Quantifying cloud development from geostationary observations

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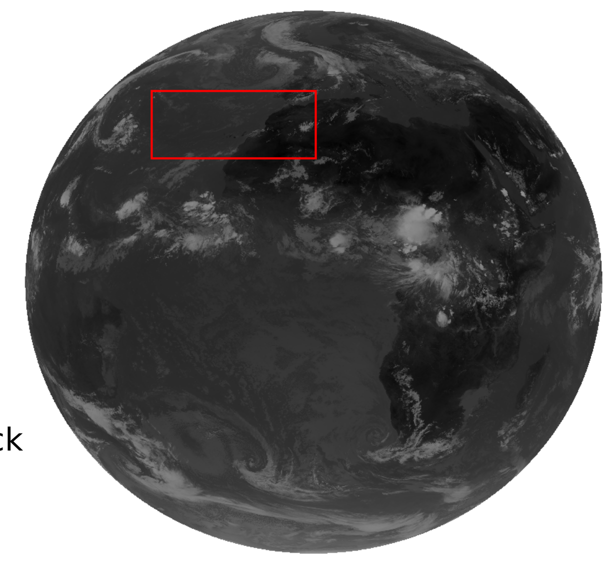
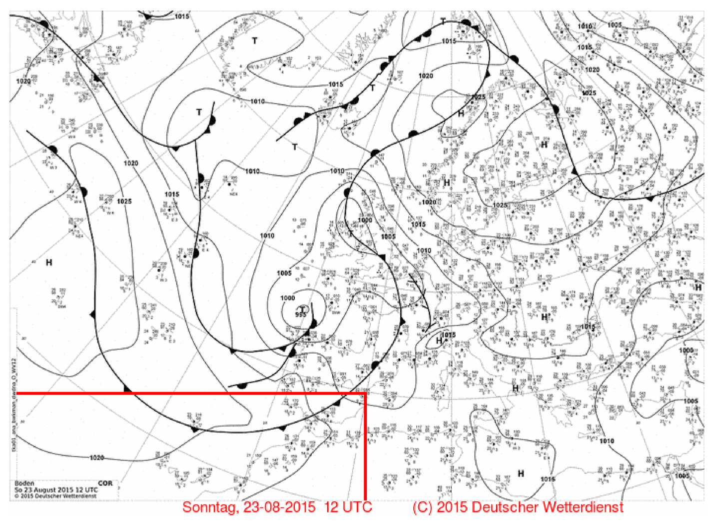
Clouds and their interaction with short- and longwave radiation represent one of the major uncertainties in our understanding of global climate change. The presence of clouds, particularly of bright low-level water clouds, doubles the Earth's albedo and clouds are responsible for half of the solar radiation reflected into space. Here, we present an innovative method to track warm low-level clouds in time-resolved geostationary measurements with the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) aboard Meteosat Second Generation. The Particle Image Velocimetry (PIV; Raffel et al., 2007; Adrian and Westerweel, 2011) method is widely used in experimental fluid mechanics and relies on basic pattern matching. The principle of pattern matching is usually referred to as cross-correlation. This cross-correlation gives information about the displacement of identified features and enables - in our application - the retrieval of cloud trajectories. We use these in combination with the CLAAS-2 data set (CM SAF CLoud property dAtAset using SEVIRI - Edition 2; Benas et al., 2017) to quantify cloud development and to characterize temporal changes of cloud properties.

Data

- MSG-SEVIRI level 1.5 (full disc) data - brightness temperature (InfraRed 10.8 µm channel)
- Nadir spatial resolution of the narrow band channel: 3 × 3 km²
- Domain: Atlantic Ocean centered approximately around Canary Islands
- Date: 23 - 24 August 2015 00:00 - 23:45 UTC
- Weather condition: trade wind, cold front passage
  - prefrontal on 23 August 2015
  - postfrontal on 24 August 2015
- Existence of well-separable low/mid level warm cumulus clouds - easily to detect and track



Brightness temperature measured with MSG-SEVIRI's (Level 1.5) 10.8 µm infrared channel on 23rd August 2015 12:00 UTC. Light/dark color refers to low/high temperature. The domain used for the case scenario is highlighted with red contour lines.



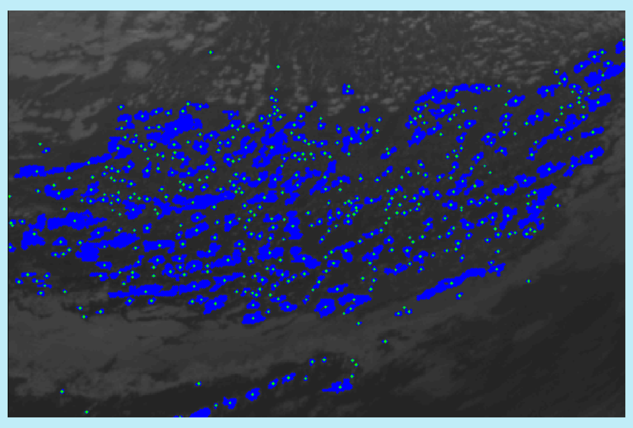
Weather condition on 23rd and 24th August 2015.

Methodology - Technical aspects

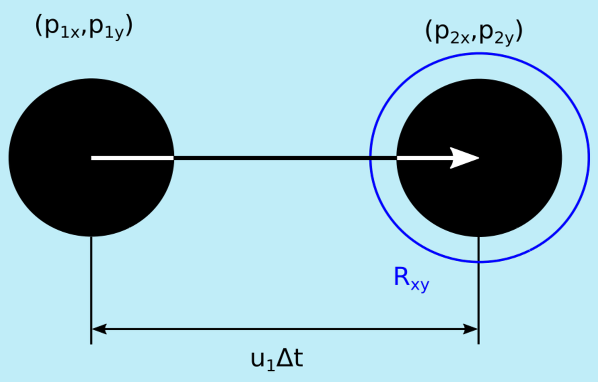
- Identification and tracking of clouds is based on four steps
  - (i) Data import of two consecutive time steps
  - (ii) Cloud identification
  - (iii) Cloud velocity calculation and
  - (iv) Linking of clouds
- The four steps are repeated until the end of the time series
- Combination with the CLAAS-2 data set (Benas et al., 2017) *→ quantification and characterization of temporal changes of cloud properties*

(ii) Cloud identification

- Based on thresholds
- Definition of a brightness temperature interval ([278.15, 298.15] K = {T_b ∈ R | 278.15 K < T_b < 298.15 K})
- Transformation into a 2d-binary image - values within the interval set to one and values outside to zero
- A subroutine calculates object properties: centroid (centre of mass), area, cloud pixel position, effective cloud radius, bounding box etc.



(iv) Linking of clouds from t_0 to $t_0 + \Delta t$



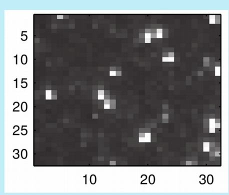
Mean square error: $R_{xy} = \|p_{1x} + u_1\Delta t - p_{2x}\|^m$, *with* $m = 2$

- If R_{xy} < max. deviation → the cloud we are looking for has been found
- If R_{xy} > max. deviation → the cloud split/dissolved → trajectory stops
- Note, „m and max. deviation" are tuning parameter!

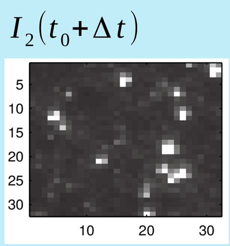
(iii) Cloud velocity calculation

- Obtained with Particle Image Velocimetry (PIV; Raffel et al., 2007; Adrian and Westerweel, 2011)
- PIV: contactless optical measurement method widely used in experimental fluid mechanics or in the industry and relies on basic pattern matching
- Principle of pattern matching is usually referred to as cross-correlation
- Determination of displacements of well-separable and sufficiently small object/particles within two consecutive images with known time-step Δt

$I_1(t_0)$



$I_2(t_0+\Delta t)$

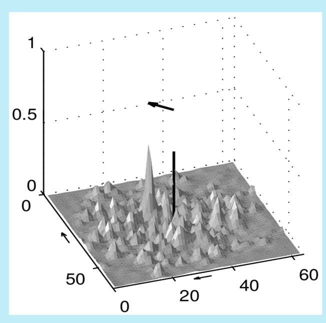


Cross-correlation

$$R_K(m,n) = \sum_{i=0}^{M-1}\sum_{j=0}^{N-1} g_1(i,j)\, g_2(i+k, j+l)$$

$g_{1,2}$ ... grey values of the respective sub-windows (interrogation window) I_1 and I_2
i,j ... pixel position in the matrix of the particular interrogation window
M,N ... size of sub-windows (interrogation windows)
k,l ... shift in x,y direction

Correlation-map



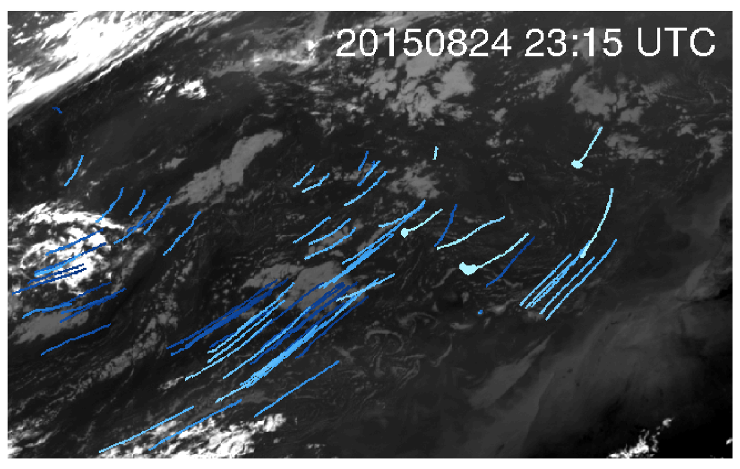
- Strong peak at (26,25)
- Shifted compared to the center of the correlation map
- Displacement: $(\Delta x, \Delta y) = (-6, -7)$
- Transformation into physical units due to relation between pixel and world coordinates (calibration)

$$u = \lim_{\Delta t \to 0} \Delta x/\Delta t \qquad v = \lim_{\Delta t \to 0} \Delta y/\Delta t$$

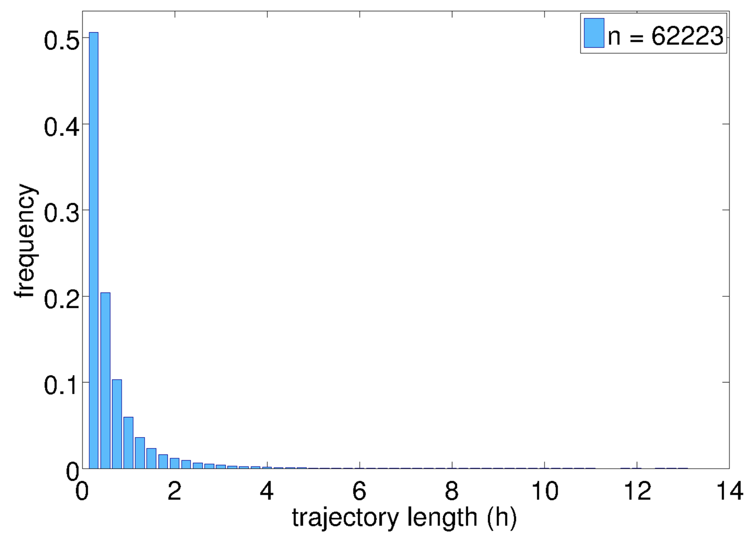
- Represent a mean over Δt
- Ignores fluctuations within this interval

Sveen, J. K.: *An introduction to MatPIV v. 1.6.1.*, eprint series, Dept. of Math. University of Oslo, Mechanics and Applied Mathematics, No. 2, ISSN 0809-4403, August 2004.
Sveen, J. K. and Cowen E.A.: *Quantitative imaging techniques and their application to wavy flows.* In "PIV and Water Waves" pages 1–49, 2004

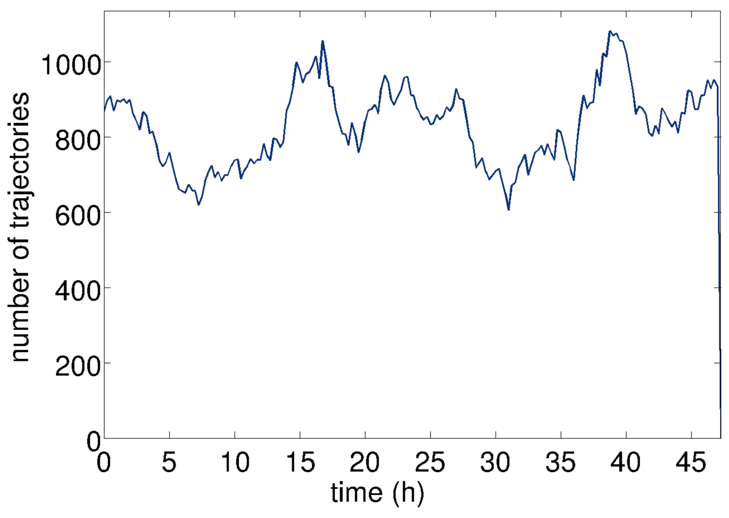
Results - (i) Cloud lifetime



Cloud trajectories with lifetimes greater equal 7 hours (the 90 longest trajectories) at the end of the time series. The darker the older the trajectory.



Histogram showing the frequency of clouds as function of trajectory length. The sample consists of 62223 clouds. Almost 85% of the identified and tracked clouds have trajectory length lower equal 1 hour.



Temporal development of trajectory number. Diurnal variation appears with minima in the wee hours of the morning and maxima during afternoon.

Summary

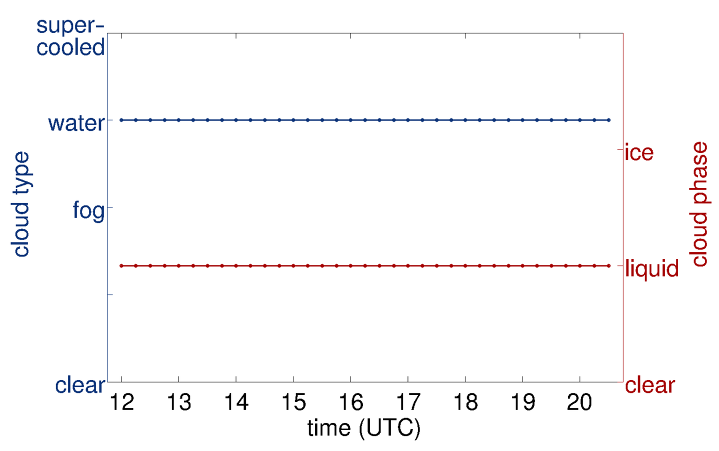
Geostationary observations can be used to quantify the development of selected clouds with respect to their optical, geometrical and microphysical properties!

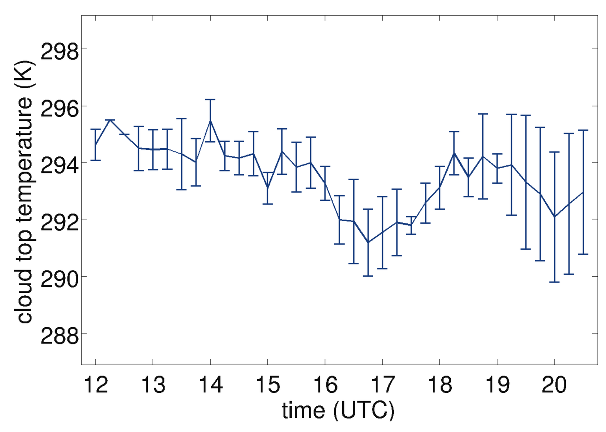
Future activities

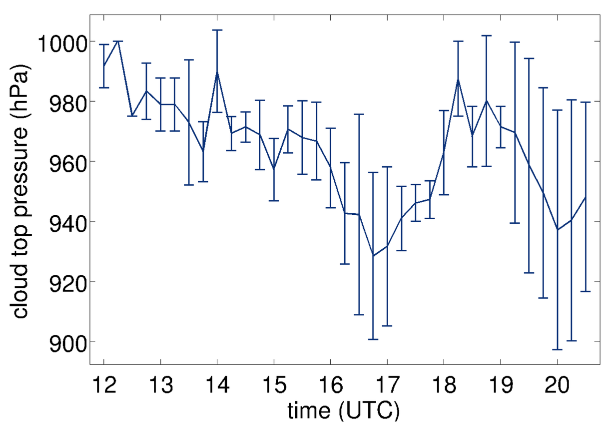
- Velocity refinement of PIV using global optical flow
- Cloud identification improvement
- Cloud-velocity estimation
- Comparison and validation with cloud resolving models
- Use the novel characterization of cloud development to identify the stage in the life cycle of clouds observed with A-Train sensors

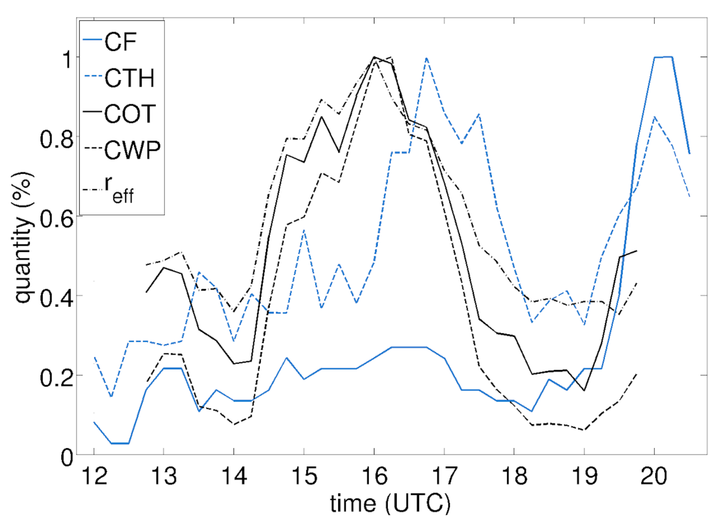
(ii) Individual cloud development/lifetime

CLAAS-2 cloud physical properties are available at daytime. Therefore, we present the longest daytime trajectory. The cloud has a lifetime of 8 hours and 30 minutes and develops northwest of the Canary Islands at 12:00 UTC on 23rd August 2015 in the prefontal environment. The cloud fraction (CF) is constant for many hours. Around 19:00 UTC the cloud fraction start to grow for 1 hour and reaches its maximum. Then the cloud fraction decreases. We assume, the cloud dissolves or splits up and the trajectory ends on 20:30 UTC on 23rd August 2015. During lifetime the cloud consists of liquid water. The cloud top temperature (CTT) ranges from 296 to 290 K. CTT decrease until 16:45 UTC indicating to vertical growth and increase after 16:45 UTC within 2 hours and again decreases assuming vertical decay/growth. It is conform with increase/decrease/increase of cloud top height and decrease/increase/decrease of cloud top pressure. During phase of vertical growth until 16:45 UTC COT, CWP and r_{eff} grow too, but contrary reach there maximum at 16:00 UTC. Then COT, CWP and r_{eff} decrease assuming there is probably precipitation.









Property (*cloud mean)	Abbreviation	Scaling factor (max. quantity)	Unit
Cloud fraction	CF	569.4785	km²
Cloud top height *	CTH	702.67 ± 270.50	m
Atmosphere optical thickness due to cloud *	COT	3.24 ± 0.35	
Atmosphere mass content of cloud condensed water *	CWP	0.0612 ± 0.0184	kg/m²
Effective radius of cloud condensed water particles at cloud top *	r_{eff}	$2.5585 \cdot 10^{-5} \pm 0.8995 \cdot 10^{-5}$	m

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Raffel et al. (2007). Particle Image Velocimetry: A practical guide. Springer-Verlag.
Adrian, R. J. and Westerweel, J. (2011). Particle Image Velocimetry. Cambridge University Press.