Numerical modeling of air flows in an underground cavity connected to the surface by a shaft

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Plan

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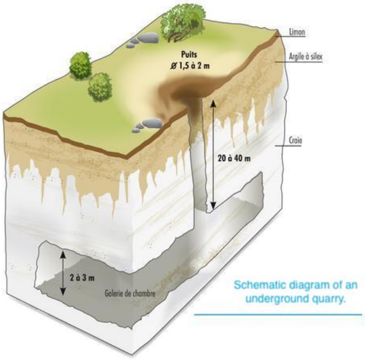
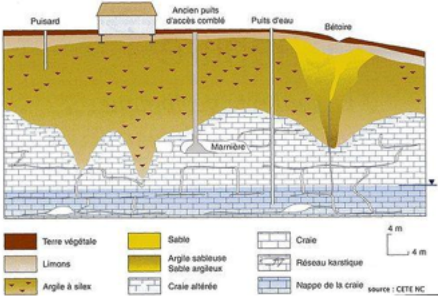
- Morphology of an underground cavity[1]
  - ∗ Dug in the 19th century to extract chalk,
  - ∗ Approximately 120,000 in the Normandy region,



Schematic diagram of an underground quarry.



[1] C. Fauchard, P. Pothérat, P. Côte, and M. Mudet. Détection de cavités souterraines par méthodes géophysiques. Guide technique- Laboratoire central des ponts et chaussées, 2004.

* Shaft filled with heterogeneous materials (planks, rocks, debris),
* Climate change: acceleration of collapses.

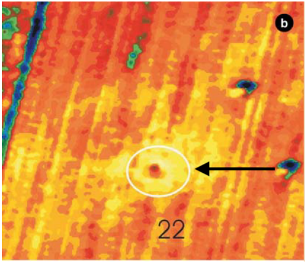
well blocked by rocks (view from inside the underground cavity) - Collapse under a house.

- Presence of multiple detection methods:
  - ∗ Microgravimetry, geological radar, electrical methods, seismic methods,
  - ∗ Each method has its own advantages and disadvantages.
- Search for a flexible method:
  - ∗ Thermal camera carried by drone,
  - ∗ A cost-effective and high-yield method.

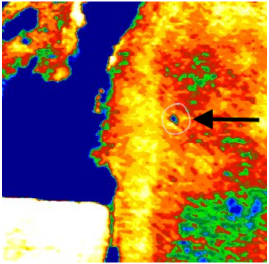
Drone DJI M600 Pro + Thermal camera[2]

[2] ENDSUM-Rouen Team, Cerema

Objective: Characterize heat transfer between the cavities and the atmosphere; evaluate the potential of thermal infrared observation.



winter



summer

Surface temperatures observed by airplane using a thermal camera showing the thermal signature of two invisible wells, with a contrast between 2 and 4 degrees[3]

[3] Fauchard, 2004, Pothérat, 2000

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Geophysical Introduction: Framing Our Study

Mathematical model for natural convection

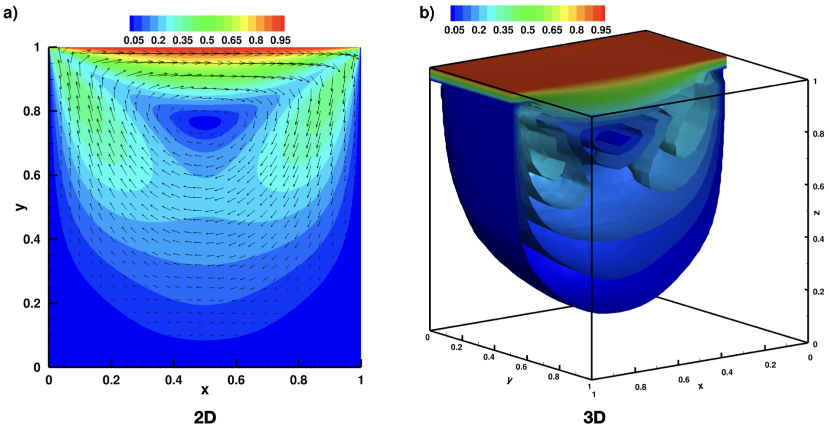
Application to the Barcq cavity

Conclusion and perspectives

Concepts of natural convection

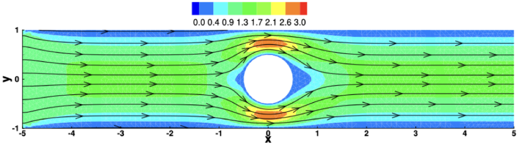
Forging the numerical solutions of progressively complex PDEs using FreeFem++[4] to craft a model of an underground cavity.

- Stokes equation: $\begin{cases} -\nu\Delta\mathbf{v} + \nabla p = 0 \text{ in } \Omega, \\ \nabla\cdot\mathbf{v} = 0 \text{ in } \Omega. \end{cases}$

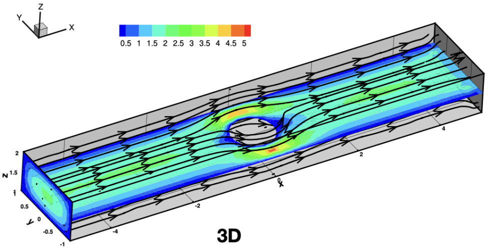


[4] https://freefem.org

- Navier-Stokes: $\begin{cases} \frac{\partial \mathbf{v}}{\partial t} - \nu \Delta \mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} + \nabla p = 0 \text{ in } \Omega, \\ \nabla \cdot \mathbf{v} = 0 \text{ in } \Omega. \end{cases}$

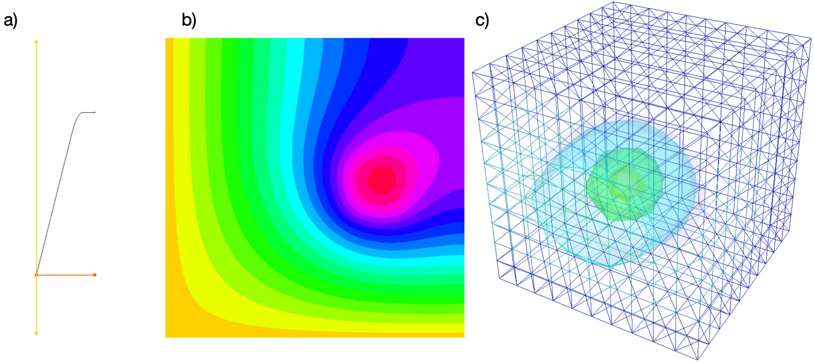


2D



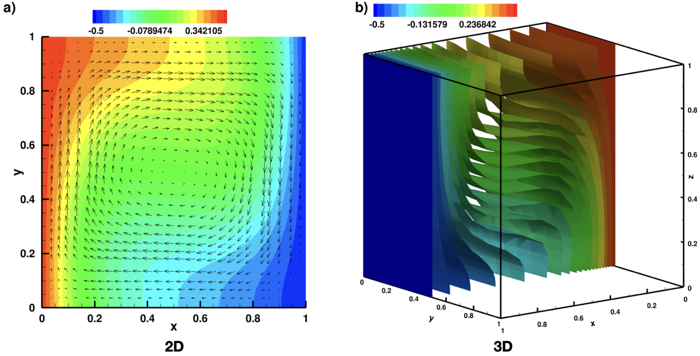
3D

- Heat equation: $$\begin{cases} \dfrac{\partial T}{\partial t} - K\Delta T = f \text{ in } \Omega, \\ T(t=0) = T_0, \\ K \cdot \dfrac{\partial T}{\partial n} + \alpha \cdot (T - T_e) = 0 \text{ on } \Gamma_2 \cup \Gamma_3, \\ T = T_e \text{ sur } \Gamma_1 \cup \Gamma_4. \end{cases}$$



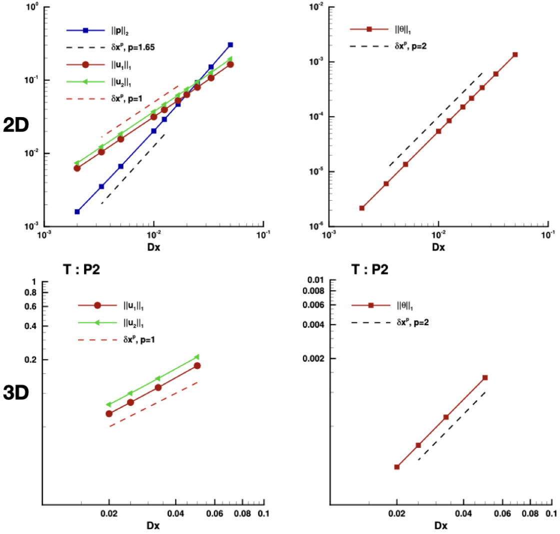
- System of equations for natural convection[5]:

$$
\left\{
\begin{array}{rcl}
\nabla \cdot \mathbf{v} & = & 0, \\
\dfrac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \nabla p - \dfrac{1}{Re}\nabla^2 \mathbf{v} - f_B(T)\, \mathbf{e}_y & = & 0, \\
\dfrac{\partial T}{\partial t} + \nabla \cdot (T\mathbf{v}) - \dfrac{1}{Re.Pr} K \Delta T & = & 0.
\end{array}
\right.
$$



[5] Georges Sadaka, Aina Rakotondrandisa, Pierre-Henri Tournier, Francky Luddens, Corentin Lothode, and Ionut Danaila. Parallel finite-element codes for the simulation of two-dimensional and three-dimensional solid-liquid phase-change systems with natural convection. Computer Physics Communications, 257:107492, 2020.

- Mathematical validation of methods, spatial convergence using the Burggraf solution (Velocity: P1b, Pressure: P1, Temperature: P2).



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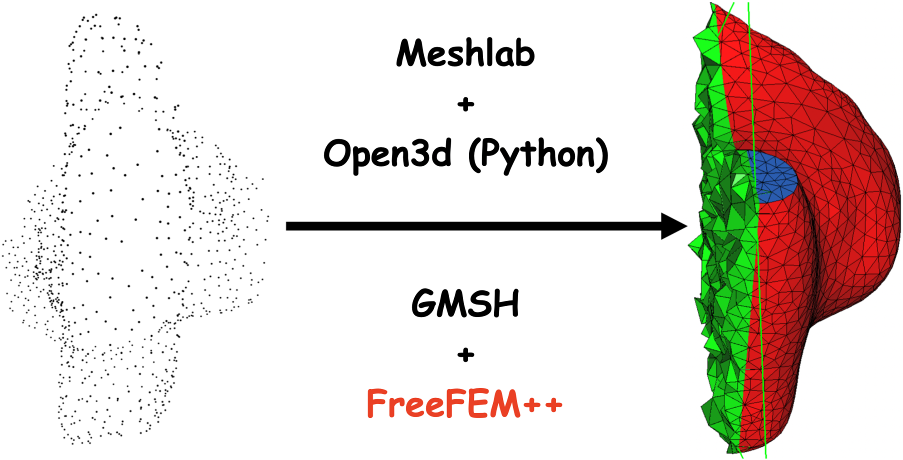
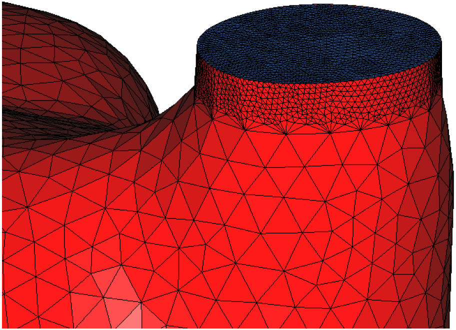
- Generation of the 3D mesh of the Barcq [6] underground cavity:

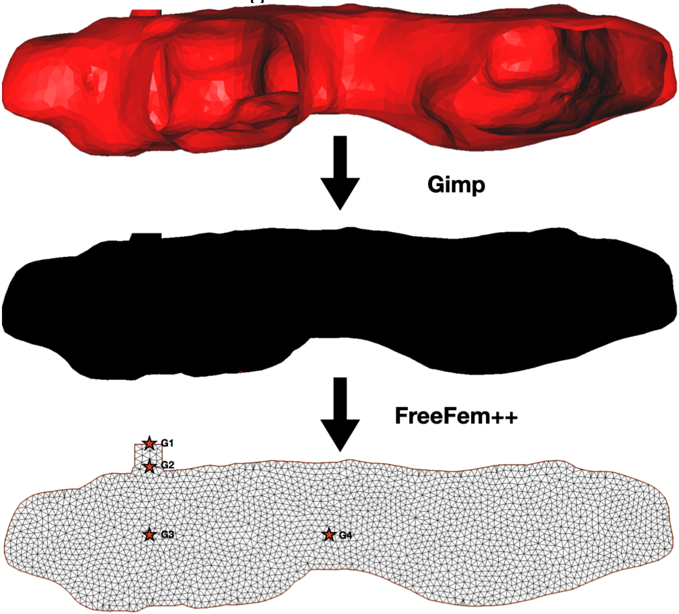


[6] 27170 - Eure - France

```
int[int] labs = [0];
meshL ThL = extract(ThSBarc,label=labs);
// compute the barycenter of the meshL ThL
real bx=int1d(ThL)(x)/ThL.measure;
real by=int1d(ThL)(y)/ThL.measure;
real bz=int1d(ThL)(z)/ThL.measure;
meshL ThLup = movemeshL(ThL,transfo=[(x-bx)*.97+bx,(y-by)*.97+by,bz+2.],region=labS);
meshL ThLmiddle = ThL + ThLup;
include "buildmeshS.idp"
meshS Thcylmiddleup = buildmeshSLap(ThLmiddle,1);
meshS Thcyldown = buildmeshSLap(ThL,1);
meshS ThSfinal = Thcyldown + Thcylmiddleup + ThSBarc;
```



- Transition to 2D meshing

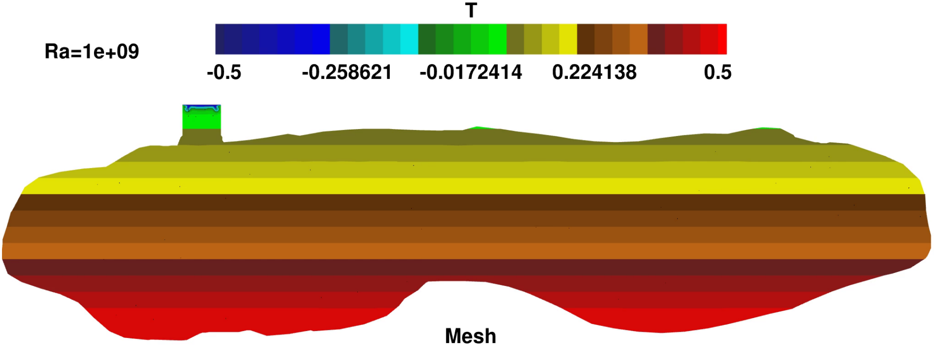


- Concepts about the Rayleigh number: $\mathcal{R}a = \frac{g\beta H^3 \delta T}{\nu\alpha}$
  - g, β, ν, $\alpha \longrightarrow$ Constants (gravitational acceleration, thermal expansion coefficient, viscosity, thermal diffusivity),
  - $\delta T \longrightarrow$ Low temperature difference,
  - $H^3 \longrightarrow$ volume of the cavity,
- Example of Rayleigh:
  - $\mathcal{R}a = 10^9 \Longleftrightarrow \delta T = 1^\circ$ et $H^3 = 10m^3$
- Following simulations carried out in non-dimensional case.

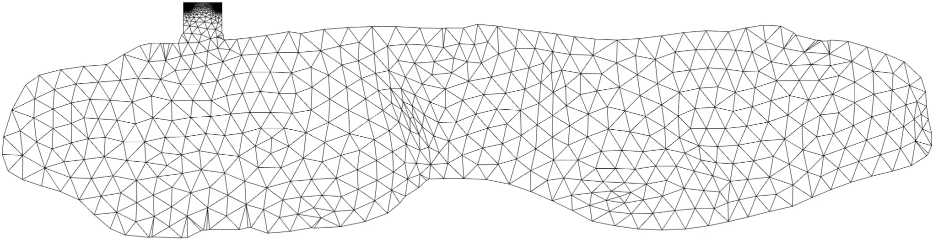
Solvers used from the `PETSc`[7] library ((Portable, Extensible Toolkit for Scientific Computation)

- Direct solver used for the 2D case:
  `"-pc_type lu -ksp_type preonly"`,
- For the 3D problem, we used the following set of parameters:
  `"-ksp_converged_reason -pc_type asm -pc_asm_overlap 1 -ksp_pc_side left -ksp_type gmres -ksp_gmres_restart 50 -ksp_max_it 100 -ksp_atol 1e-5 -sub_pc_type lu -sub_pc_factor_mat_solver_type mumps -ksp_rtol 1e-6"`.

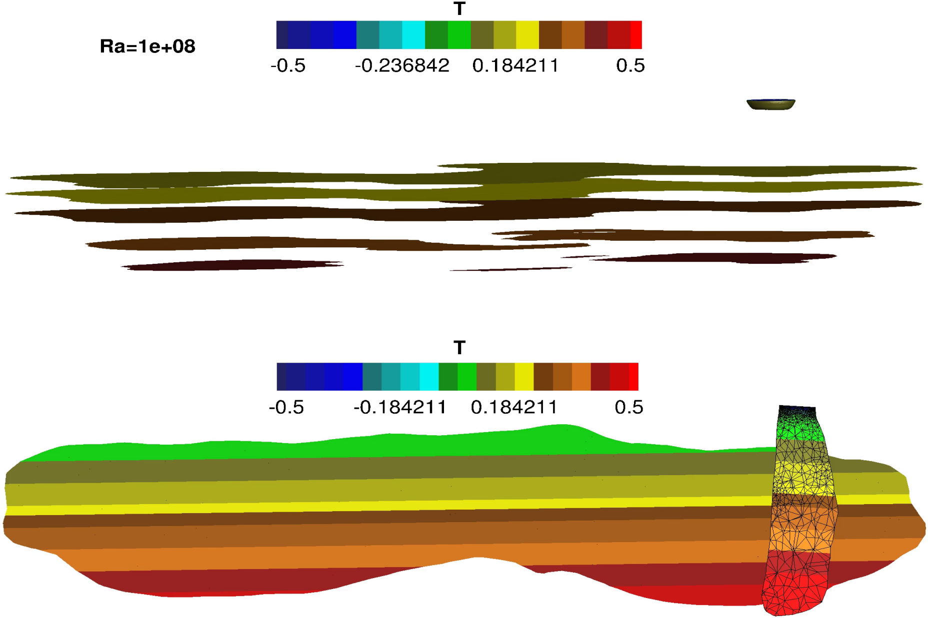
[7] https://www.mcs.anl.gov/petsc/



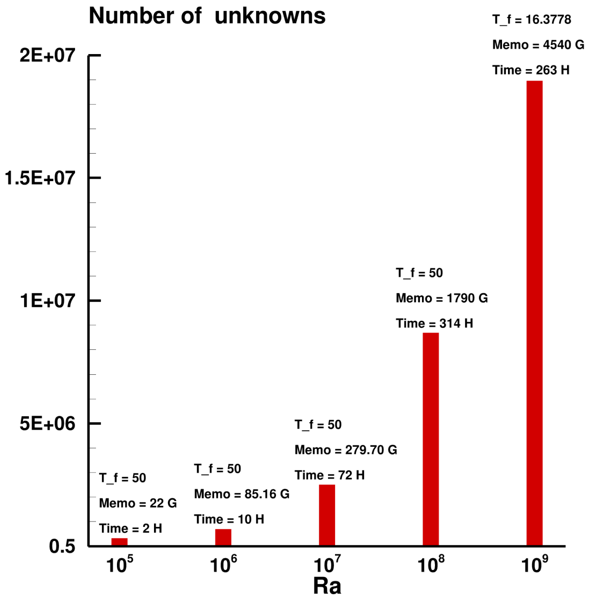
Mesh



2D Natural convection with $Ra = 10^9$.



3D Natural convection with $Ra = 10^8$.


Number of unknowns
2E+07
1.5E+07
1E+07
5E+06
0.5
T_f = 50
Memo = 22 G
Time = 2 H
T_f = 50
Memo = 85.16 G
Time = 10 H
T_f = 50
Memo = 279.70 G
Time = 72 H
T_f = 50
Memo = 1790 G
Time = 314 H
T_f = 16.3778
Memo = 4540 G
Time = 263 H
10^5
10^6
10^7
10^8
10^9
Ra

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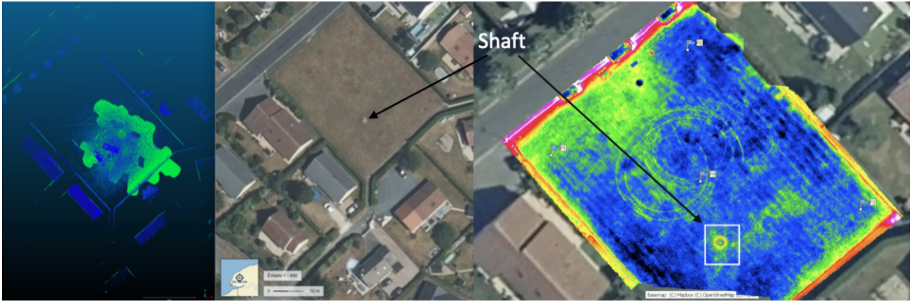
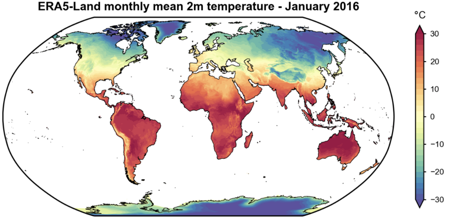
- **Conclusion** :
  - * The geological context in the Normandy region obstructs the discovery of cavities. The thermal infrared method shows great potential for overcoming these challenges.
  - * Simulating natural convection within the cavity using FreeFem++ .
  - * Observing the initiation of natural convection, as well as changes in heat flux and the quantity of convection cells, based on the Rayleigh number.

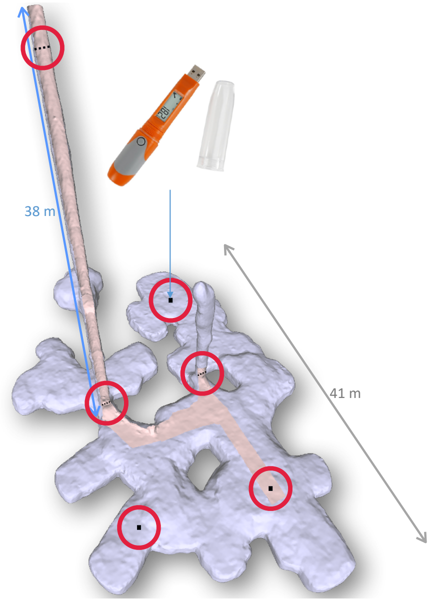
- **Conclusion** :
  * The geological context in the Normandy region obstructs the discovery of cavities. The thermal infrared method shows great potential for overcoming these challenges.
  * Simulating natural convection within the cavity using FreeFem++ .
  * Observing the initiation of natural convection, as well as changes in heat flux and the quantity of convection cells, based on the Rayleigh number.
- **Perspectives** :
  * The 3D case requires improvement in terms of the solver.
  * Integration of geophysical parameters into the simulation for enhanced realism.
  * Incorporating data from thermocouples and radiation sensors to validate and compare our simulation results with actual parameters.



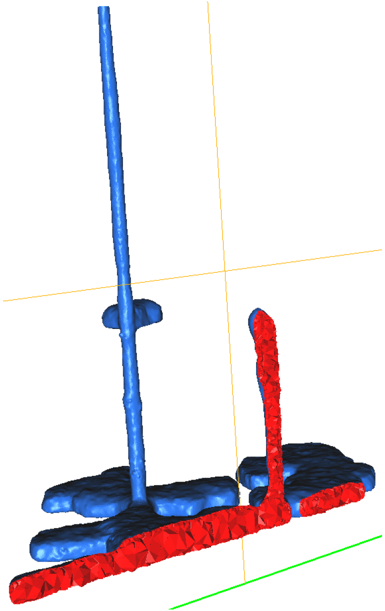
Point cloud, visible, and thermal images of the Goderville cavity (Normandy).



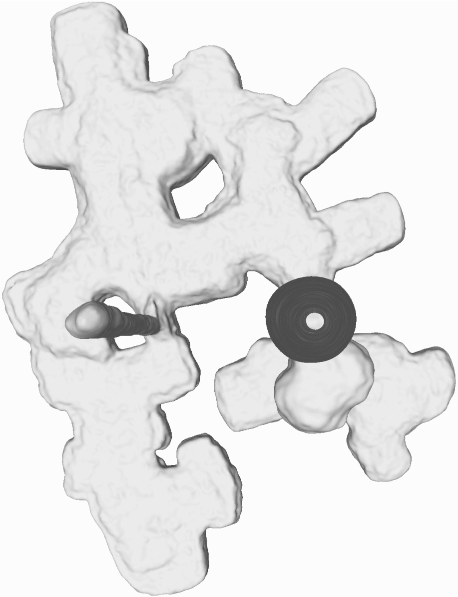
ERA5-Land hourly data from 1950 to present.



Measuring campaign.



Mesh of the cavity.



Thank you for your attention.