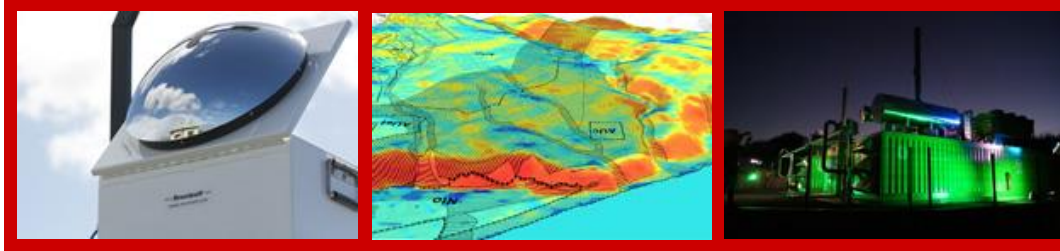


# — Reuniwatt —



## Satellite-based solar irradiance assessment and forecasting in tropical insular areas

Sylvain Cros, Maxime De Roubaix, Mathieu Turpin, Patrick Jeanty

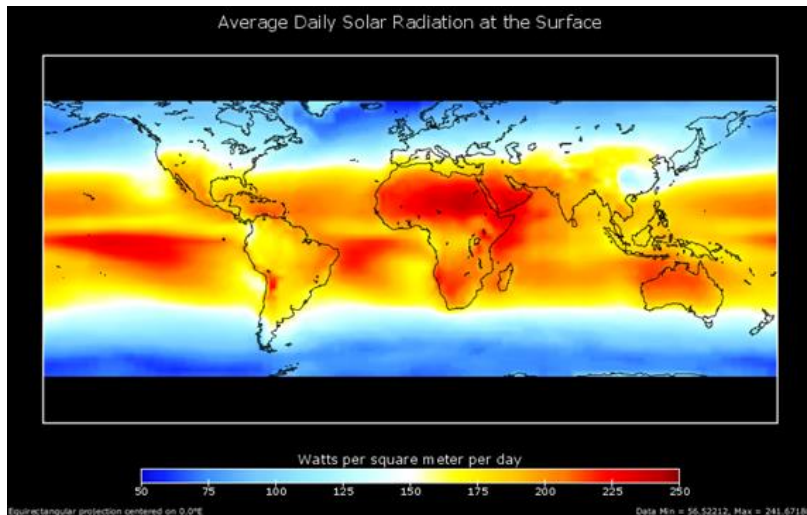
16th EMS Annual Meeting & 11th European Conference on Applied Climatology (ECAC) | 12–16  
September 2016 | Trieste, Italy

They support us:



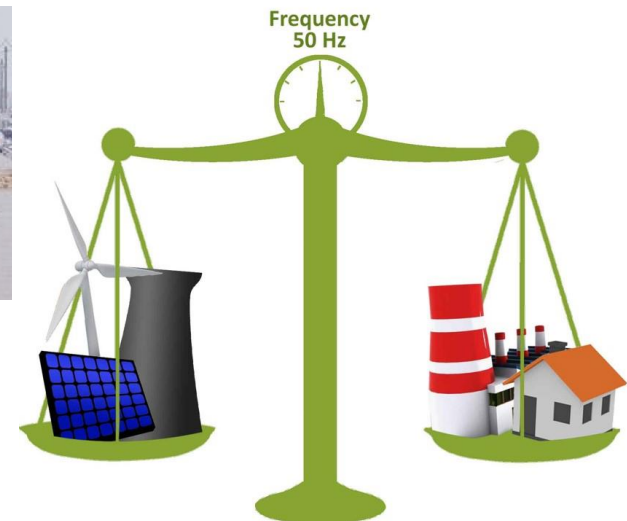
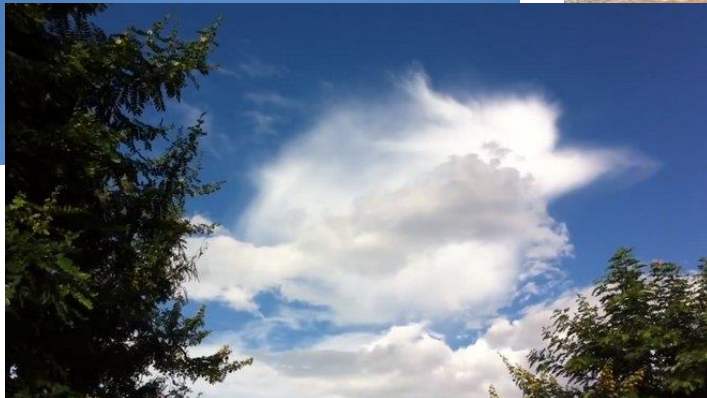
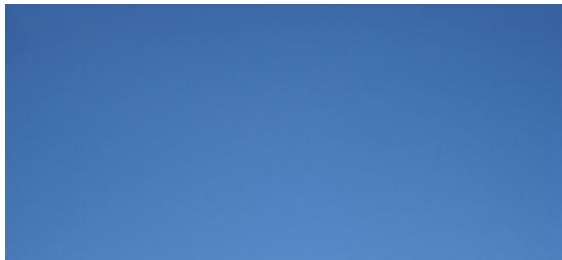
# Solar energy in tropical islands – Opportunities

- Production of an affordable, low-carbon and locally produced energy
- Contribution to a low-carbon development in very populated territories
- High solar yield



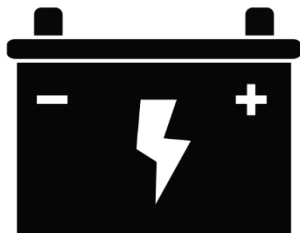
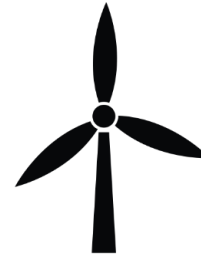
# Solar energy in tropical islands – Some issues

- Solar energy is **variable**
- Insular tropical weather shows high solar irradiance **variability** and **amplitude**
- Islands are **non-interconnected areas**. Electricity compensation must be locally produced



# Managing variable power in Non-Interconnected Territories

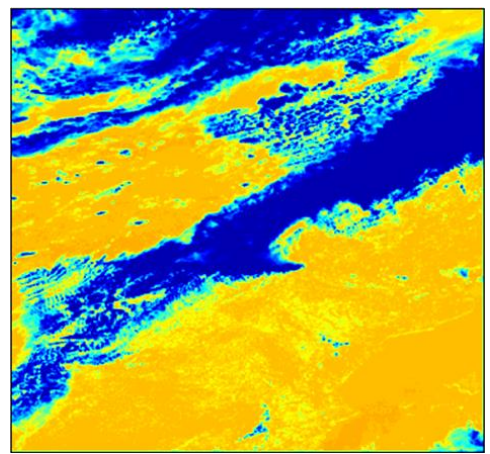
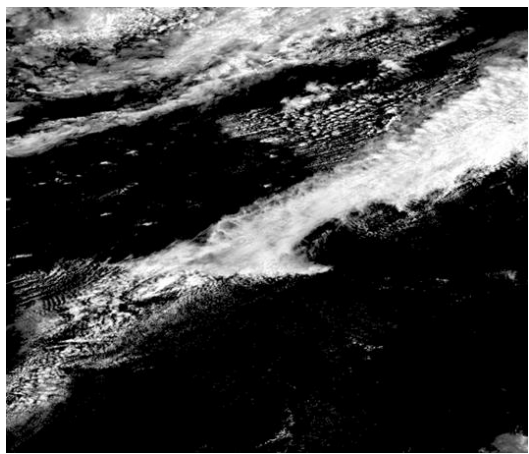
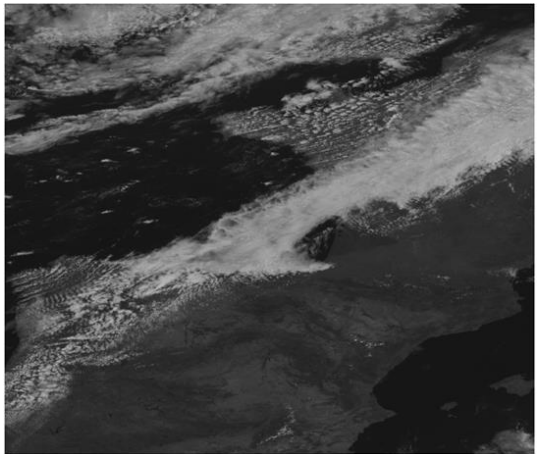
- Forecasting variable energy helps to schedule **compensation needs** (conventional electricity, storage ... )



- **Intraday forecast** of PV production is a necessity

# Satellite-based forecasts – Cloud index and irradiance mapping

- For intraday forecast (up to 6 hours), satellite image processing provides more accurate results than NWP



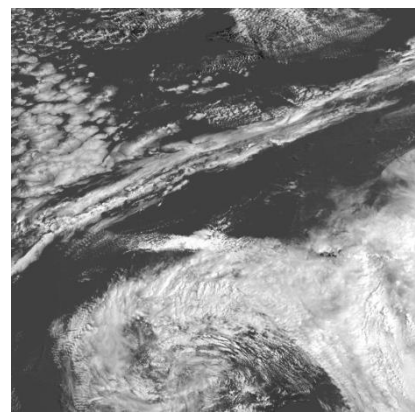
**Meteosat-9 raw image**  
(June 6th 2012, 1200 UTC)

**Cloud index:** comparison between actual and clear sky reflectance for a given pixel

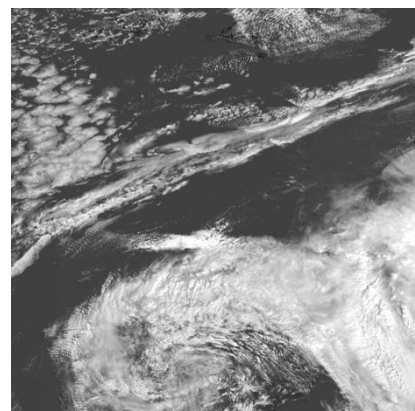
**GHI:** global horizontal irradiation at ground level

Based on Heliosat-2 method. Rigollier et al., (2004); Cros (2004)

# Satellite-based forecasts – Motion analysis & extrapolation

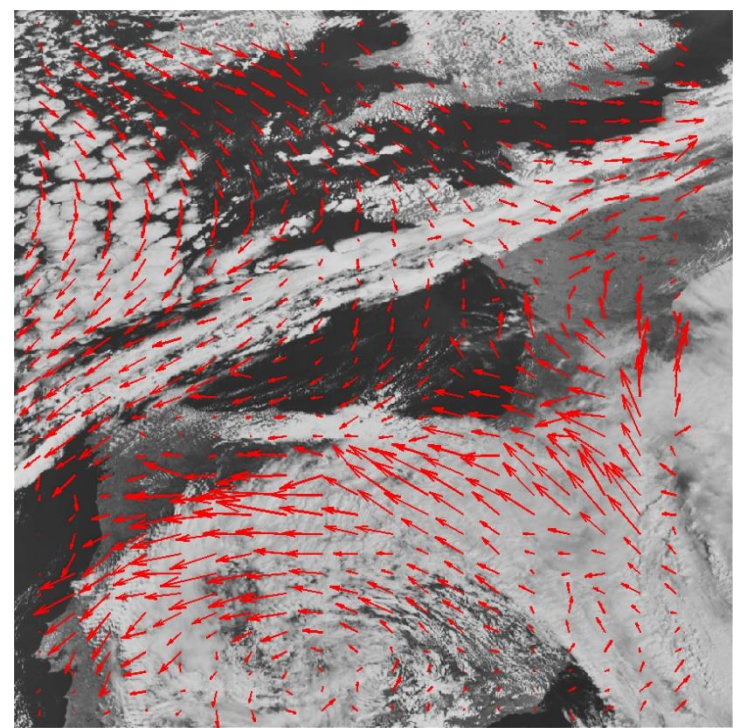


T0 – 15 min. Cloud index map



T0 Cloud index map

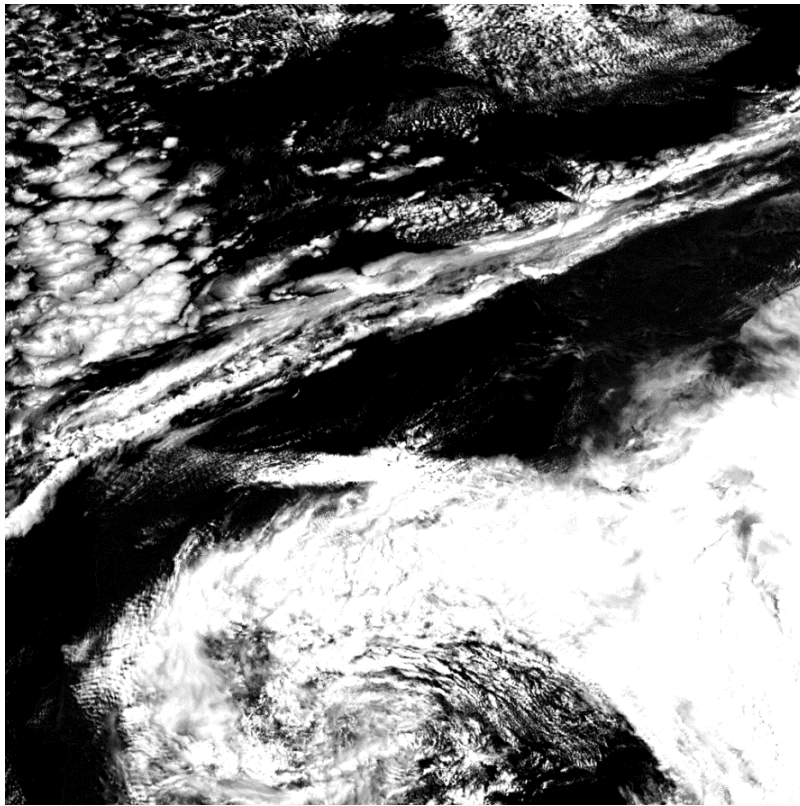
Optical flow analysis by Lucas-Kanade method



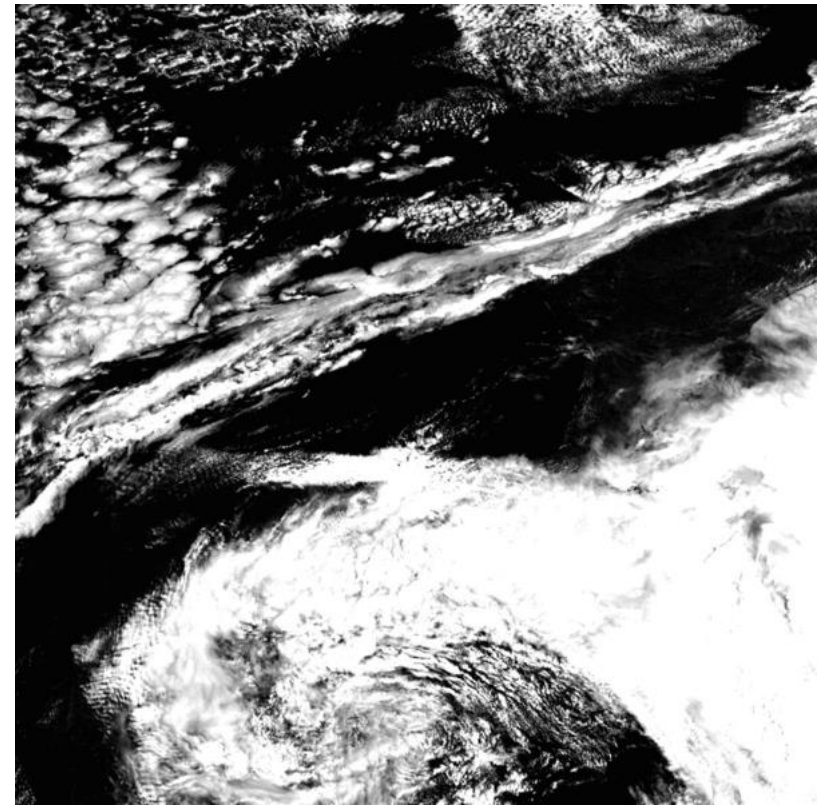
Cloud motion vector field on T0 HRV map

Lucas and Kanade (1981)  
Cros *et al.* (2014)

# Satellite-based forecasts – Motion analysis & extrapolation



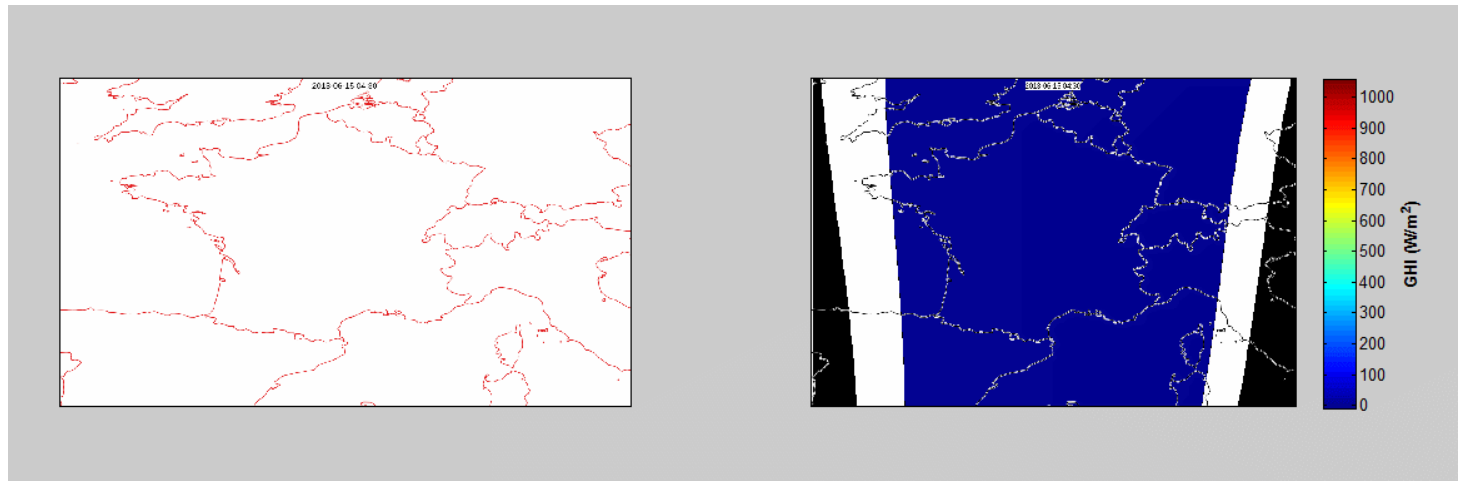
Original T0 Cloud Index map



Forecasted Cloud index maps – Up to 6 hours (step 15 min)

# Satellite-based forecasts – Motion analysis & extrapolation

- Proven quality forecast over Europe
- But this method assumes :
  - Cloud are single layered
  - Cloud motion is only due to horizontal advection (forming and dissolving clouds are ignored)

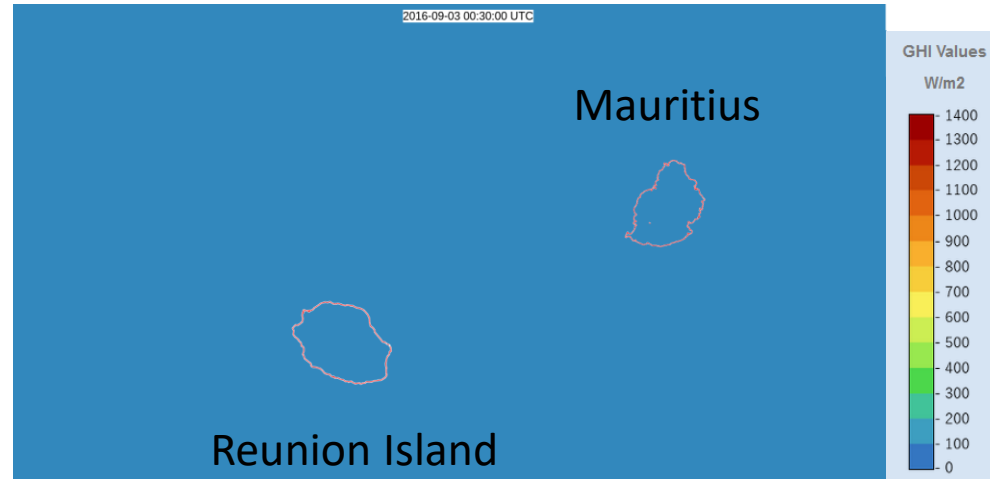


Derived from Meteosat-10 images (EUMETSAT)

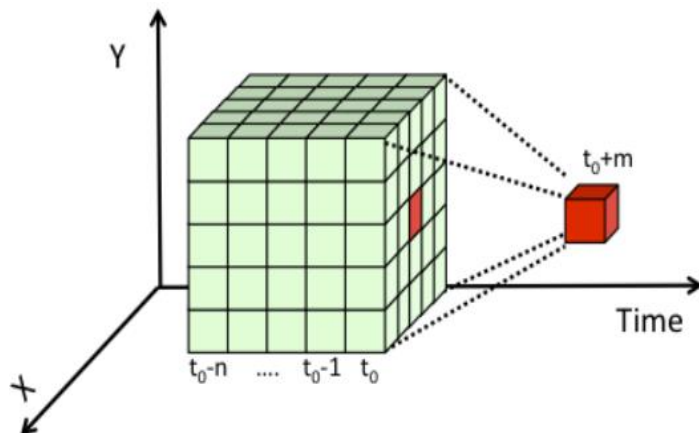


# Satellite-based forecasts – Autoregression of cloud index patterns

- Assumption of cloud advection for tropical islands is not obvious:
  - Coastal and mountainous areas are zones of frequent cloud formation and dissipation
  - Tropical atmospheric profiles lead to frequent convection situations
  - Advection concerns mostly larger scales than cloud cover evolution over the island



Derived from Meteosat-7 images (EUMETSAT)

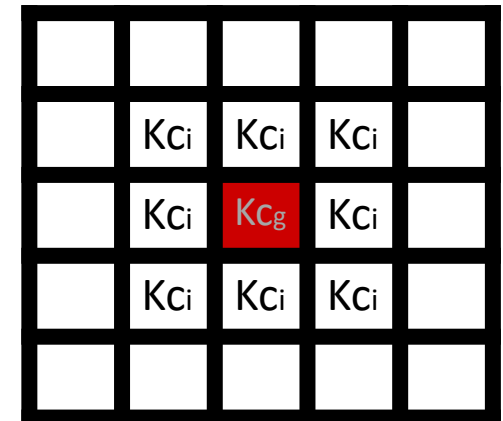


- An alternative is the time-series modeling applied on 2D cloud index maps
  - Statistical information on diurnal cycle
  - Quality less dependent on weather situation, robustness
  - Good candidate to complete a motion analysis scheme

# ARX implementation

- Autoregressive model with exogenous data (ARX) Dambreville *et al.*, 2014
  - Considering 1-D **time series of pyranometer measurements**, converted into clear sky index  $K_{c_g}(t)$ . Normalized values => stationary time-series.
  - $K_{c_i}$  : exogenous variables computed from satellite-based cloud indices (the X of ARX)

Does all the  $K_{c_i}$  are equally important for ARX ?



A spatial analysis can identify the locations of **the most relevant surrounding pixels**  
 $\Delta K_c$  spatial intercorrelation with given site between T0 and various lag

# Spatial analysis in Carpentras

Carpentras, south of France

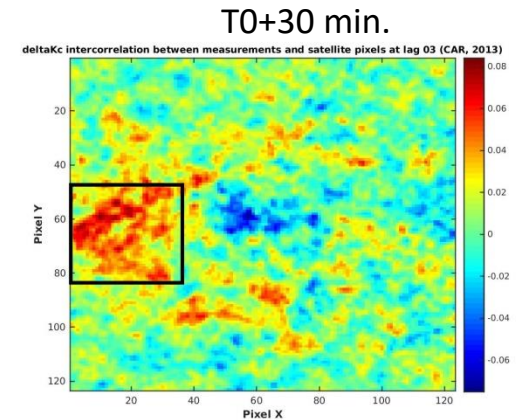
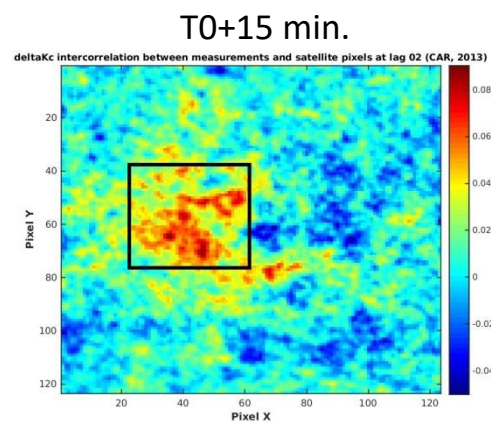
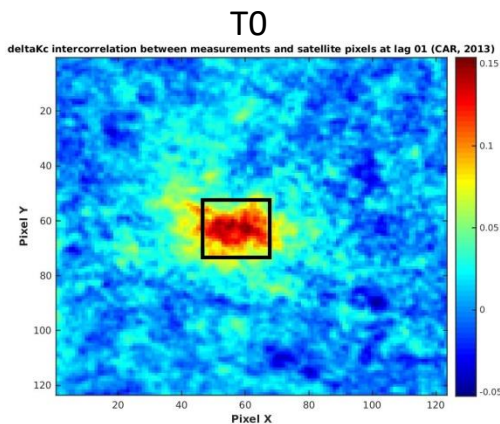
(44.08° ; 5.04°)

Year 2013

BSRN pyranometer

Kc computed using

McClear Clear sky model



Sky state changes are coming from the west, consistent with averaged wind direction

# Spatial analysis in Reunion Island

Saint-Benoît

(-21.05° ; 55.70°)

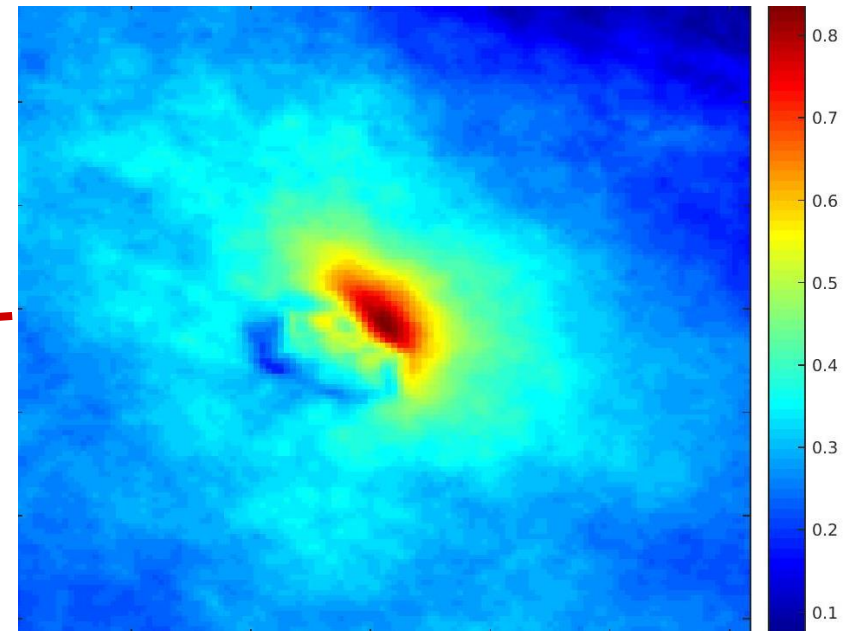
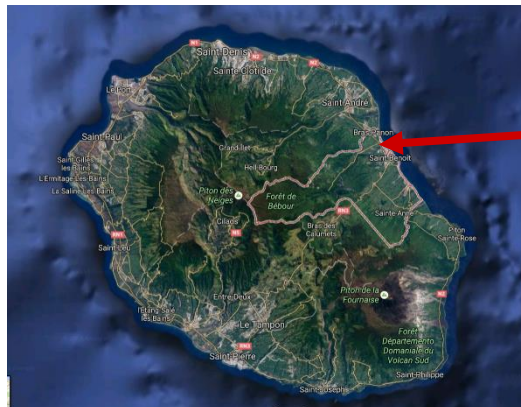
Year 2013

GHI data from Reuniwatt sensor

Kc computed using

McClear Clear sky model

Intercorrelation map between  
T0 and T0+30



# Spatial analysis in Reunion Island

Saint-Benoît

(-21.05° ; 55.70°)

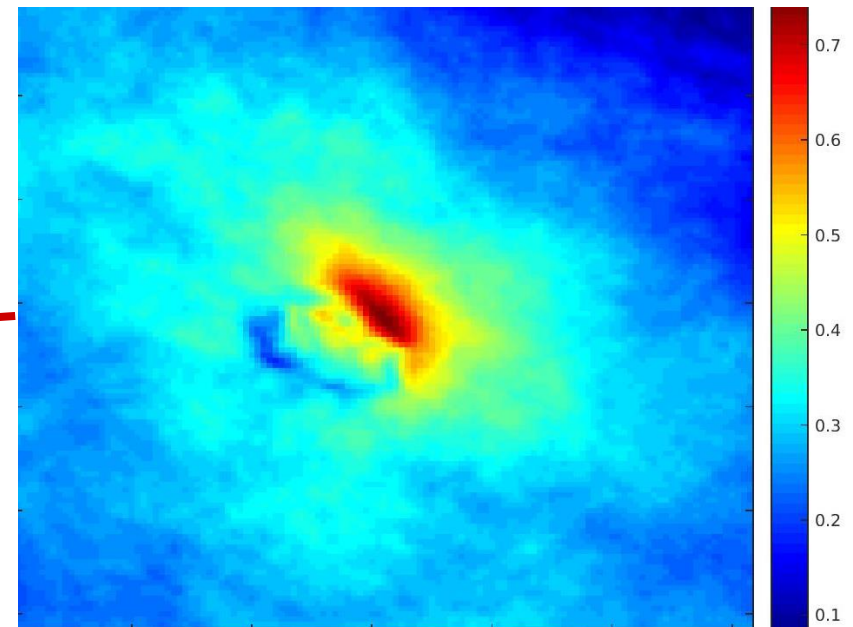
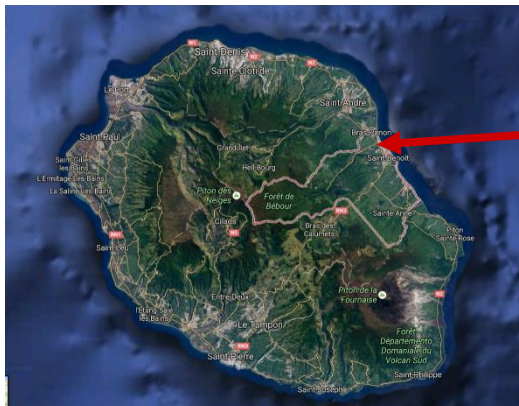
Year 2013

GHI data from Reuniwatt sensor

Kc computed using

McClear Clear sky model

Intercorrelation map between  
T0 and T0+60 min



# Spatial analysis in Reunion Island

Saint-Benoît

(-21.05° ; 55.70°)

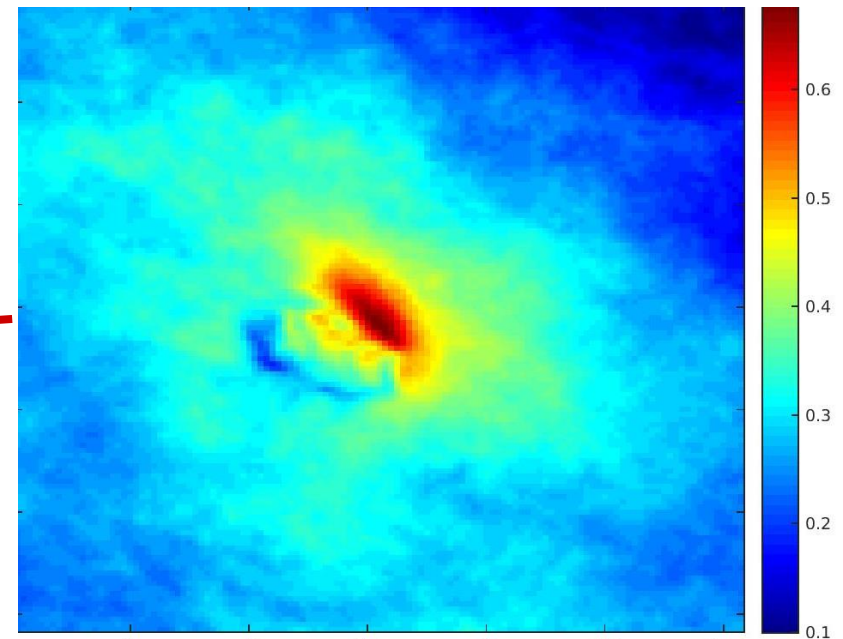
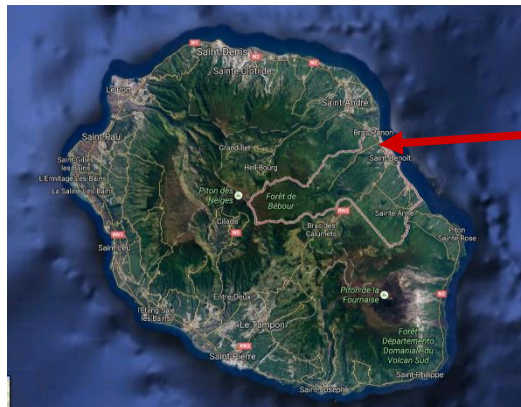
Year 2013

GHI data from Reuniwatt sensor

Kc computed using

McClear Clear sky model

Intercorrelation map between  
T0 and T0+90 min



# Spatial analysis in Reunion Island

Saint-Benoît

(-21.05° ; 55.70°)

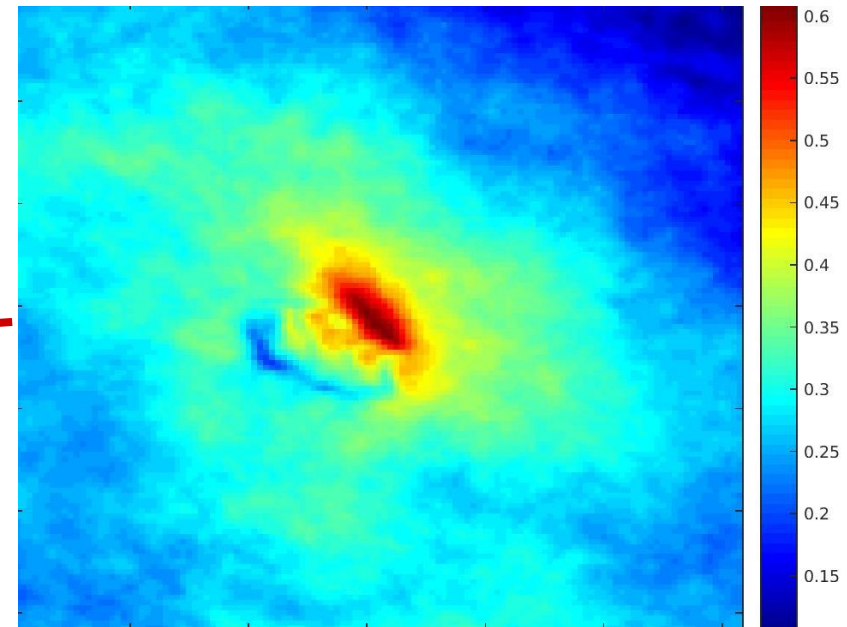
Year 2013

GHI data from Reuniwatt sensor

Kc computed using

McClear Clear sky model

Intercorrelation map between  
T0 and T0+120 min



# Spatial analysis in Reunion Island

Saint-Benoît

(-21.05° ; 55.70°)

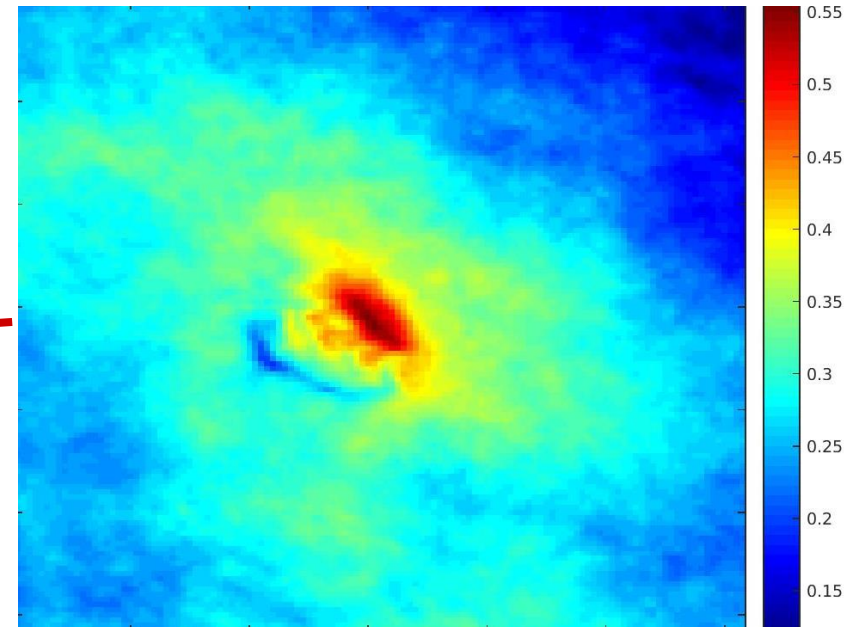
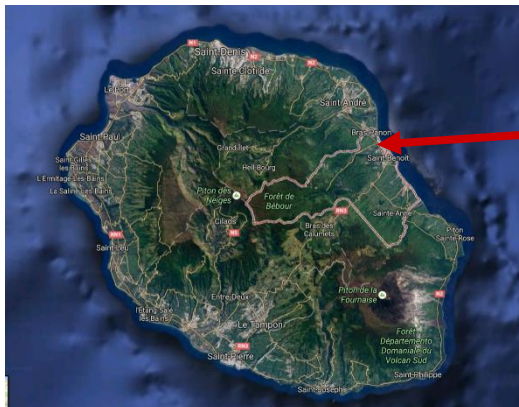
Year 2013

GHI data from Reuniwatt sensor

Kc computed using

McClear Clear sky model

Intercorrelation map between  
T0 and T0+150 min





# Spatial analysis in Reunion Island

Saint-Benoît

(-21.05° ; 55.70°)

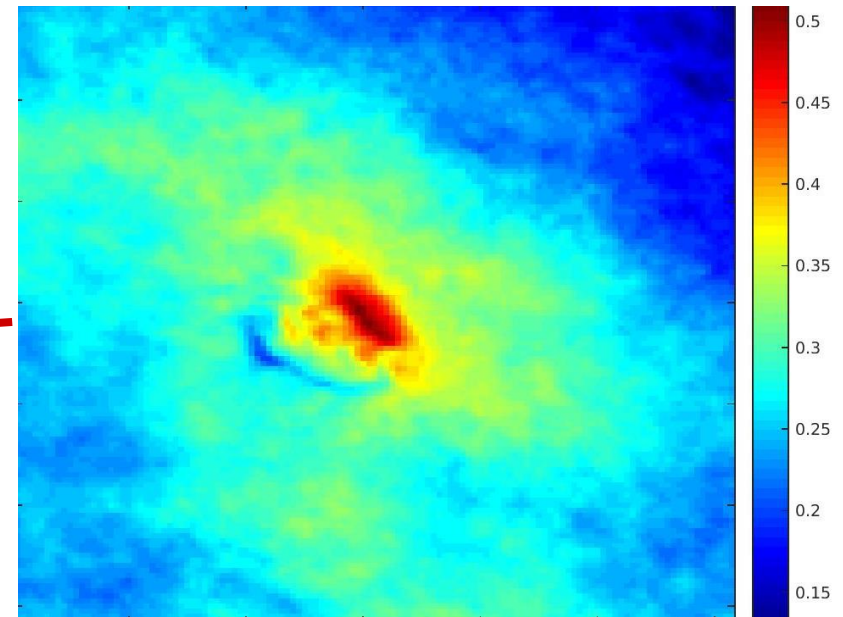
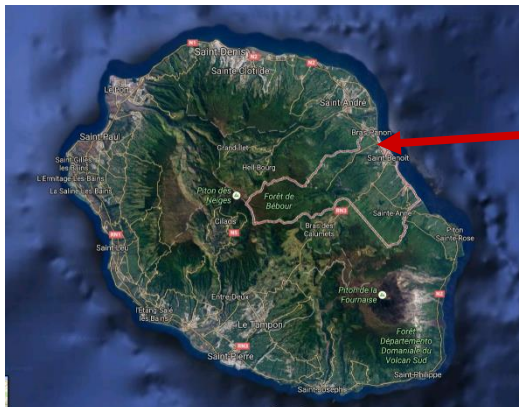
Year 2013

GHI data from Reuniwatt sensor

Kc computed using

McClear Clear sky model

Intercorrelation map between  
T0 and T0+180 min



# Spatial analysis in Reunion Island

Moufia – Saint-Denis

(-20.91° ; 55.48°)

Year 2013

GHI data from pyranometer

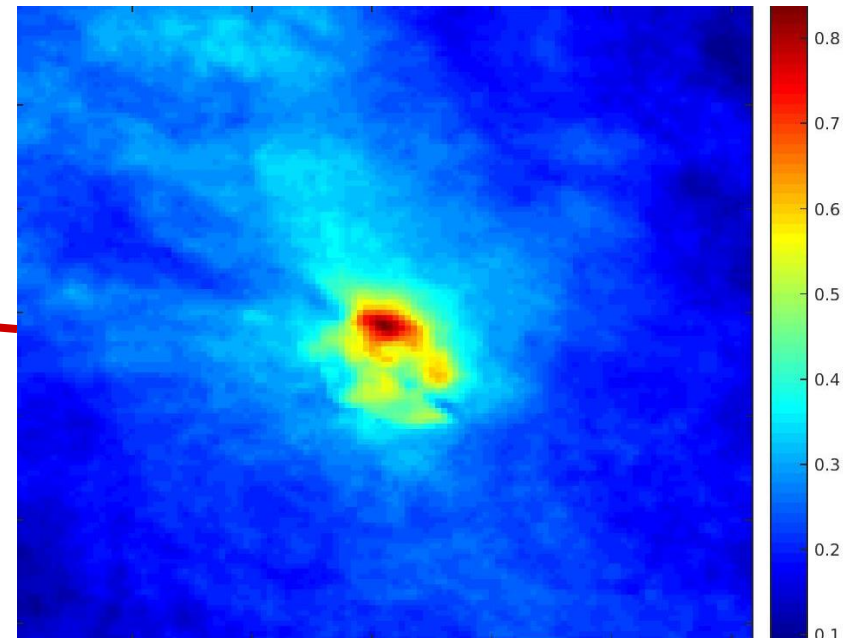
LE2P, université de La Réunion

Kc computed using

McClear Clear sky model



Intercorrelation map between  
T0 and T0+30 min



# Spatial analysis in Reunion Island

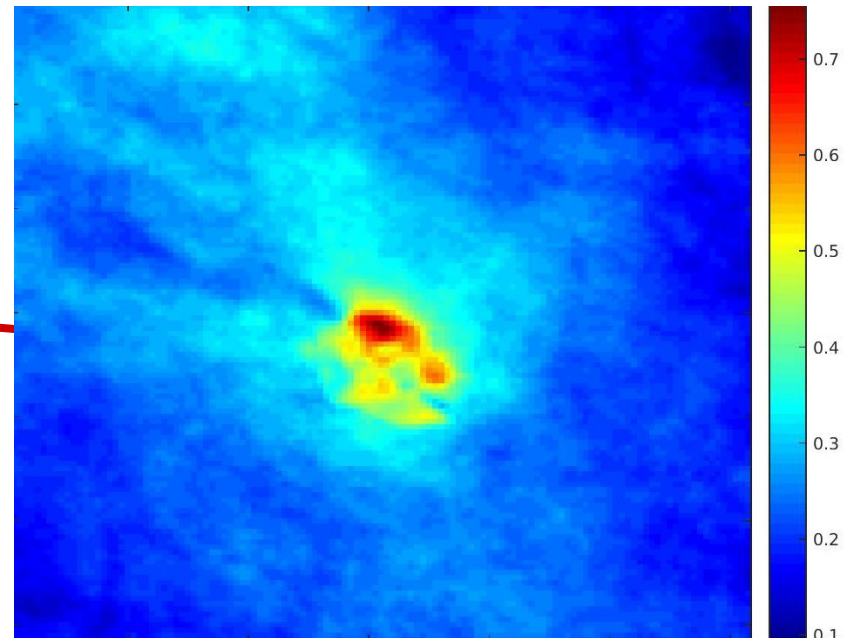
Moufia – Saint-Denis  
 (-20.91° ; 55.48°)

Year 2013

GHI data from pyranometer  
 LE2P, université de La Réunion

Kc computed using  
 McClear Clear sky model

Intercorrelation map between  
 T0 and T0+60 min



# Spatial analysis in Reunion Island

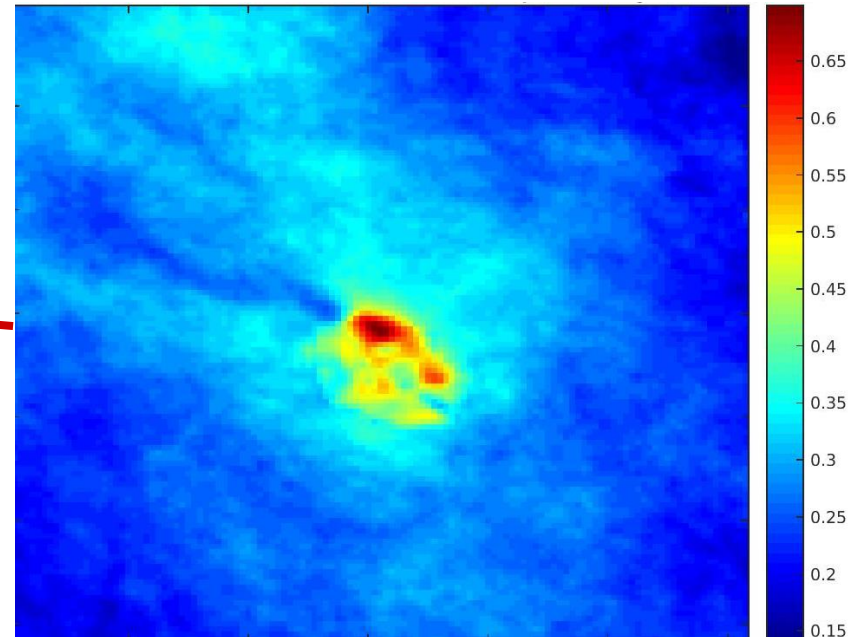
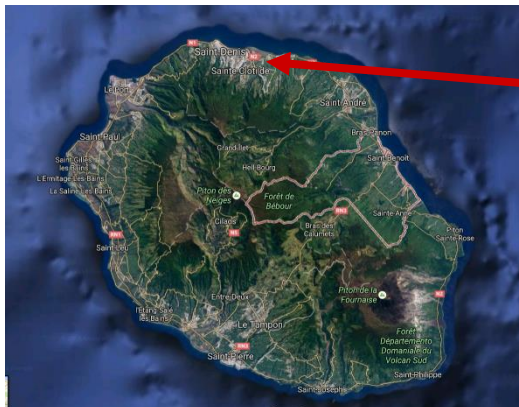
Moufia – Saint-Denis  
 (-20.91° ; 55.48°)

Year 2013

GHI data from pyranometer  
 LE2P, université de La Réunion

Kc computed using  
 McClear Clear sky model

Intercorrelation map between  
 T0 and T0+90 min



# Spatial analysis in Reunion Island

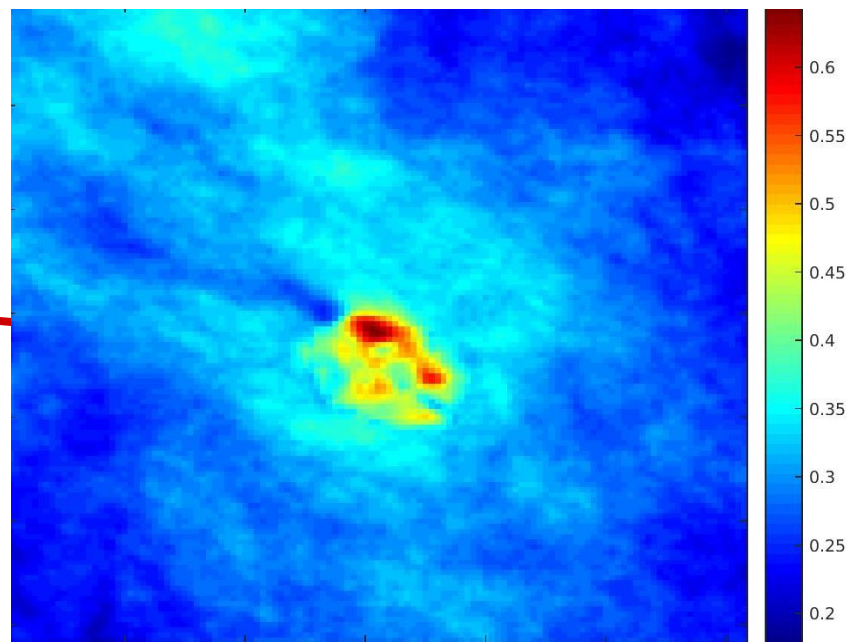
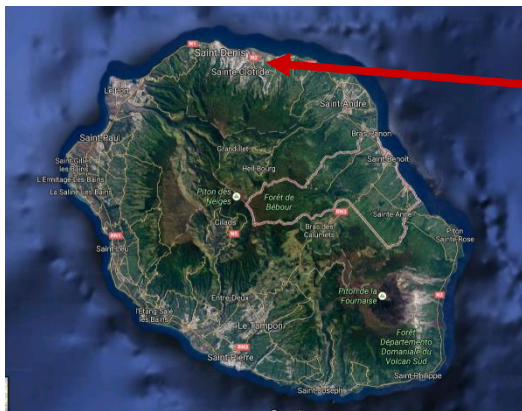
Moufia – Saint-Denis  
(-20.91° ; 55.48°)

Year 2013

GHI data from pyranometer  
LE2P, université de La Réunion

Kc computed using  
McClear Clear sky model

Intercorrelation map between  
T0 and T0+120 min



# Spatial analysis in Reunion Island

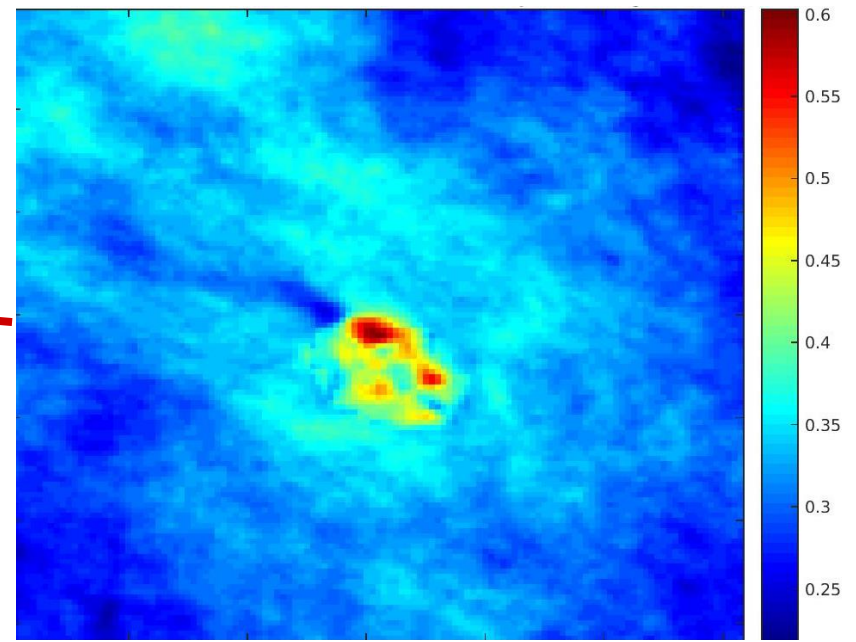
Moufia – Saint-Denis  
 (-20.91° ; 55.48°)

Year 2013

GHI data from pyranometer  
 LE2P, université de La Réunion

Kc computed using  
 McClear Clear sky model

Intercorrelation map between  
 T0 and T0+150 min



# Spatial analysis in Reunion Island

Moufia – Saint-Denis

(-20.91° ; 55.48°)

Year 2013

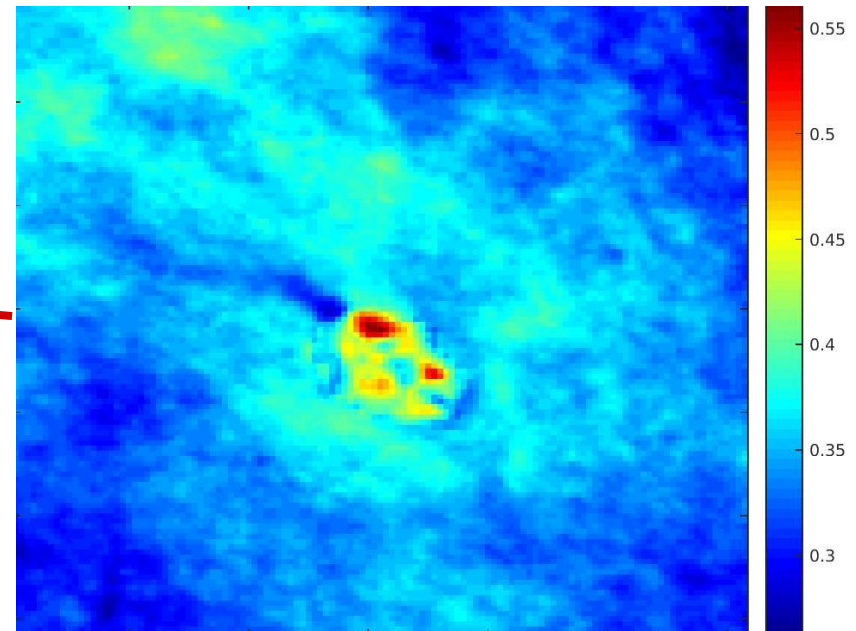
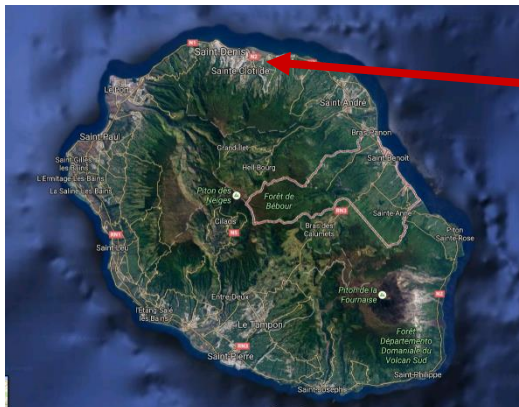
GHI data from pyranometer

LE2P, université de La Réunion

Kc computed using

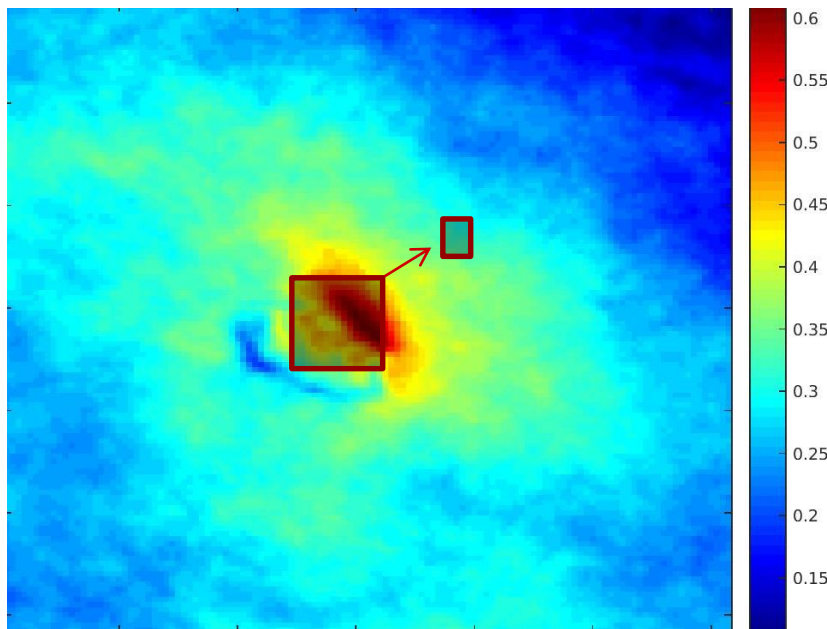
McClea Clear sky model

Intercorrelation map between  
T0 and T0+180min



# Combining auto-regression and motion analysis

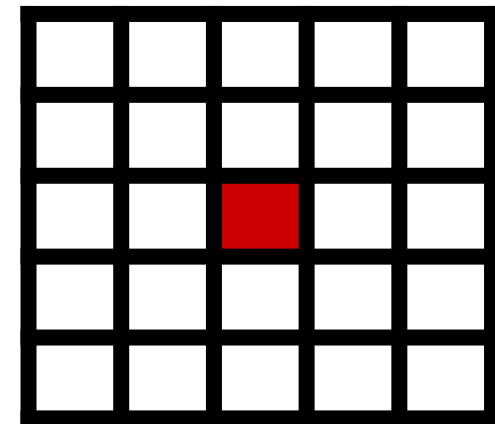
- Location of priority exogenous data is not so obvious than in mainland
- We choose to use the CMV model to deduce priority pixels at each time step, instead of spatial analysis over one year





# Implementation in Reunion Island

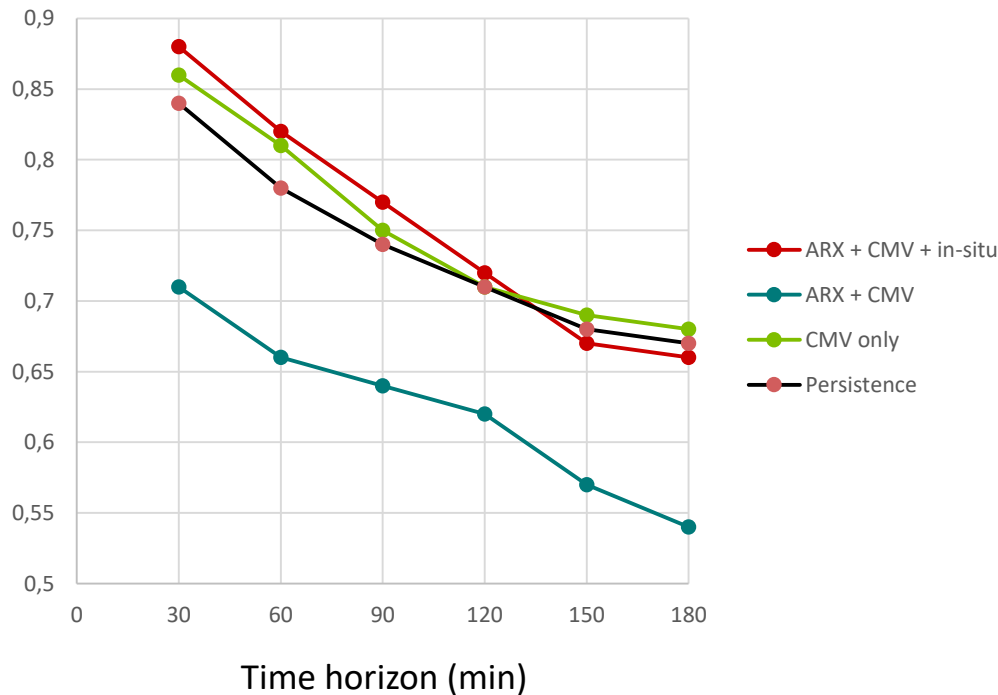
- ARX model trained on 2013 Kc data for both sites **Le Moufia and Saint-Benoît**
- Training on a half of 2013 values (randomly selected)
- Model assessed on the other half of the values
- Two options:
  1. Kc on the site is computed from **in-situ** data
  2. Kc on the site is computed from **satellite** assessment  
(if customer does not have historical measurement)



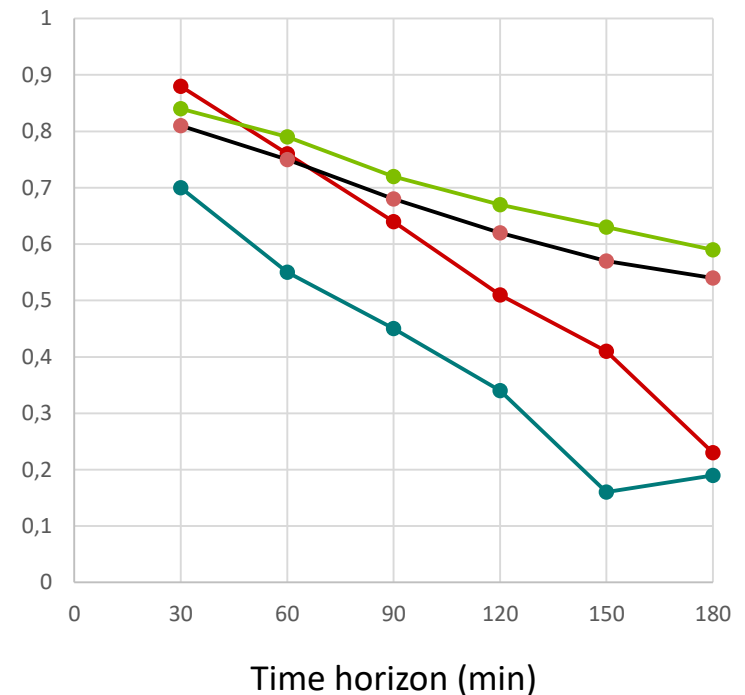
Meteosat-7 pixels

# Results - Correlation

Correlation coefficient - Saint-Benoît (La Réunion)

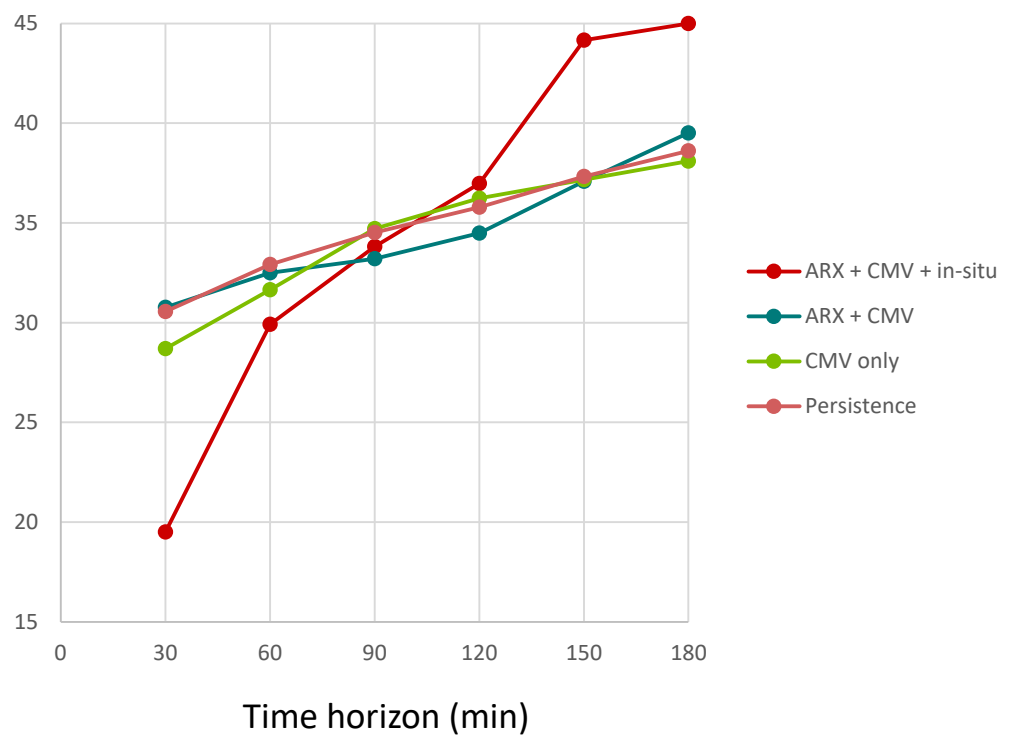


Correlation Coefficient - Le Moufia

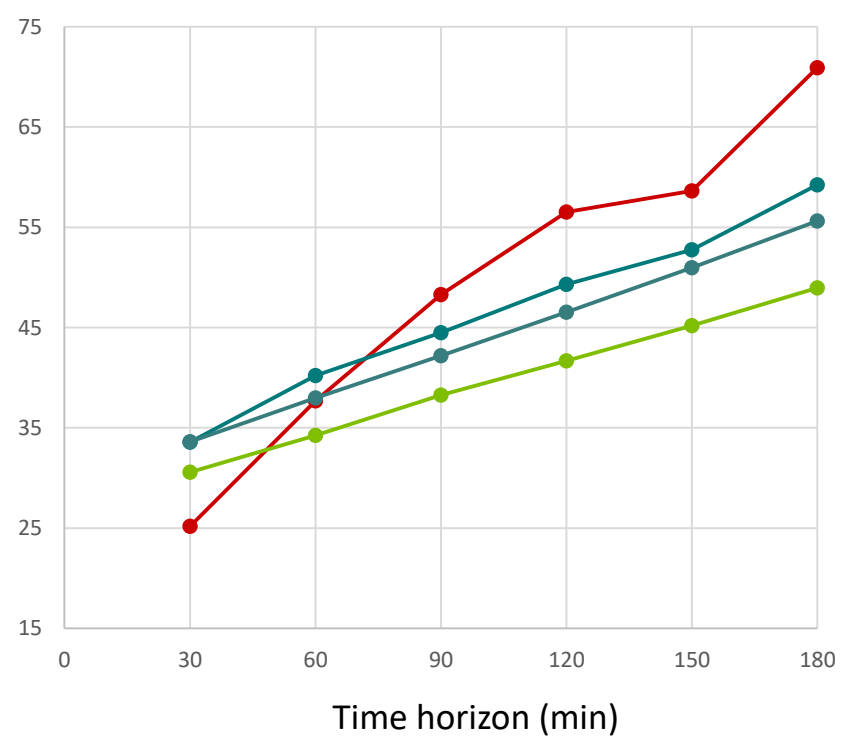


# Results – RMSE

Relative RMSE (%) - Saint-Benoît

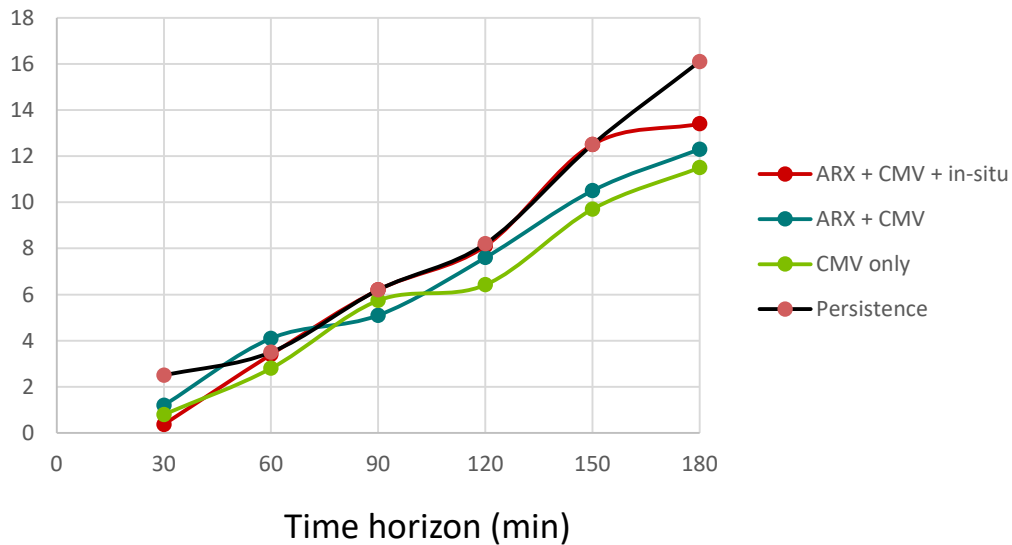


Relative RMSE (%) - Le Moufia

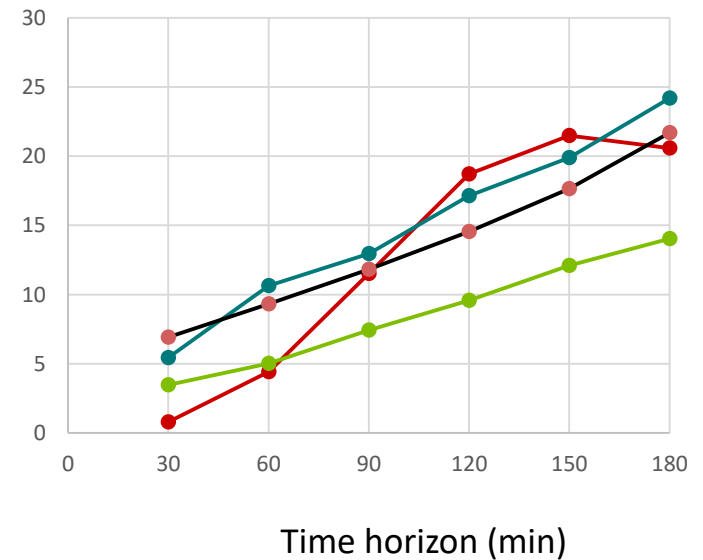


# Results – Bias

Mean Bias Error (%) - Saint-Benoît



Mean Bias Error (%) - Le Moufia



# Conclusion

- Autoregressive and motion analysis forecast models using satellite images have been evaluated on tropical insular areas in 2 sites of Reunion Island
- This work demonstrate that ARX model is a valuable complement for cloud motion-based model, especially for very short-term forecast (up to 60-90 min.)
- ARX model without in-situ measurements is much less accurate - historical measurements on-site are necessary
- Meteosat-7 has a time resolution of 30 min. Improvements are expected when MSG-1 will operate at longitude  $40.5^\circ$  (higher spatial resolution, 1 image every 15 min.)
- Local specific studies can be undertaken for further improvements (evolution of other parameters, e.g. temperature, humidity)

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