Notebooks on the Water Cycle of the Lake : Using SIRTA data to introduce students to key concepts of hydrology

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Outline :

- The concepts introduced in the lecture and developped with notebooks, particularly those using SIRTA data.
- An example of results from a notebook : The evolution of the lake of Polytechnique under climate change.
- Practical aspects of using notebooks in class.

Introduction

- Climate science has become data rich in the last 20 years.
- Our sciences are excellent applications of some basic physical theories (hydrodynamics, Thermodynamics, radiation, …).
- The interactions of processes are too complex for an analytical approach. The classical blackboard exercises are not possible.
- Computer and high level coding languages, allow students to play with data and test their understanding much more easily.
- This evolution probably also requires an evolution of the pedagogy.
- At a minimum, the practical exercises allows to test the concepts introduced in the lecture with actual data.
- The usage of Jupyter notebooks for the lecture on hydrology and water resources at Ecole Polytechnique (MEC_51058) is presented.

Objectives of the lecture on hydrology and water resources (MEC_51058)

Students should gain an understanding of the following aspects of the water cycle :

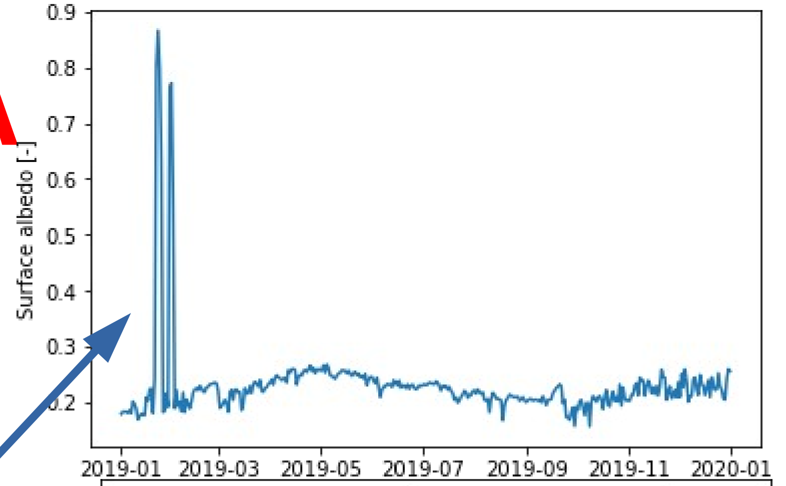
- Stores and fluxes of the hydrological cycle.
- Their interactions with the energy and carbon cycles.
- The physical laws and biological processes which govern the processes.
- How is the water cycle observed.
- Tools available to monitor and predict the state of our water resources.
- Impact of climate change and land use on water resources.

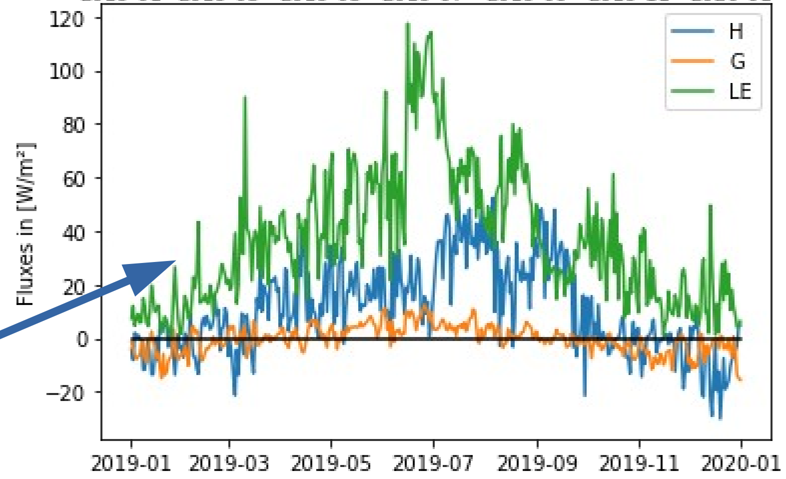
Concepts presented and tested in the Notebooks

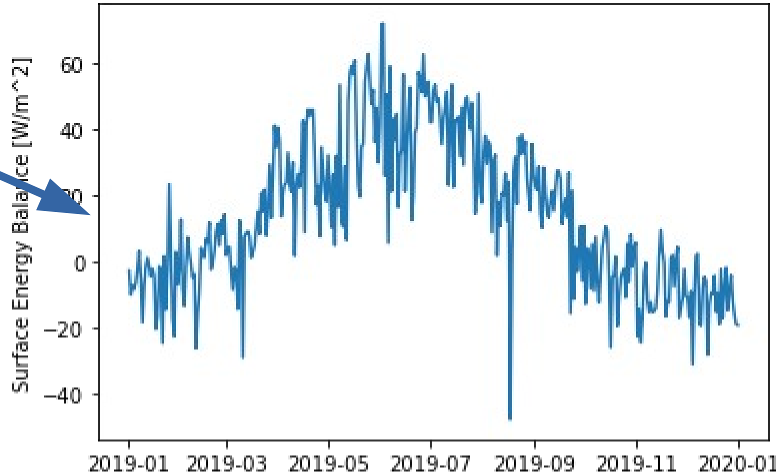
- The surface energy balance and the coupling to the water cycle
  - Evaporation is the link between the energy and water cycles.
  - The energy balance over the year at the SIRTA site.
  - Contrasting the energy balance between a wet and dry years at the Puéchabon site.
- Role of transpiration by the vegetation
- The water balance of a catchment
- Near surface turbulence
- The unsaturated zone
- Using parsimonious hydrological models
- Impact of climate change on the water cycle
- Some general notions of thermodynamics

The surface energy balance at SIRTA

- The ReObs dataset is provided to the students for the years 2015 to 2021.
- Each student should choose a different year.
- The following steps are executed :
  - Compute and examine the annual cycle of albedo and explain the variations.
  - Compare the annual cycles of net solar and net longwave radiation and discuss the differences.
  - Compare the 3 diffusive fluxes in the energy balance.
  - Estimate the annual mean closure of the energy balance. Demonstrates the observational difficulties.
- The steps are repeated with the diurnal cycle

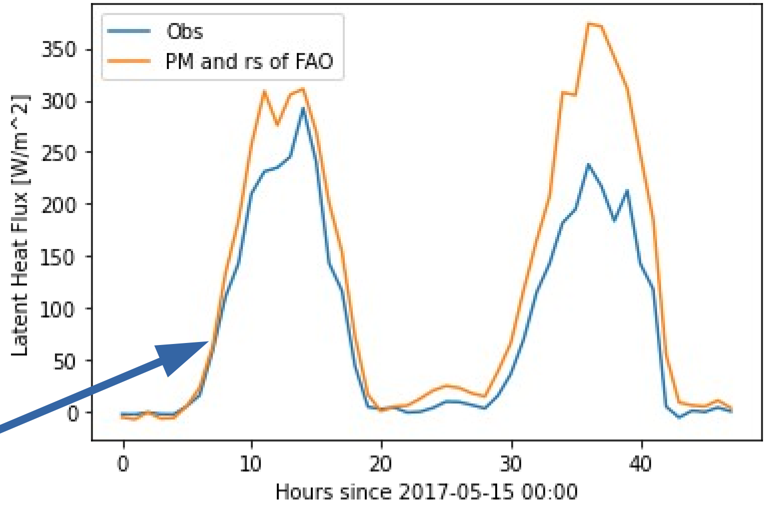


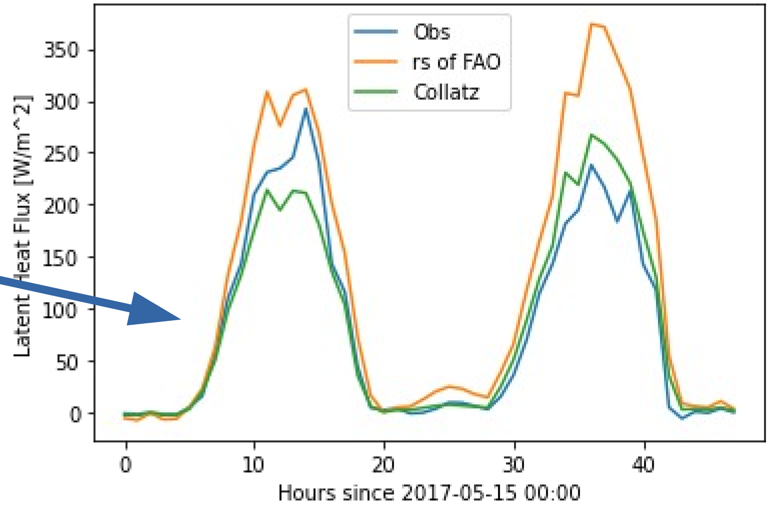




The role of plant transpiration at SIRTA

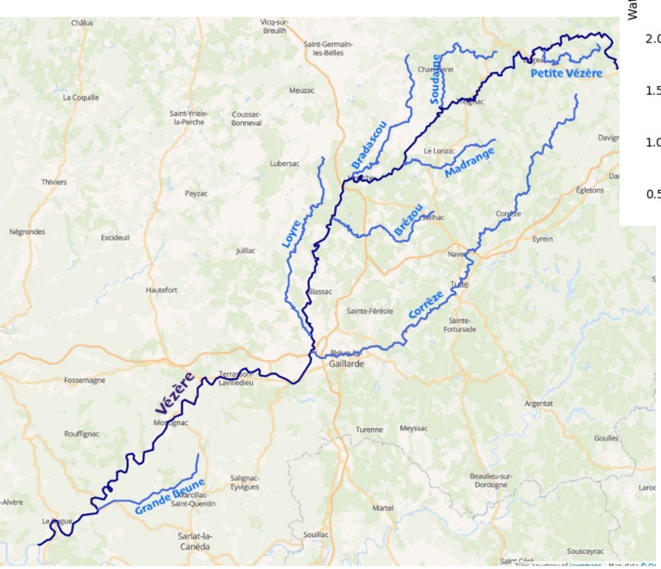
- Students are first introduced to the Collatz model of stomatal conductance in a separate Notebook.
- The using ReObs (on the days of their choice) evaporation will be computed using different assumptions.
  - The Penman-Monteith equation for evaporation is explained first (Was already introduced in the lecture).
  - It is then applied with a constant surface resistance, i.e. no plant transpiration/photosynthesis.
  - The role of the various forcing is discussed and the systematic bias determined.
  - The stomatal resistance is simulated (using the Collatz model) and discussed.
  - Finally evaporation is computed taking into account the photosynthesis of grass.
- It should be apparent to the students that even over the grass of SIRTA, vegetation plays an important role in regulating evaporation.

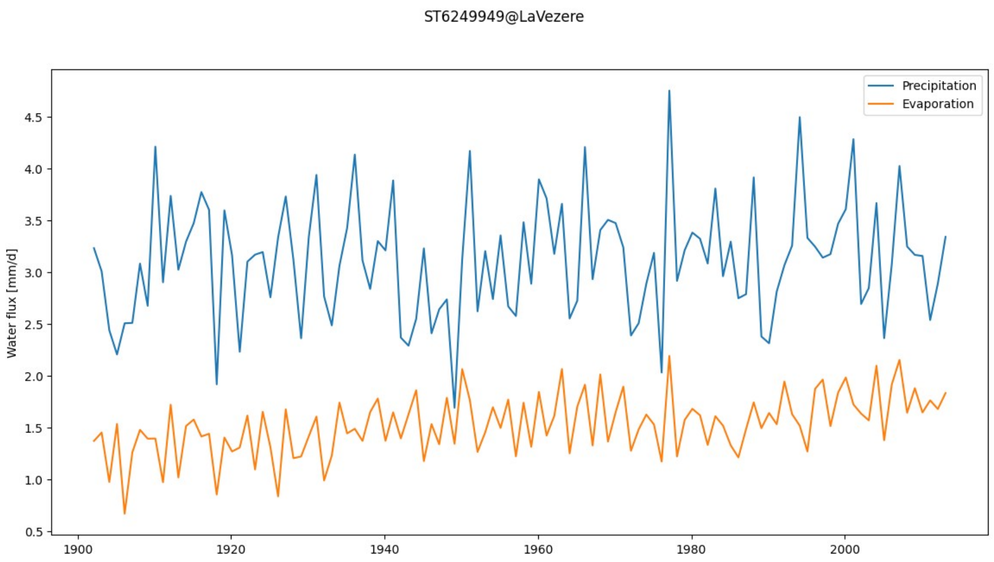




Water Balance of a Catchment

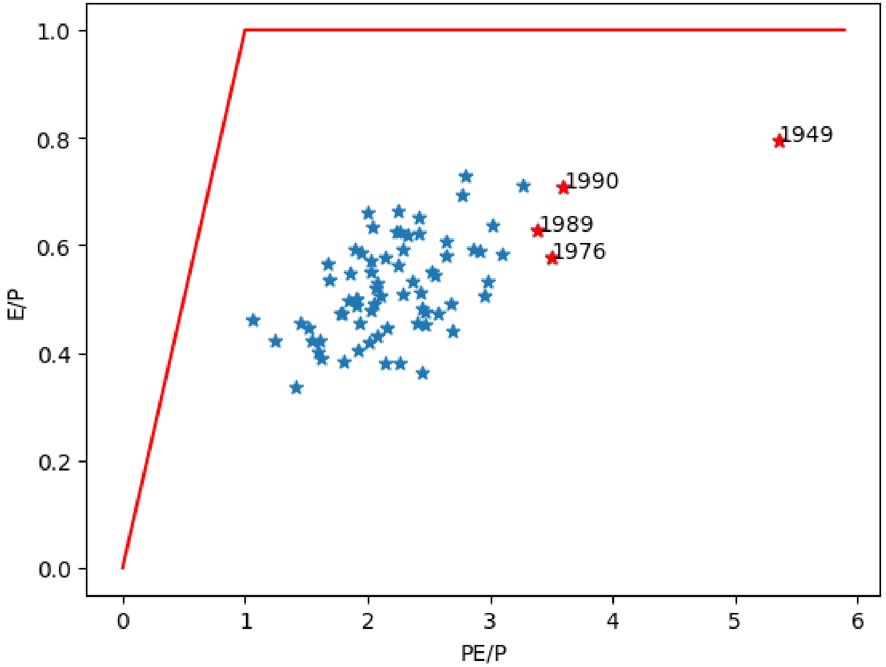
- Analysed over the Vézère catchment at Montignac
- The Budyko model is presented and evaluated over that basin.
- The approach later re-used for the lake of Polytechnique



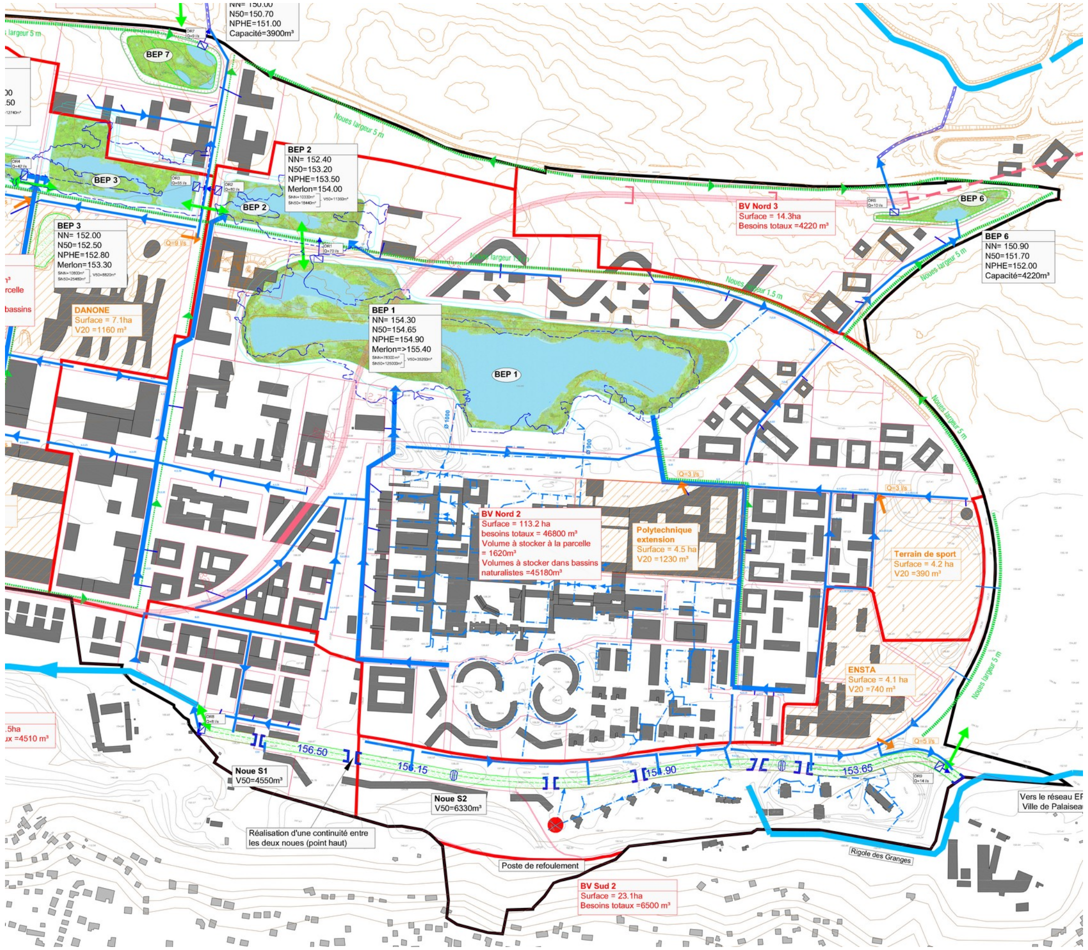


Highlights the difference in inter-annual variability of precipitation and evaporation. Explains the discharge fluctuations.

The Budyko plot allows to characterise years in terms of aridity and evaporation efficiency.



Applying the Water Balance to the Lake of Polytechnique



- Area of catchment (A_c) : 1.130 10^6 m^2
- Area of lake (A_l) : 125. 10^3 m^2

- The students are presented with the hydrological history of the plateau.
- The evolution of the catchment of the campus.
- As this is an exercise on the impact of climate change on water resources, two further elements are needed :
  - How climate is simulated at scales compatibles with the campus (CORDEX).
  - How climate change is projected with these models.
- The students have observations and model output for : P, E & PE
- The students are asked to develop a model which predicts the water mass in the lake or lake level.

The two possible lake models :

The continuity equation allows to write the following mode for discharge from the lake (Q) over the sill :

$$Q = (A_c - A_l)(P - E) + A_l(P - PE)$$

This is not satisfactory as it does not take into account the fact that once the level of the lake is below the sill Q=0.

Assuming that volume variations are small enough that they are proportional to the level of the lake we can write :

$$A_l \frac{\partial h_l}{\partial t} = (A_c - A_l)(P - E) + A_l(P - PE) - Q$$

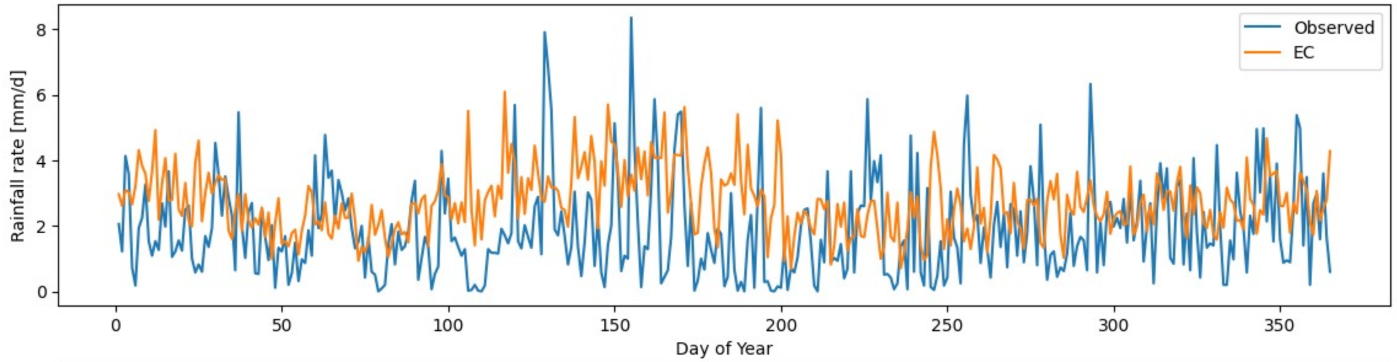
$$h_l < 0 \rightarrow Q = 0 : Level\ below\ sill$$

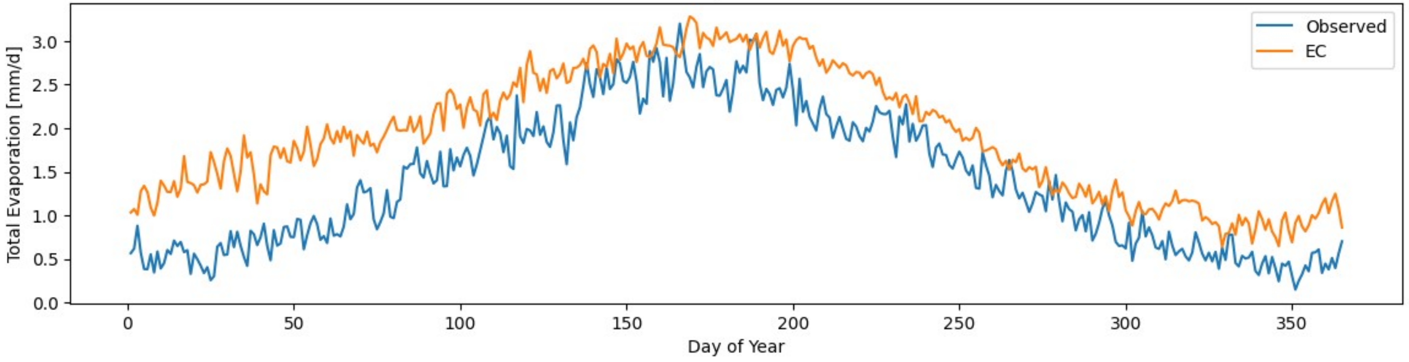
$$h_l \geq h_l \rightarrow Q > O : Level\ above\ sill$$

This model is simple enough but still relevant for a climate change impact study !

Evaluating the climate models for the Plateau

- Students are provided with CORDEX output for 3 model pairs. Each group chooses one.
- The students then evaluate the chosen model using the SIRTA observations.





The students should recognise that all models capture the main features of the local climate.

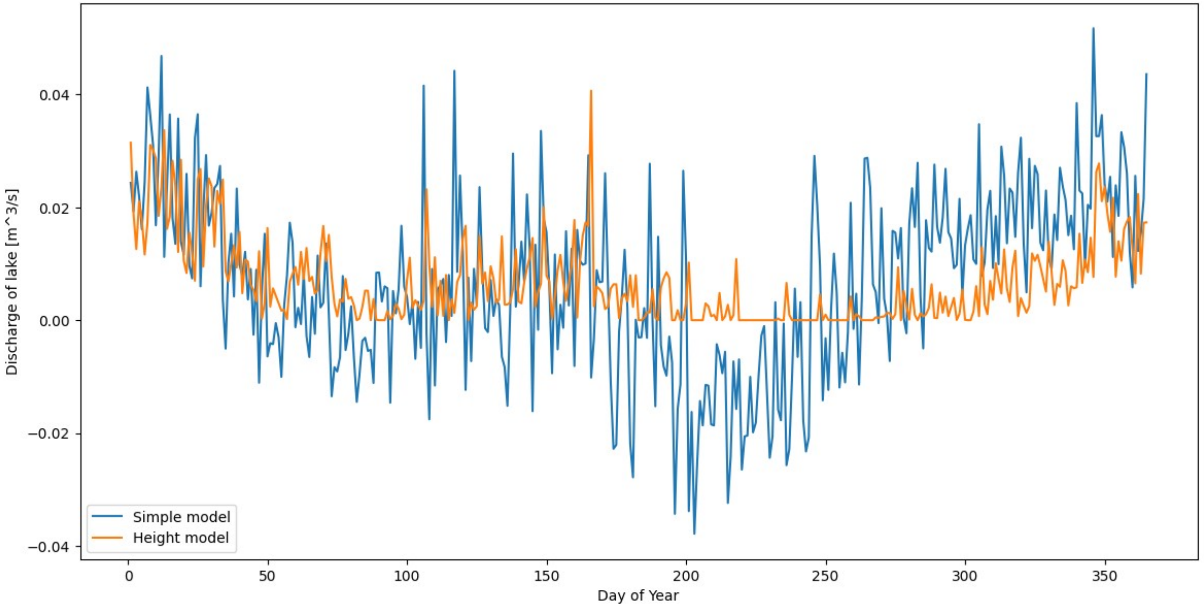
Still there are biases which need to be taken into account.

As these variables are inputs to the lake models, the biases will impact the predictions for lake level.

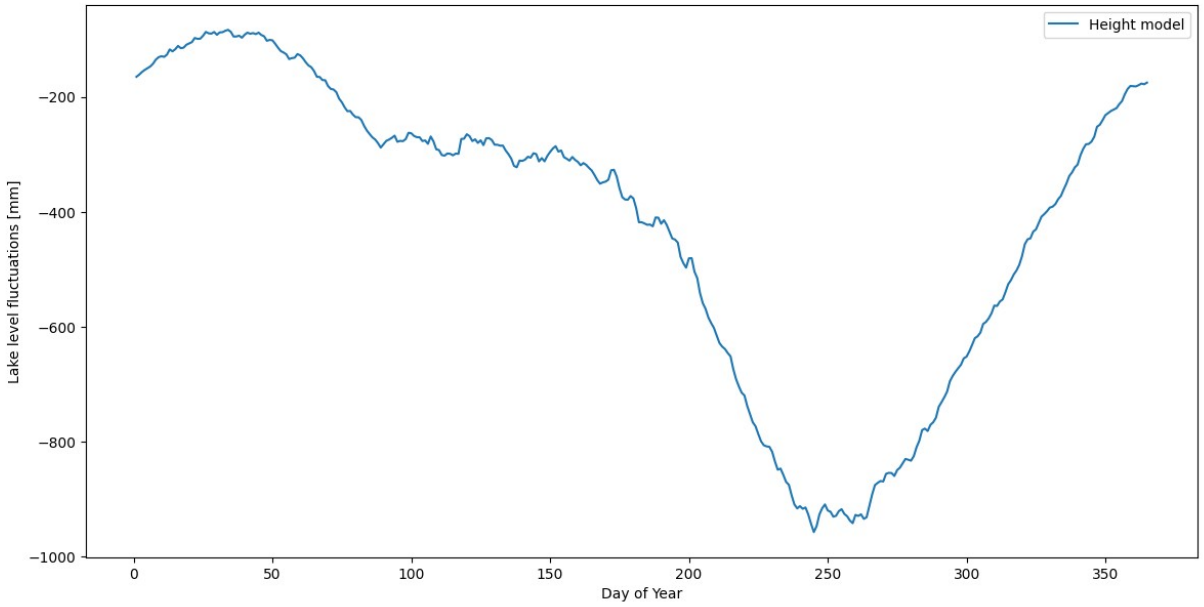
Bias correction methods are discussed.

Evaluating the climatology of the lake model

Simulated discharge [m³/s]

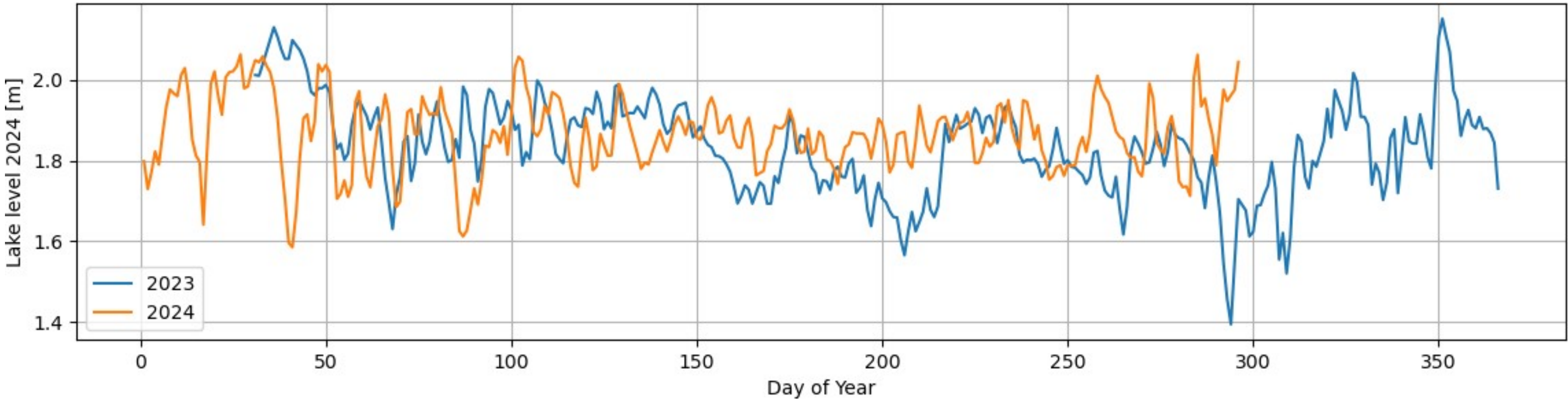


Lake level [mm]



Observed maximum outflow over the sill : 0.007 m^3/s

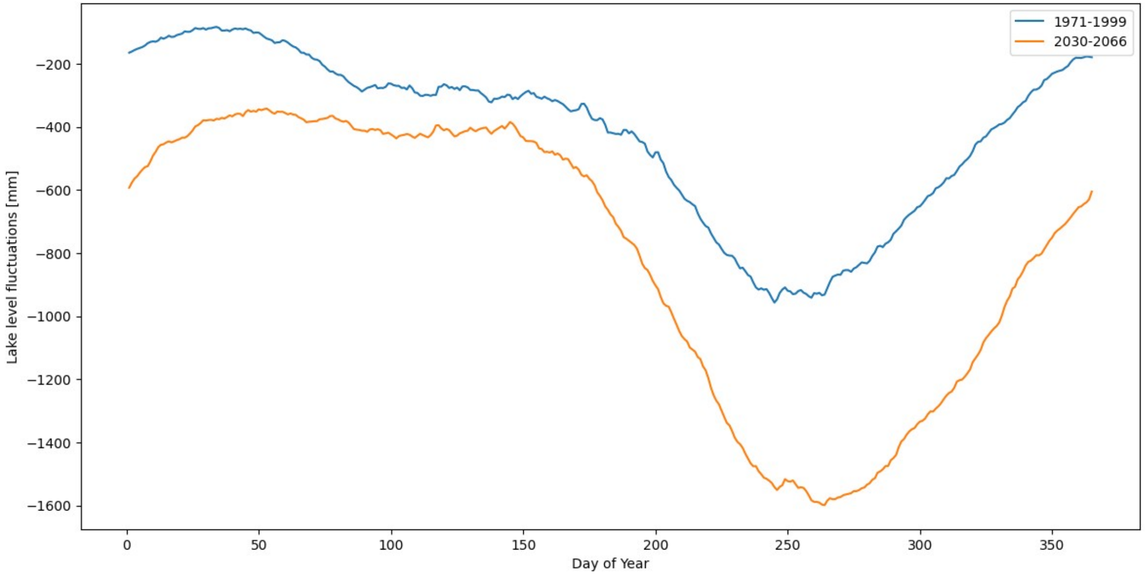
Observed lake levels [m]



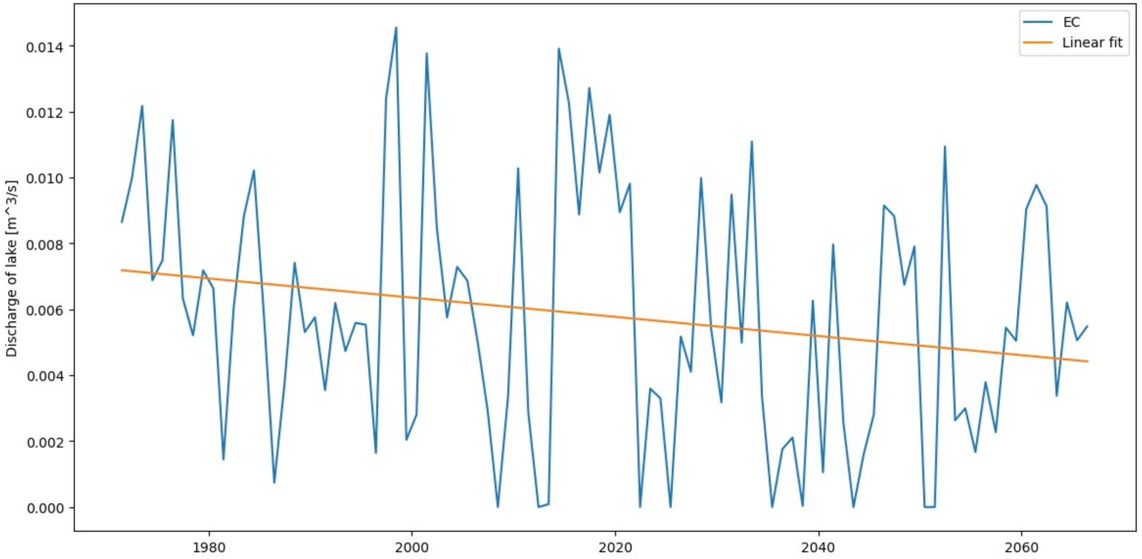
Exploring the evolution of the lake under climate change

- The students are also provided with the CORDEX output for the future projections (RCP 4.5).
- The lake model can thus be run over the period 1970 to 2100

Changes in Lake level [mm]



Simulated trend in discharge [m³/s]



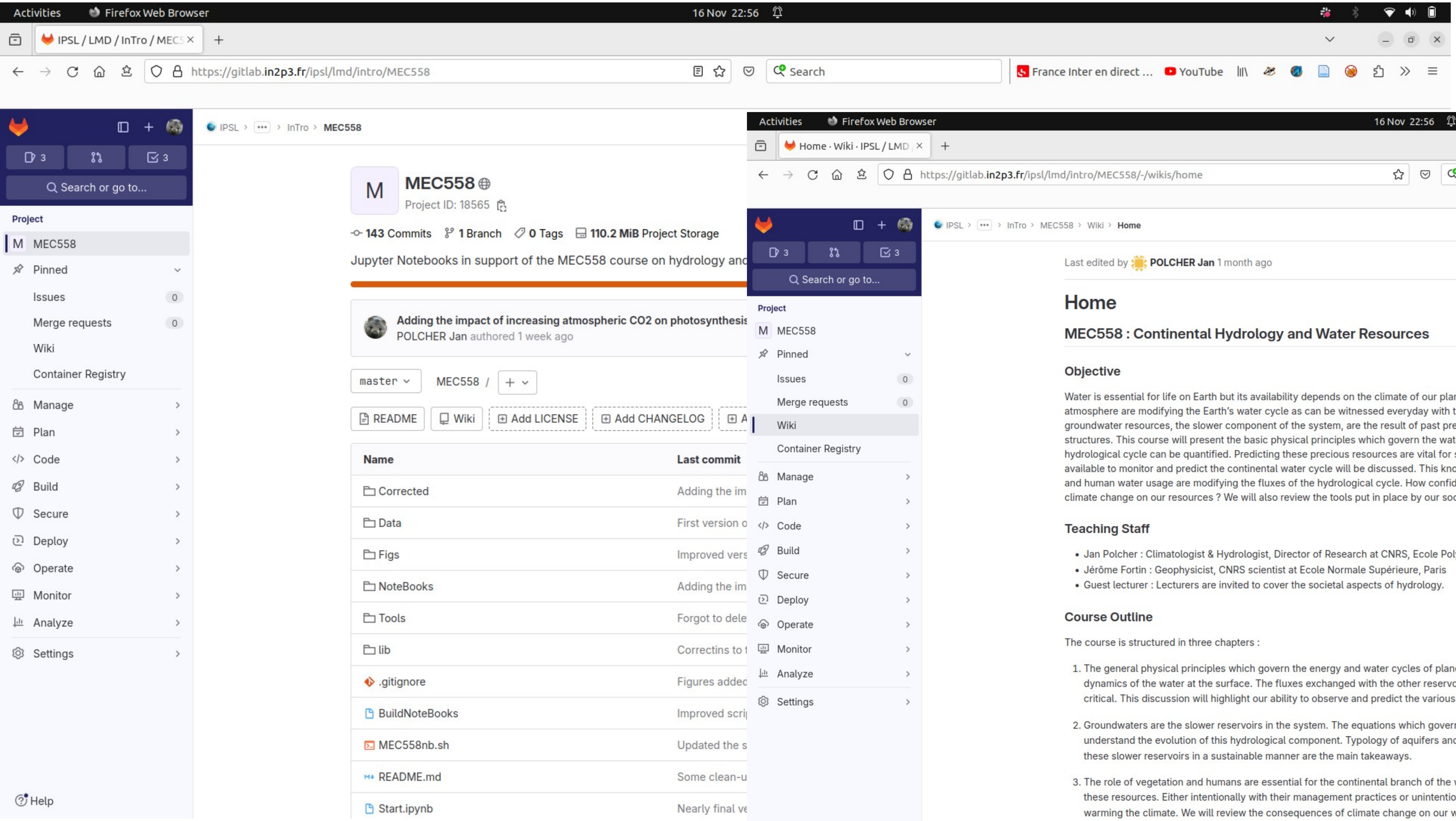
The rest of the notebook then analyses the origin of these changes of the lake (essentially PE increase !) and verifies that it is consistent with our physical understanding for the three models.

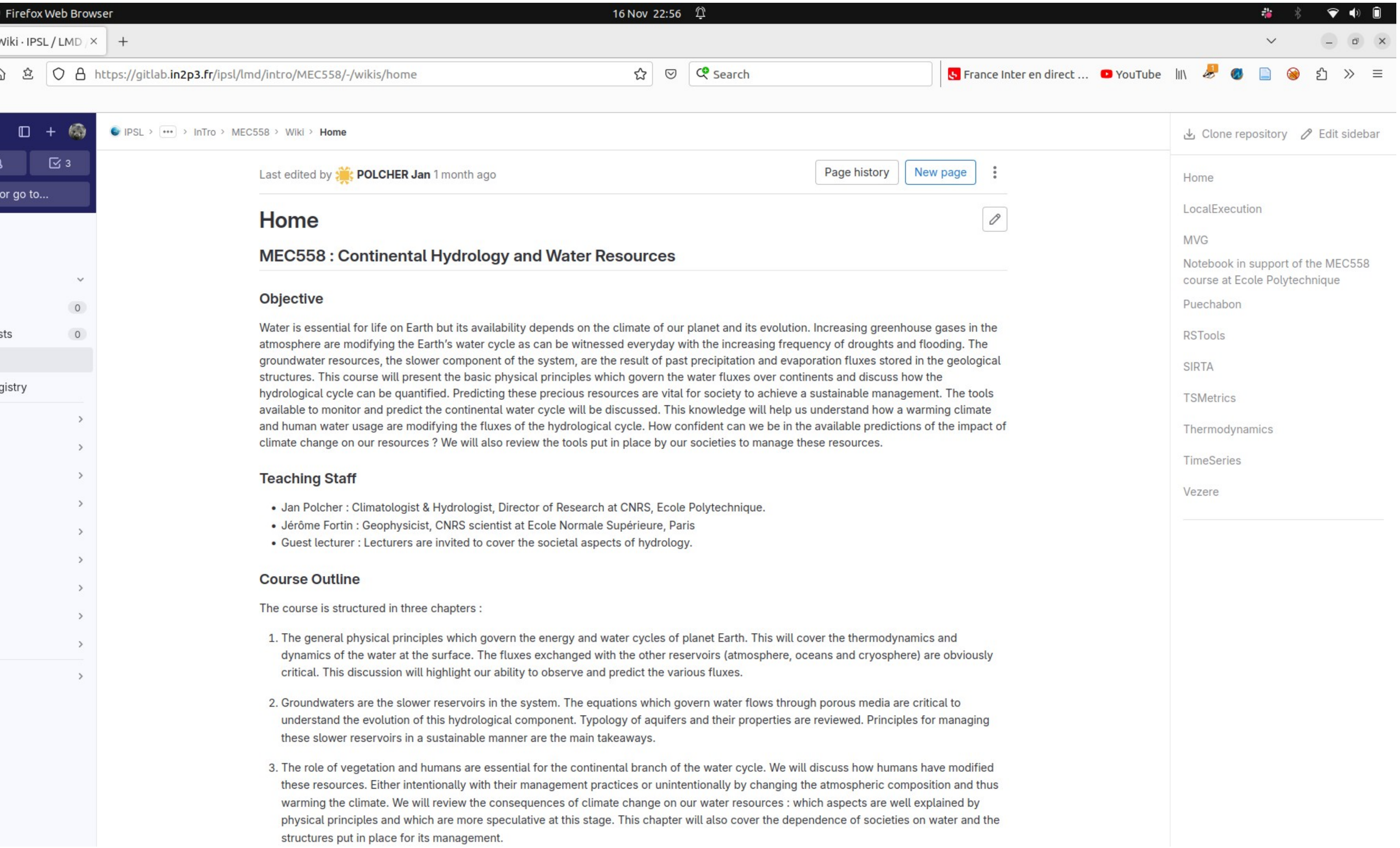
Practical aspects

- Developments occurs on the “corrected notebooks”. They are also distributed to the students.
- The notebook to be completed by the students are generated automatically by removing the answers.
- In principle the notebooks can be executed on any laptop. The needed datasets should be download. A script is provided for this task.
- The virtual machine (used on JupyterHub) which includes the notebooks also contains the data.
- Each time a virtual machine is started, the latest version of the notebooks is downloaded from the gitlab server.
- The students can use the notebooks at any moment : Obviously during the practical exercises but also at home while preparing exams.

Freely available code and on-line documentation

https://gitlab.in2p3.fr/ipsl/lmd/intro/MEC558/





Some thoughts on pedagogy

- Each student can look at different data (day or year). The differences in results can be discussed with all students.
- Looking at the data and evaluating the orders of magnitude of the fluxes (in all cases units are given !) is important.
- Showing the limitations of the theory seems to be appreciated.
- The students like to see the code first before executing it.
- The students are mostly coding the plots. In the end, it is the teacher who does it on his laptop … this method needs to be re-examined !
- The equations to be solved are generally simple. The students could prepare them while the teacher codes the figures.
- The students have just learned the theory during the morning lecture. It is difficult for them to apply it directly.

Conclusions

- The notebooks allow the students to confront the theory learned in the lecture hall with actual observations on campus.
- In particular it allows to get a better grasp of complex variables like evaporation.
- It requires basic Python knowledge to compute the diagnostics and plot the results.
- It is also an opportunity to demonstrate how climate change impact should be done.
- Many more dataset and observations could be distributed to the students through this method.
- In principle they could explore the content of the course by themselves with the notebooks. So it could support a “learn by doing” approach.