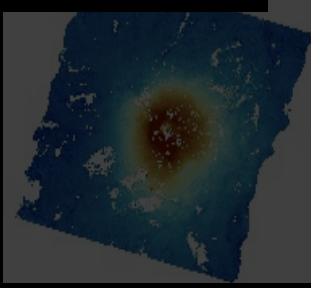
3

2

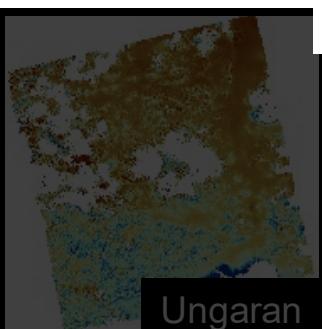
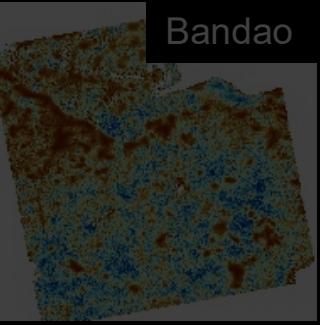
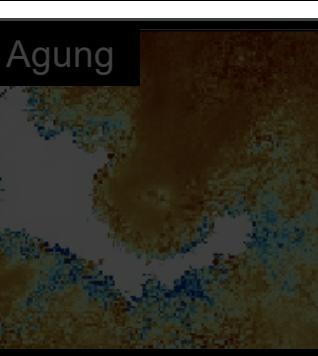
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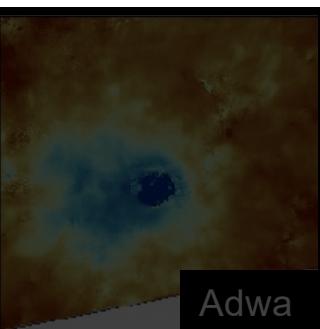
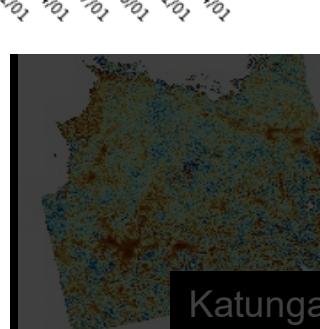
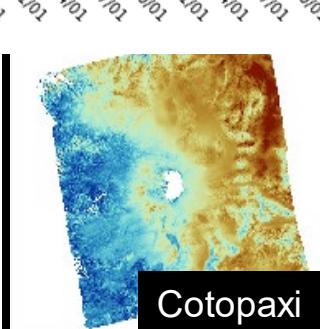
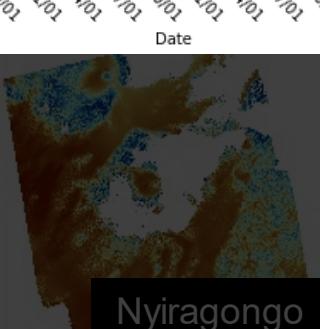
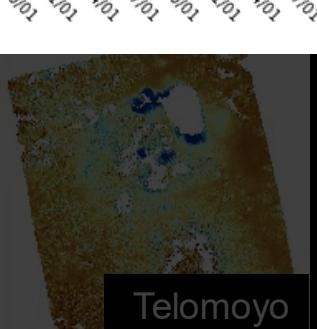
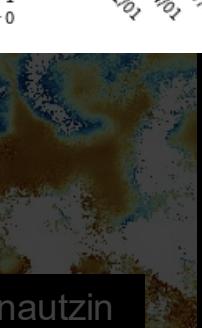
Nevados de Chillán



Agung



Chichinautzin



Ungaran

Chichinautzin

Telomoyo

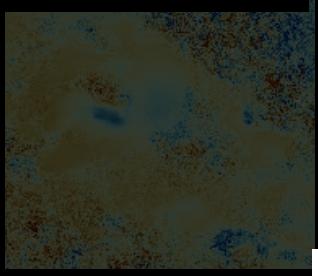
Nyiragongo

Cotopaxi

Katunga

Adwa

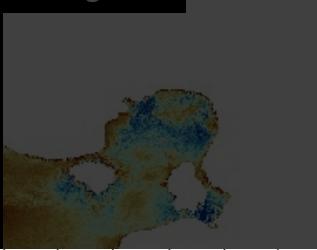
Ceboruco



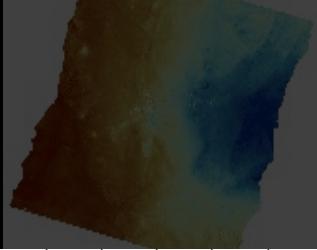
Askja



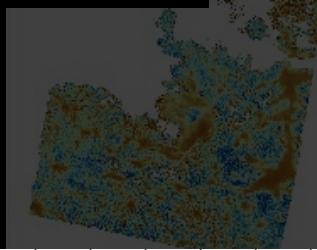
Adagdak



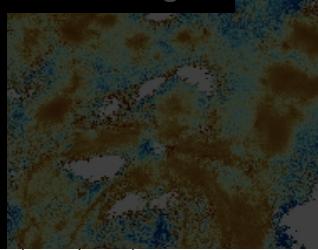
San Pedro-Pellado



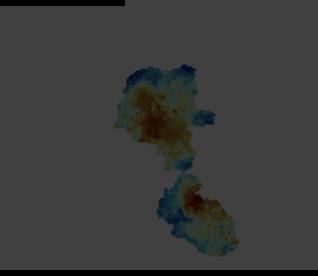
Sinabung



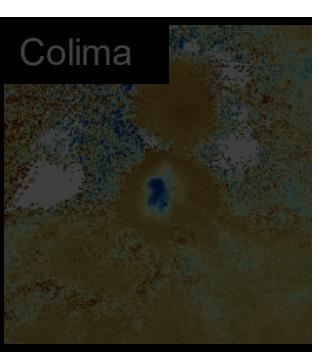
Acatenagoi



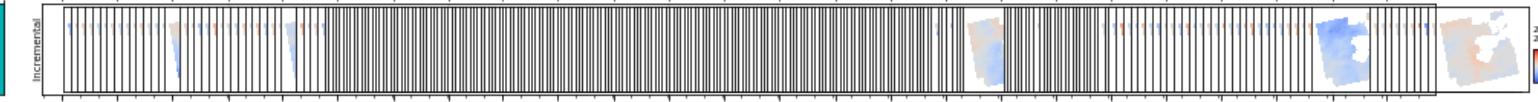
Lipari



Colima



Incremental



-1.68 °

IC 0

IC 1

IC 2

IC 3

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IC 6

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IC 10

IC 11

IC 12

IC 13

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IC 287

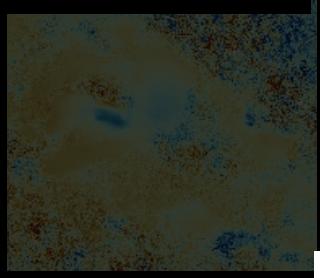
IC 288

IC 289

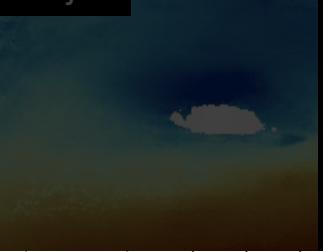
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IC 291

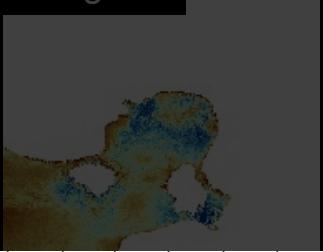
Ceboruco



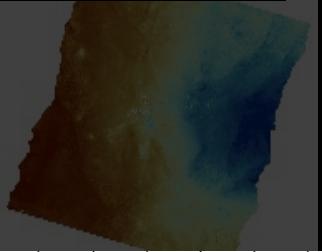
Askja



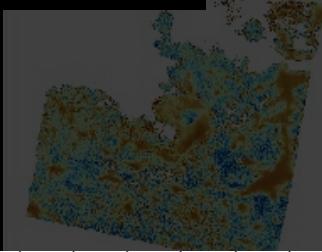
Adagdak



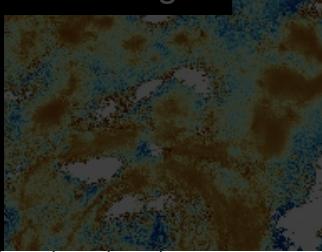
San Pedro-Pellado



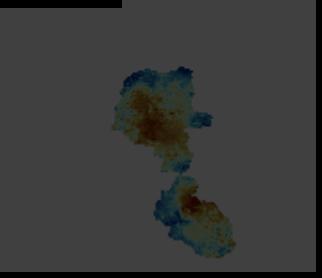
Sinabung



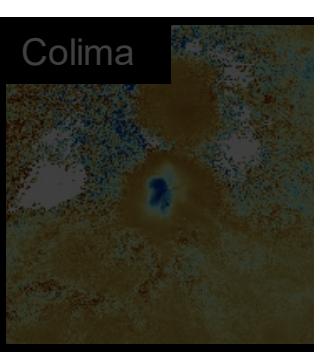
Acatenango



Lipari

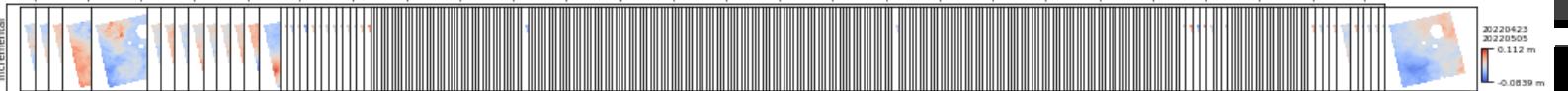


Colima

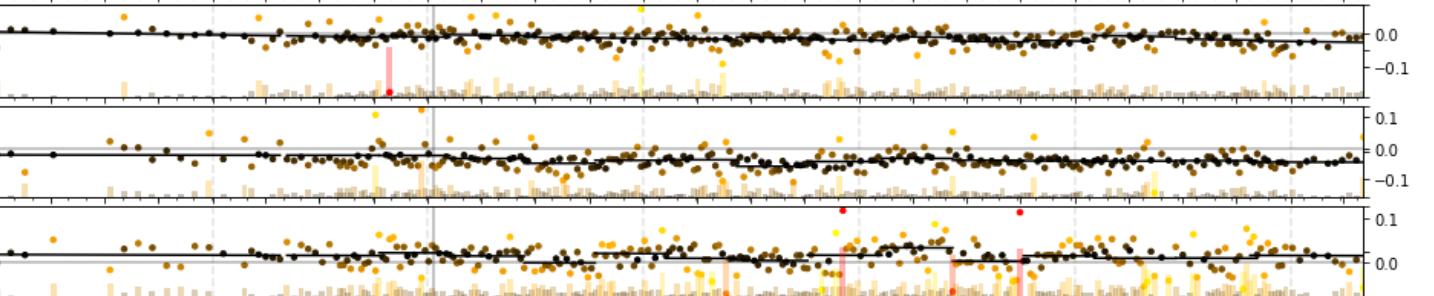


-7.19°

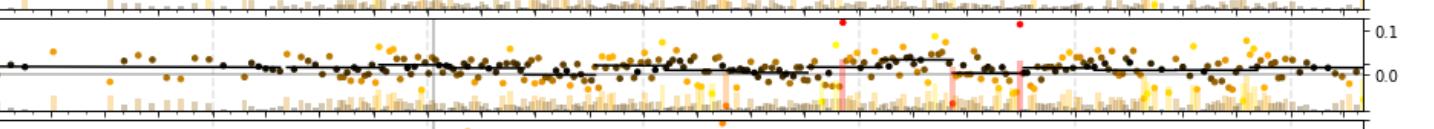
Incremental



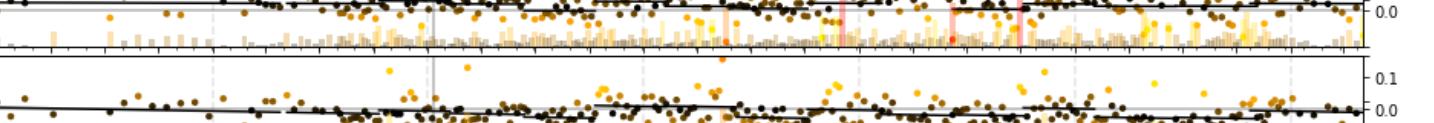
IC 0



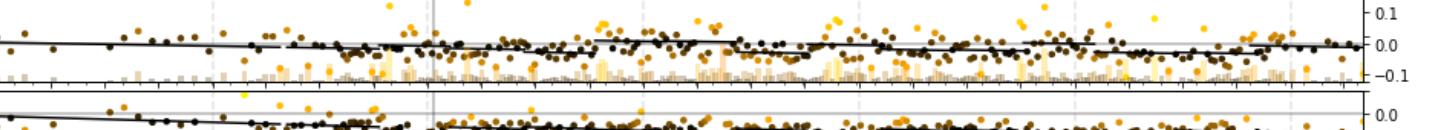
IC 1



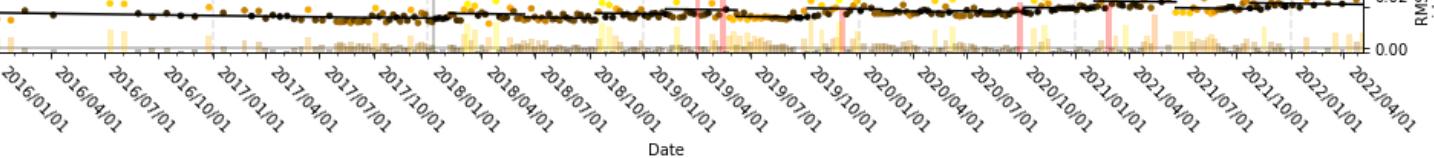
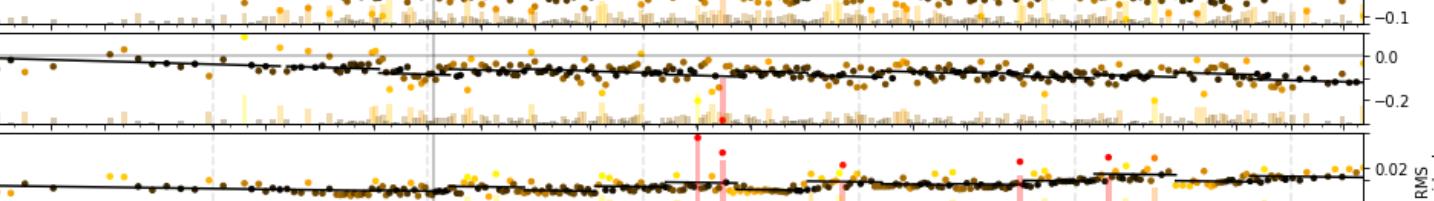
IC 2



IC 3



IC 4

 $\sigma$  from trend line

5

4

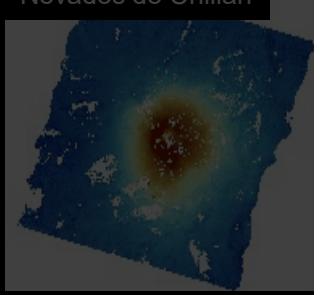
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2

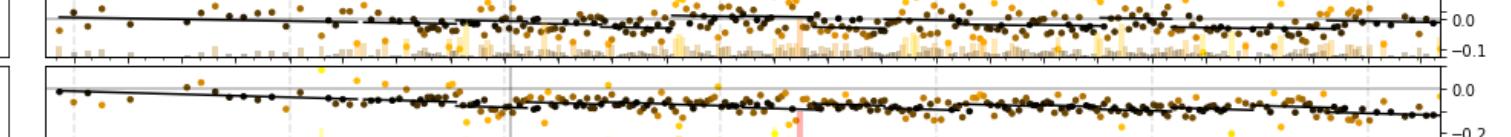
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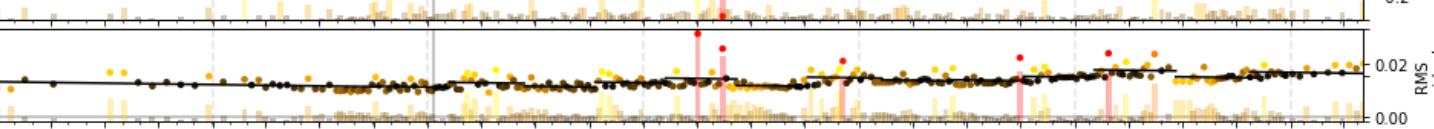
Nevados de Chillán



IC 0



IC 1



IC 2



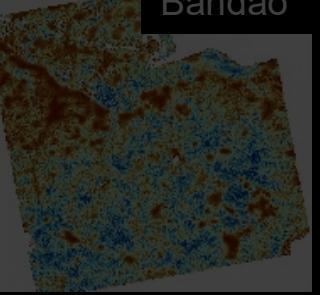
IC 3



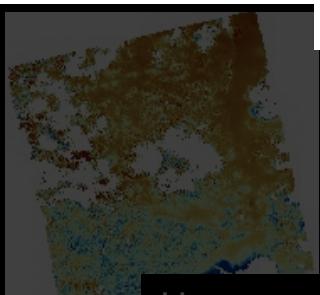
IC 4



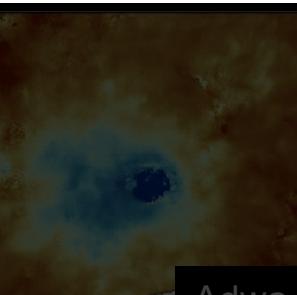
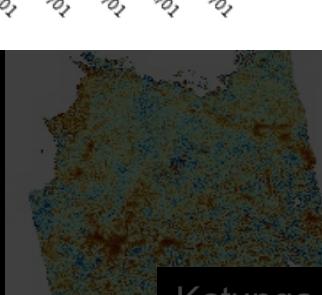
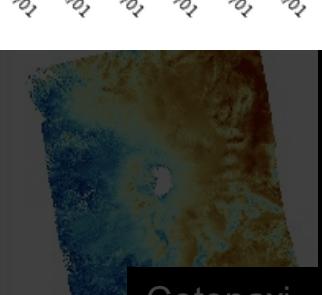
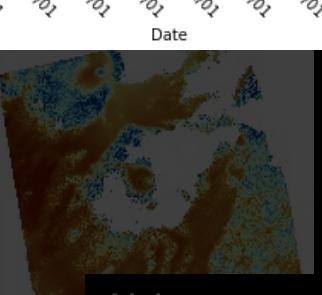
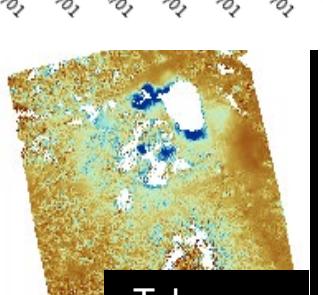
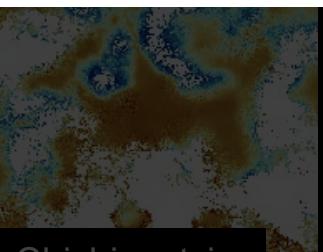
Bandao



Ungaran

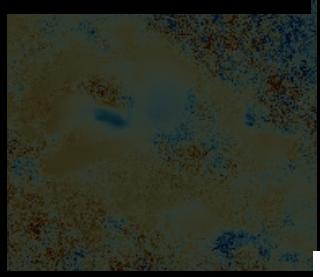


Chichinautzin



Adwa

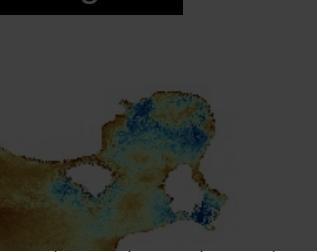
Ceboruco



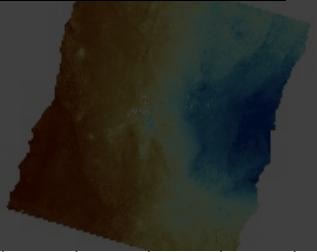
Askja



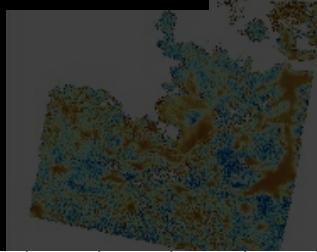
Adagdak



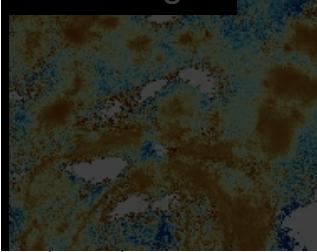
San Pedro-Pellado



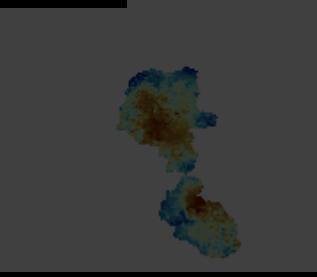
Sinabung



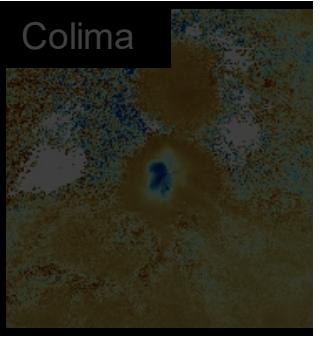
Acatenango



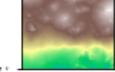
Lipari



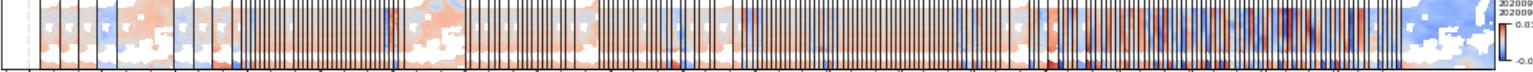
Colima



19.19°



Incremental



IC 0



IC 1



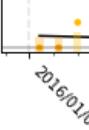
IC 2



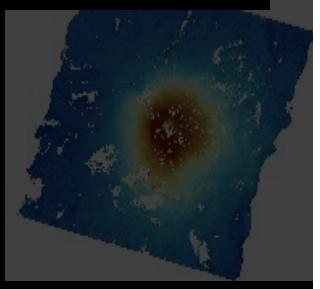
IC 3



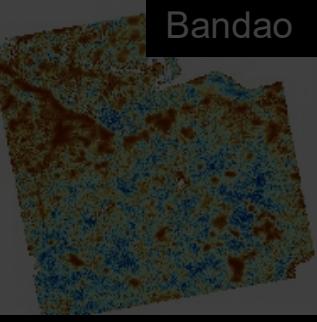
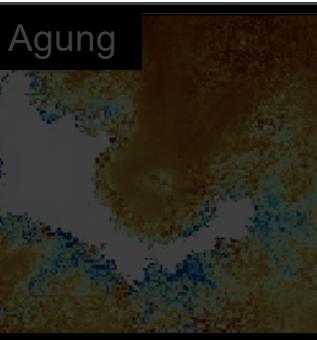
IC 4



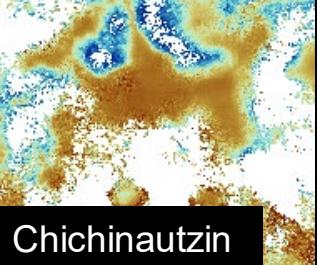
Nevados de Chillán



Agung



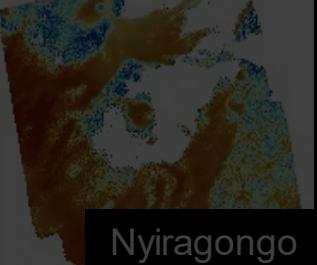
Ungaran



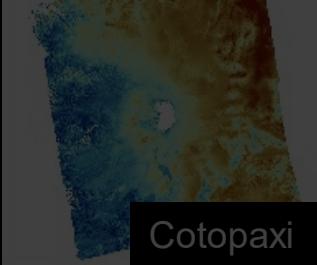
Chichinautzin



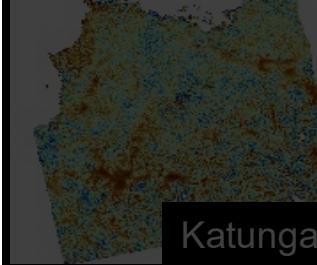
Telomoyo



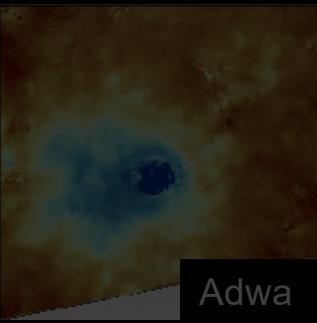
Nyiragongo



Cotopaxi

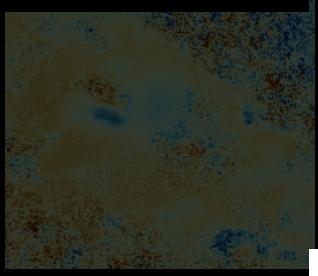


Katunga



Adwa

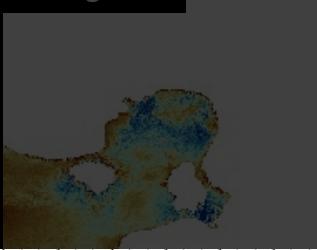
Ceboruco



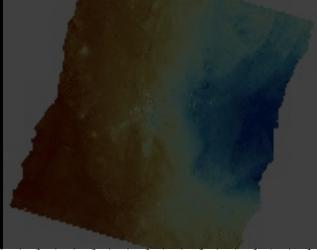
Askja



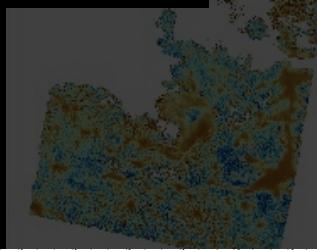
Adagdak



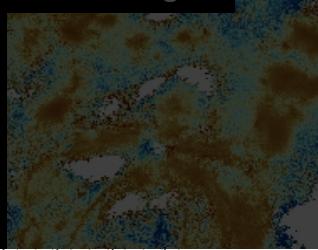
San Pedro-Pellado



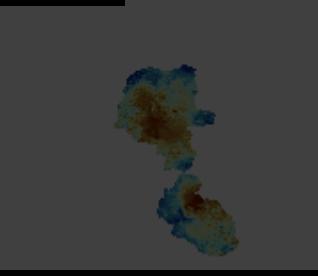
Sinabung



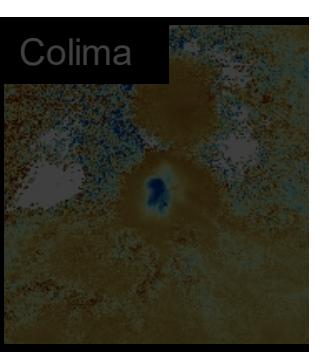
Acatenagoi



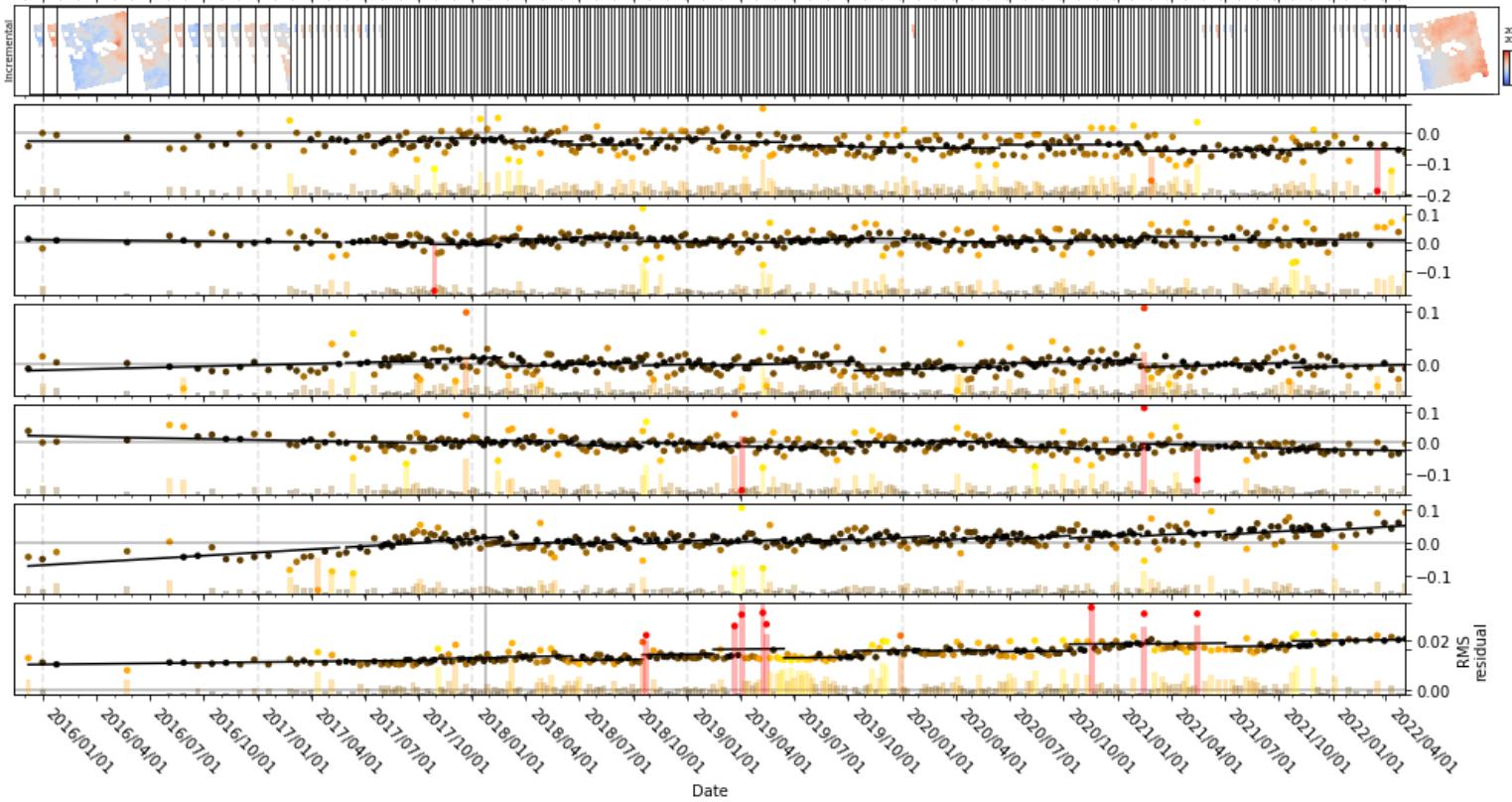
Lipari



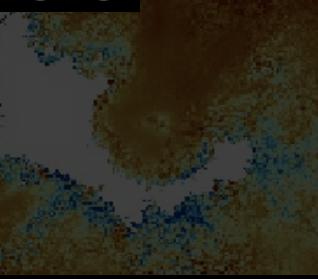
Colima



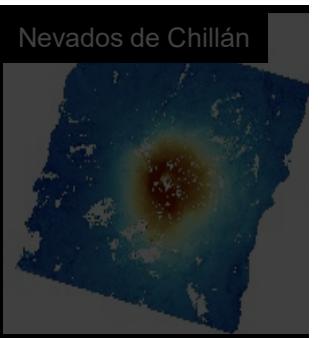
IC 0



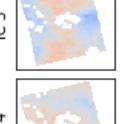
Agung



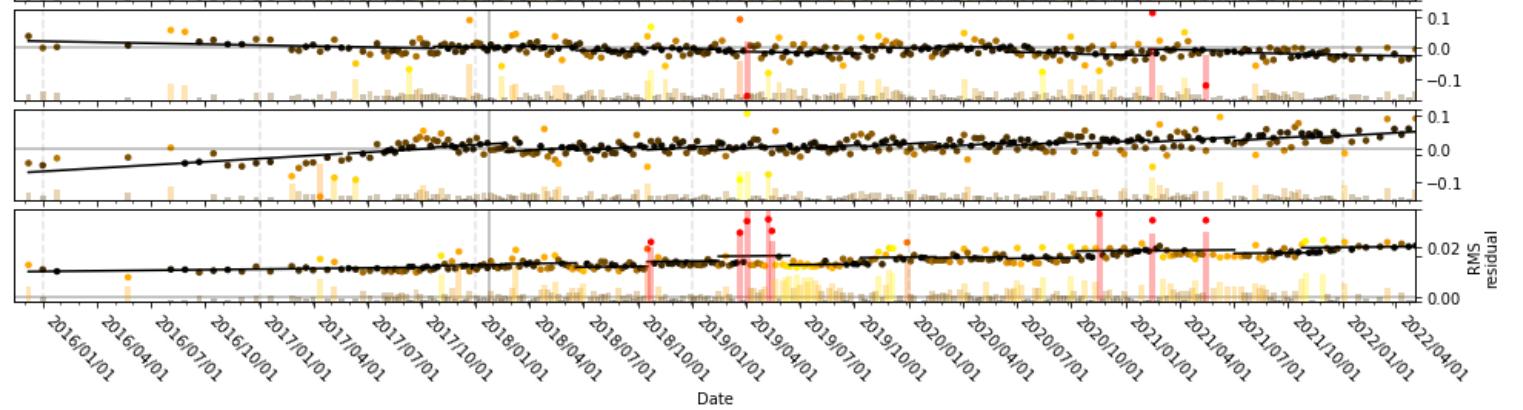
Nevados de Chillán



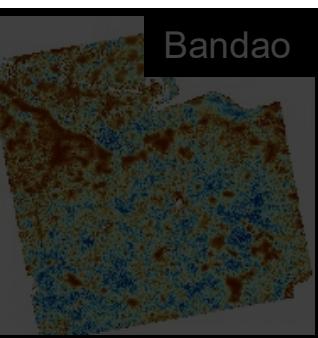
IC 0



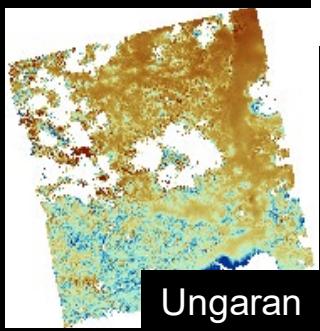
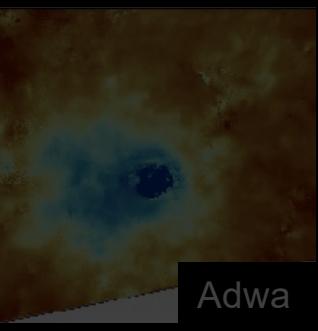
IC 1



Bandao



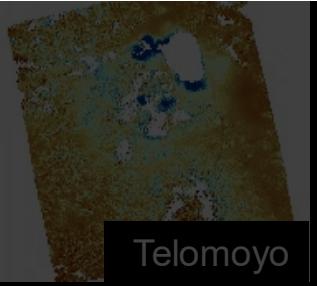
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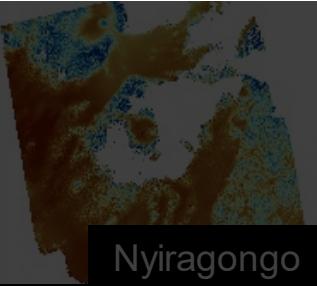
Chichinautzin



Telomoyo



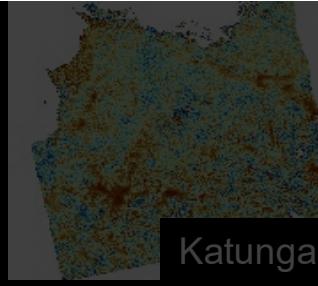
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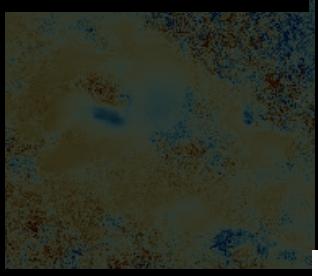
Cotopaxi



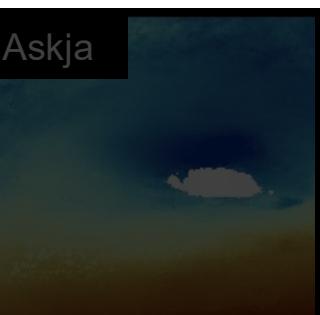
Katunga



Ceboruco



Askja



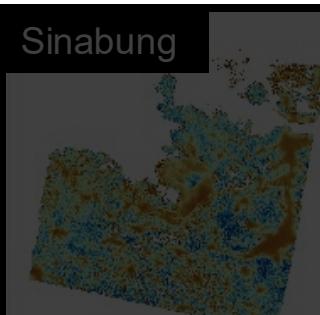
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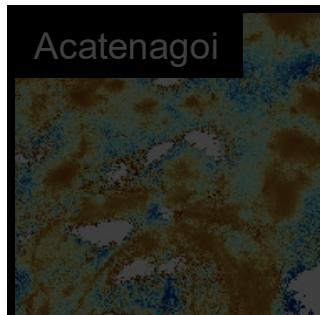
San Pedro-Pellado



Sinabung



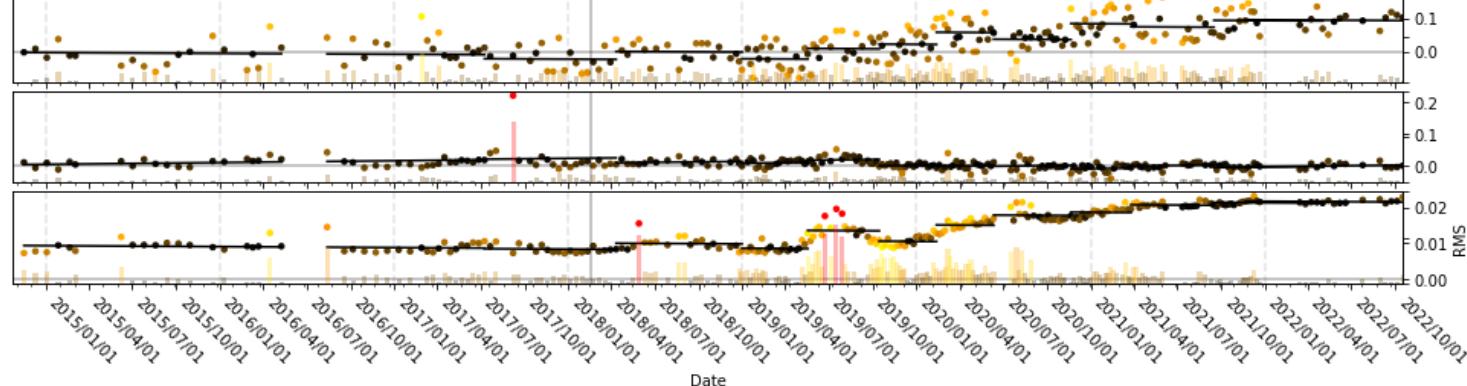
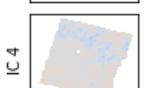
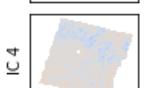
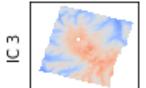
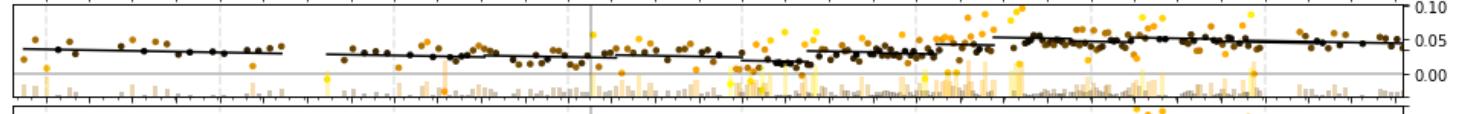
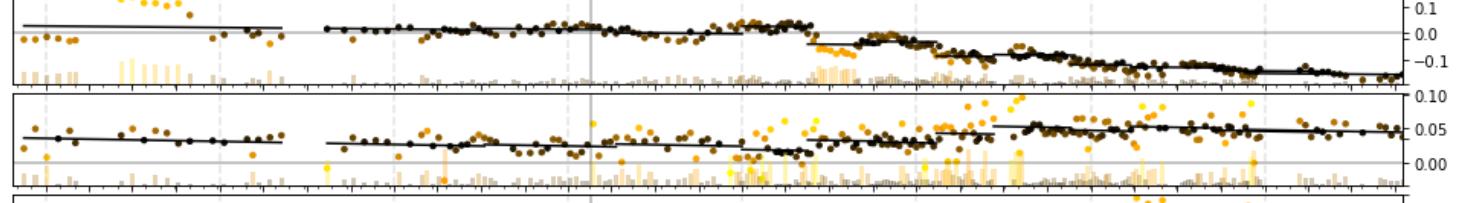
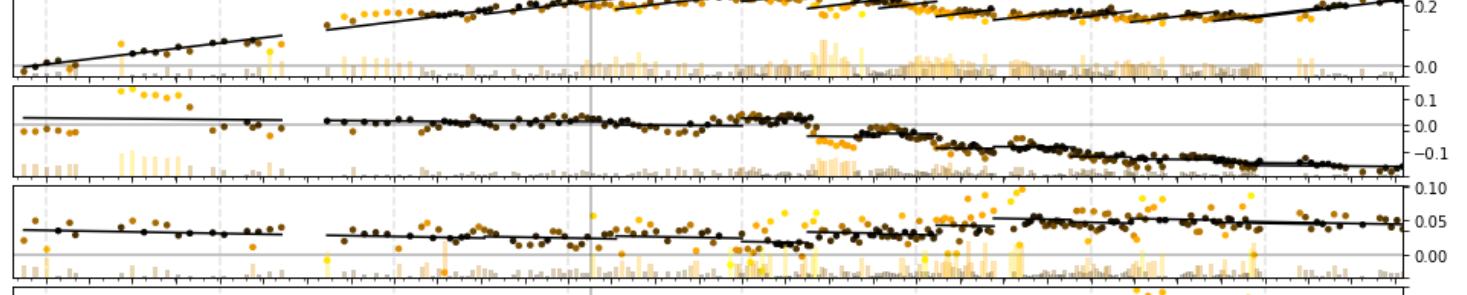
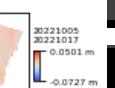
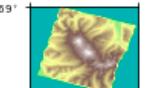
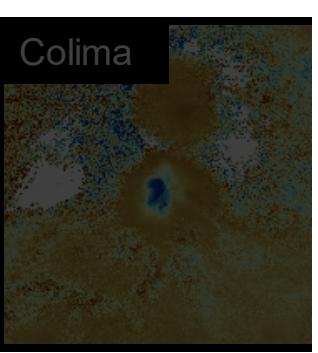
Acatenagoi



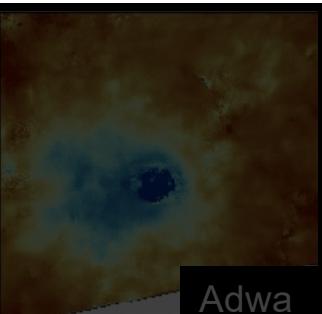
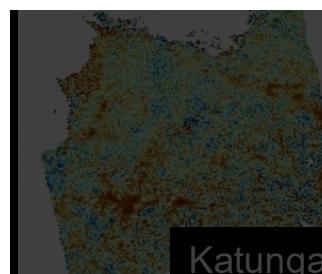
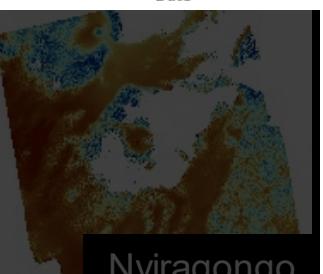
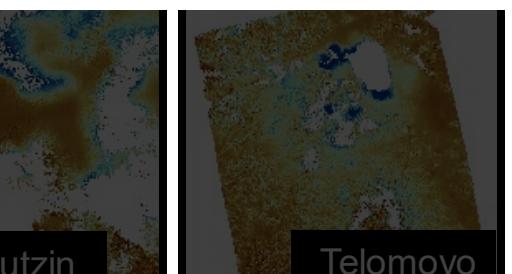
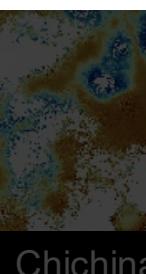
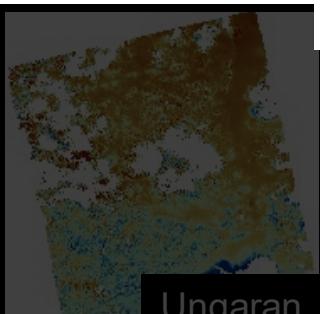
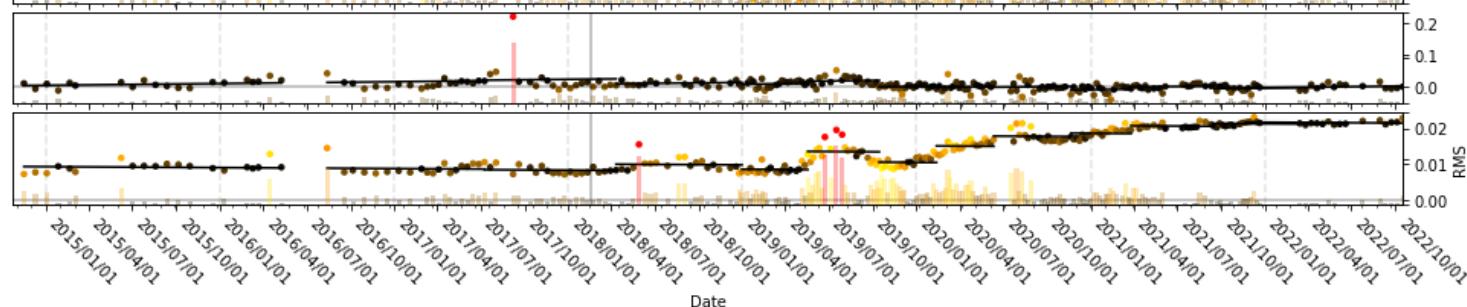
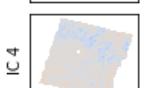
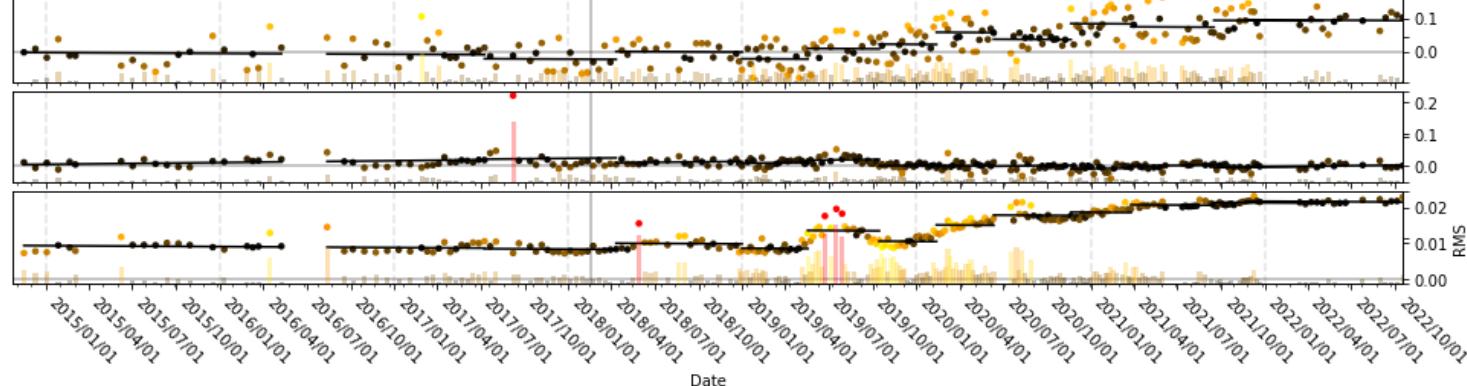
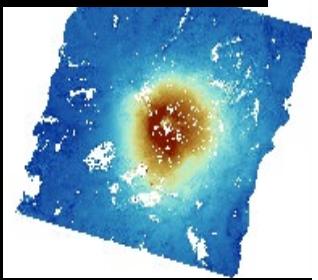
Lipari



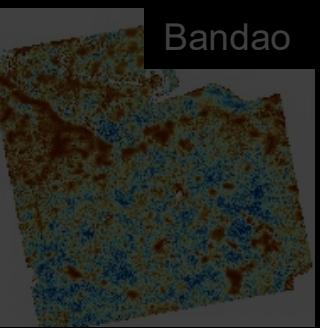
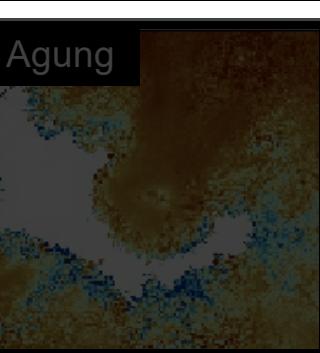
Colima



Nevados de Chillán

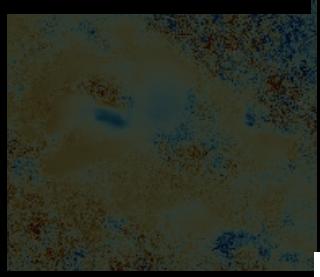


Agung



Adwa

Ceboruco



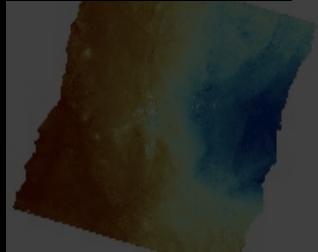
Askja



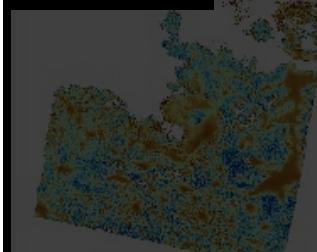
Adagdak



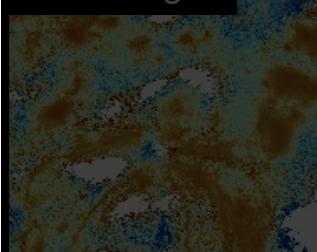
San Pedro-Pellado



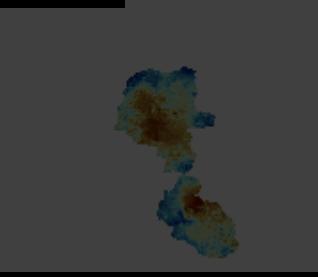
Sinabung



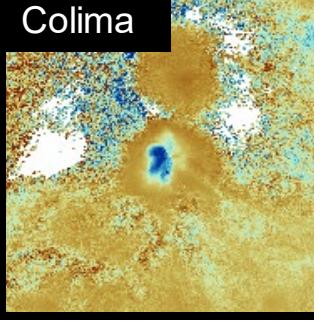
Acatenango



Lipari



Colima



19.03°



Incremental

Date

IC

0

1

2

3

4

IC (m)

5

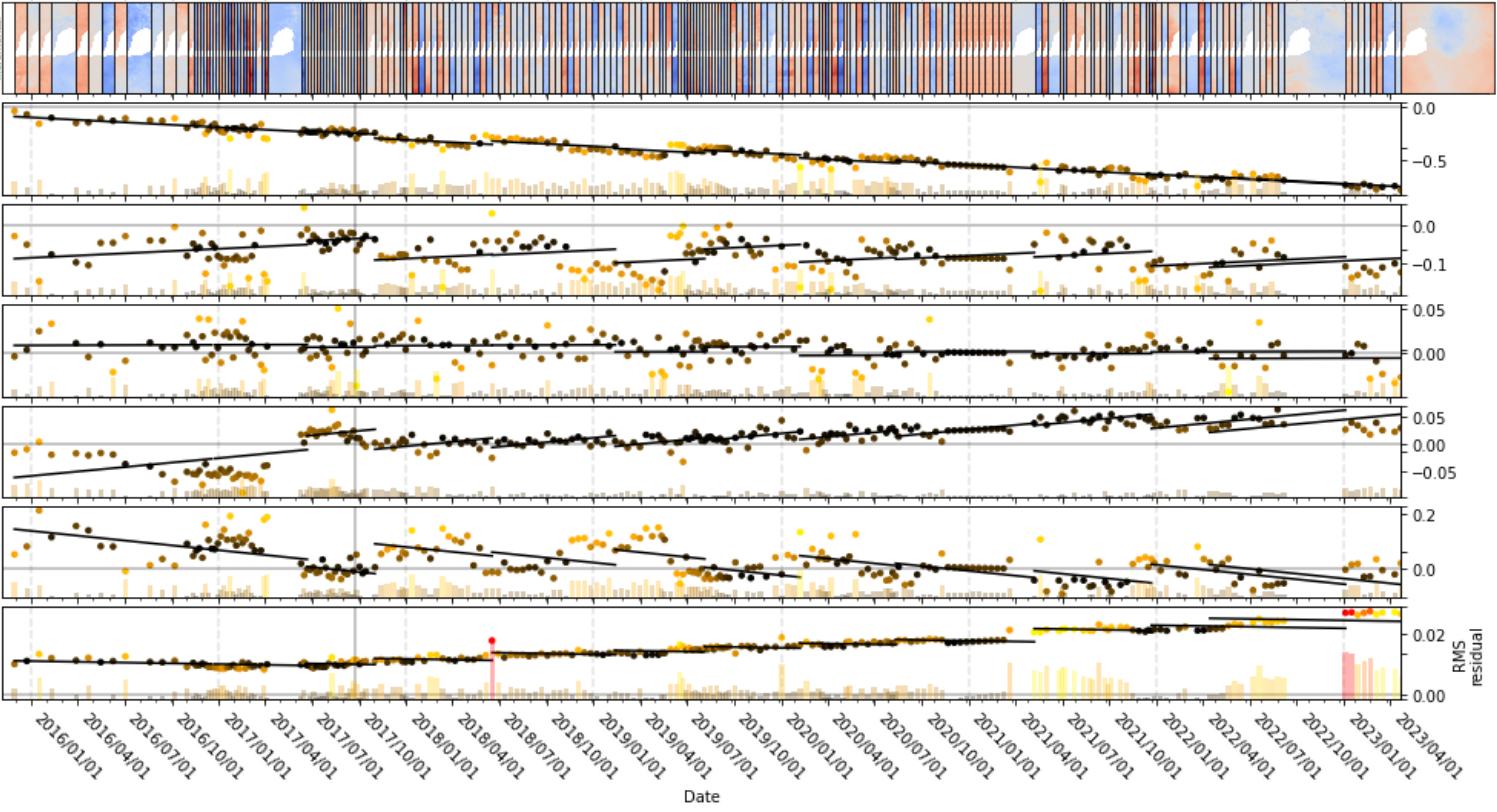
4

3

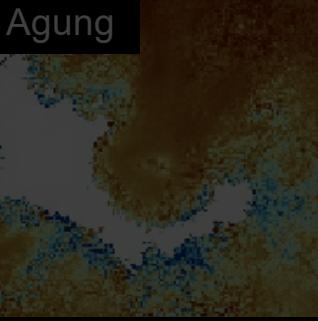
2

1

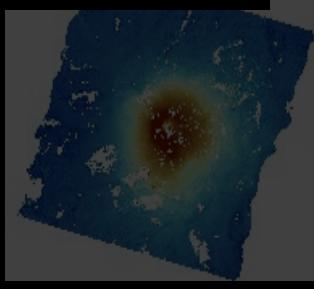
0



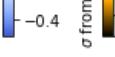
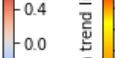
Agung



Nevados de Chillán



19.4°



Incremental

Date

IC

0

1

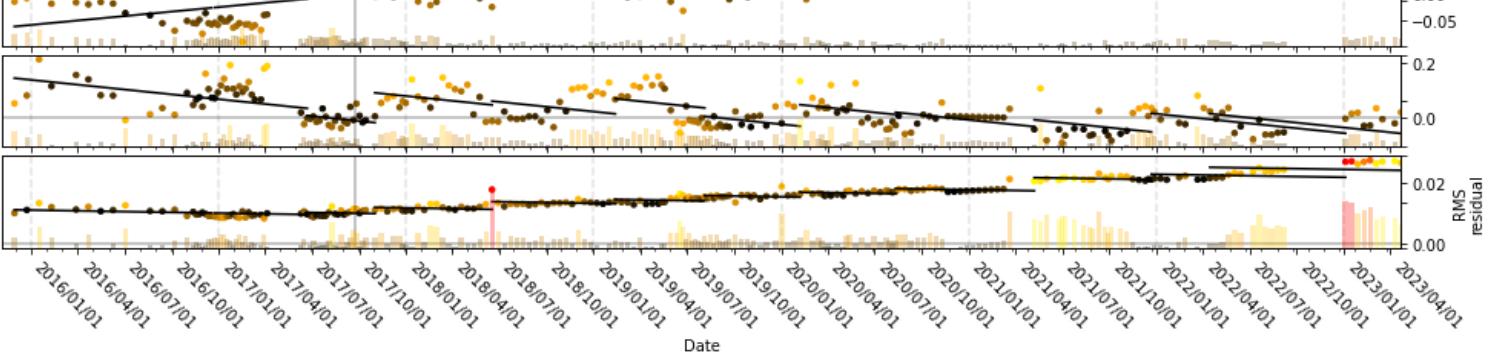
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3

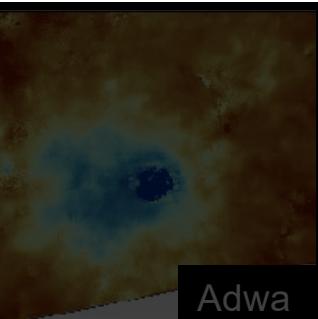
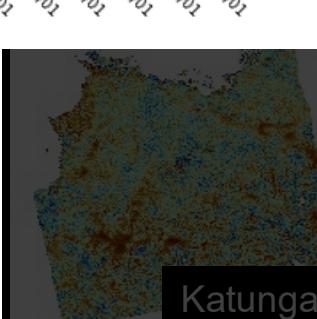
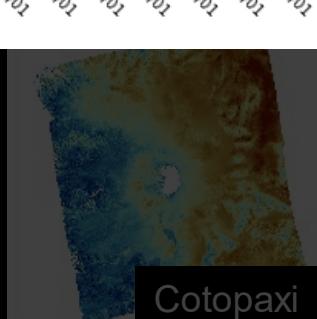
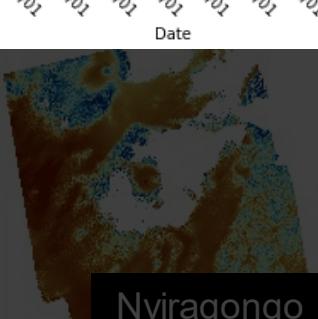
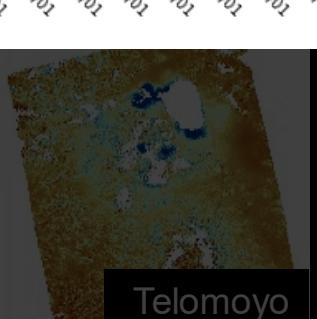
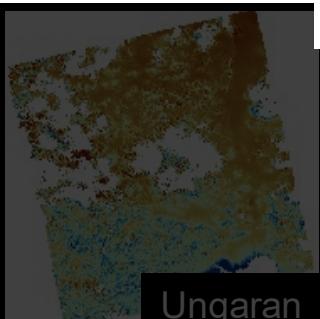
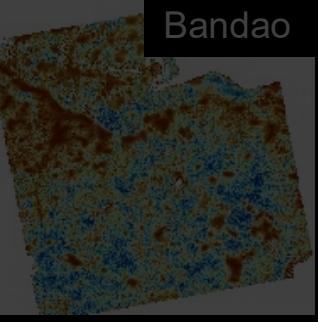
2

1

0



Bandao



Ungaran

Chichinautzin

Telomoyo

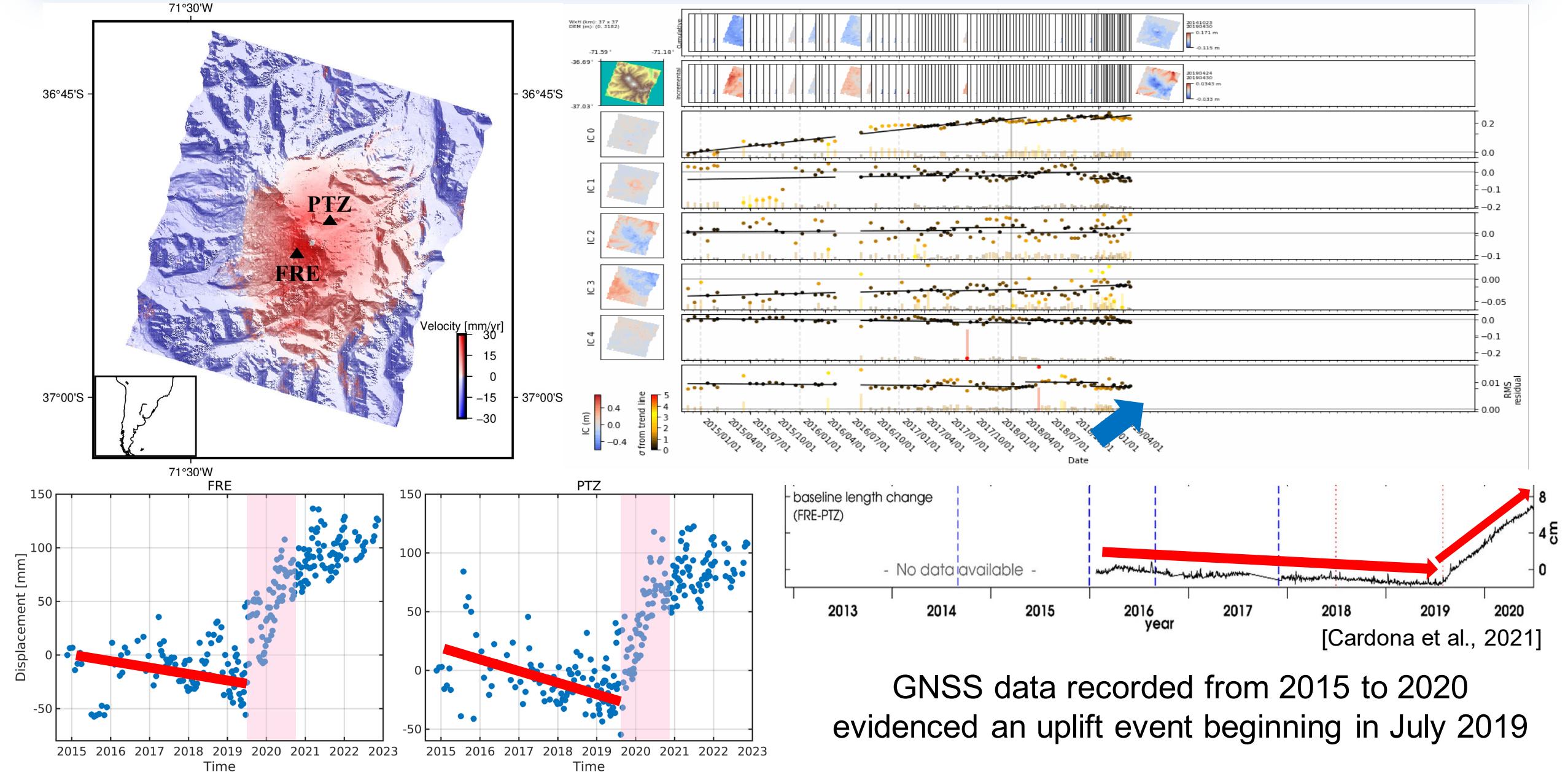
Nyiragongo

Cotopaxi

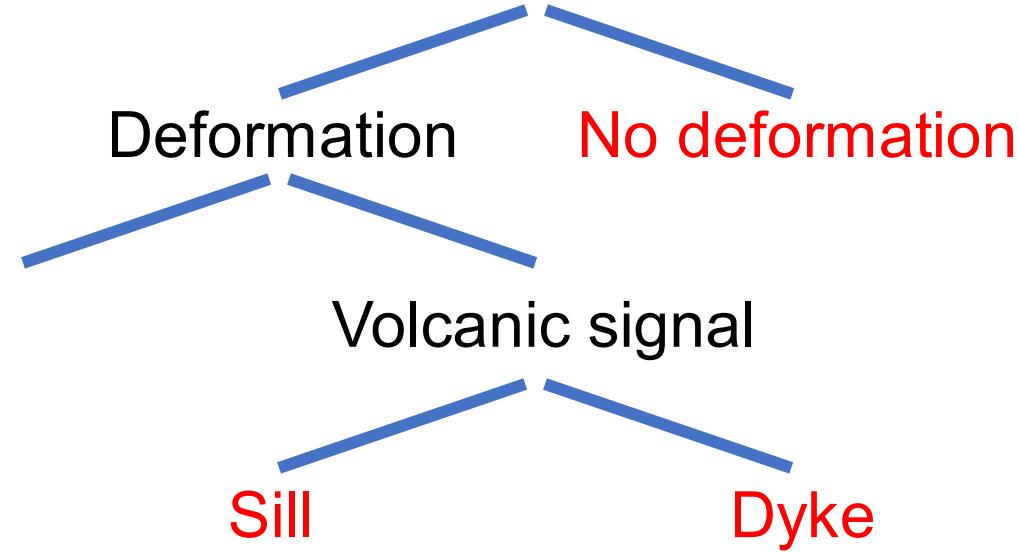
Katunga

Adwa

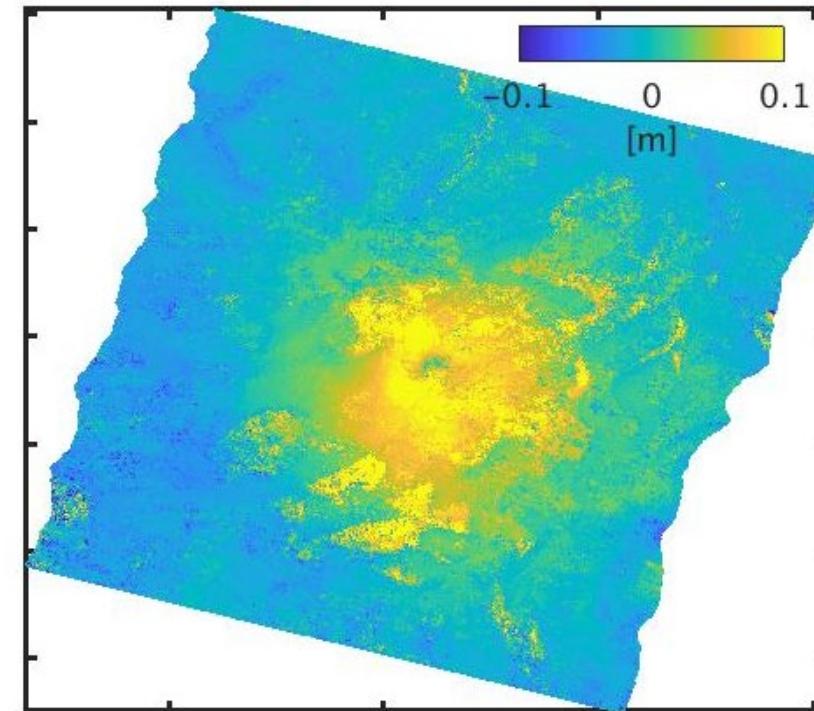
# Automatic detection of changes in deformation signals



# Volcanic deformation detection and classification using a developed convolutional neural network (CNN)



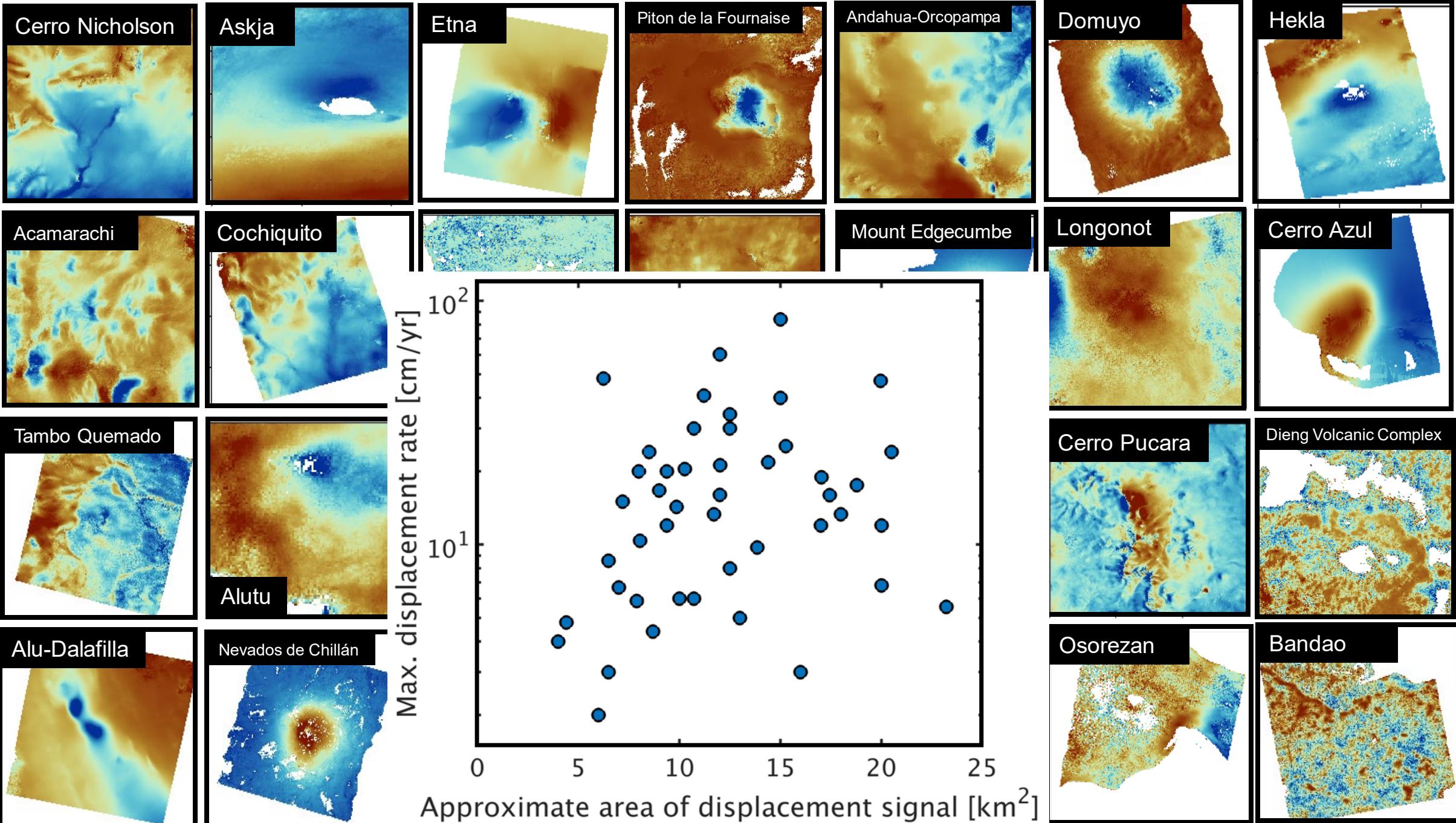
Cumulative displacement  
[20141023 – 20221017]



sill: 0.65  
dyke: 0.34  
no.def: 0.01  
sill

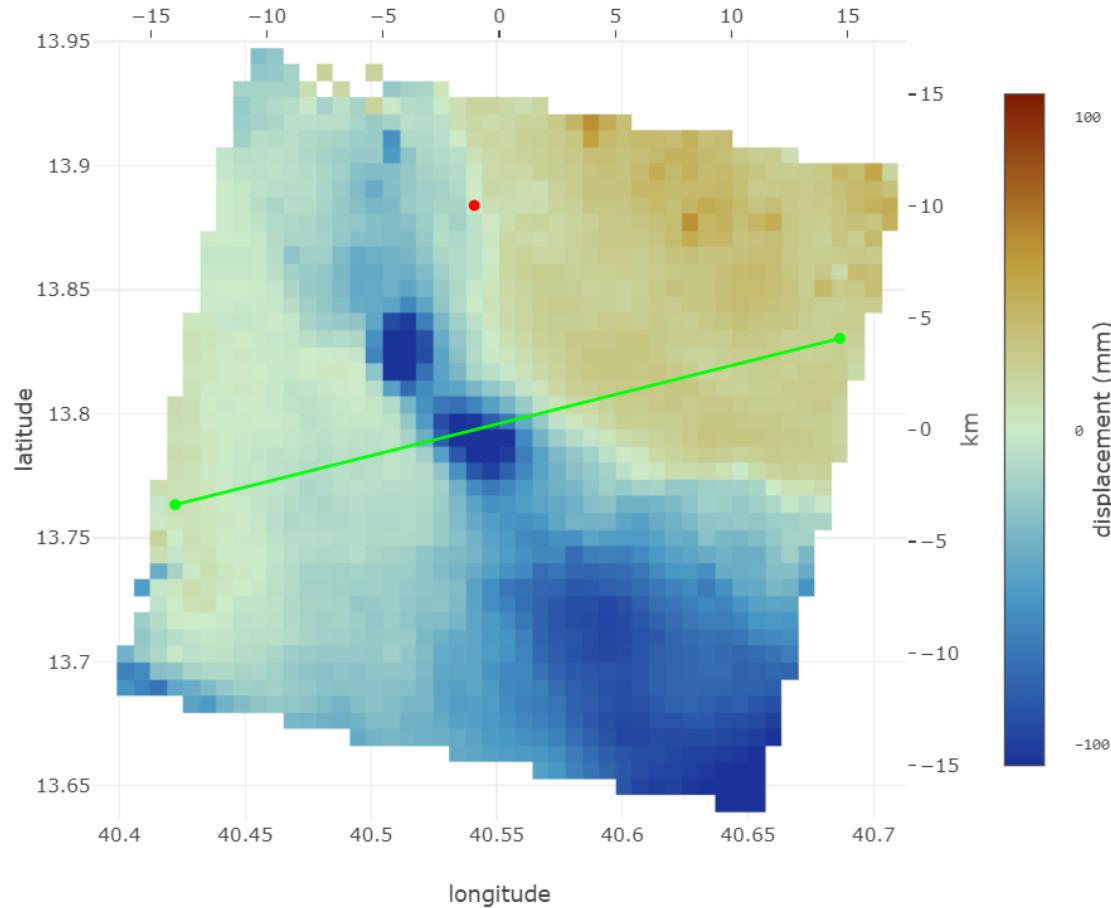
- ❖ VUDLNet\_21 [Gaddes et al., in review]  
[https://github.com/matthew-gaddes/VUDLNet\\_21](https://github.com/matthew-gaddes/VUDLNet_21)
- 500,000 labelled Sentinel-1 interferograms
  - Synthetic interferograms
  - Real dataset of 15 volcanoes from Volcnet

This observational database makes a significant increase in the number of volcanoes for network training

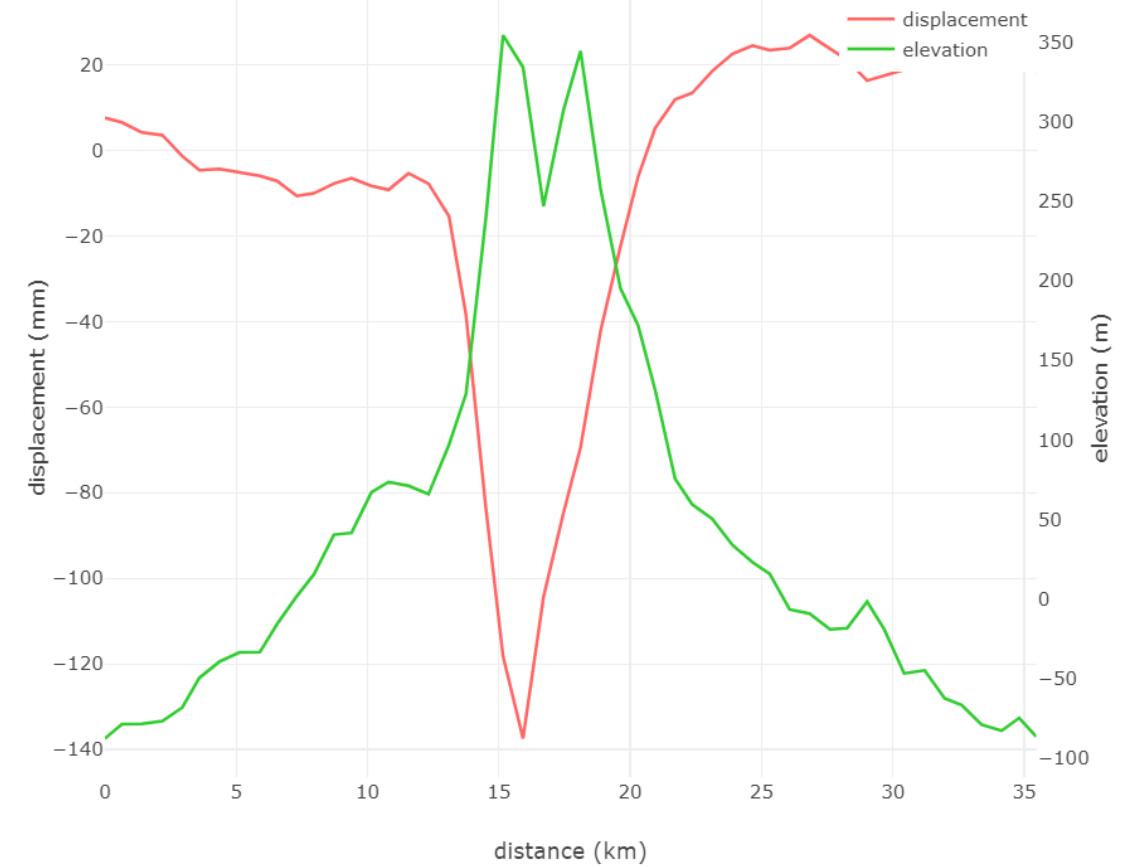


# Data visualization in the COMET volcanic and magmatic deformation portal

❖ <https://comet.nerc.ac.uk/comet-volcano-portal>



displacement	coherence
points to plot	reference area
save data as csv	surface plot



plot	sentinel-2 map
time series	profile
save data as csv	

# Take home messages

- ❖ We developed an approach to automatically derive high-resolution displacement time series for global subaerial volcanoes
- ❖ We provided a database for machine learning to automatically detect, classify and potentially forecast volcano deformation
- ❖ Online interactive visualization and data request are supported by the COMET Volcanic and Magmatic Deformation Portal
- ❖ The database will be shared publicly under an open source license, and made available through other relevant projects such as the European Plate Observing System (EPOS) and the Global Volcano Model (GVM)



European Research Council  
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