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Integration of Climate Data in the SAVi Irrigation Model

C3S_428h_IISD-EU: Sustainable Asset Valuation (SAVi): Demonstrating the Business Case for Climate-Resilient and Sustainable Infrastructure

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1 About this Report

This report outlines the integration of authoritative Copernicus Climate Data from the Climate Data Store (CDS) into a Sustainable Asset Valuation (SAVi). It describes how several climate indicators obtained from the CDS were integrated into the SAVi Irrigation model and how the analysis performed by SAVi has improved as a result. In light of this integration, IISD is able to generate sophisticated SAVi-derived analyses on the costs of climate-related risks and climate-related externalities.

The integration of Copernicus Climate Data into other SAVi models for energy, roads, wastewater treatment infrastructure, buildings, and nature-based infrastructure can be found here.

This document presents:

- A summary of the literature review on the impact of climate on irrigation infrastructure, including equations that link climate variables to the economic performance of irrigation projects.
- How the above information was used to select relevant indicators from the Copernicus database.
- How outputs of the CDS datasets are integrated into the SAVi System Dynamics (SD) Irrigation model.
- How simulation results can be affected by these new and improved set of indicators.

This report is organized as follows.

Literature review

The literature review contains the following subsections for each of the climate variables discussed for irrigation infrastructure:

- Subsection 1: An overview of climate impacts on the asset (e.g., how precipitation affects irrigation infrastructure).
- Subsection 2: A presentation of papers/reports that provide case studies that summarize the range of impacts estimated or observed (e.g., across countries).
- Subsection 3: A description of the methodology found in the literature for the calculation of climate impacts on the infrastructure asset.
- Subsection 4: A selection of CDS datasets required by the equations.

Integration of the Literature Review with the CDS Dataset

This section summarizes information on what datasets are being used from the Copernicus database and what additional processing was applied before integration into the SAVi Irrigation model. We first review the equations to determine their usefulness for SAVi models. We then assess what data requirements for each of the equations are available in the Copernicus database and create indicators for climate variables that are relevant for the equations selected. Finally, in certain cases, we create indicators in the CDS Toolbox for first-order impacts on infrastructure. Second- and third-order impacts will be estimated with SAVi, making use of additional equations included in the SD model.

Integration of Climate Indicators Into the SAVi Irrigation Model

This section explains how the CDS indicators are used in the SAVi SD model for irrigation infrastructure. It includes an identification of specific performance indicators for each asset impacted by climate indicators (e.g., efficiency and cost).

Behavioural Impacts Resulting From the Integration of Climate Variables

This sections discusses how climate variables affect asset performance in the SD model, providing early insights as to how the results of the SAVi analysis may change when equipping the model with more and better refined climate indicators (e.g., with the cost of infrastructure being higher due to increased maintenance, the economic viability of the infrastructure asset, expressed as the Internal Rate of Return [IRR], will be lower than expected).

Simulation Results

The final section of this paper presents the equations used and quantitative results emerging from the inclusion of climate indicators in the SAVi Irrigation model under various climate scenarios. This is the end product of the enhanced SAVi model, which is used to inform policy and investment decisions for infrastructure. Table 1 provides an overview of climate drivers, impacts, and relevant SAVi output indicators.

The CDS datasets are accessed via the CDS application programming interface (API), and additional processing and packaging for use in SAVi is done offline. Technical information about the offline code is found in Annex I. We also selected a subset of the most-used indicators and created an app in the CDS Toolbox with interactive visualization for demonstration purposes.

Table 1. Overview of variables and impacts implemented in the SAVi Irrigation model

SAVi module	Implemented impact	Main climate drivers	Affected output indicators
Irrigation	Seasonal precipitation	• Precipitation	• Irrigation water requirements • Crop water supply • Average crop yields

SAVi module	Implemented impact	Main climate drivers	Affected output indicators
	Average precipitation	• Precipitation	• Irrigation water requirements • Crop water supply • Average crop yields
	Seasonal temperature	• Temperature	• Irrigation water requirements • Crop water supply • Average crop yields
	Average temperature	• Temperature	• Irrigation water requirements • Crop water supply • Average crop yields
	Net irrigation requirements per hectare	• Precipitation	• Water cost for irrigation • Average crop yields
	Total irrigation requirements per hectare	• Precipitation	• Total annual irrigation requirements • Water cost for irrigation
	Indicated surface water supply	• Precipitation • Temperature	• Annual water supply from surface water sources • Quantity of water available for irrigation from surface water • Water stress • Water balance
	Indicated groundwater supply	• Precipitation • Temperature	• Annual water supply from surface water sources • Quantity of water available for irrigation from surface water • Water stress • Water balance

2 Irrigation

2.1 Literature review

2.1.1 Demand for irrigation

Crop efficiency, or land productivity, depends on soil quality, climate and human inputs. Climate considers precipitation, evapotranspiration, moisture, and more. Water availability is critical for agriculture production, but its relevance changes depending on the type of crop considered. This is due to varying degrees of resilience to water scarcity, as well as to different growing cycles.

There is an optimal amount of water required for each crop. To realize the maximum yield potential, the water that is not made available by precipitation has to be provided by irrigation infrastructure. Weather can also impact the irrigation system regarding different water pumping technologies such as photovoltaic, diesel motors or grid efficiency.

2.1.1.1 Water and irrigation requirement

- **Climate impact**

Precipitation influences the amount of water a crop has at his disposal (this is called rainfed agriculture in the absence of irrigation infrastructure). In the case of water shortages, a crop either grows less or doesn't grow at all.

- **Summary of results**

Yield decrease relative to changes in air temperatures depends on type of field, location, and several ecological indicators.
We found that for each 1˚C increase in temperature, the impact on [Wheat; Rice; Maize; Soybean; Barley] would be a decrease in yield of [-6.0 ± 2.9% per °C increase in temperature and -50 to 100% under RCP 2.6-8.5; -3.2 ± 3.7%; −7.4 to -4 ± 4.5%; -3.1%; -50 to 100% under RCP 2.6-8.5] respectively.
In a specific study for maize, the crop water use efficiency was 1.53 kg/m^3 and the irrigation or field water use efficiency was 1.74 kg/m^3. Crop water use efficiency is the yield of the crop per unit of water lost through evapotranspiration of the crop. In contrast, field water use efficiency is the ratio of yield of the crop to total amount of water used in the field. So, the difference between the two indicators is that the field water use efficiency considers water losses, while the crop water use efficiency only considers the water directly used by the plant.
For Winter Wheat/Barley and fodder Maize, under RCP 2.6 and RCP 8.5, the irrigation water requirement will increase by 38-79% and 0.7-4.1% respectively.
For the irrigation system, using solar PV for water pumping, from an optimal threshold of 28˚C, for each 1˚C increase in temperature, there will be a decrease of 0.45% in efficiency.
For more information, Figure 26; Figure 27 and Figure 28 clearly display those results.

- **Results**

Impact of temperature increases on crop yields (Zhao, et al., 2017):
Zhao et al. (2017) investigated the impacts of temperature on yields of four crops by compiling extensive published results from four analytical methods: global grid-based and local point-based models, statistical regressions, and field-warming experiments. The four crops analyzed are wheat, rice, maize and soybean, which are the most important crops for global food supply. The results from the four different methods demonstrated negative temperature impacts on global crop yields (effects without CO_2 fertilization, effective adaptation, and genetic improvement): each degree-Celsius increase in global mean temperature would, on average, reduce global yields of

- Wheat by 6.0%,
- Rice by 3.2%,
- Maize by 7.4%,
- Soybean by 3.1%.

The results are heterogeneous across crops and geographical areas, sometimes increasing temperatures even have positive impacts. Projected changes in yield due to temperature changes by the end of the 21st century are showed in Figure 26. (CIs of 95% are given in square brackets).

Figure 1 - Projected changes in yield due to changes in temperature

	Yield changes (%) due to temperature changes by the end of century				
Scenario	Wheat	Rice	Maize	Soybean	Mean
RCP2.6	-6.9 [-15.0, -1.4]	-3.3 [-9.2, 0.8]	-8.6 [-18.6, -1.8]	-3.6 [-11.2,1.7]	-5.6 [-14.4, -0.1]
RCP4.5	-11.4 [-21.7, -3.9]	-5.5 [-13.8, 1.0]	-14.2 [-27.9, -4.9]	-5.9 [-17.0, 3.1]	-9.2 [-21.2, -0.3]
RCP6.0	-14.0 [-25.7, -5.1]	-6.8 [-16.8, 1.3]	-17.4 [-33.1, -5.8]	-7.2 [-20.2, 3.6]	-11.3 [-25.6, 0.1]
RCP8.5	-22.4 [-40.2, -8.5]	-10.8 [-25.3, 2.4]	-27.8 [-50.4, -9.7]	-11.6 [-31.0, 6.0]	-18.2 [-38.6, -0.7]

A limitation of Zhao et al. (2017) is that it is based on the assumption that yield responses to temperature increase are linear, while yield response differs depending on growing season temperature levels.

According to Zhao et al. (2017), the impacts of increasing temperatures differ considerably for the four crops modeled. Impacts also differ in the crop's main producer countries.
The yield lost for each °C increase is largest for maize: −7.4 ± 4.5% per °C. This impact varies in the four largest maize producer countries: United States (−10.3 ± 5.4% per °C), China (−8.0 ± 6.1% per °C), Brazil (−5.5 ± 4.5% per °C), and India (−5.2 ± 4.5% per ° C).

For wheat, yields are modeled to decrease by 6.0 ± 2.9% per °C increase in temperature. Impacts are spatially very heterogeneous: United States (−5.5 ± 4.4% per °C), France (−6.0 ± 4.2% per °C), India (−9.1 ± 5.4% per °C), Russia (−7.8 ± 6.3% per °C), and China (-2.6 ± 3.1% per °C).
The impact of temperature increases on rice is smaller than for maize or wheat. Yields might decrease by 3.2 ± 3.7% per °C. We see a large impact in India (−6.6 ± 3.8% per °C).
The impact of rising temperatures on soybean yields (-3.1% per °C) is not statistically significant due to large uncertainties in each method. Impacts in Brazil, Argentina, and Paraguay might be similar to the -3.1% per °C. The largest reduction is in the United States (−6.8 ± 7.1% per °C).

Water use efficiency (Djaman, et al., 2018):
In the southwest of the United States, Djaman et al. (2018) assessed crop water use for water management and planning under conservation agriculture. Precisely, they assessed maize water use and water productivity under full irrigation from 2011-2014 and 2017, in the Four Corners region of New Mexico. The result was that:

- Maize crop water use efficiency ranged from 1.3 to 1.9 kg/m3 and averaged 1.53 kg/m3.
- Evapotranspiration water use efficiency values were higher than crop water use efficiency and varied from 2.0 to 2.3 kg/m3, averaging 2.1 kg/m3

Maize irrigation water use efficiency varied with years and averaged 1.74 kg/m3

Yield depending on available water (Mirgol, Nazari, & Eteghadipour, 2020):
The study investigated the impact of climate change on the future irrigation water requirement (IR) and yield of three crops: winter wheat, barley, and fodder maize. The study analyzed these impacts specifically for the semi-arid Qazvin Plateau in Iran for the periods 2016–2040, 2041–2065, and 2066–2090. For the projection of the monthly minimum and maximum temperature as well as the regional monthly precipitation, Mirgol et al. used the Canadian Earth System Model (CanESM2) and applied the IPCC scenarios RCP2.6, RCP4.5, and RCP8.5

They found out that the precipitation will decrease (1%–13%) under all scenarios in all months of the future periods, (except in August, September, and October).
The irrigation water requirement of winter wheat and barley will increase by 38%–79% (scenarios rcp2.6 and rcp8.5). The increase in the IR of fodder maize will be very slight (0.7%–4.1%). For more details on the irrigation water requirements see Figure 27.
The yield of winter wheat and barley will decrease by ~50%–100% (scenarios rcp2.6 and rcp8.5). The reduction in the yield of maize will be about 4%. For details on the yield see Figure 28.

Figure 2 Change of irrigation water requirements

Table 6. Change values of the irrigation water requirement (IR) of winter wheat under scenarios rcp2.6 and rcp8.5 for periods 2016–2040, 2041–2065, and 2066–2090 versus the baseline period.

Scenario	Periods	Feb	Mar	Apr	May	Jun	Total (%)
rcp2.6	2016–2040 vs. observed	635	50.5	37.9	29.4	21.2	38
rcp2.6	2041–2065 vs. observed	895	96.1	42.4	43.8	32.9	55
rcp2.6	2066–2090 vs. observed	1300	127.9	59.7	48.7	34.9	69
rcp8.5	2016–2040 vs. observed	625	72.4	37.4	32.8	20.8	42
rcp8.5	2041–2065 vs. observed	1025	103.9	46.8	48.5	36.6	60
rcp8.5	2066–2090 vs. observed	1180	139.3	61.1	64.4	41.6	79

Figure 3 Change of yields

Table 9. Results of the change percentage of the crops under scenarios rcp2.6 and rcp8.5 in periods 2016–2040, 2041–2065, and 2066–2090 versus the baseline period in the Qazvin Plateau.

Scenario		Winter Wheat	Barley	Fodder Maize
rcp2.6	%(2016–2040) vs. obs	−58.24	−48.48	−3.20
	%(2041–2065) vs. obs	−75.10	−65.78	−1.47
	%(2066–2090) vs. obs	−89.86	−80.72	1.99
rcp8.5	%(2016–2040) vs. obs	−62.86	−53.21	0.18
	%(2041–2065) vs. obs	−80.69	−71.57	−3.22
	%(2066–2090) vs. obs	−99.02	−89.92	−6.70

Solar-Powered Irrigation Systems (Schnetzer & Pluschke, 2017):
Air temperature has an influence on SPIS systems. (optimum performance of PV panels around 28°C average with a decrease in efficiency of 0.45 percent for every degree above optimum temperature as rule of thumb) and the depth of the water source relative to the altitude where the water is utilized (pumping head; typically up to 70 m, but greater heads are technically feasible). They also report from 3 different references: (Ould-Amrouche, Rekioua, & Hamidat, 2010); (GIZ, 2016); (Parliamentary Office of Science and Technology (POST), 2011): The emissions of CO^2 for solar, diesel and grid efficiency:

Figure 4 – CO^2 emissions from 3 different technologies.

	Unit	Solar PV	Grid electricity	Diesel
GIZ 2016	g CO^2-eq/kWh	16-32	600	1000
POST 2011	g CO^2-eq/kWh	75-116	488-990	-
Ould-Amrouche et al. 2010	g CO^2/m^3	0	-	480-2230

- **Methodology**

1. Irrigation water requirement

$$NWA = PR + DP + Ro - Pe / Eff$$

Whereby:
NWA = Net Water Available in mm per month
PR = pre-irrigation, soil moisture change between t0 and t-1 in mm per month
DP = Deep percolation in mm per month
Ro = Runoff in mm per month
Pe = monthly precipitation in mm per month
Eff = efficiency of the center pivot installed within the field

2. Crop yield depending on irrigation water requirement changes (Mirgol, Nazari, & Eteghadipour, 2020)

They used the Stewart model to estimate the effect of irrigation water requirement changes on the yield of the crops:

$$1 - \frac{Y_a}{Y_m} = K_y\left(1 - \frac{ET_a}{ET_m}\right)$$

Where Y_a is the actual yield (ton ha^{-1}), Y_m is the maximum yield (ton ha^{-1}), ET_a is the actual evapotranspiration (mm d-1), ET_m is the maximum evapotranspiration, and K_y is the coefficient of the reaction of crop yield to water stress. See Figure 30 for Y_m and K_y. Higher K_y numbers indicate higher sensitivity to water stress. See more in another article of the FAO (1979).

Figure 5 Maxiumum yield and reaction coefficient

Table 4. Total cultivation area, maximum yield (Y_m), and the coefficient of the reaction of crop yield to water stress (K_y) for winter wheat, barley, and fodder maize in the Qazvin Plateau (Najarchi et al., 2011).

Crop	Total Cultivated Area (ha)	Y_m (ton ha^{-1})	K_y
Winter wheat	66000	6	1.2
Barley	36358	4.7	1.1
Fodder maize	28621	10	1.5

Higher K_y numbers indicate higher sensitivity of the crop to water stress.

3. Estimation of the water pumping energy demand (Ould-Amrouche, Rekioua, & Hamidat, 2010)

The peak power of the PV generator is given by:

$$P_{pv} = E_{pv}\frac{G}{E_s}$$

Where G is the peak solar radiation intensity (1 kW/m^{2}), E_s is the annual average of solar radiation on a horizontal surface (5.5 kW h/ m^2 day).

4. Pumping water energy cost calculator (Engineering ToolBox, 2009):

The energy cost per hour for pumping water can be calculated in imperial units as

$$C = 0.746\ Q\ h\ c\ /\ (3960\ \mu_p\ \mu_m) \qquad (1)$$

where

C = cost per hour (USD/hour, EUR/hour, ...)

Q = volume flow (US gpm)

h = differential head (ft)

c = cost rate per kWh (USD/kWh, EUR/kWh, ...)

μ_p = pump efficiency (0 - 1)

μ_m= motor efficiency (0 - 1)

Alternative calculation in metric units

$$C = q\ \rho\ g\ h\ c\ /\ (3.6\ 10^6\ \mu_p\ \mu_m)$$

$$= q\ p\ c\ /\ (3.6\ 10^6\ \mu_p\ \mu_m) \qquad (2)$$

where

q = volume flow (m^3/h)

ρ = density (1000 kg/m^3)

h = differential head, height (m)

g = acceleration of gravity (9.81 m/s^2)

5. Solar photovoltaic water pumping (Maupoux, 2010)

Estimation of requirements for effective water pumping system from solar PV system:

i. The hydraulic energy required (kWh/day) = volume required (m³/day) x head (m) x water density x gravity / (3.6 x 106) = 0.002725 x volume (m³/day) x head (m)
ii. The solar array power required (kWp) = Hydraulic energy required (kWh/day) / Av. daily solar irradiation (kWh/m²/day x F x E)

With:

F = array mismatch factor = 0.80 on average (a safety factor for real panel performance in hot sun and after 10-20 years)

E = daily subsystem efficiency = 0.25 - 0.40 typically

Considerations for integration in the CDS toolbox

1. Water delivery from precipitation (mm / month):

Parameter in the model = total water from precipitation

$$Pmonth = (TPt - TPt\text{-}1) * 1000$$

Pmonth = monthly precipitation
TPt = total precipitation in month t
TPt-1 = total precipitation in month t-1
1000 = conversion from m to mm per month

2. Runoff (mm / month):

Parameter in the model = Runoff

$$E\ month = (Rt - Rt\text{-}1) * 1000$$

R month = monthly runoff
Rt = total runoff in month t
Rt-1 = total runoff in month t-1
1000 = conversion from m to mm per month

3. Rainfall per month (mm/month):

Parameter in the model = seasonal precipitation

$$Pmonth1 = SUM\ (precipitation\ fluxmonth1)$$

Pmonth1 = monthly precipitation in month 1 (January)
Precipitation fluxmonth1 = total rainfall in month 1 (January)

4. Long term average precipitation (mm/month):

Parameter in the model = Long term average precipitation

$$LTMPt0 = Average\ (Pmonth1\text{-}12\ over\ the\ last\ 20years)$$

LTMPt0 = long term monthly precipitation at time t

5. Rainfall per day (mm/day):

Parameter in the model = daily precipitation

$$Pday1 = SUM\ (precipitation\ fluxday1)$$

Pday1 = daily precipitation in day 1
Precipitation fluxday1 = total rainfall during day 1.

The same approach applies to all other days of the month.

6. Rainy spell

Parameter in the model = Consecutive days of rain

Consecutive days with raint0 = IF "Rainfall per day"t0 > 0,
THEN "1 + Consecutive days with raint-1", ELSE "0"

Rainfall per dayt0 = the indicated rainfall for today
Consecutive days with raint-1 = previous consecutive days with rain (if any)

Data inputs

- Soil moisture (%) - Soil moisture gridded data from 1978 to present
- Runoff (m) - ERA5-Land monthly averaged data from 1981 to present
- Precipitation (m) - ERA5-Land monthly averaged data from 1981 to present

2.1.1.2 Efficiency (evapotranspiration)

- **Climate impact**

To express which percentage of irrigation water is used efficiently and which percentage is lost, the term irrigation efficiency is used. The scheme irrigation efficiency (*e* in %) is that part of the water pumped or diverted through the scheme inlet which is used effectively by the plants (Brouwer, Prins, & Heibloem, 1989).

- **Results**

The FAO indicates that depending on the type of irrigation method surface, sprinkler, drip, field efficiency will vary from 60% to 75% and 90% respectively. (Brouwer, Prins, & Heibloem, 1989)

- **Methodology**

Method 1 (Brouwer, Prins, & Heibloem, 1989)

The scheme irrigation efficiency can be subdivided into:
1. The conveyance efficiency (ec) which represents the efficiency of water transport in canals
2. The field application efficiency (ea) which represents the efficiency of water application in the field.

NIRcrop = ETcrop / IE / WCE

NIRcrop = Net irrigation requirements in mm per hectare per month
Etcrop = Crop evapotranspiration in mm per month
IE = Irrigation efficiency in %
WCE = Water conveyance efficiency in %

Net irrigation water demand depends on the application efficiency of irrigation systems and the water conveyance efficiency. For the examples provided below (irrigation methods), WCE will be kept constant (0.9), due to a lack of information on the length of the irrigation channels.

A calculation of IE is provided:

$$e = \frac{ec \times ea}{100}$$

with

e = scheme irrigation efficiency (%)
ec = conveyance efficiency (%)
ea = field application efficiency (%)

A scheme irrigation efficiency of 50-60% is good; 40% is reasonable, while a scheme Irrigation efficiency of 20-30% is poor.

We also extracted Figure 32 and Figure 31 (Brouwer, Prins, & Heibloem, 1989):

Figure 7 Field application efficiency

Irrigation methods	Field application efficiency
Surface irrigation (border, furrow, basin)	60%
Sprinkler irrigation	75%
Drip irrigation	90%

Figure 6 Conveyance efficiency

	Earthen canals			Lined canals
Soil type	**Sand**	**Loam**	**Clay**	
Canal length				
Long (> 2000m)	60%	70%	80%	95%
Medium (200-2000m)	70%	75%	85%	95%
Short (< 200m)	80%	85%	90%	95%

<u>Method 2 </u>(Das, et al., 2018)

If the crop is more environmental friendly (organic) we can use this formula:

NIRcrop organic = NIRcrop × (irrigation system) × 0.86

Whereby:
NIRcrop organic = net irrigation requirements organic crops in mm/ha/month
NIRcrop (irrigation system) = net irrigation requirements conventional crops by for flood, sprinkler and drip irrigation in mm / ha / month
0.86 = Multiplier reducing irrigation requirements by 14%.

Considerations for integration in the CDS toolbox

Evapotranspiration (Brouwer & Heibloem, 1986):

1. The crop water need (ET crop) is defined as the depth (or amount) of water needed to meet the water loss through evapotranspiration. In other words, it is the amount of water needed by the various crops to grow optimally.

2. The crop water need and factor (Kc) depend on:

- The climate: in a sunny and hot climate crops need more water per day than in a cloudy and cool climate
- The crop type: crops like maize or sugarcane need more water than crops like millet or sorghum
- The growth stage of the crop: fully grown crops need more water than crops that have just been planted.

The influence of the climate on crop water needs is given by the reference crop evapotranspiration ETo. The ETo is usually expressed in millimeters per unit of time, e.g. mm/day, mm/month, or mm/season.

We estimate the crop water need (ET crop) in mm/day with its evapotranspiration (ETo) in mm/day and its factor (Kc):

$$ETcrop = ETo * Kc$$

Kc estimation:
Step 1 - Determination of the total growing period of each crop
Step 2 - Determination of the various growth stages of each crop
Step 3 - Determination of the Kc values for each crop for each of the growth stages

Climate adjusted Kc (Brouwer & Heibloem, 1986):

Kc climate =
Kcbase + IF u< 2: AND: RH >80% THEN "-0.05" ELSE "0" + IF u>5:
AND: RH<50% THEN "0.05"ELSE "0"

Whereby:
Kcbase = Baseline crop factor based on crop and development stage
u = wind speed (m/s)
RH = Relative humidity

"Kc values should be reduced by 0.05 if the relative humidity is high (RH > 80%) and the wind speed is low (u < 2 m/sec), e.g. Kc = 1.15 becomes Kc = 1.10. The values should be increased by

0.05 if the relative humidity is low (RH < 50%) and the wind speed is high (u > 5 m/sec), e.g. Kc = 1.05 becomes Kc = 1.10."

Climate adjusted Kc (includes plant height) (Djaman, et al., 2018)

$$\text{Kc Stage} = \text{KcStage} + [0.04(u_2 - 2) - 0.004(\text{RHmin} - 45)]\left(\frac{h}{3}\right)^{0.3}$$

KcStage is the standard value according to FAO-56 approach (Allen, Pereira, Raes, & Smith, 2006)
U_2 is the value for daily wind speed at 2 m height over grass during the growth stage (m/s)
RHmin is the value for daily minimum relative humidity during the growth stage (%)
H is the Plant height for each growth stage (m) (0.1 m–10 m)

Increased evapotranspiration due to temperature (dimensionless) (Kosa, 2011)

Parameter in the model = Effect of temperature on evapotranspiration

$$Eto = -0.028x^2 + 1.7608x - 22.932$$

Eto = Actual daily evapotranspiration
x = daily temperature in °C

This model is based on Kosa (2011) and has a R^2 value of 0.987, which could be used to establish a multiplier for evapotranspiration based on a set point (say 17°C).

Data required:

- Evapotranspiration (m of water equivalent): ERA5-Land monthly averaged data from 1981 to present
- Wind speed (m/s): ERA5 monthly averaged data on single levels from 1979 to present
- Humidity (%):ERA5 monthly averaged data on pressure levels from 1979 to present
- Evapotranspiration (m of water equivalent): ERA5-Land monthly averaged data from 1981 to present

2.2 Integration of literature review with the CDS datasets

See general instructions in the energy section.

Datasets:

- ERA5 monthly data on single level
- CMIP5 monthly data on single level
- ERA5 daily data on single level

Indicators created:

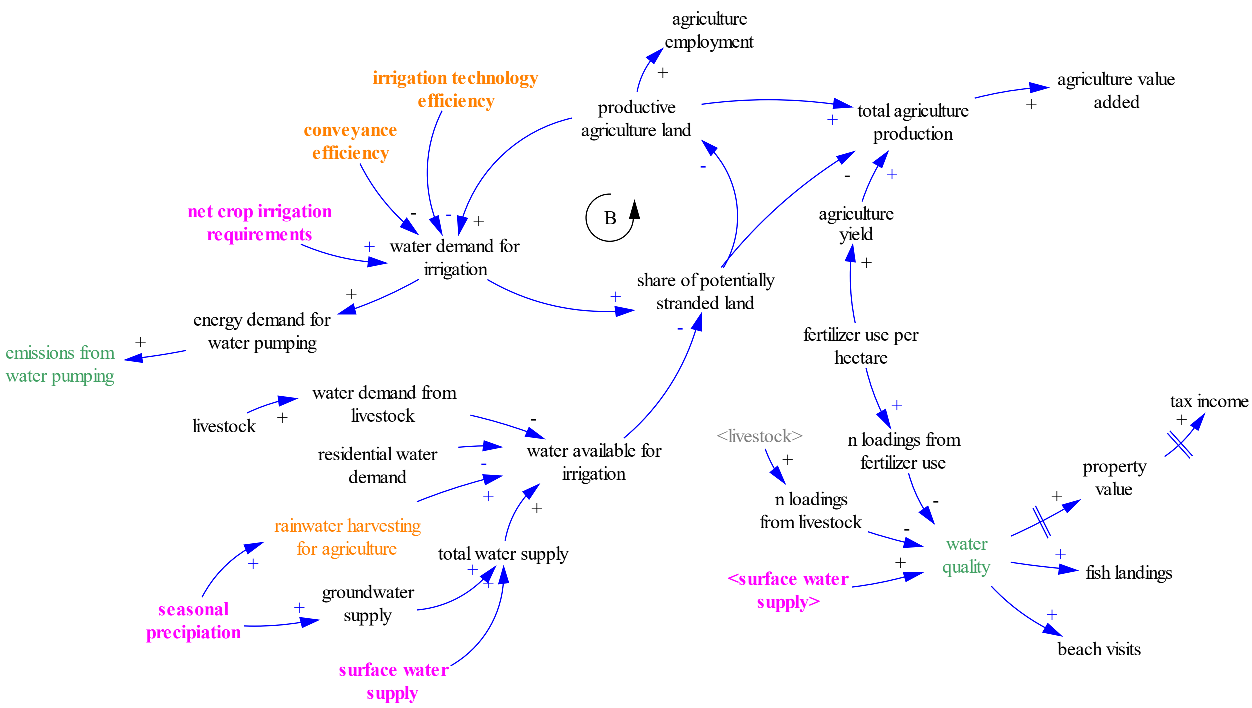
- **Precipitation**:
  - Units: mm per month
  - Frequency: monthly
  - ERA5 variable: “Mean total precipitation rate”
  - CMIP5 variable: “Mean precipitation flux“
  - Note different: original units in mm/s
- **Evaporation**
  - Units: mm per month
  - Frequency: monthly
  - ERA5 variable: “Mean evaporation rate”
  - CMIP5 variable: “Evaporation“
  - Note different: original units in mm/s, sign convention in ERA5 adjusted to CMIP5 convention (positive)
- **Runoff**
  - Units: mm per month
  - Frequency: monthly
  - ERA5 variable: “Mean runoff rate”
  - CMIP5 variable: “Runoff“
  - Note different: original units in mm/s
- **Air temperature**
  - Units: degrees Celsius
  - Frequency: monthly
  - ERA5 variable: “2 m temperature”
  - CMIP5 variable: “2 m temperature“
  - Note different: original units in Kelvin
- **Relative humidity**
  - Units: %
  - Frequency: monthly
  - ERA5 variable: calculated from “2 m temperature” and “2 m dewpoint temperature”
  - CMIP5 variable: near_surface_relative_humidity“
  - Note: see energy asset for more information
- **Daily maximum temperature**
  - Units: degrees C
  - Frequency: monthly
  - ERA5 variable: “2m_temperature” aggregated from hourly data
  - CMIP5 variable: near_surface_relative_humidity“
  - Note: optional asset (implemented by not added by default to the asset bundle because it takes a long time to calculate)

More detailed information about precipitation variable in ERA5/CMIP5 can be found in the road asset (“road runoff”).

2.3 Integration of climate indicators into the SAVi irrigation model

Figure 33 shows the CLD of the SAVi Irrigation model including indicators developed for the CDS toolbox (highlighted in pink). CDS toolbox climate indicators related to irrigation include seasonal precipitation (including extreme events), net crop water requirements, and available surface water supply.

Figure 8 Causal Loop Diagram for the irrigation sector - CDS variables included



The CDS indicator seasonal precipitation refers to the precipitation per month in a given geographical context. Data on seasonal precipitation obtained from the CDS toolbox will hence provide location-specific information concerning total rainfall and extreme weather events, such as floods or droughts. Further, data will be available with monthly time steps, allowing to estimate changes in the rainy season where relevant, and related impacts on the growing season and suitability of crops.

Net irrigation requirements in the CDS toolbox provide information about the amount of water required for irrigation to ensure maximum yields. This parameter accounts for crop water requirements, precipitation and evaporation and hence provides net irrigation requirements per hectare, depending on the type of crop. It will support the assessment of required investments in irrigation.

Available surface water supply depends on total rainfall, evaporation and groundwater recharge, all of which are obtained from the CDS database. In the SAVi model, available water supply from surface water is used to calculate the water supply and demand balance and to analyze potential conflicting uses for water (e.g. potable use versus irrigation).

2.4 Behavioral impacts resulting from the integration of climate variables

The use of the seasonal precipitation indicator obtained from the CDS replaces the less dynamic formulation concerning precipitation in the SAVi model with location-specific information. This supports assessing irrigation requirements by providing more accurate data on precipitation, both historical and future, and by allowing to generate forecasts using a variety of climate scenarios. Precipitation will affect crop productivity, with and without irrigation, production and revenues, and hence will determine the economic viability of agriculture production.

Obtaining net irrigation requirements from the CDS toolbox leads to improved forecasts or total irrigation requirements and potential future water shortages on a monthly or seasonal basis. This will impact the total water used for irrigation, irrigation-related energy use and total irrigation cost (total capacity requirement, related capital and O&M cost, and employment creation). Further, the implementation of this indicator into the CDS toolbox allows to replace existing variables and equations in the SAVi model, making projections more accurate.

The estimation of surface water supply allows for a system-wide analysis of water scarcity impacts, going beyond irrigation. It will inform whether a reduction in agriculture land will emerge, because of lower yields, leading to loss of employment. The use of this CDS indicator in the SAVi model will affect water availability for potable, industrial and agricultural use and affect water available for irrigation, depending on water resource allocation.

2.5 Simulation results

Required irrigation and related water use are heavily dependent on climate variables such as precipitation and temperature. Four indicators were developed for the integration of climate variables from the CDS database into SAVi Irrigation: (1) irrigation requirements per hectare, (2) total irrigation requirements per hectare (including water conveyance loss), (3) indicated surface water supply, and (4) indicated groundwater supply.

2.5.1 Net and total irrigation requirements

In the SAVi model, irrigation requirements refer to the amount of water that is required for irrigation accounting for evaporation and precipitation. Total irrigation requirements refer to the total amount of water required per hectare considering the efficiency of water conveyance infrastructure and installed irrigation systems. Both formulations use monthly precipitation and monthly crop water requirements to estimate the water required for irrigation. The equation used for net irrigation requirements is based on the crop water requirements indicated in Table 10.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
120	60	0	0	0	0	0	80	120	120	120	120

Table 2: Indicated crop water requirements per month, in mm per hectare

The equation used for calculating the irrigation requirements per crop uses the indicated crop water requirements and an evaporation fraction based on local data (e.g. 45%).

*Net irrigation requirements per hectare = MAX(0, Indicated crop water requirement per hectare – (monthly precipitation * (1 – Evaporation fraction)))*

The MAX function is applied to prevent net irrigation requirements from taking negative values in case that monthly precipitation exceeds the required crop water supply. The risk of floods is analysed separately.

The total amount of water needed to irrigate crops depends, in addition to rainfall and evaporation, on the efficiency of water conveyance infrastructure and the efficiency of irrigation technologies. To obtain the total irrigation requirements per hectare (or water demand for irrigation), an average irrigation efficiency multiplier of 50% (assuming flood irrigation) and an average water conveyance efficiency of 95% are applied to the net irrigation water demand per hectare. The equation used is documented below

Total irrigation requirements per hectare = Net irrigation requirements per hectare / Efficiency of irrigation technology / Efficiency of water conveyance infrastructure

The results for net irrigation requirements per hectare are presented in monthly averages per decade and based on the IPSL RCP8.5 scenario. The results for the average net irrigation required per month for maize is presented in Table 11 for each decade from 1980-1990 to 2090-2100.

Decade	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**	*relative to 1980-1990*
1980-1990	33.2	14.7	0.0	0.0	0.0	0.0	0.0	72.7	103.8	62.5	51.5	44.5	**382.8**	
1990-2000	56.2	17.9	0.0	0.0	0.0	0.0	0.0	71.1	100.0	59.4	51.3	44.7	**400.6**	*4.6%*
2010-2020	48.8	14.7	0.0	0.0	0.0	0.0	0.0	72.1	105.5	81.4	61.4	60.6	**444.5**	*16.1%*
2040-2050	55.9	10.5	0.0	0.0	0.0	0.0	0.0	71.1	105.8	80.9	59.8	50.2	**434.2**	*13.4%*
2070-2080	54.9	17.8	0.0	0.0	0.0	0.0	0.0	77.3	104.5	74.8	60.8	48.5	**438.5**	*14.6%*
2090-2100	65.7	32.3	0.0	0.0	0.0	0.0	0.0	77.8	103.1	77.8	56.4	57.7	**470.8**	*23.0%*

Table 3: Net irrigation requirements, monthly averages per decade

The results in Table 11 indicate a relative increase of 4.6% between the decades 1980-1990 and 1990-2000. By 2090-2100, the net irrigation requirements per hectare are projected to increase by 23% compared to 1980-1990 driven by the decline in precipitation. The absolute increase between 1980-1990 and 2090-2100 is 88 mm per year, which is equivalent to 880,000 litres per hectare per year in additional water requirements. Figure 34 below illustrates the development of net irrigation requirements per hectare for the area of Johannesburg.

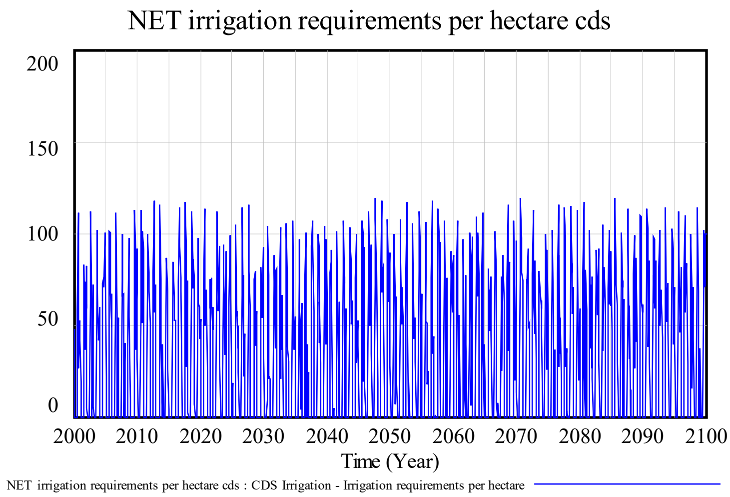


Figure 9: Net irrigation requirements per hectare for Johannesburg, IPSL RCP8.5 scenario

The trend in total irrigation water requirements per hectare is identical to the trend in irrigation requirements per hectare, unless there is a change in irrigation efficiency or the efficiency of water conveyance infrastructure. Table 12 shows how total irrigation water requirements compare to irrigation requirements in each decade. For months without irrigation, the value is 1. During the decade 1980-1990, total irrigation water requirements are on average 2.11 times higher than crop water requirements. By 2090-2100, total irrigation water requirements are on average 2.97 times higher than during the decade 1980-1990. Considering the monthly crop water demand during the decade 2090-2100, the results indicate that irrigation requirements may be almost 5 times as high (February) as net irrigation requirements.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1980-1990	2.11	2.11	1.00	1.00	1.00	1.00	1.00	2.11	2.11	2.11	2.11	2.11
1990-2000	3.56	2.56	1.00	1.00	1.00	1.00	1.00	2.06	2.03	2.00	2.10	2.12
2010-2020	3.09	2.11	1.00	1.00	1.00	1.00	1.00	2.09	2.14	2.74	2.51	2.87
2040-2050	3.54	1.50	1.00	1.00	1.00	1.00	1.00	2.06	2.15	2.73	2.44	2.38
2070-2080	3.48	2.55	1.00	1.00	1.00	1.00	1.00	2.24	2.12	2.52	2.48	2.30
2090-2100	4.16	4.62	1.00	1.00	1.00	1.00	1.00	2.25	2.09	2.62	2.31	2.73

Table 4: Relative water use total irrgation requirements vs net irrigation requirements

Between 1979 and 2100, the cumulative difference between net and total irrigation requirements is 55,871 mm per hectare, which is equivalent to 550,871,000 litres or 4,667,467 litres per hectare per year on average. If an irrigation efficiency of 75% is assumed, the cumulative difference declines from 55,871 mm per hectare to 20,398 mm per hectare, which is a net reduction of 63.5% in irrigation water use compared to the scenario with 50% irrigation efficiency.

2.5.2 Surface and groundwater supply

Surface and groundwater supply indicate the amount of renewable surface and groundwater sources available per hectare. Both indicators are calculated based on monthly precipitation, the evaporation fraction and the percolation fraction (the share of precipitation that reaches groundwater aquifers). The equations used for the calculation of the indicated surface and groundwater supply are presented below.

*Indicated surface water supply = Monthly precipitation * Evaporation fraction * (1 - Percolation fraction)*

*Indicated groundwater supply = Monthly precipitation * Evaporation fraction * Percolation fraction*

The results indicate the monthly availability of ground and surface water respectively. Simulation results for indicated surface water supply and indicated groundwater supply are presented in Figure 35and Figure 36 respectively, using the IPSL RCP8.5 projections for Johannesburg.

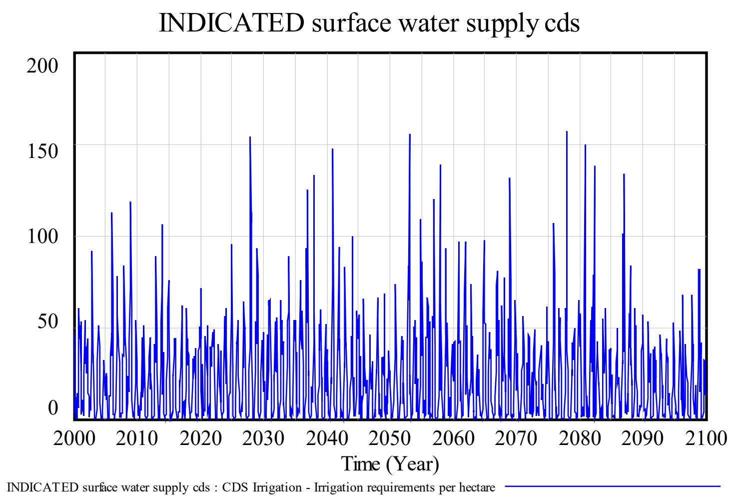


Figure 10: Indicated surface water supply per hectare, IPSL RCP8.5 scenario

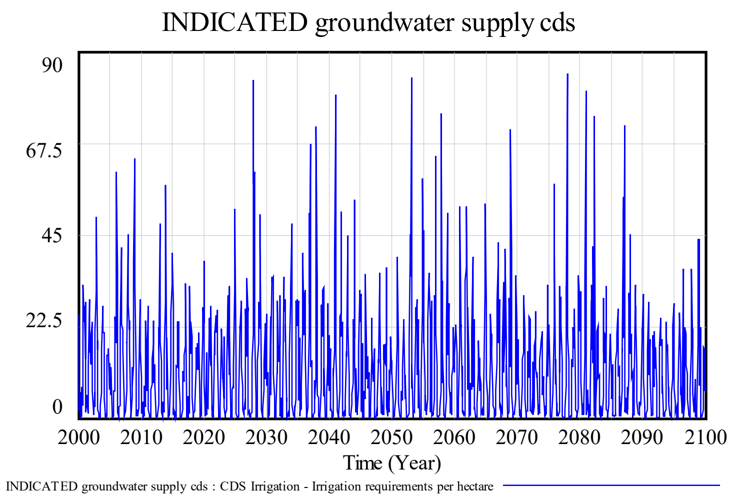


Figure 11: Indicated groundwater supply per hectare, IPSL RCP8.5 scenario

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Annex I: Code for establishing the CDS Toolbox-SAVi link

Code related to offline processing of CDS Toolbox and CDS API data for the C3S_428h_IISD-EU project.

How does this code relate to the CDS API ?

This code builds on the powerful CDS API but focuses on local impact analysis specific for the C3S_428h_IISD-EU project. It makes it easier to retrieve a time series for a specific location or region, and save the result to a CSV file (a simpler format than netCDF for most climate adaptation practitioners). Additionally, the code combines variables across multiple datasets, aggregate them into asset classes (such as all energy-related variables) and perform actions such as bias correction (use of ERA5 and CMIP5).

Code available for download

The easy way is to download the zipped archive: - latest (development): https://github.com/perrette/iisd-cdstoolbox/archive/master.zip - or check stable releases with description of changes: https://github.com/perrette/iisd-cdstoolbox/releases (see assets at the bottom of each release to download a zip version)

The hacky way is to use git (only useful during development, for frequent updates, to avoid having to download and extract the archive every time):

- First time: `git clone https://github.com/perrette/iisd-cdstoolbox.git`

- Subsequent updates: `git pull` from inside the repository

Installation steps

- Download the code (see above) and inside the folder.
- Install Python 3, ideally Anaconda Python which comes with pre-installed packages
- Install the CDS API key: https://cds.climate.copernicus.eu/api-how-to
- Install the CDS API client: pip install cdsapi
- Install other dependencies: conda install --file requirements.txt or pip install -r requirements.txt
- *Optional* dependency for coastlines on plots: conda install -c conda-forge cartopy or see docs
- *Optional* dependency: CDO (might be needed later, experimental): conda install -c conda-forge python-cdo

Troubleshooting: - If install fails, you may need to go through the dependencies in requirements.txt one by one and try either pip install or conda install or other methods specific to that dependency. - In the examples that follow, if you have both python2 and python3 installed, you might need to replace python with python3.

CDS API

Download indicators associated with one asset class.

Examples of use:

```
python download.py --asset energy --location Welkenraedt
```

The corresponding csv time series will be stored in `indicators/welkenraedt/energy`. Note that raw downloaded data from the CDS API (regional tiles in netcdf format, and csv for the required lon/lat, without any correction) are stored under `download/` and can be re-used across multiple indicators.

The `indicators` folder is organized by location, asset class, simulation set and indicator name. The aim is to provide multiple sets for SAVi simulation. For instance, `era5` for past simulations, and various `cmip5` versions for future simulations, that may vary with model and experiment. For instance the above command creates the folder structure (here a subset of all variables is shown):

```
indicators/
  welkenraedt/
    energy/
      era5/
        2m_temperature.csv
        precipitation.csv
        ...
      cmip5-ipsl_cm5a_mr-rcp_8_5/
        2m_temperature.csv
        precipitation.csv
        ...
      ...
```

with two simulation sets `era5` and `cmip5-ipsl_cm5a_mr-rcp_8_5`. It is possible to specify other models and experiment via `--model` and `--experiment` parameters, to add further simulation sets and thus test how the choice of climate models and experiment affect the result of SAVi simulations.

Compared to raw CDS API, some variables are renamed and scaled so that units match and are the same across simulation sets. For instance, temperature was adjusted from Kelvin to degree Celsius, and precipitation was renamed and units-adjusted into mm per month from original (mean_total_precipitation_rate (mm/s) in ERA5, and mean_precipitation_flux (mm/s) in CMIP5). Additionally, CMIP5 data is corrected so that climatological mean matches with ERA5 data (climatology computed over 1979-2019 by default).

Additionally to the files shown in the example folder listing above, figures can also be created for rapid control of the data, either for interactive viewing (`--view-timeseries` and `--view-region`) or or saved as PNG files (`--png-timeseries` and `--png-region`), e.g.

```
python download.py --asset energy --location Welkenraedt --png-timeseries --
png-region
```

Single indicators can be downloaded via:

```
python download.py --indicator 2m_temperature --location Welkenraedt
```

The choices available for `--indicator` , `--asset` and `--location` area defined in the following configuration files, respectively:

- controls which indicators are available, how they are renamed and unit-adjusted: indicators.yml (see sub-section below)
- controls the indicator list in each asset class: assets.yml
- controls the list of locations available: locations.yml

Full documentation, including fine-grained controls, is provided in the command-line help:

```
python download.py --help
```

Visit the CDS Datasets download pages, for more information about available variables, models and scenarios:

- ERA5: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form

- CMIP5: `https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip5-monthly-single-levels?tab=form`

In particular, clicking on “Show API request” provides information about spelling of the parameters, e.g. that “2m temperature” is spelled `2m_temperature` and “RCP 8.5” is spelled `rcp_8_5`.

Indicator definition

This section is intended for users who wish to extend the list of indicators currently defined in indicators.yml. It can be safely ignored for users who are only interested in using the existing indicators.

Let’s see how `10m_wind_speed` is defined:

```
- name: 10m_wind_speed
  units: m / s
  description: Wind speed magnitude at 10 m
```

The fields `name` and `units` define the indicator. Description is optional, just to provide some context. It is possible to provide `scale` and `offset` fields to correct the data as `(data + offset) * scale`. Here for `2m temperature`:

```
- name: 2m_temperature
  units: degrees Celsius
  description: 2-m air temperature
  offset: -273.15  # Kelvin to degrees C
```

# denotes a comment to provide some context. Some indicators have different names in ERA5 and CMIP5, and possibly different units. That can be dealt with by providing `era5` and `cmip5` fields, which have precedence over the top-level fields. Here the `evaporation` definition:

```
- name: evaporation
  units: mm per month
  era5:
    name: mean_evaporation_rate  # different name in ERA5
    scale: -2592000  # change sign and convert from mm/s to mm / month
  cmip5:
    scale: 2592000  # mm/s to mm / month
```

In that case both scaling and name depend on the dataset. In CMIP5 which variable name is identical to our indicator name, the `name` field can be omitted. In ERA5, evaporation is negative (downwards fluxes are counted positively), whereas it is counted positively in ERA5.

Indicators composed of several CDS variables can be defined via `compose` and `expression` fields. Let's look at `100m_wind_speed`:

```
- name: 100m_wind_speed
  units: m / s
  description: Wind speed magnitude at 100 m
  era5:
    compose:
      - 100m_u_component_of_wind
      - 100m_v_component_of_wind
    expression: (_100m_u_component_of_wind**2 + _100m_v_component_of_wind**2)
**0.5
  cmip5:
    name: 10m_wind_speed
    scale: 1.6  # average scaling from 10m to 100m, based on one test locatio
n (approximate!)
```

In ERA5, vector components of 100m wind speed are provided. Our indicator is therefore a composition of these two variables, defined by the `expression` field, which is evaluated as a python expression. Note that variables that start with a digit are not licit in python and must be prefixed with an underscore _ in the `expression` field (only there).

For complex expressions, it is possible to provide a `mapping` field to store intermediate variables, for readability. This is used for the `relative_humidity` indicator:

```
- name: relative_humidity
  units: '%'
  era5:
    compose:
```

```
      - 2m_temperature
      - 2m_dewpoint_temperature
    expression: 100*(exp((17.625*TD)/(243.04+TD))/exp((17.625*T)/(243.04+T)))
    mapping: {T: _2m_temperature - 273.15, TD: _2m_dewpoint_temperature - 273
.15}
  cmip5:
    name: near_surface_relative_humidity
```

where T and TD are provided as intermediary variables, to be used in expression.

ERA5-hourly dataset can be retrieved via `frequency: hourly` field, and subsequently aggregated to monthly indicators thanks to pre-defined functions `daily_max`, `daily_min`, `daily_mean`, `monthly_mean`, `yearly_mean`. For instance:

```
- name: maximum_daily_temperature
  units: degrees Celsius
  offset: -273.15
  cmip5:
    name: maximum_2m_temperature_in_the_last_24_hours
  era5:
    name: 2m_temperature
    frequency: hourly
    transform:
      - daily_max
      - monthly_mean
```

This variable is available directly for CMIP5, but not in ERA5. It is calculated from `2m_temperature` from ERA5 hourly dataset, and subsequently aggregated. Note the ERA5-hourly dataset takes significantly longer to retrieve than ERA5 monthly. Consider using in combination with `--year 2000` to retrieve a single year of the ERA5 dataset.

Currently CMIP5 daily is not supported.

Netcdf to csv conversion

Convert netcdf time series files downloaded from the CDS Toolbox pages into csv files (note: this does not work for netcdf files downloaded via the cds api):

```
python netcdf_to_csv.py data/*nc
```

Help:

```
python netcdf_to_csv.py --help
```

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