GOBIERNO DE ESPAÑA

MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Instituto Geológico y Minero de España

# Simulation of impacts of potential future climate change scenarios on SCA in Sierra Nevada by using a cellular automata model

E. Pardo, AJ. Collados, **D. Pulido**

(Researcher Fellow, Spanish Geological Survey, IGME)

**COST Action ES1404**:

A Euroepan network for a harmonised monitoring of snow for the benefit of climate change scenarios, hydrology and numerical weather prediction

# **INTRODUCTION** (MOTIVATION): **Practical interest** of knowing SCA evolution

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- **SCA** variable ⇒ operational modelling in **METEOROLOGY & HYDROLOGY**

- SCA REMOTELY SENSED observations ⇒ Most investigated measurements in hydrology (Liu et al., 2012)⇒ **SCA products** with **≠ s&t resolution** & **historical period** (eg. MODIS, NOAA)

- **ISSUE**: SCA period without satellite information ⇒ eg. cloudy days, low temporal resolution satellite, short available historical periods

  - **Estimation** of historical periods without data
  - **Prediction** of future values (data assimilation techniques)
  - Simulation of **future potential climate change scenarios**

# INTRODUCTION (MOTIVATION): Practical interest of knowing SCA evolution

## TECHNIQUES TO ESTIMATE SCA (IN PERIODS WITHOUT DATA):

### ❑ DETERMINISTIC MODELS

- CONCEPTUAL MODELS: Eg. SNOWMELT RUNOFF MODEL (Martinec *et al.*, 1994); DEGREE-DAY METHODS [empiric approach very employed (Hock, 2003)]. HYBRID-DEGREE-DAY METHODS = VARIABILITY (*s&t*
- ENERGY BALANCE MODELS: (eg. *Eg. Plüss, 1997; Herrero, 2007*)

### ❑ NON-DETERMINISTIC MODELS (↑interest in cases with ↓ nº data)

- REGRESSION TECHNIQUES (Richer et al., 2012; Mir et al., 2015)
- ARTIFICIAL NEURAL NETWORKS (Hou and Huang, 2014)
- ***CELLULAR AUTOMATA*** (Pardo-Igurquiza et al., 2016; Leguizamón, 2006)

# INTRODUCTION (MOTIVATION): Review
# Cellular Automata technique

## Cellular Automata HISTORY & GENERAL CONCEPTS:

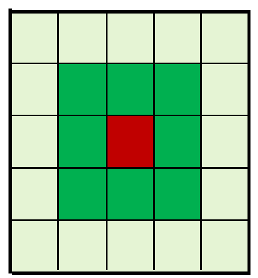
- Neumann & Ulam, 1940's ⇒ COMPLEX, DYNAMIC, DISCRETE (s&t) model SYSTEMS (computational TH, maths, physics, biology & microstructure modelling)

$$\mathbf{S^i(t)=f(S^i(t-1), S^j(t-1), TransitionRules)}$$

$\mathbf{S^i(t)}$ =future state of pixel i; $\mathbf{S^i(t-1)}$ =previous state of pixel i; $\mathbf{S^j(t-1)}$ =previous state of pixel j)

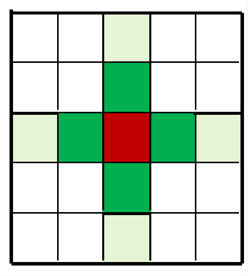
**COMPONENTS** = REGULAR GRID OF CELLS + TIME STEPS

- Cell state = finite nº of possible states (k) in each cell (nº or properties)
- Neighbourhood = set of cells that influence on new state.



Neumann (only ) neighborhood

Extended Neumann Neighborhood (also )



Moore (only ) neighborhood

Extended Moore (also ) neighborhood

- Transition rules = "If" rules (driving variables) to approach system dynamic

# INTRODUCTION (MOTIVATION): Review
# Cellular Automata technique

## Cellular Automata HISTORY & GENERAL CONCEPTS

### Classic Example of CA application. THE GAME OF LIFE (Conways´s Rules)

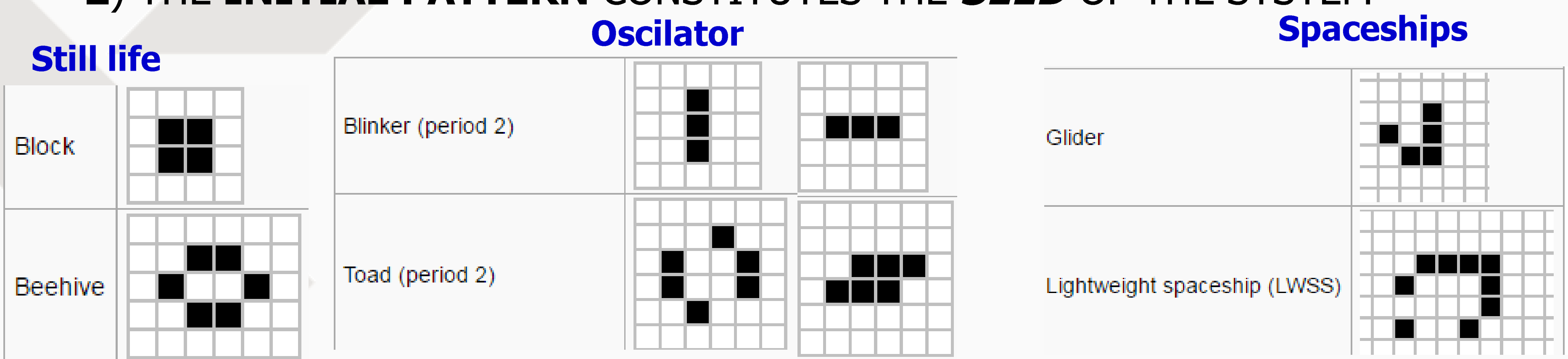
Analogies with the rise, fall and alternations of living organisms

**1) THE RULES**

**- For a space that is 'populated':**
Each cell with one or no neighbors dies, as if by solitude.
Each cell with four or more neighbors dies, as if by overpopulation.
Each cell with two or three neighbors survives.

**- For a space that is 'empty' or 'unpopulated'**
Each cell with three neighbors becomes populated.

**2**) THE **INITIAL PATTERN** CONSTITUTES THE ***SEED*** OF THE SYSTEM




https://en.wikipedia.org/wiki/Conway%27s_Game_of_Life

(HTTPS://EN.WIKIPEDIA.ORG/WIKI/CONWAY%27S_GAME_OF_LIFE)

# INTRODUCTION (MOTIVATION): Review
# Cellular Automata technique

## Cellular Automata SNOW applications

- ❑ **Snow Avalanches** (eg. Kronholm and Birkeland 2005, Faillettaz et al., 2004)

- ❑ **Crystal Growth** (Ning et al., 2007)

- ❑ **SCA evolution** (Pardo-Igurquiza et al., 2017; Leguizamón, 2006)

Pardo-Iguzquiza, E., Collados-Lara, A.J., Pulido-Velazquez, D., 2017. Estimation of the spatiotemporal dynamics o
snow cover area by using cellular automata models. **J. of Hydrology** 550: 230–238

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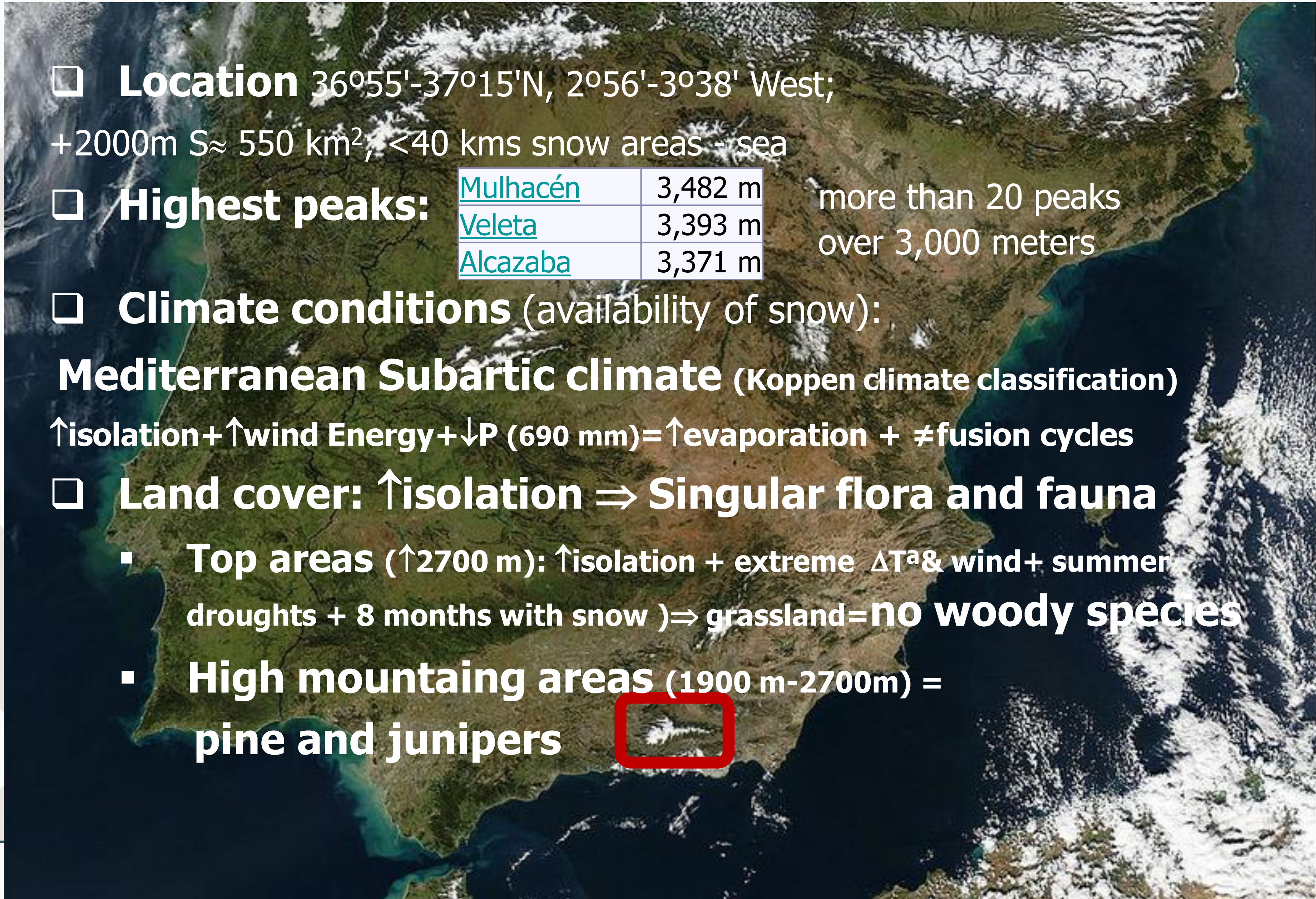
# METHOD and MATERIAL: CA application = SIERRA NEVADA MOUNTAINS



- **Location** 36º55'-37º15'N, 2º56'-3º38' West;

+2000m S≈ 550 km$^2$; <40 kms snow areas - sea

- **Highest peaks:**

| | |
|---|---|
| Mulhacén | 3,482 m |
| Veleta | 3,393 m |
| Alcazaba | 3,371 m |

more than 20 peaks over 3,000 meters

- **Climate conditions** (availability of snow):

**Mediterranean Subartic climate (Koppen climate classification)**

**↑isolation+↑wind Energy+↓P (690 mm)=↑evaporation + ≠fusion cycles**

- **Land cover: ↑isolation ⇒ Singular flora and fauna**
  - **Top areas (↑2700 m): ↑isolation + extreme ΔTª& wind+ summer droughts + 8 months with snow )⇒ grassland=no woody species**
  - **High mountaing areas (1900 m-2700m) = pine and junipers**

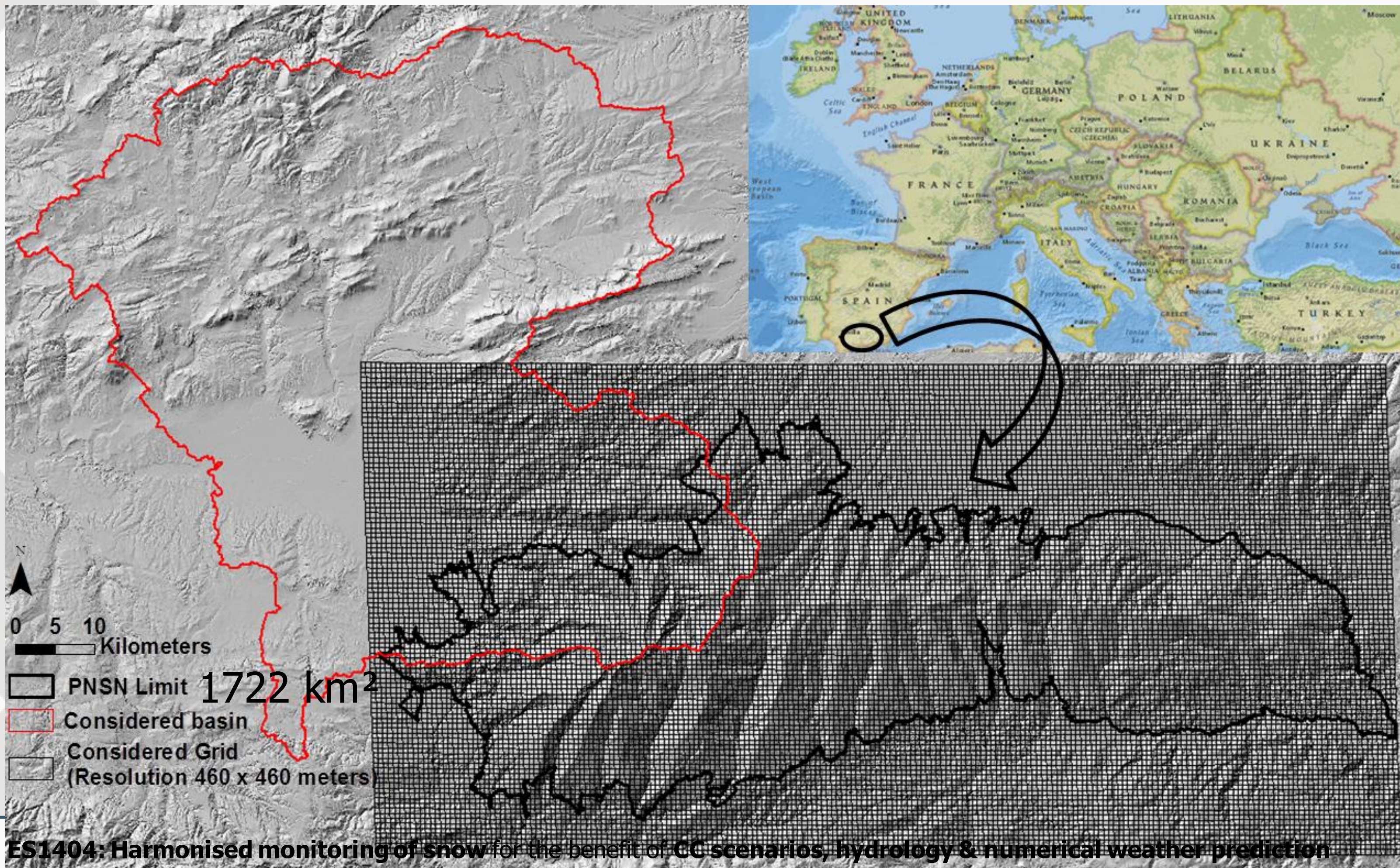
# METHOD and MATERIAL: CA technique application (Sierra Nevada Mountain)

**CA** to simulate **daily SCA in S. Nevada**

$\mathbf{S_i(t)=f(S_i\,(t-1),\ S_j(t-1),\ TransitionRules)}$

1) **Definition of CA components**
2) Calibration & validation

**1**A) Definition of a REGULAR GRID (460x460 m cells) in S. Nevada (Spain).



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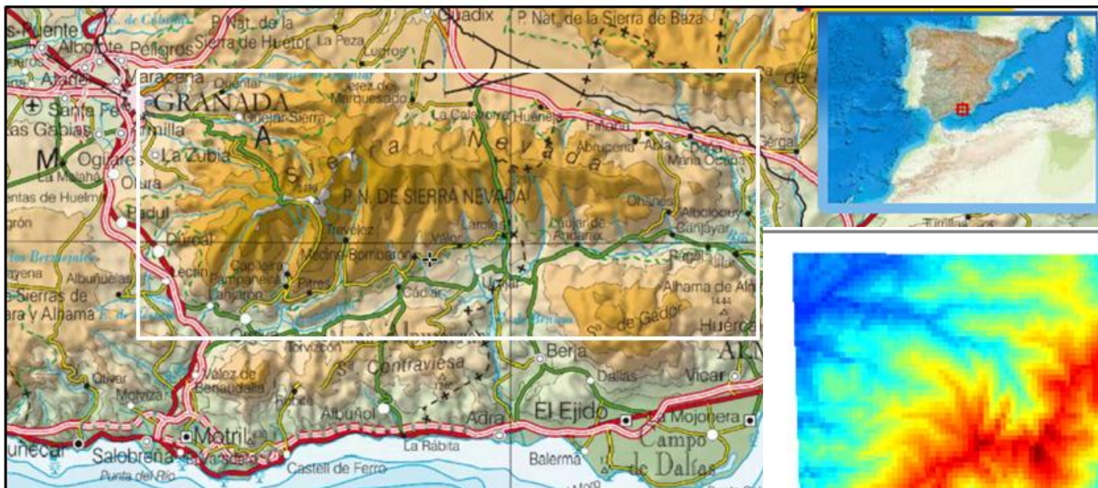


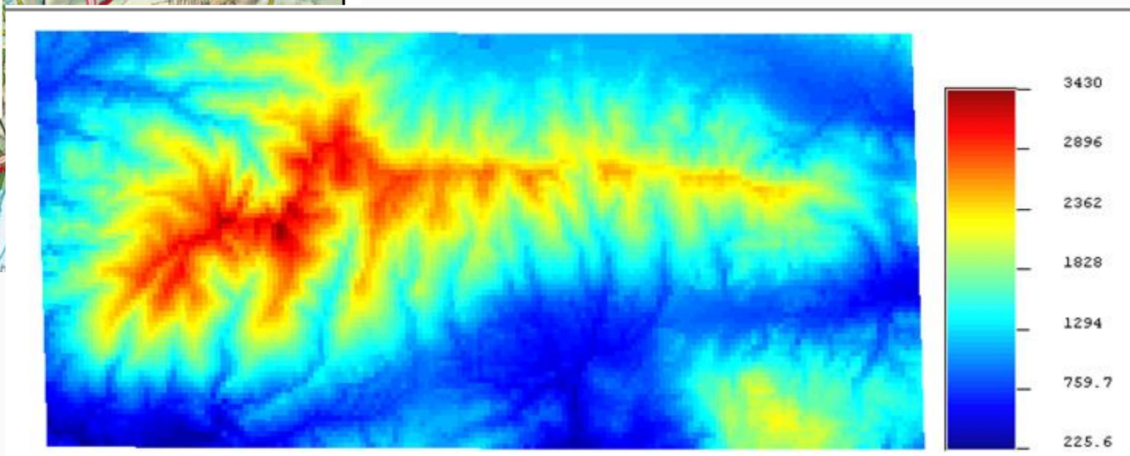


## 1A) DAILY TIME STEPS

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# METHOD and MATERIAL: CA technique application (Sierra Nevada Mountain)

**CA** to simulate **daily SCA in S. Nevada**

$$S_i(t)=f(S_i(t-1), S_j(t-1), \text{TransitionRules})$$

**1) Definition of CA components**

2) Calibration & validation

**1**B) Finite **possible states** (k) in each cell (n$^{os}$ or properties): **S = 0** (without snow) **S = 1** (with snow)

4 possibilities:

$S_i(t) = 0$ & $S_i(t-1) = 0$ ; $S_i(t) = 0$ & $S_i(t-1) = 1$;

$S_i(t) = 1$ & $S_i(t-1) = 1$ ; $S_i(t) = 1$ & $S_i(t-1) = 0$;

**1**C) Neighbourhood = set of cells that influence on new state

| | | | | |
|---|---|---|---|---|
| 11 | 12 | 13 | 14 | 15 |
| 10 | 2 | 3 | 4 | 16 |
| 9 | 1 | 0 | 5 | 17 |
| 24 | 8 | 7 | 6 | 18 |
| 23 | 22 | 21 | 20 | 19 |

Extended Neumann Neighborhood

# METHOD and MATERIAL: CA technique application (Sierra Nevada Mountain)

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**CA** to simulate **daily SCA in S. Nevada**

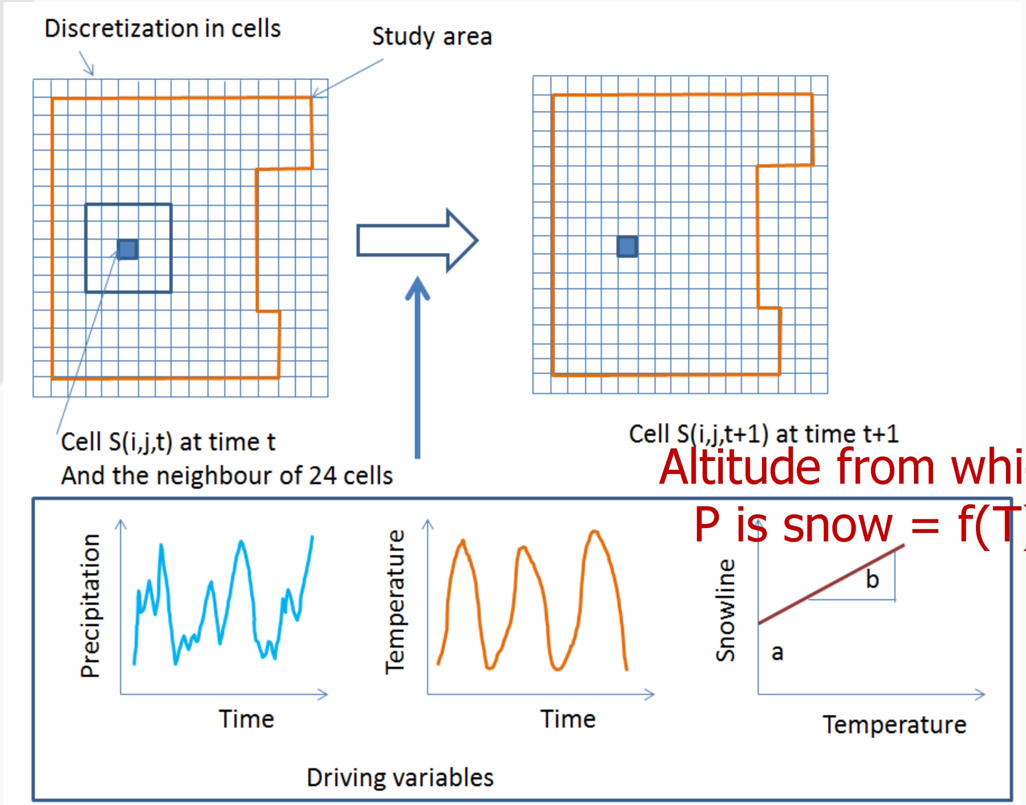
$$S^i(t)=f(S^i(t-1), S^j(t-1), \text{TransitionRules})$$

**1) Definition of CA components**

2) Calibration, valid, simul future CC

**1D) Transition rules** "If" rules (DRIVING VARIABLES) to approach system dynamic

**DRIVING VARIABLES (LUMPED CLIMATOLOGIC INDICES)**




Altitude from which P is snow = f(T)

# METHOD and MATERIAL: CA technique application (Sierra Nevada Mountain)

**CA** to simulate **daily SCA in S. Nevada**

**$S^i(t)=f(S^i(t-1), S^j(t-1), TransitionRules)$**

1) **Definition of CA components**

2) Calibration, valid, simul future CC

## 1D) TRANSITION RULES "If" rules (DRIVING VAR) to approach system dynamic

- If $P(t) \geq P_0$ and $H(t) > H_k = \mathbf{a} + \mathbf{b}T \Rightarrow$ there is snow (1)

- If $P(t) < P_0$;
  - $T(t) \leq T_c \Rightarrow$ the state remains = previous one
  - $T(t) > T_c \Rightarrow$
    - Previous state 0 remains 0 (no snow)
    - Previous state 1 (snow) $\Rightarrow$ SNOWMELT = **CA** changes to 0 (if N(I,J) with 1 (snow) $\leq N_m$)

**PARAMETERS ($P_0$, $T_c$, a, b, $N_m$)**

# METHOD and MATERIAL: CA technique application (Sierra Nevada Mountain)

**CA** to simulate **daily SCA in S. Nevada**

**$S^i(t)=f(S^i(t-1), S^j(t-1), TransitionRules)$**

**1) Definition of CA components**

2) Calibration, valid, simul future CC

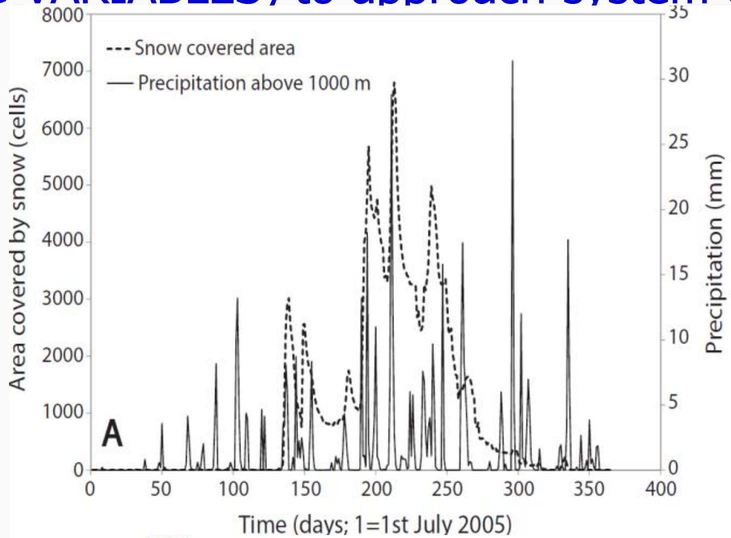
## **1**D) **Transition rules** "If" rules (DRIVING VARIABLES) to approach system dynamic

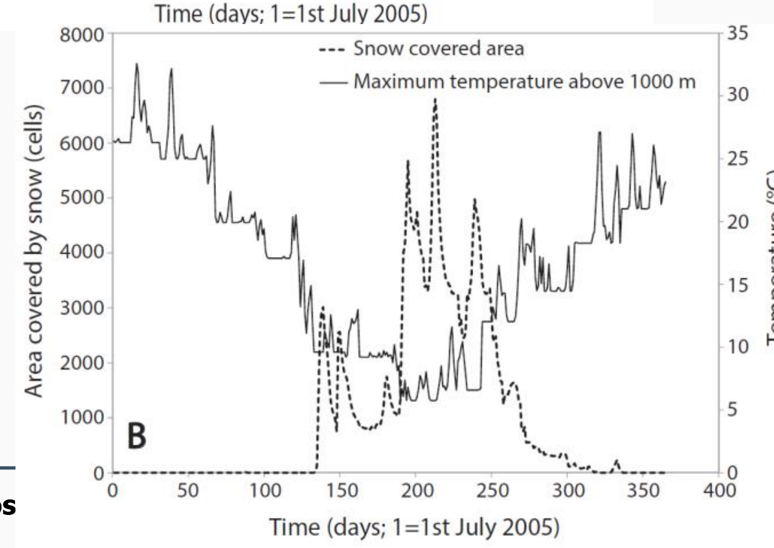
**≠ LUMPED CLIMATOLOGIC INDICES** considered as **driving variables**

- Mean **P** over an altitude threshold (1000, 1500, 2000, 2500, 3000 m a.s.l)

- Mean, min and max **T** over an altitude threshold (1000, 1500, …, m a.s.l);

- Snowline $H_k$ = f(T) = a+bT.
= linear relationship



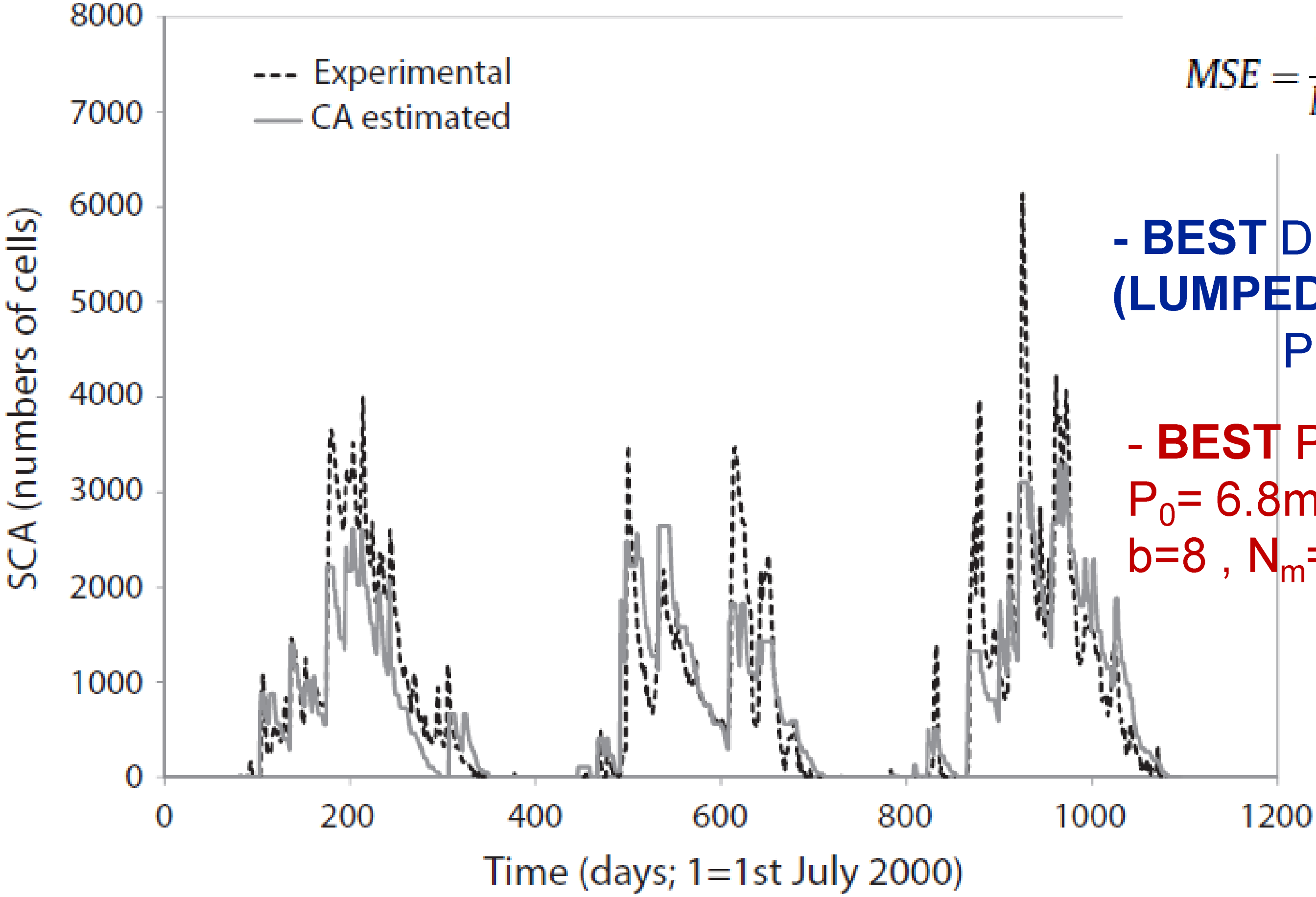



# APLICATION TO A CASE STUDY (Sierra Nevada Mountains): RESULTS AND DISCUSSION

## ❑ AUTOMATIC CALIBRATION of the CA model.

**Exhaustive search in a grid ⇒ Unbiased (ME≈0) & minimun MSE**

$$MSE = \frac{1}{N}\sum_{t=1}^{N}\left(SCA^{*}(t) - SCA(t)\right)^{2}$$



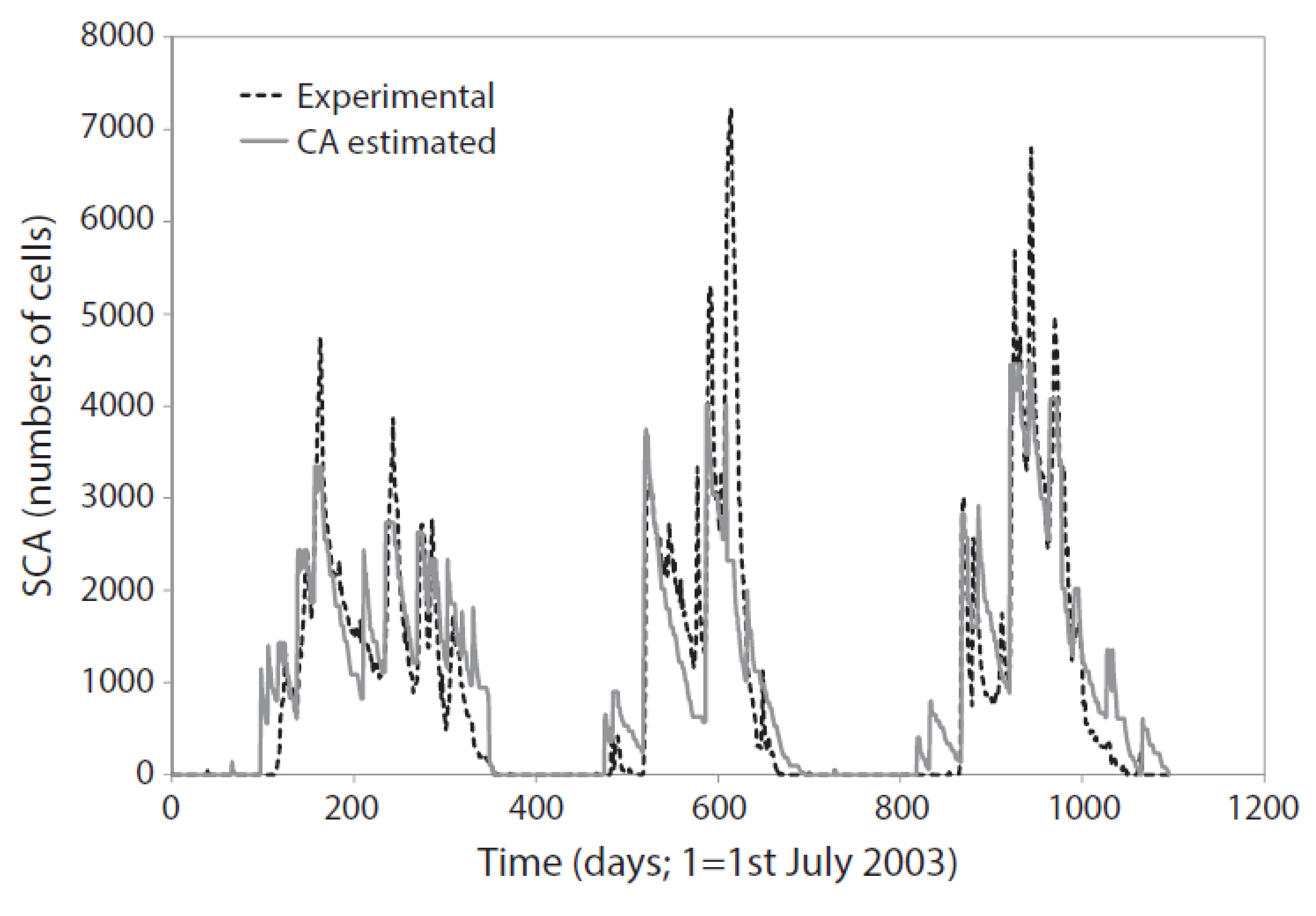

- **BEST** DRIVING VARIABLES **(LUMPED climatic indices):** $P_{1000}$, $MaxT_{1000}$

- **BEST** PARAMETERS: $P_0$= 6.8mm, $T_c$=0 , a=1170 , b=8 , $N_m$= 14

Experimental and simulated SCA for the yearS 2000-2003

# APLICATION TO A CASE STUDY (Sierra Nevada Mountains): RESULTS AND DISCUSSION

## ❑ VALIDATION of the CA model



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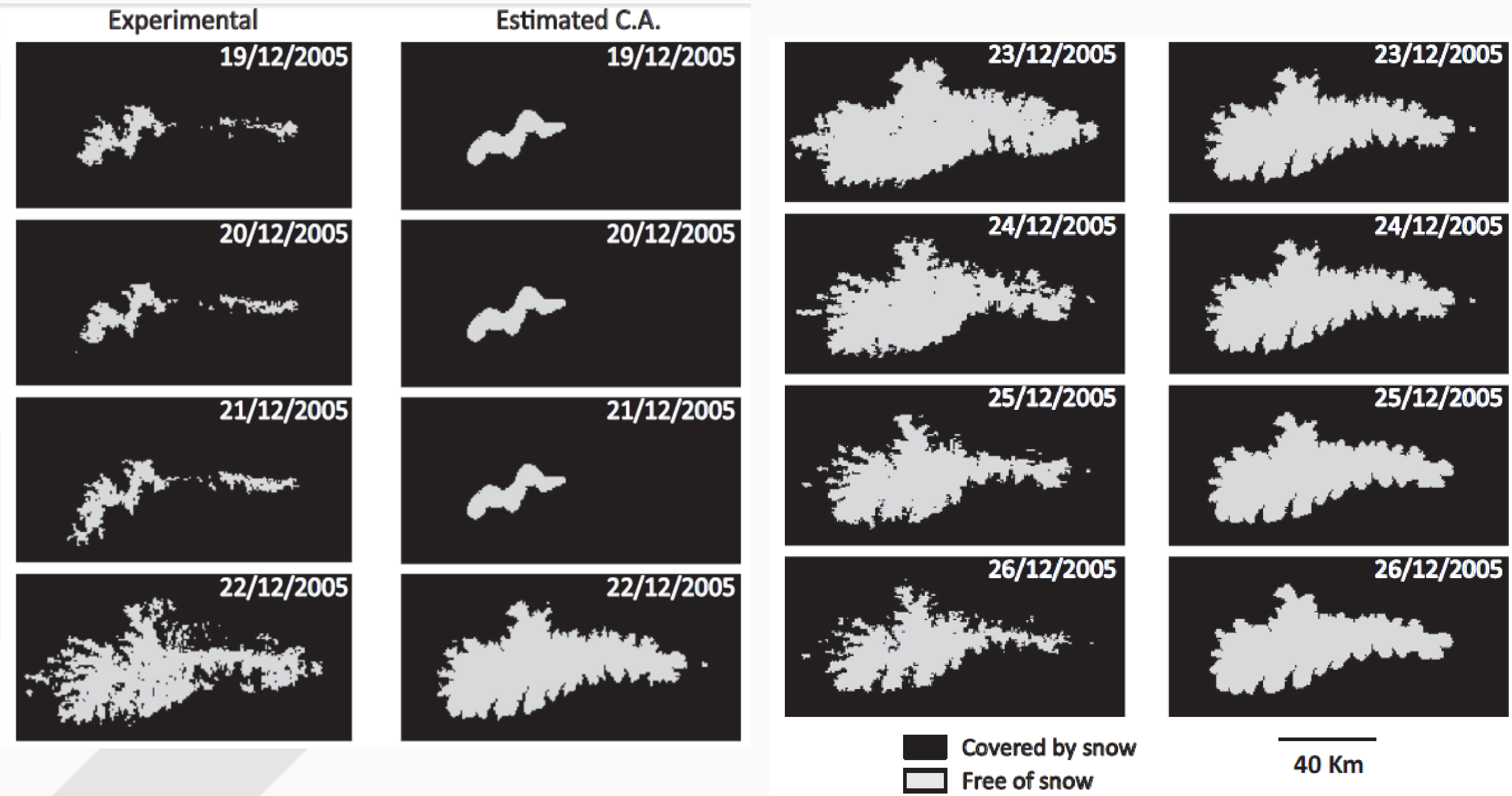
# APLICATION TO A CASE STUDY (Sierra Nevada Mountains): RESULTS AND DISCUSSION

## ❑ Validation of the CA model

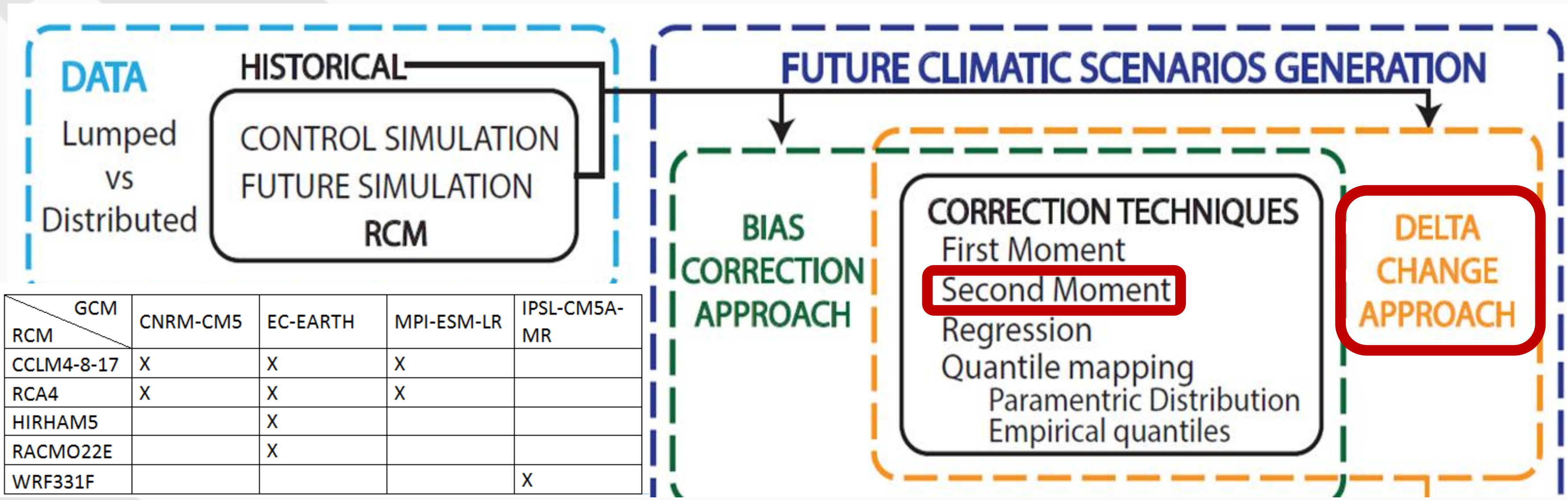


# APLICATION TO A CASE STUDY (Sierra Nevada Mountains): RESULTS AND DISCUSSION

## ❑ Simulation of potential future climate change scenarios

**FUTURE potential SERIES OF DRIVING CLIMATOLOGICAL VARIABLES (P, T)**

**HORIZON 2071-2100; RCP 8.5**



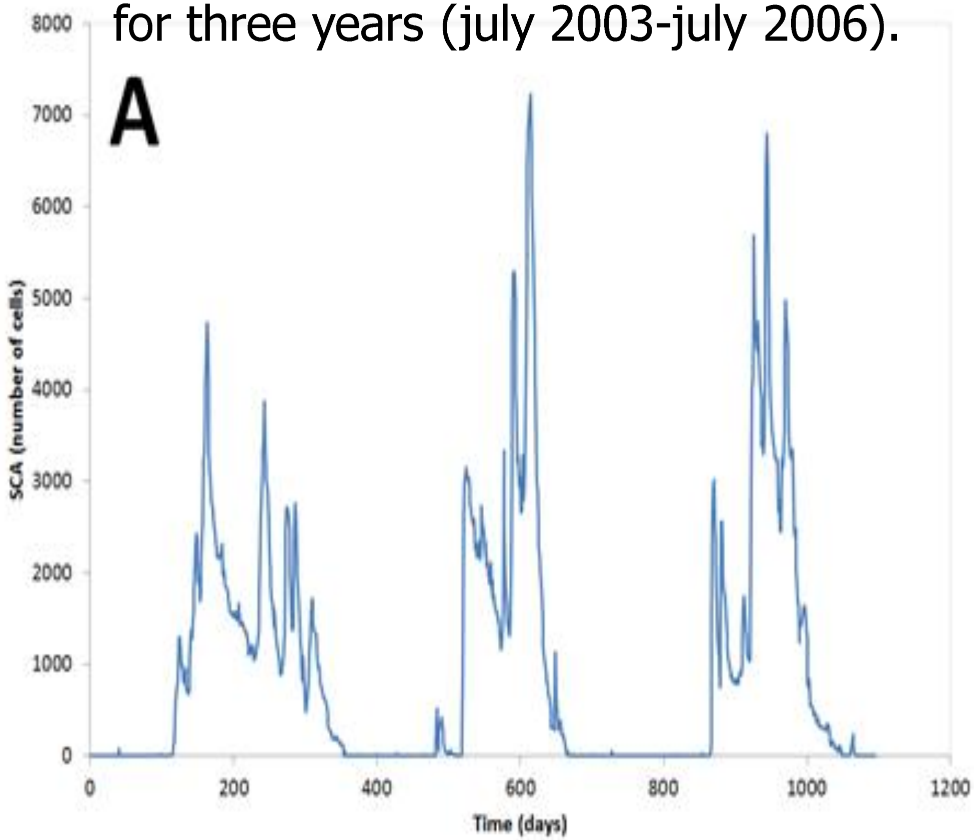

| GCM / RCM | CNRM-CM5 | EC-EARTH | MPI-ESM-LR | IPSL-CM5A-MR |
|---|---|---|---|---|
| CCLM4-8-17 | X | X | X | |
| RCA4 | X | X | X | |
| HIRHAM5 | | X | | |
| RACMO22E | | X | | |
| WRF331F | | | | X |

**EQUIFEASIBLE ENSEMBLE OF SIMILATIONS = MORE PLAUSIBLE SCENARIOS**

# APLICATION TO A CASE STUDY (Sierra Nevada Mountains): RESULTS AND DISCUSSION

## ❑ Simulation of potential future climate change scenarios

Experimental evolution of the SCA for three years (july 2003-july 2006).

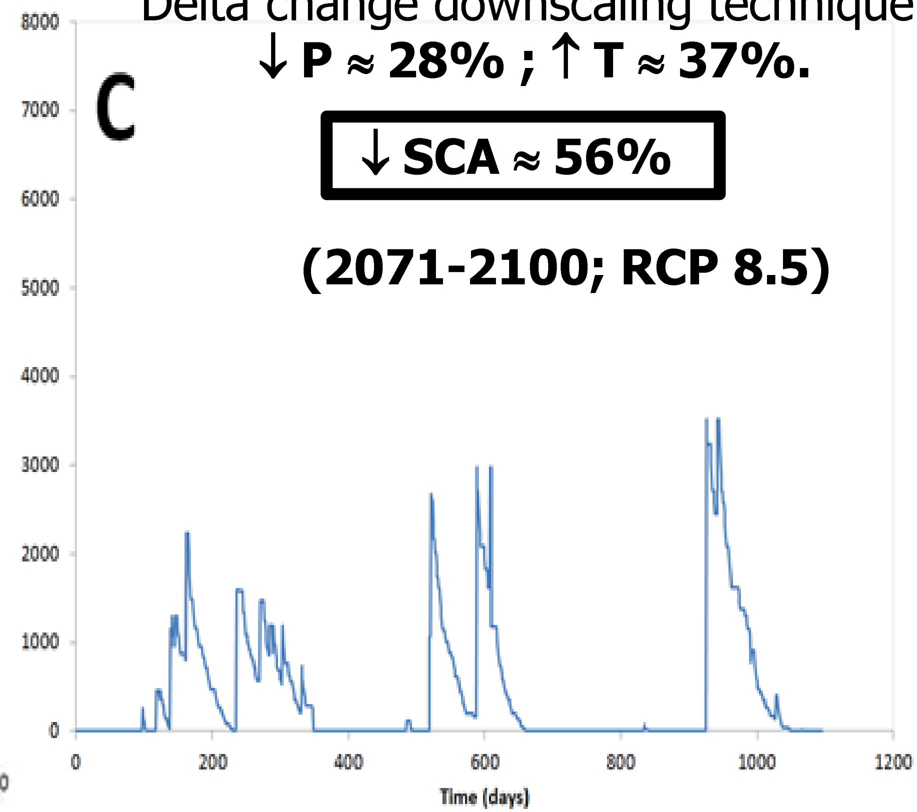



CA Simulated evolution of the SCA. Delta change downscaling technique.

**↓P ≈ 28% ; ↑T ≈ 37%.**

**↓SCA ≈ 56%**

**(2071-2100; RCP 8.5)**




There is an **increment in the bimodality of the SCA** or a **reduction of the number of days** with snow

## CONCLUSIONS:

- **A non-deterministic method to simulate SCA** by using **CA** is proposed:
  1) DEFINITION OF CA COMPONENTS
     - a) REGULAR GRID OF CELLS
     - b) Finite possible states (k) in each cell (n$^{os}$ or properties)
     - c) Neighbourhood = set of cells that influence on new state.
     - 4) Transition rules
     - 5) Initial conditions
  2) CALIBRATION 3) VALIDATION 4) SIMULATION
- **It has been use to simulate impacts of future CC scenarios on SCA**
- **More research works in progress = DISTRIBUTED FORCING VARIABLES, LONGER HISTORICAL PERIODS**
  - **Estimate** historical periods without data
  - **Predicting** future values (data assimilation techniques)
  - **Simulating potential future CC** scenarios

# THANK YOU
# FOR YOUR ATTENTION!!