

# Objective characterization of mesoscale cloud patterns from graph theory and an Ising-like model (BICIM) Supplementary Material

Methodology

Complete Theorem

First Results

ummary

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Context &

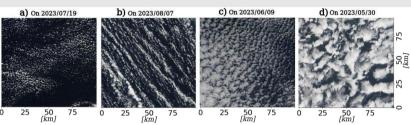
Methodology

#### Section 1

Context & Methodology

# Observed cloud field organizations





Context & Methodology

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Figure: Example of satellite observations

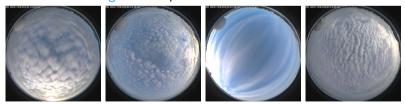


Figure: Example of ground-based observations (from a Sky Camera)

#### Context: West Coast of Sweden



- Oceans play a major role in the climate system — 70% of Earth's surface.
- Focus region: North Sea, West of Sweden (56°-59°N, 3°-12°E).
- Northern Europe = convergence zone for diverse air masses:
  - $\hookrightarrow$  mP, mT, cP, mA, cA
- Region strongly influenced by pressure oscillations (e.g., NAO).

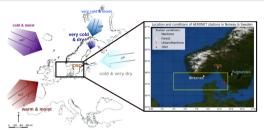


Figure: Left: Air mass types. Right: Study area

- Onsala Space Observatory (OSO): ideal for atmospheric studies
  - → Located in "clean" air, land/sea interface

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# Methodology







## (1) Modelisation (Bldimentional Cloud Ising Model)

- ightarrow BICIM simulations & sensitivity tests using OSO measurements as input data
- → Cloud Field Characterization via Graph Theory

# ② Observations

- ightarrow To collect 250 satellite observations (or observations from Sky camera)
- ightarrow Cloud Field Characterization via Graph Theory

#### 3 Mascol

ightarrow Automatic identification of similar cloud field organizations using the  $\operatorname{MASCOL}$  metric.

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Section 2

**BICIM** model

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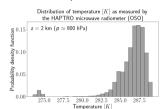
## Modelisation – Input Data for BICIM

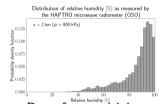


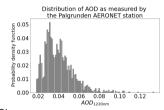




#### Input data for BICIM simulations (1, 11, 111 & $IV \rightarrow \text{see Poster}$ ):







Input Data for sensitivity tests:

Day classification based on Wei et al. (2021)

 $\hookrightarrow$  Clear:  $RH \le 85\%$  from 0 to 10km

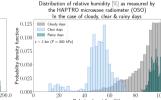
 $\hookrightarrow$  Cloudy: RH < 85% below 600m.

RH > 84% above

→ Rainy: 20 min continuous rain with RH > 84% from 0 to 10 km

the HAPTRO microwave radiometer (OSO) In the case of cloudy, clear & rainy days Cloudy days Clear days Point days z = 2 km (P ~ 800 hPs) 2005 280.0 282.5 285.0 287.5 290.0

Distribution of temperature |K| as measured by



BICIM model

Wei et al. (2021), Remote Sensing, doi: 10.3390/rs13132527 Temperature [K] Relative humidity 1% Characterization of mesoscale cloud patterns using Graph Theory & BICIM F. Mascaut & O. Puiol & P. Forkman

## Modelisation - Sensitivity tests







- The model shows consistent behavior across all cases:
  - $\hookrightarrow$  100% cloudy grid: more clouds for "cloudy" input; quick clearing for "clear"
  - $\hookrightarrow$  Random grid: "rainy" case  $\rightarrow$  more clouds at first, then decrease (rain consumes clouds).
- Tests: each flux excluded one at a time:
  - $\hookrightarrow$  Conductive flux  $\Phi^{dif} = 0$ : Slight delay in flocculation (+25k draws), but similar final state.
  - $\hookrightarrow$  **Surface flux**  $\Phi_s = 0$ : small impact

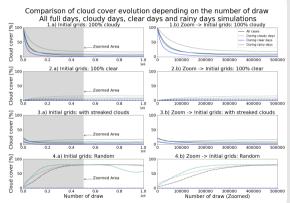


Figure: Cloud cover evolution depending on day type

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Section 3

Graph Theory & MASCOL

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BICIM mode

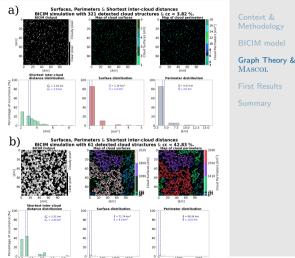
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# **Graph Theory**



- **Graph theory** ⇒ to objectively quantify cloud field organization.
  - $\hookrightarrow N_C$ : Number of cloud structures
  - $\hookrightarrow$  CC: Cloud cover (%)
  - $\hookrightarrow$  Distributions of cloud surface areas (S)
  - $\hookrightarrow$  Cloud **Perimeters**  $(P_r)$
  - $\hookrightarrow$  Shortest inter-cloud distances  $(d_m)$
- Example shown for 2 cloud fields: isolated clouds (a) vs. flocculated field (b):
  - $\hookrightarrow$  Case a): CC, S,  $P_r$  lower;  $d_m$ ,  $N_C$  higher
  - $\hookrightarrow$  Case b): CC, S,  $P_r$  higher;  $d_m$ ,  $N_C$  lower
- These metrics (CC,  $N_C$ , S,  $P_r$ ,  $d_m$ ) form the basis of our automatic identification method.



#### Mascol metric









а b

Figure:  $S_a = S_b = 6 \text{ km}^2$ , but  $P_{r,a} < P_{r,b}$  $\Rightarrow \frac{S}{P^2}$  higher for cloud a.

- Ratio  $S/P_r^2$  informs about cloud compactness.
- Higher value ⇒ more compact cloud.

Same cloud patterns, different scales  $\rightarrow$ different CC and  $N_C$ 

- Similar cloud shapes can have different spatial impact.
- Weighting CC and  $N_C$  emphasizes scale consistency.

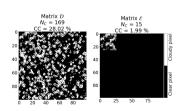


Figure: Cloud fields with similar structures

 Lower value ⇒ more spread-out shape. but different scales. Characterization of mesoscale cloud patterns using Graph Theory & BICIM — F. Mascaut & O. Pujol & P. Forkman

Graph Theory & MASCOL

#### **MASCOL**







# Metric for Assessing Similarity between Cloud Organization Layouts (MASCOL):

 $\mathcal{M} = \alpha K S_{S/P_r^2} + \beta K S_{d_m} + \gamma D_{CC} + \delta D_{N_C} \qquad_{(\alpha = \beta = 1, \gamma = \delta = 2)}$ 

- Cloud cover and number of clouds weighted more heavily (scale-sensitive)
- $\mathcal{M}=0$ : identical fields;  $\mathcal{M}=6$ : totally different fields

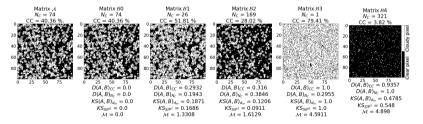


Figure: Example matrices with increasing  $\mathcal M$  vs reference matrix  $\mathcal A$ .

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BICIM model

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Section 4

First Results

Context &



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- BICIM is used as a reference.
- We compare model outputs to satellite observations.
- 9 example outputs from selected for comparison.

- Observations:
  - → 250 satellite images from NASA Worldview
  - $\hookrightarrow$  Region:  $56^{\circ}N-59^{\circ}N$ ,  $3^{\circ}E-12^{\circ}E$
- Methodology applied to both model and observations.

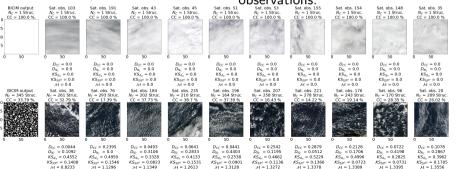
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Summary



Characterization of mesoscale cloud patterns using Graph Theory & BICIM



Sat. obs. 225 No = 209 Struc.

CC = 11.88 %

 $D_{CC} = 0.0274$ 

 $D_{v_{-}} = 0.2482$ 

 $KS_{-} = 0.0594$ 

 $KS_{S(0)} = 0.1671$ 

M = 0.7777

Sat. obs. 20

Nc = 209 Struc

CC = 26.02 %



Sat. obs. 214  $N_C = 213$  Struc.

CC = 5.46 %

 $D_{CC} = 0.1025$   $D_{W_{c}} = 0.2338$ 

 $KS_{d_{-}} = 0.0$ 

 $KS_{SW} = 0.1704$ 

M = 0.8431

Sat. obs. 197

 $N_C = 154 \text{ Struc}$ 

CC = 19.72 %







M = 0.2272

Sat. obs. 109

 $N_C = 174 \text{ Struc}$ 

CC = 29.13 %

 $D_{CC} = 0.0206$ 

 $D_{N_c} = 0.0169$ 

 $KS_{d_{-}} = 0.0105$ 



 $D_{cc} = 0.0184$ 

 $D_{V_{-}} = 0.0847$ 

 $KS_{d_{m}} = 0.0167$ 



Nc = 181 Struc

CC = 22.59 %

 $D_{CC} = 0.0546$ 

 $D_{N_c} = 0.0$ 

 $KS_{d_{v}} = 0.2014$ 

 $KS_{root} = 0.1387$ 

M = 0.4493

Sat. obs. 156

 $N_c = 48 \text{ Struc}$ 

Sat. obs. 76

Nc = 293 Struc

CC = 17.39 %



 $N_C = 176 \text{ Struc}$ 

CC = 21.32 %

 $D_{cc} = 0.0721$ 

 $D_{v_{-}} = 0.0056$ 

 $KS_{st.} = 0.1295$ 

 $KS_{root} = 0.1704$ 

M = 0.4555

Sat. obs. 145

Nc = 66 Struc

 $N_c = 258 \text{ Struc.}$ 

CC = 16.43 %



 $D_{cc} = 0.0098$ 

 $D_{v_{-}} = 0.0395$ 

 $KS_{d_{m}} = 0.3015$ 

 $KS_{rot} = 0.1584$ 

M = 0.5586

Sat. obs. 100 No = 97 Struc

 $D_{CC} = 0.0536$ 

Sat. obs. 176

 $N_c = 243$  Struc.

CC = 19.14 %



Sat. obs. 215

 $N_c = 246 \text{ Struc}$ CC = 15.87 %

 $D_{CC} = 0.0153$ 

 $D_{\nu_{-}} = 0.1151$ 

 $KS_{d_{-}} = 0.1562$ 

 $KS_{S0^{12}} = 0.116$ 



Sat. obs. 180

 $N_C = 242 \text{ Struc.}$ 

CC = 18.25 %

 $D_{CC} = 0.0432$   $D_{N_C} = 0.1295$ 

 $KS_{d_{-}} = 0.0676$ 

 $KS_{S0^2} = 0.1713$ 

M = 0.5843

Sat. obs. 89





 $KS_{\text{curl}} = 0.1803$ 

A4 = 0.727

Sat. obs. 34

 $N_c = 42 \text{ Struc}$ 

Sat. obs. 39  $N_C = 225$  Struc.

CC = 10.89 %

 $D_{CC} = 0.039$ 

 $D_{\nu_{-}} = 0.1906$ 

 $KS_{d_{-}} = 0.1392$ 

 $KS_{SP} = 0.1486$ 

M = 0.7471

Sat. obs. 238

Nc = 155 Struc









 $KS_{cort} = 0.1414$  $KS_{cort} = 0.1944$ M = 0.3515M = 0.4173Sat. obs. 46 Sat. obs. 186  $N_c = 74 \text{ Struc}$  $N_c = 59 \text{ Struc}$ CC = 48.88 %











 $D_{W_c} = 0.1469$ 

 $KS_{\text{cut}} = 0.1852$ 

M = 0.6265

Sat. obs. 30

 $KS_{d_{m}} = 0.0333$ 



 $KS_{d_n} = 0.1248$ 

 $KS_{\text{cort}} = 0.1768$ 

M = 0.7063

Sat. obs. 55

 $N_c = 46 \text{ Struc}$ 

CC = 55.09 %





 $N_c = 132 \text{ Struc}$ 

CC = 42.7 %



 $D_{cc} = 0.0638$  $D_{\nu} = 0.0519$  $KS_{d..} = 0.0333$  $KS_{cipl} = 0.2513$ M = 0.5162

 $D_{cc} = 0.1038$  $D_{N_c} = 0.0043$  $KS_{d_{-}} = 0.1294$  $KS_{cipl} = 0.1812$ M = 0.5269

 $D_{cc} = 0.0896$  $D_{v_{i}} = 0.0519$  $KS_{d_{-}} = 0.1092$  $KS_{col} = 0.2285$ 

 $D_{cc} = 0.1658$  $D_{v} = 0.0173$  $KS_{rl.} = 0.0511$  $KS_{col} = 0.2054$ M = 0.6228

 $D_{cc} = 0.0447$  $D_{N_c} = 0.1515$  $KS_{A.} = 0.0597$  $KS_{col} = 0.2496$ A4 = 0.7018

 $D_{cc} = 0.185$  $D_{vi} = 0.1515$  $KS_{A} = 0.0719$  $KS_{col} = 0.0335$ M = 0.7784

 $D_{CC} = 0.2127$  $D_{v} = 0.0606$  $KS_{d..} = 0.1481$  $KS_{col} = 0.0991$ M = 0.7937

 $D_{cc} = 0.2325$  $D_{N_c} = 0.0779$  $KS_{A.} = 0.1124$  $KS_{c(0)} = 0.139$ M = 0.8722

 $D_{vi} = 0.303$  $KS_{d.} = 0.1687$  $KS_{col} = 0.1041$ M = 0.8789

 $KS_{d_n} = 0.1439$  $KS_{S/R^2} = 0.128$ M = 0.881

First Results



- 9 categories of cloud fields from BICIM are defined (as an ex.).
- Satellite observations with  $\mathcal{M} \leq 1.5$  are matched to the most similar category (minimal  $\mathcal{M}$ ).
- If no match ( $\mathcal{M} > 1.5$  for all), the observation is labeled as *Unclassified*.

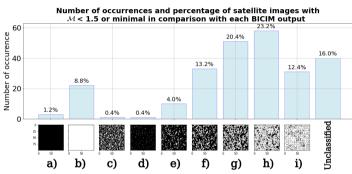


Figure: Number of satellite observations best matched (minimal  $\mathcal{M}$ ) to each output. Last bar: unmatched observations.

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Characterization of mesoscale cloud patterns using Graph Theory & BICIM — F. Mascaut & O. Pujol & P. Forkman







Section 5

Summary

Context &

# **Summary**







# (1) Modelisation (Bldimentional Cloud Ising Model)

- ightarrow capable of generating cloud fields and reproducing their specific organizations
- $\Rightarrow$  CC,  $N_C$ , S,  $P_r$  and  $d_m$  using Graph Theory

#### ② Observations

 $\Rightarrow$  CC,  $N_C$ , S,  $P_r$  and  $d_m$  using Graph Theory

 $\mathfrak{G}$  Mascol  $(\mathcal{M})$ 

ightarrow Automatic identification of similar cloud field organizations

 $\Rightarrow$  Mascol allows for the *fast* ( $\le$  10 min) and *objective* identification of cloud organizations.

 $\Rightarrow$  It is easily adaptable  $\rightarrow$  possible to extend the region and study period.

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