Physics and Chemistry of the Atmosphere

(ENV-320) Laboratory course / Travaux pratiques – 2025
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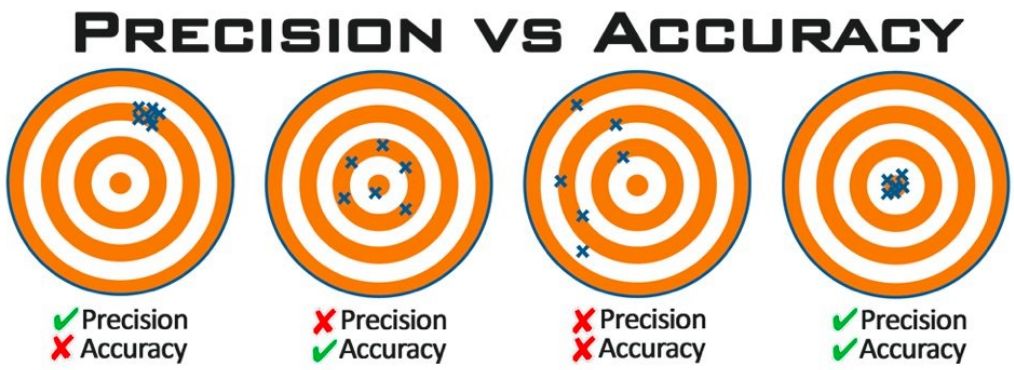
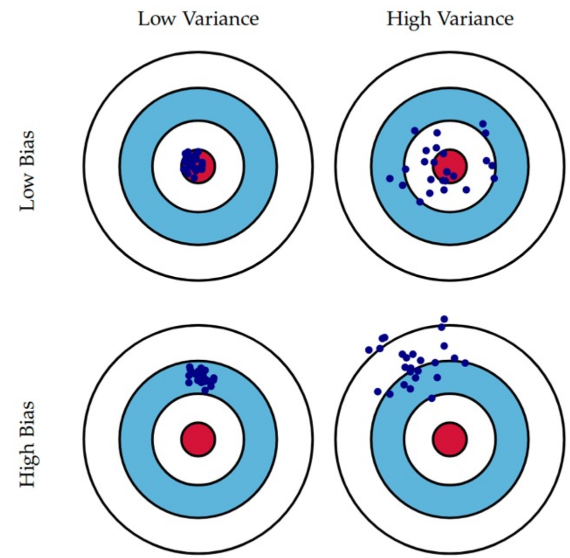
Objectives

- Measure components of the surface energy balance and of the atmosphere
- Understand physical principles of measurements
- Develop experience with lab and field measurements
- Present, analyze and discuss/interpret data and results
- Apply theory presented in the course

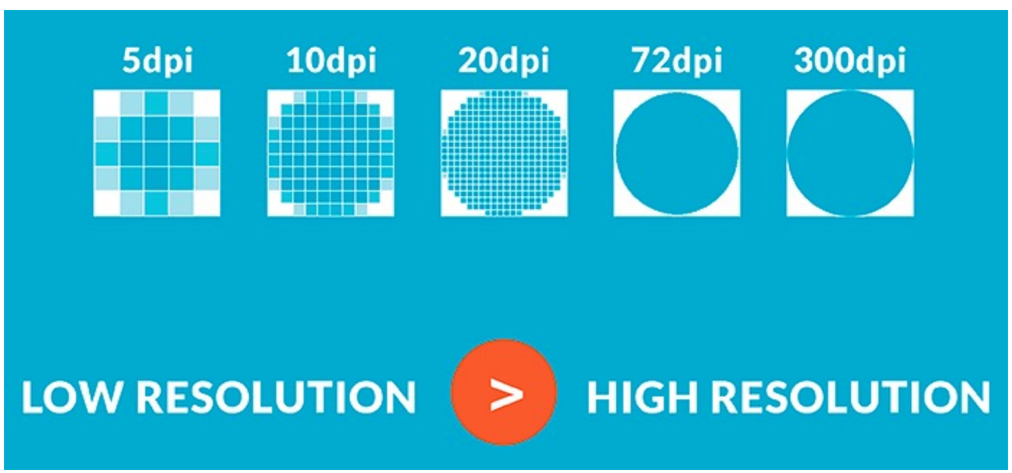
EPFL

Basic notions





Bias ← → systematic error
Var ← → random error

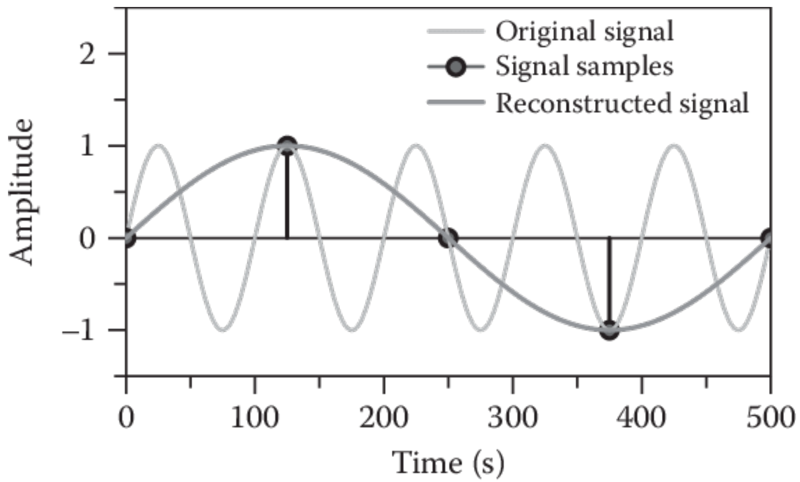


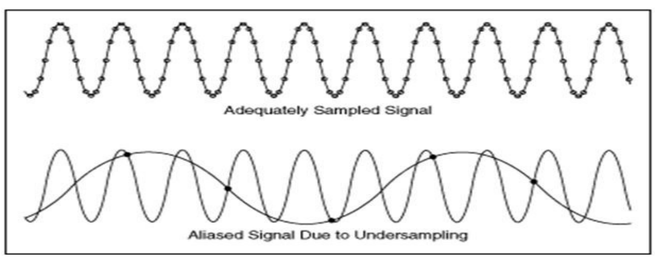
Resolution in space and time

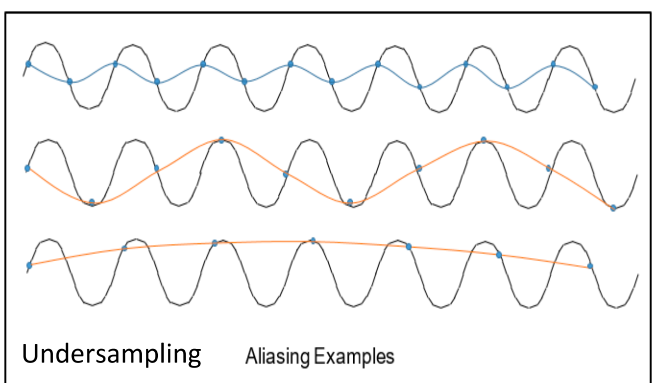
What is the variation in a natural process or signal?

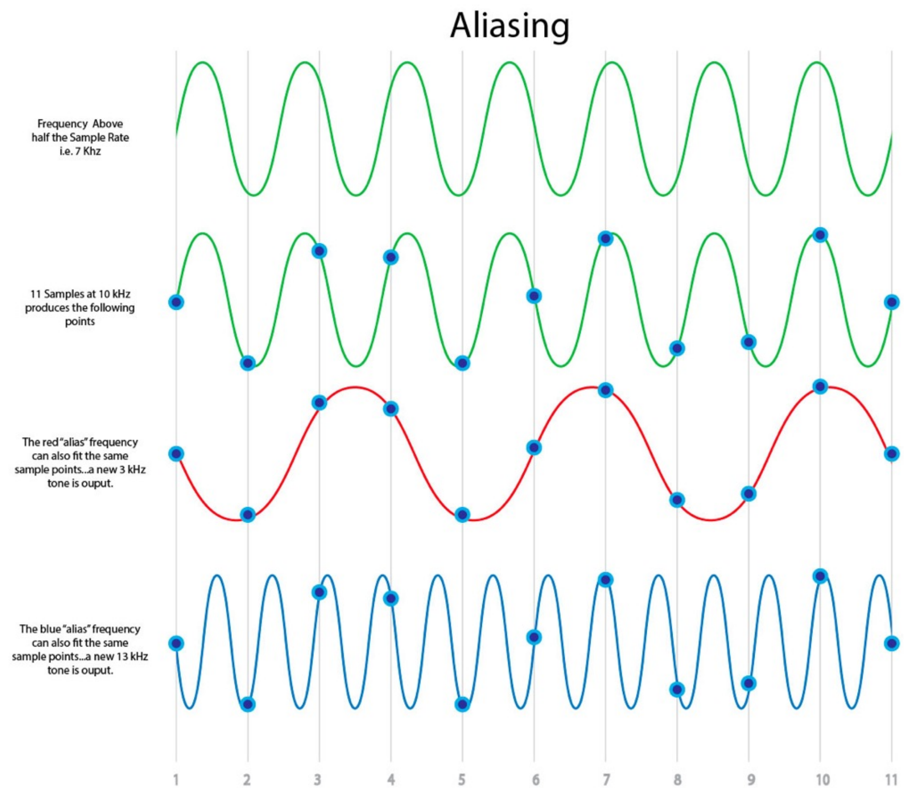
What would be an appropriate sampling interval or frequency to correctly represent the original signal?

Sampling and aliasing









Undersampling can have different effects:

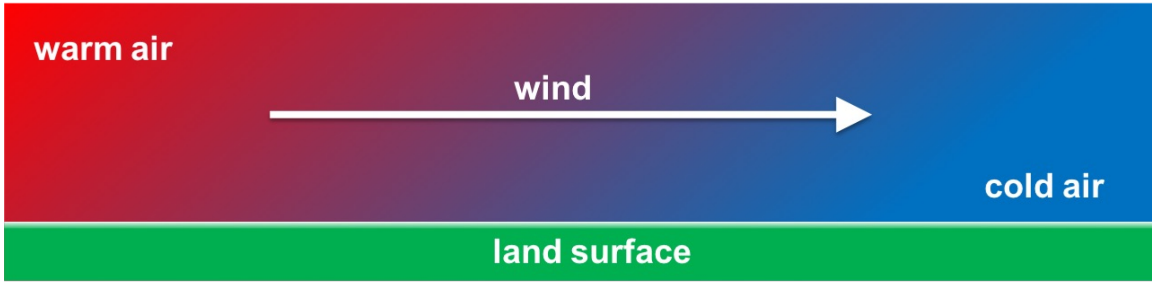
S = 2*F → Amplitude decrease and phase shift

S = 1.25*F → Frequency decrease

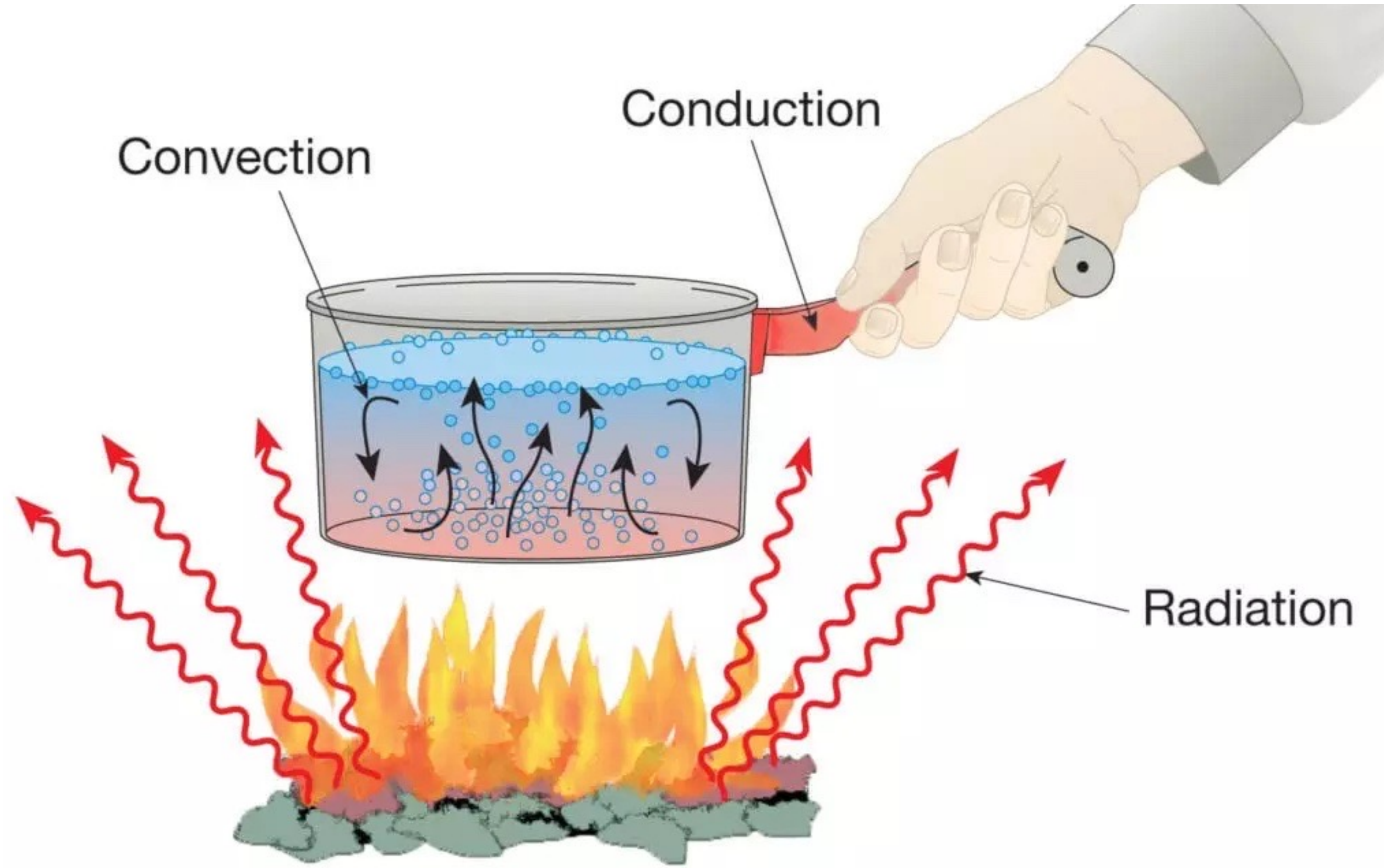
S = 0.90*F → Strong frequency shift

S = sampling frequency, F = signal frequency

Heat transfer

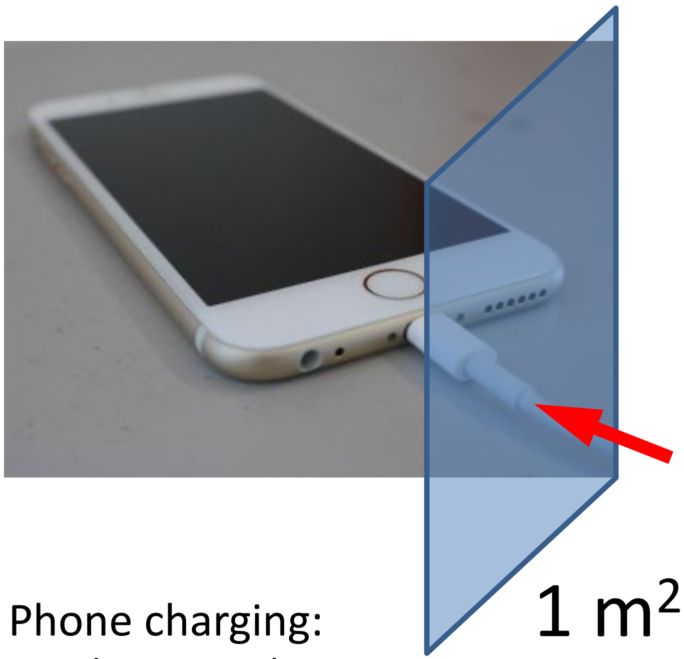


Advection



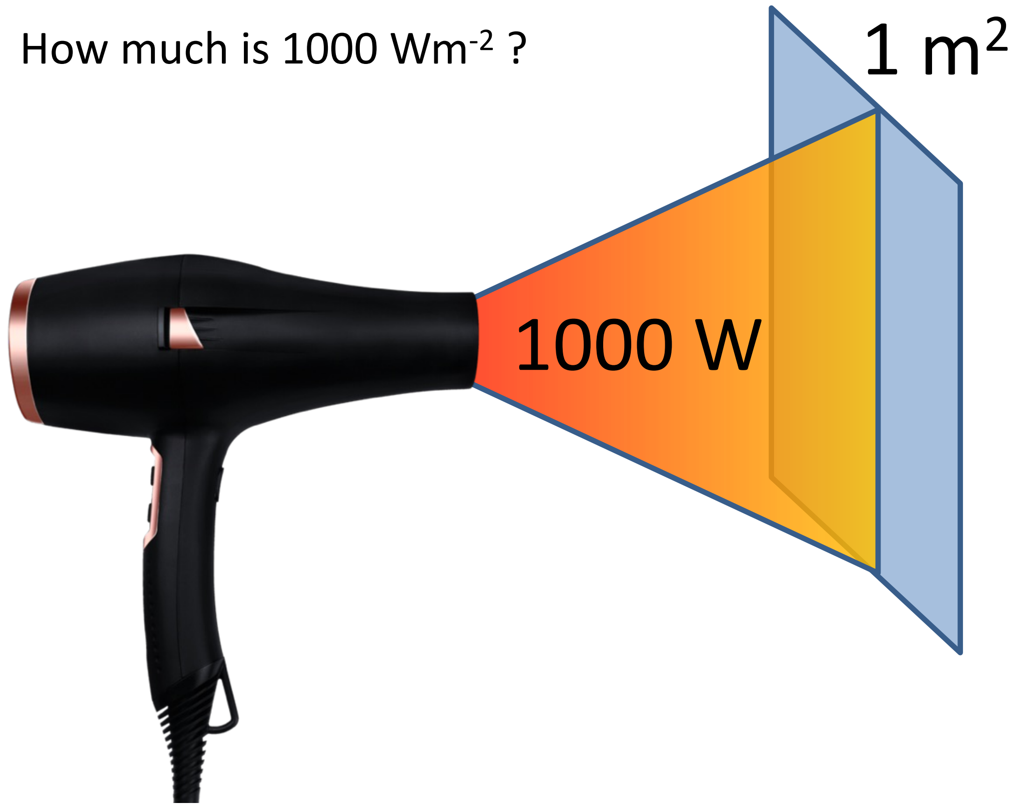
Imagining an equivalent of radiative heat flux

How much is 1 Wm^{-2} ?



Phone charging:
5W (1A @ 5V)
per 1 m^2

How much is 1000 Wm^{-2} ?



SHF measurements: “results” of previous years

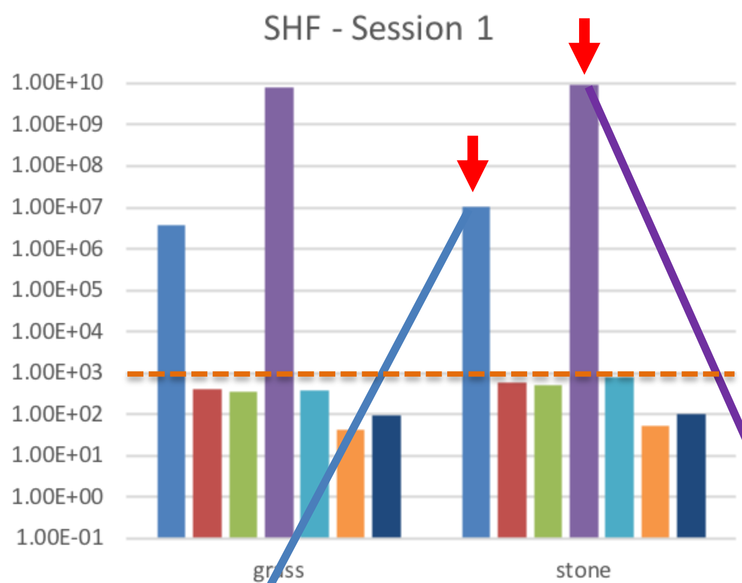
Recall solar constant: 1368Wm^{-2}

Compare with bulk formulation:

$$H = \underbrace{\rho c_p C_H u_a}_{\approx 5}(T_a - T_s)$$

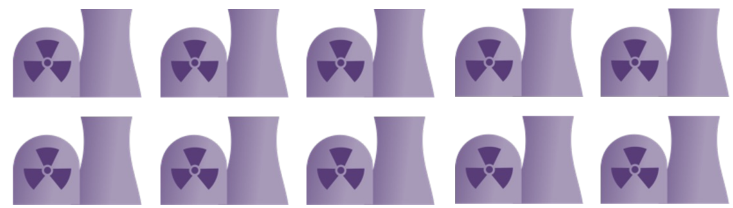
≈ 5 → $\Delta T = H/5 = 1e7/5 =$

2’000’000 K



2e6K

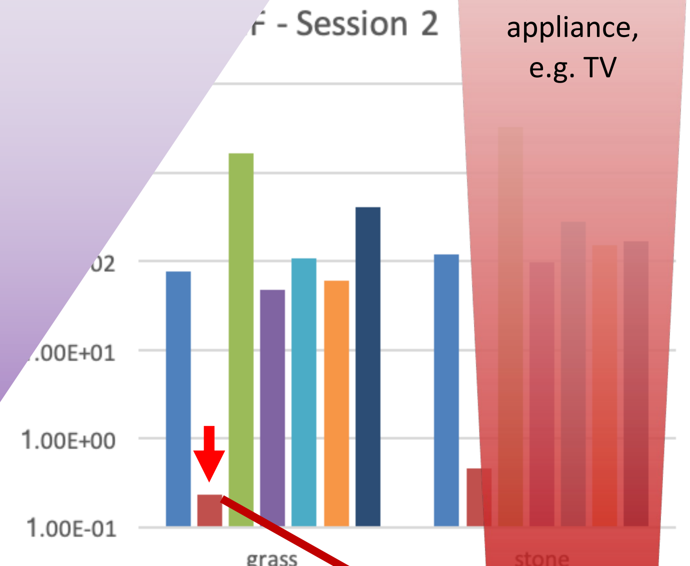
1e10W =



10 NPP of 1GW each

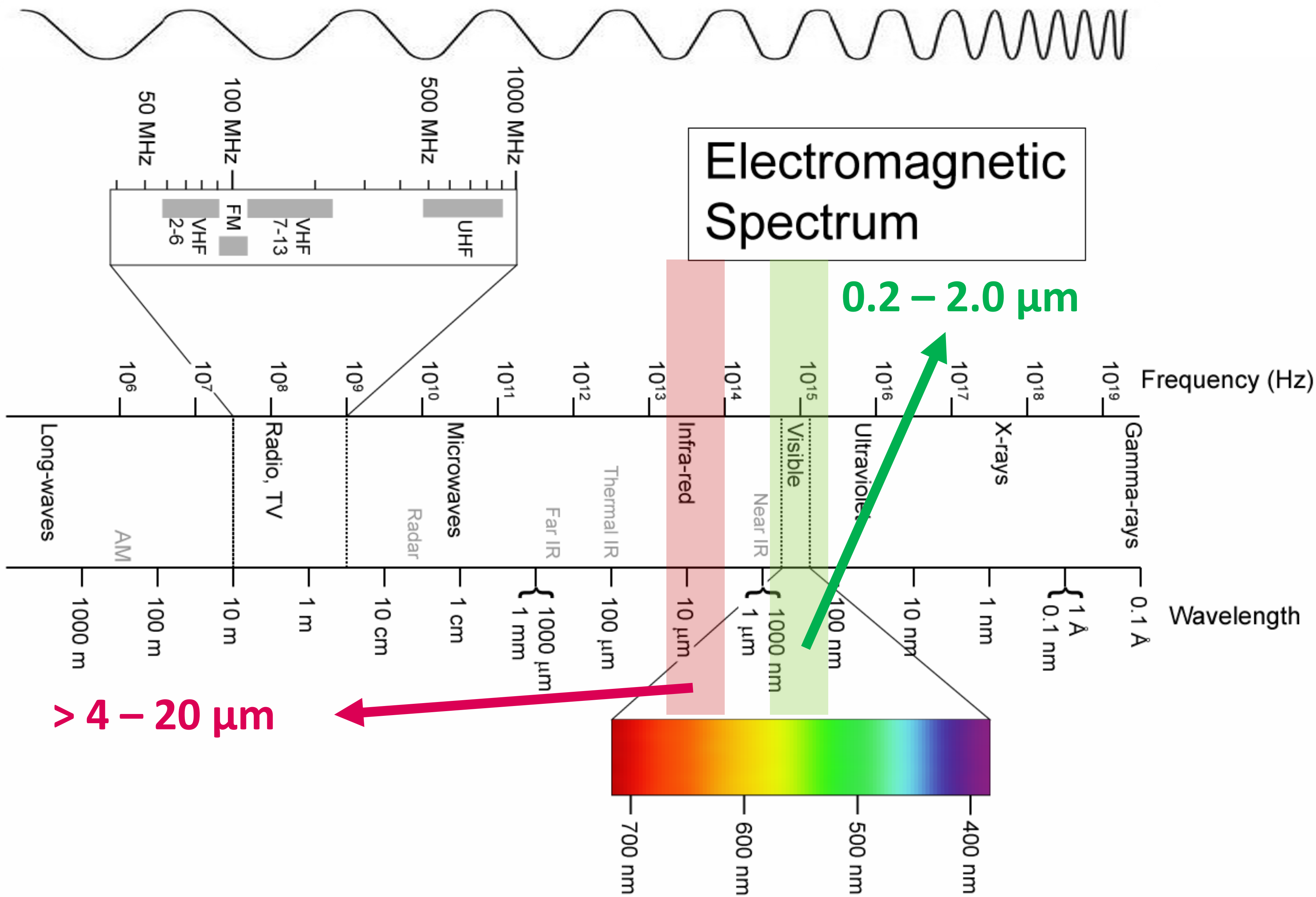
1 m²

Standby power of home appliance, e.g. TV

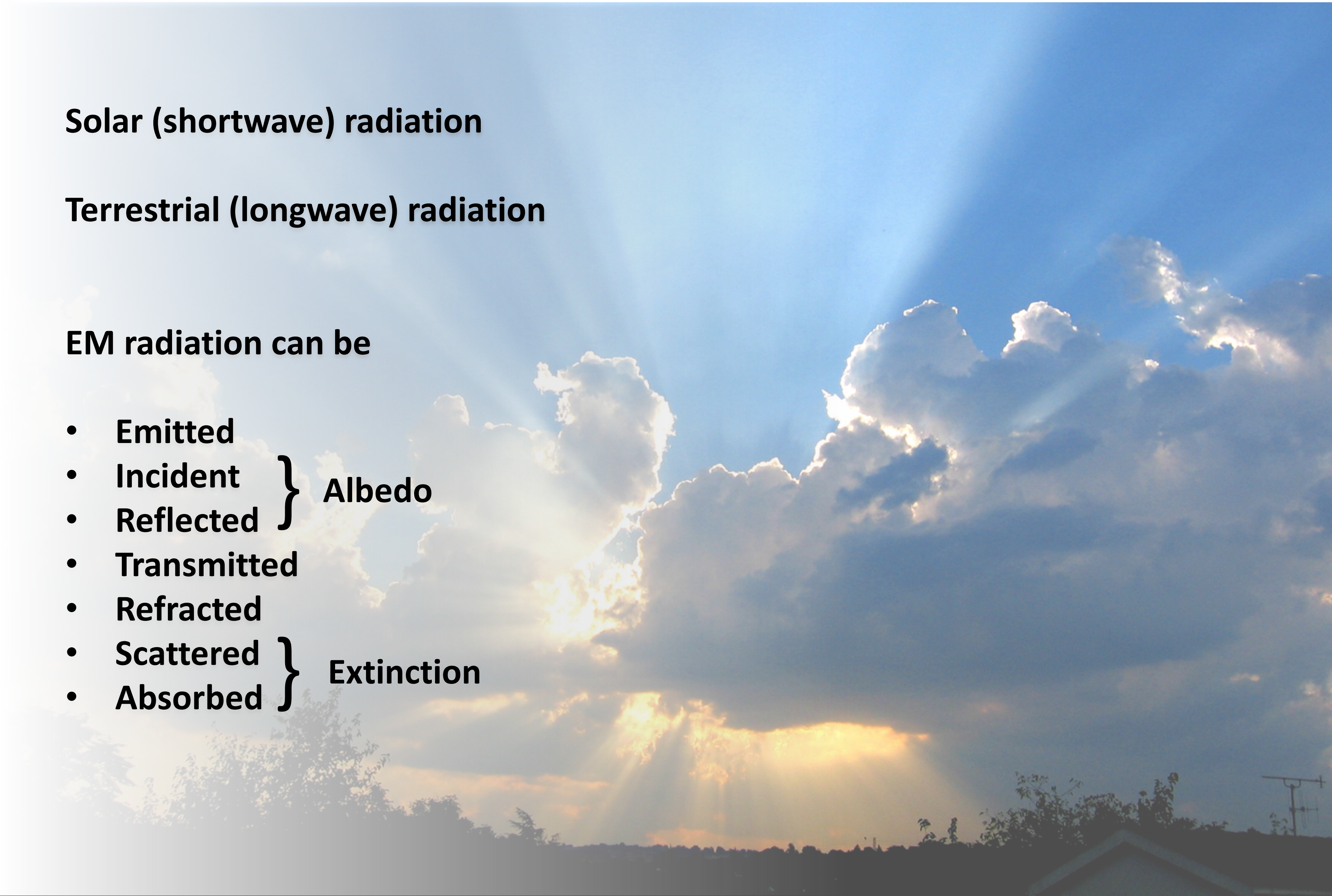


0.2W
1 m²

Electromagnetic spectrum (radiation)



Radiative heat fluxes



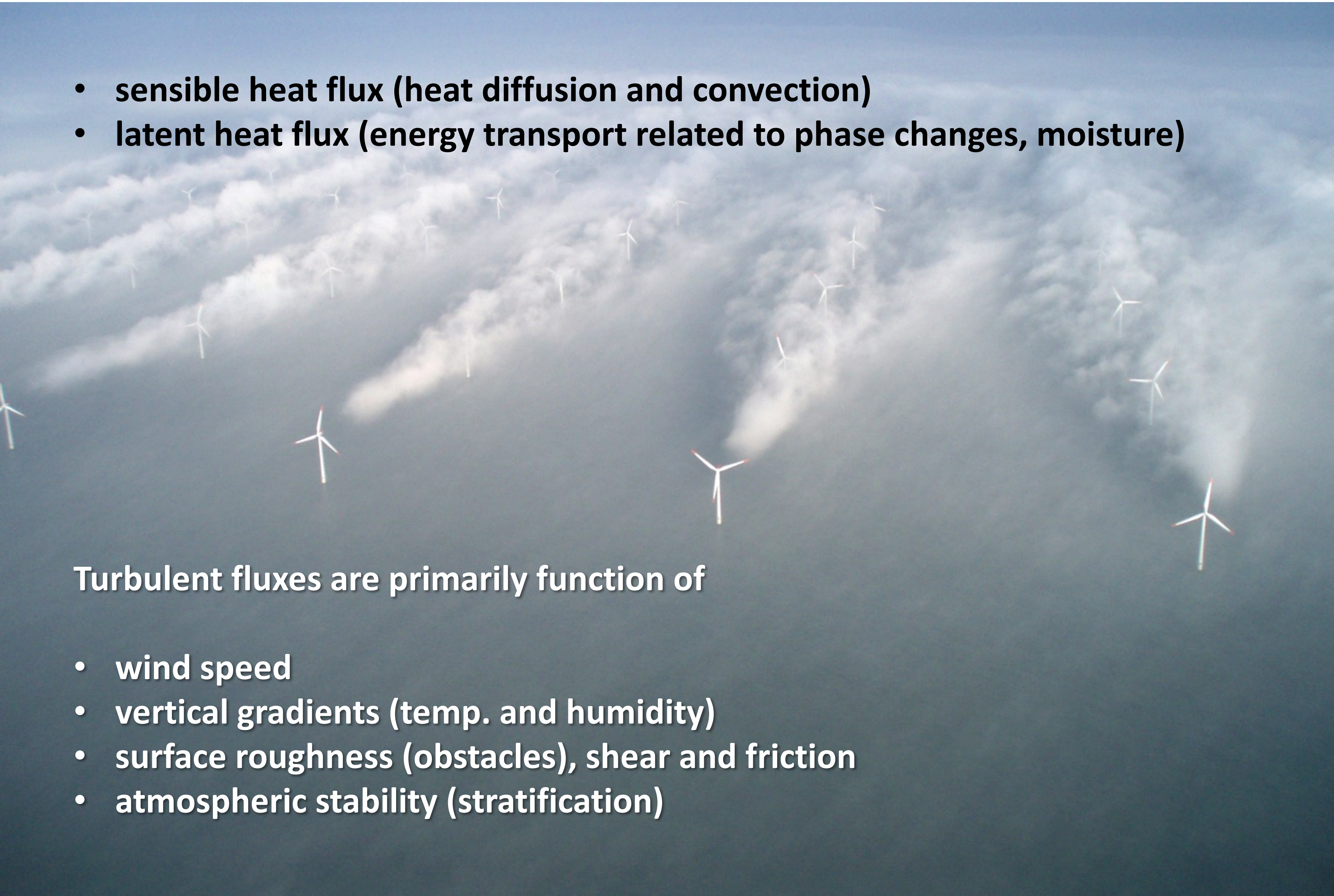
Solar (shortwave) radiation

Terrestrial (longwave) radiation

EM radiation can be

- **Emitted**
- **Incident** } **Albedo**
- **Reflected** }
- **Transmitted**
- **Refracted**
- **Scattered** } **Extinction**
- **Absorbed** }

Turbulent heat fluxes



- sensible heat flux (heat diffusion and convection)
- latent heat flux (energy transport related to phase changes, moisture)

Turbulent fluxes are primarily function of

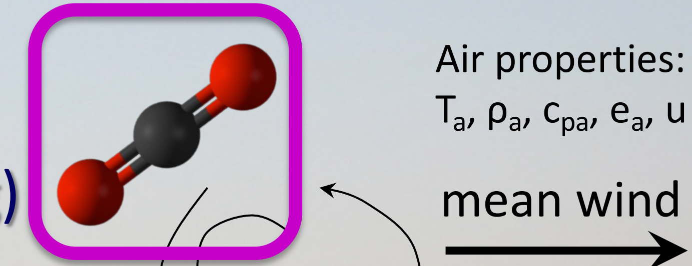
- wind speed
- vertical gradients (temp. and humidity)
- surface roughness (obstacles), shear and friction
- atmospheric stability (stratification)

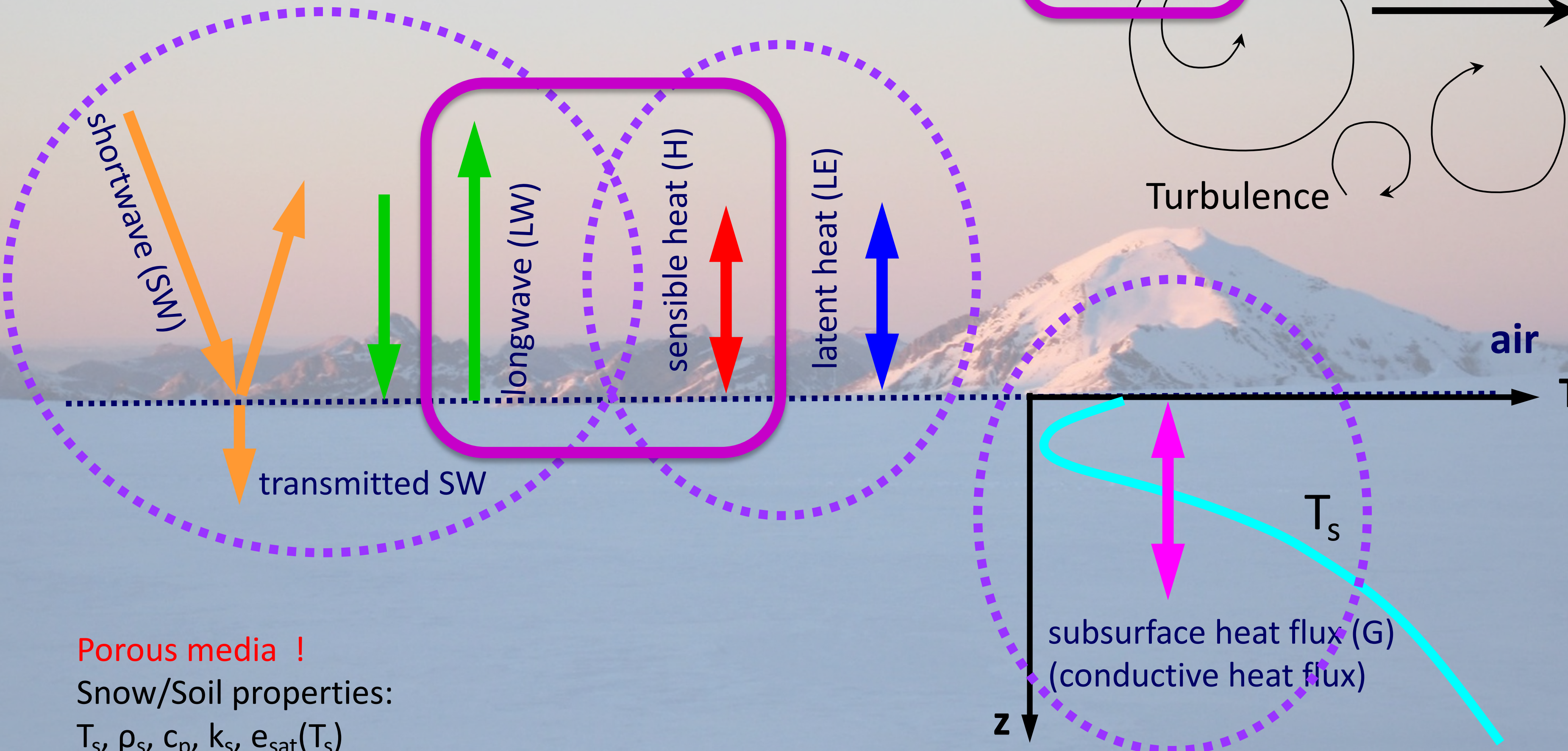
Surface energy balance

SW⇩ – SW⇧ + LW ⇩ – LW ⇧ = R (net radiation)

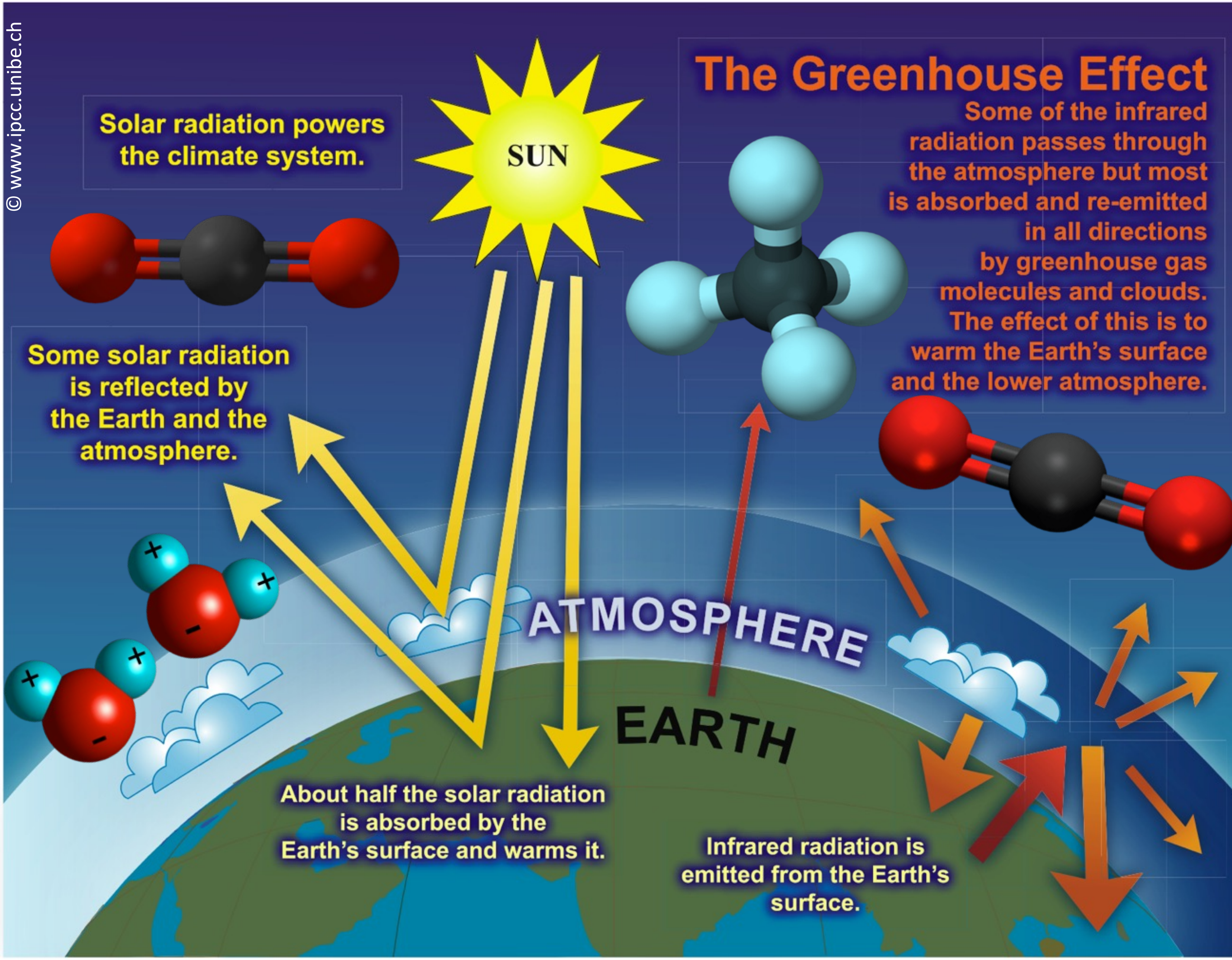
(1-α) SW⇩ = absorbed/transmitted SW

R + G + H + LE = 0 (in absence of melting)





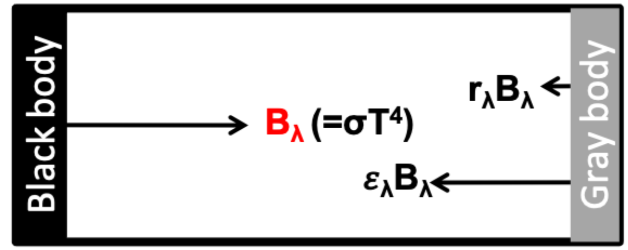
Greenhouse atmosphere



Longwave radiation (L)

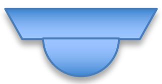
Net longwave radiation:

$$Q_{nl} = L\downarrow - L\uparrow$$



Outgoing LW radiation: (recall: B = εB + rB)

sensor



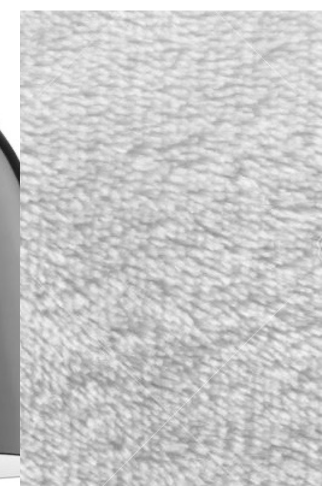
emitted reflected

$$L\uparrow \;=\; \varepsilon\sigma T_s^4 + (1-\varepsilon)L\downarrow \quad , \quad where \quad L\downarrow = \varepsilon_{air}\sigma T_{air}^4$$

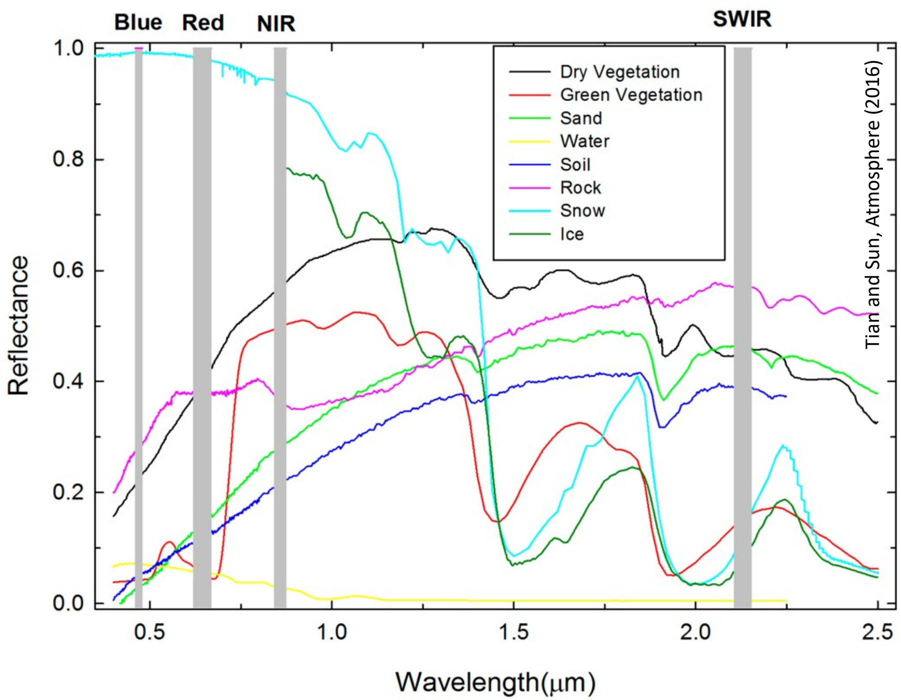
bright $\neq$ glossy
dark $\neq$ matt

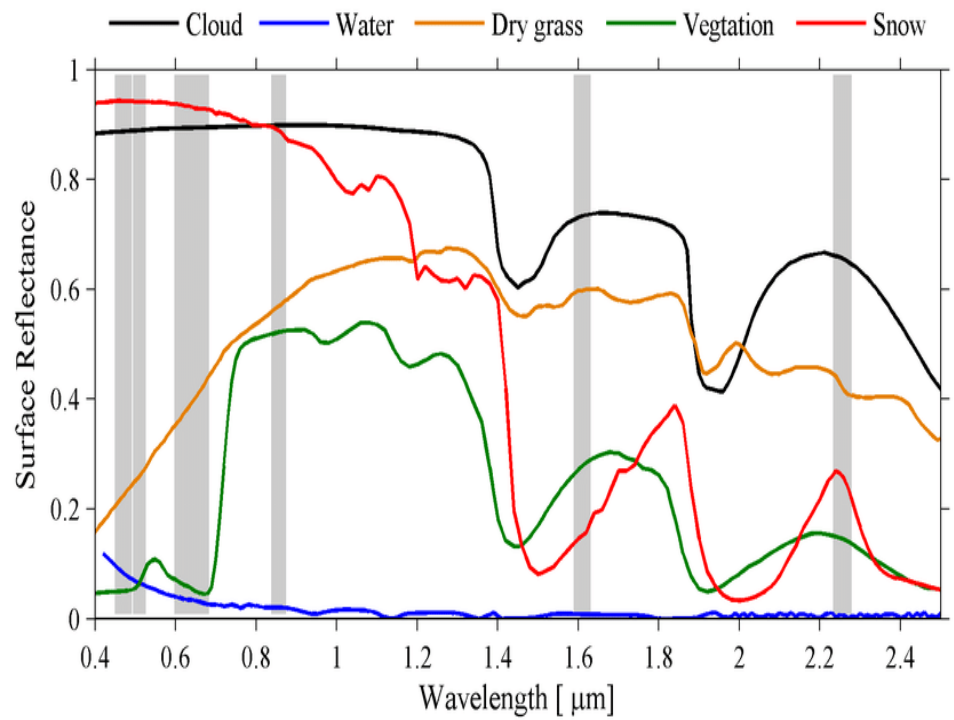
$$T_{rad} = \varepsilon^{0.25} T_{kin}$$

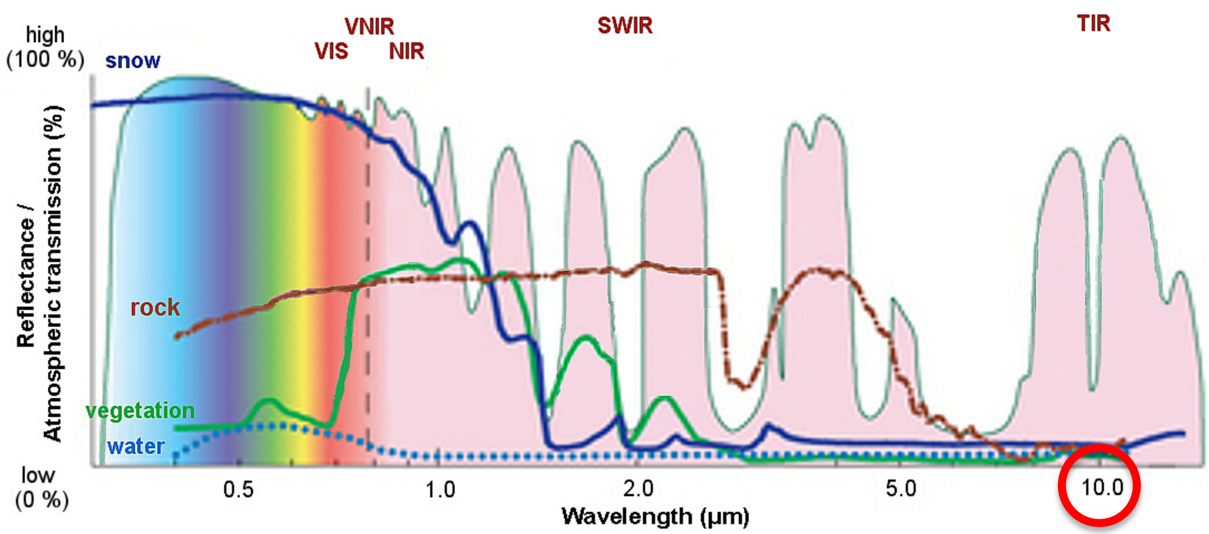
$L\downarrow$ = incident LW rad. (from atmos. & surrounding) [Wm^{-2}]
ε = emissivity of the surface [-]
σ = Stefan-Boltzmann constant = $5.67*10^{-8}$ [$Wm^{-2}K^{-4}$]
T_s = surface temperature [K]
T_{rad} = radiative temperature [K]
T_{kin} = kinetic temperature [K]



Spectral reflectance of different materials







$\varepsilon_\lambda = a_\lambda$; < 1

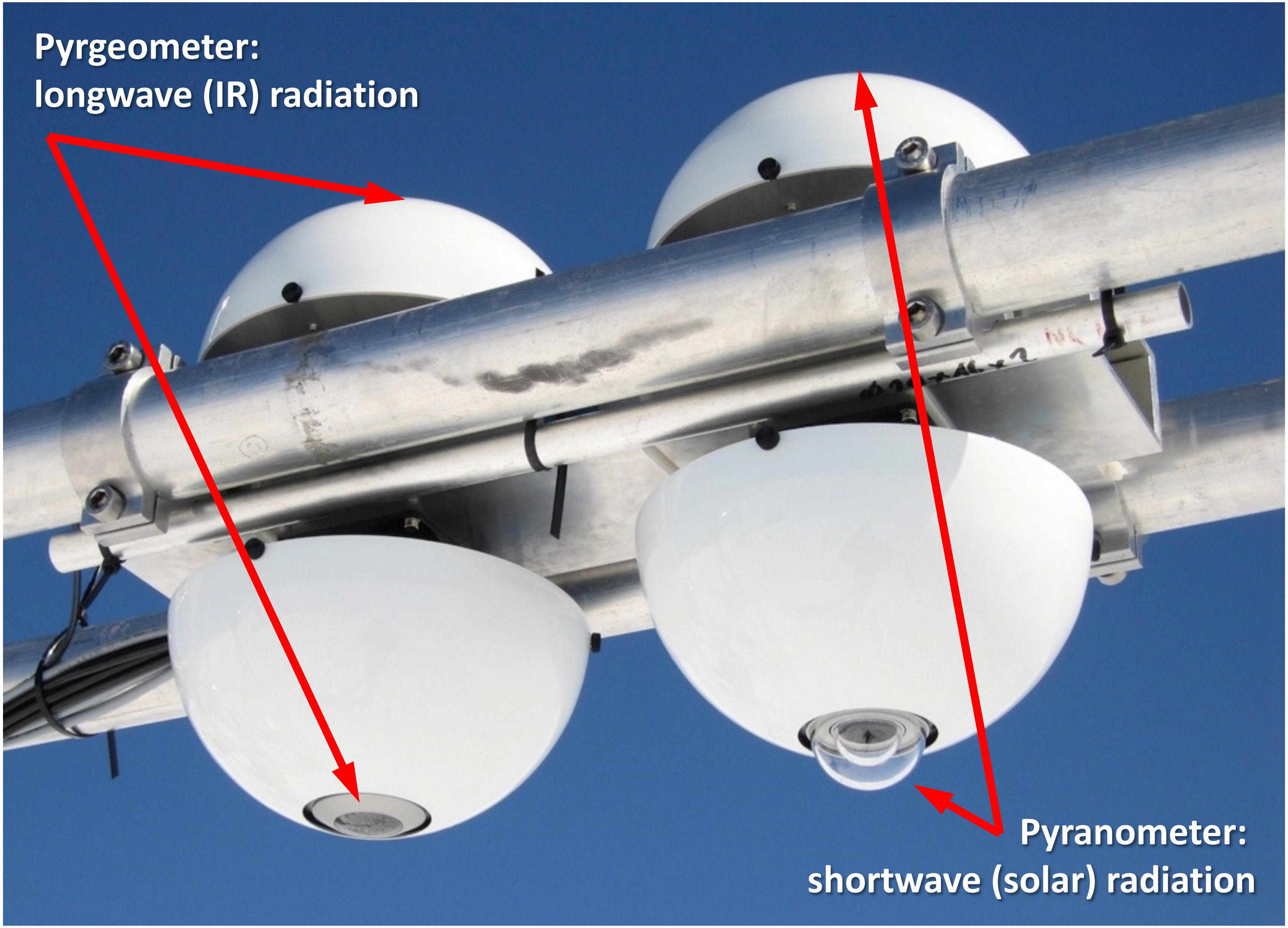
$\varepsilon_\lambda + r_\lambda = 1$

$r_\lambda = 1 - \varepsilon_\lambda$

$\varepsilon_\lambda = 1 - r_\lambda$

$\alpha_\lambda = r_{\lambda,vis}$

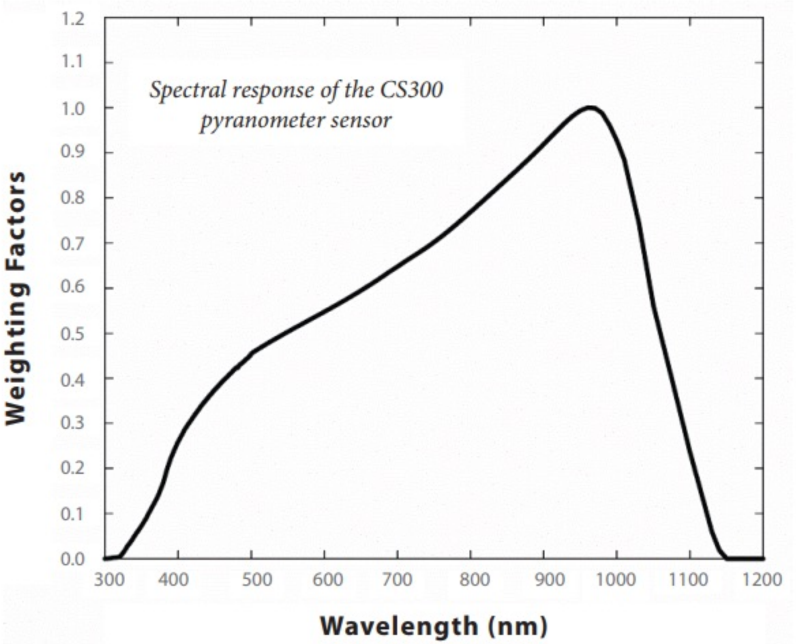
Radiation measurements: radiometers

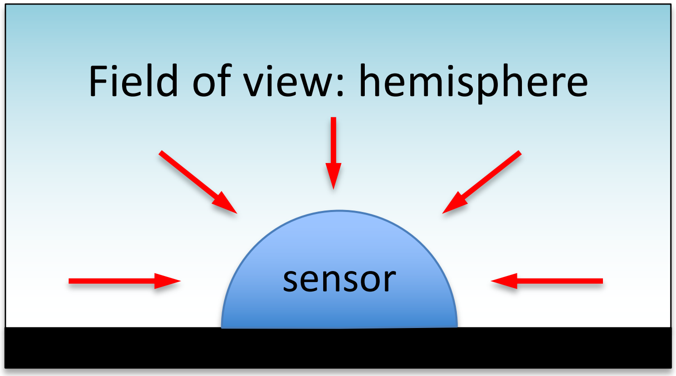


Pyranometer (shortwave radiation)

Apogee pyranometer specifications:

Light Spectrum Waveband	360 to 1120 nm
Measurement Range	0 to 2000 W/m^2 (full sunlight ≈1000 W/m^2)
Absolute Accuracy	±5% for daily total radiation
Calibration Factor	5 W/m^2/mV
Cosine Correction Error	±5% at 75° zenith angle; ±2% at 45° zenith angle
Temperature Response	0.04 ± 0.04% per °C
Response Time	< 1 ms
Output Sensitivity	0.2 mV/W/m^2
Diameter	2.4 cm (0.9 in.)
Height	2.5 cm (1.0 in.)

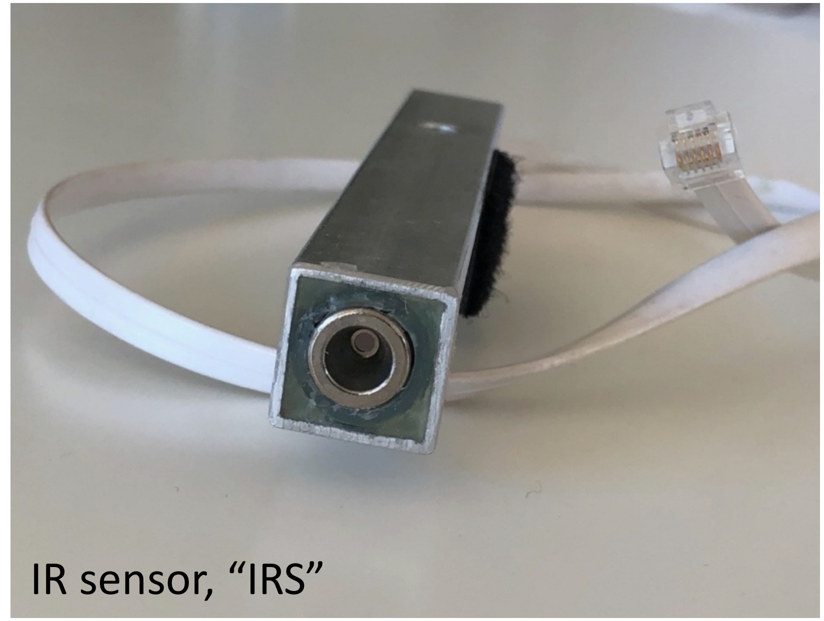


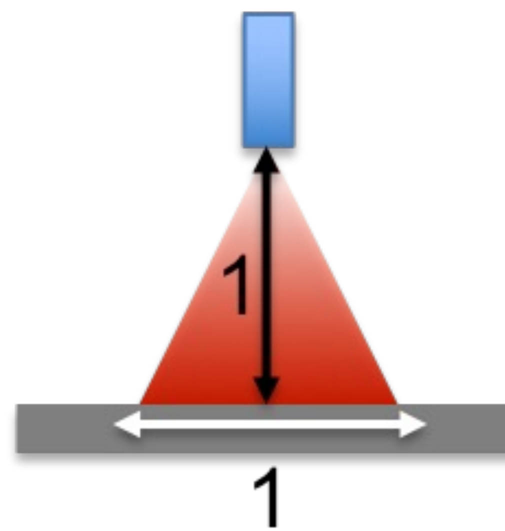


Radiation / IR temperature measurements

ZyTemp TN901 Specifications:

Compact Digital Thermopile Module
Range: -33 to 220°C
Accuracy: +/- 2%, 2°C
Resolution: 1/16°C
Response time: (90%) 1sec
Emissivity: 0.1-1, step 0.01
Wavelength: 5-14µm
Ratio Distance:Spot : 1:1 (FOV)
What is the intrinsic ε of this sensor?



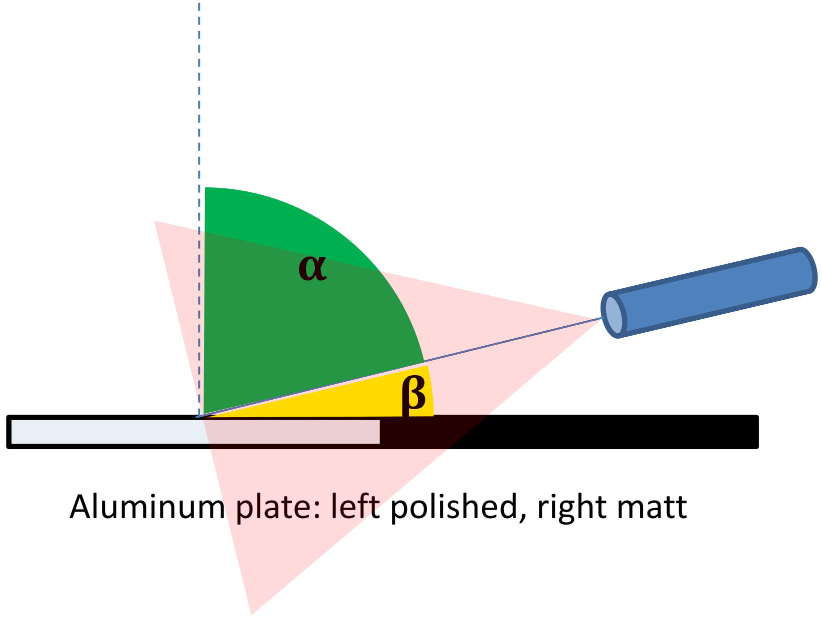


Zenith angle and field of view (fov)

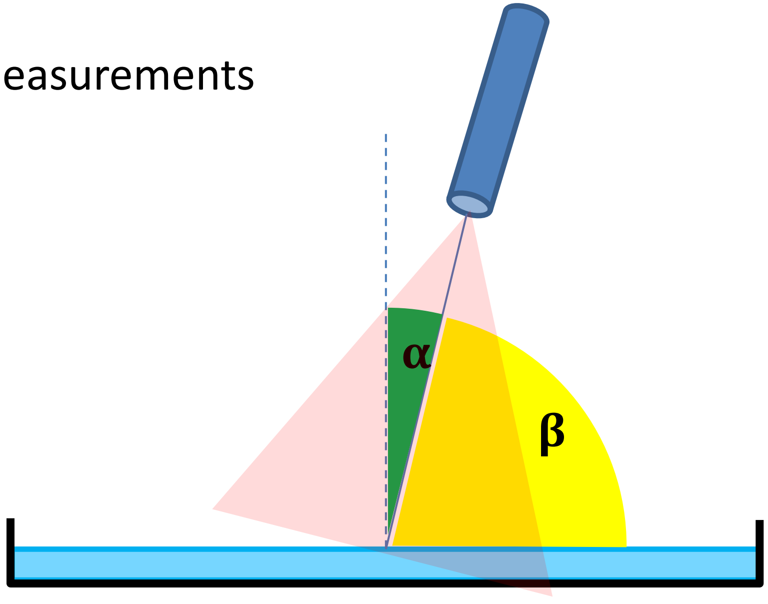
Which one is the zenith angle, **α** or **β** ?

Recall: field of view 1:1 (distance : target surface diameter)
The target footprint is a **circle** (or **ellipse** when inclined), not a square, even if the housing of the sensor is a prism with a square base…

Relevant in “ice bath”, “alu-plate”, and ”façade” measurements



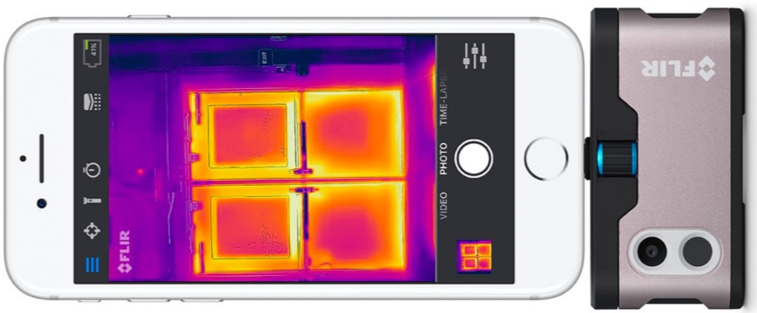
Aluminum plate: left polished, right matt



“Ice bath”: water/ice mix at 0°C

Note: the IRS has occasional periods with data gaps (sometimes only every 2nd measurement has a useful value, missing numbers are “nan”. Careful when plotting or calculating means.

Infrared cameras "IRC"



Battery autonomy: max. 45min

FLIR ONE

Wavelength sensitivity:	8 – 14 µm
Temperature range:	-20° to 120°C
Operating temperature:	0° to 35°C
Sensitivity (as low as):	0.1°C
Thermal resolution (px):	160 x 120
Accuracy:	+/- 3°C or 5%

Camera has 4 preset emissivity values, accounting for different surface types:

- matt (used for most natural materials)
- semi-matt
- semi-glossy
- glossy (for highly reflecting materials)

What are the numerical values of these?

➔ Please download and install the App "FlirONE" from the AppStore or GooglePlay

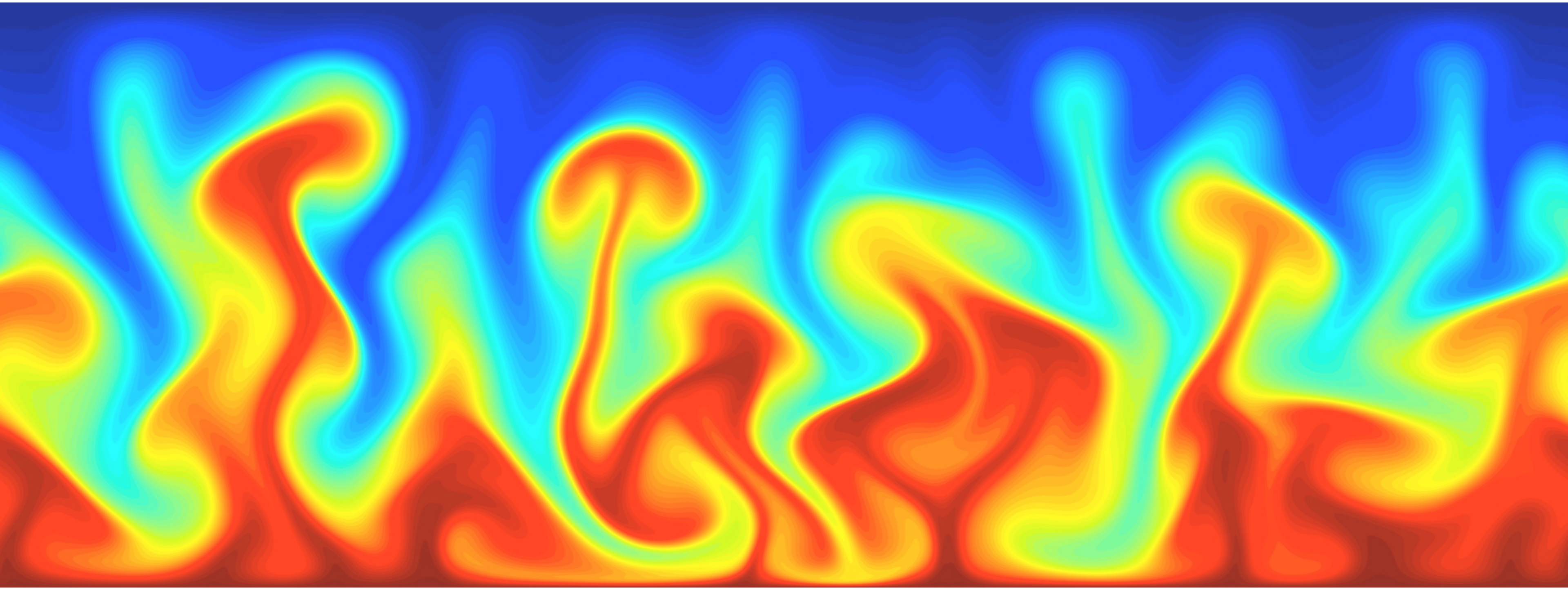
Emissivity tables and reference

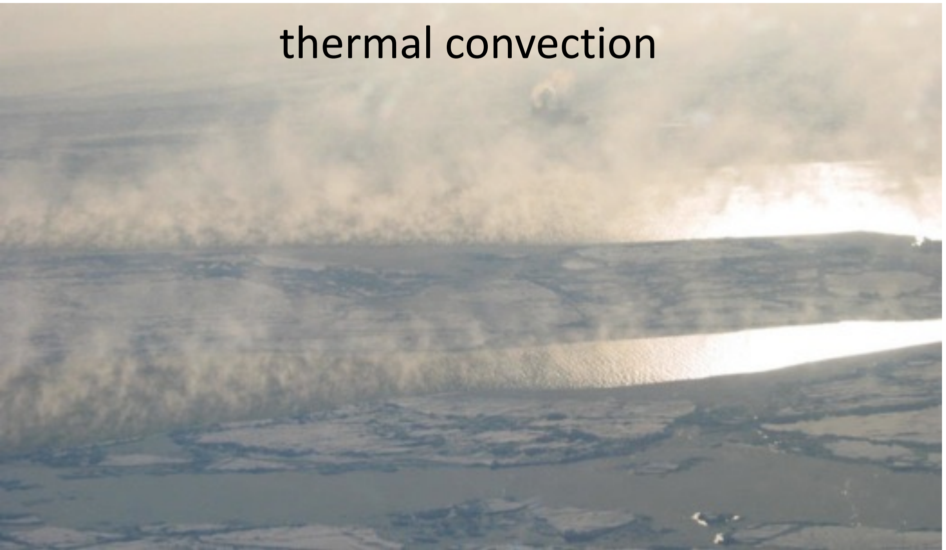
Material	Emissivity
Aluminum foil	0.03
Aluminum, anodized	0.9
Asphalt	0.88
Brick	0.90
Concrete, rough	0.91
Copper, polished	0.04
Copper, oxidized	0.87
Glass, smooth (uncoated)	0.95
Ice	0.97
Limestone	0.92
Marble (polished)	0.89 to 0.92
Paint (including white)	0.9
Paper, roofing or white	0.88 to 0.86
Plaster, rough	0.89
Silver, polished	0.02
Silver, oxidized	0.04
Snow	0.8 to 0.9
Water, pure	0.96

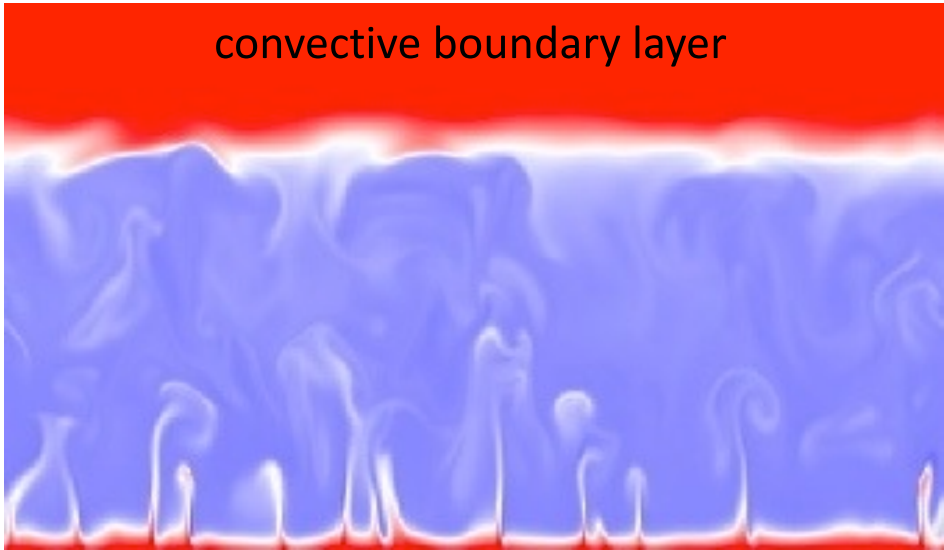
aluminium (anodised)	0.77	plastic (black)	0.95
brass (oxidised)	0.61	porcelain (glazed)	0.92
brick (red)	0.90	rubber	0.95
cement	0.54	skin (human)	0.98
copper (oxidised)	0.65	soil (dry)	0.92
glass	0.92	stainless steel	0.59
paper (white)	0.68	water	0.95
perspex	0.86	water (ice)	0.96
pipe (galvanized)	0.46	water (frost)	0.98
plastic (white)	0.84	wood (planed)	0.90

Material	Emissivity Coefficient - ε -
Water	0.993 - 0.998
Ice	0.98
Snow	0.969 - 0.997
Sand	0.949 - 0.962
Granite	0.898
Green Grass	0.975 - 0.986

Sensible heat flux – heat convection







Sensible heat flux (SHF) – heat convection

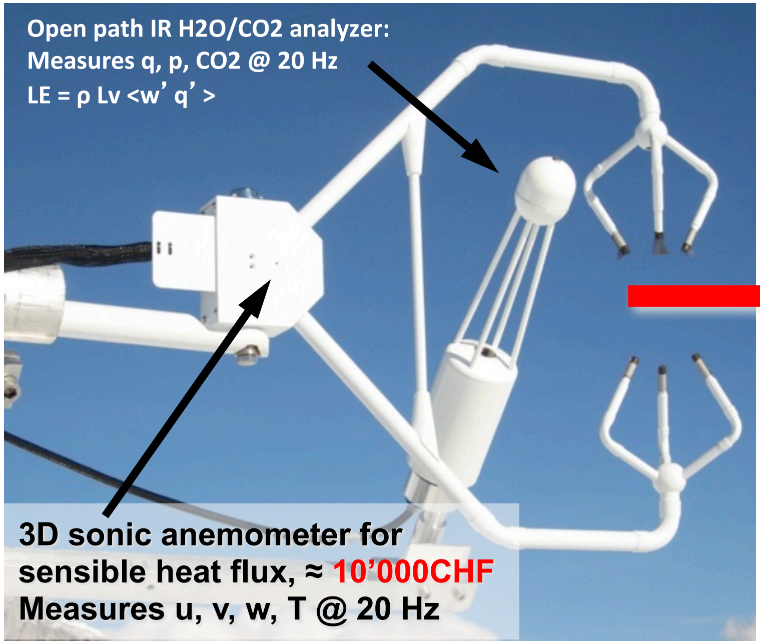
Turbulent flux of sensible heat (convection), [Wm^{-2}]:
Heat exchange between land (water) surface and the atmosphere;

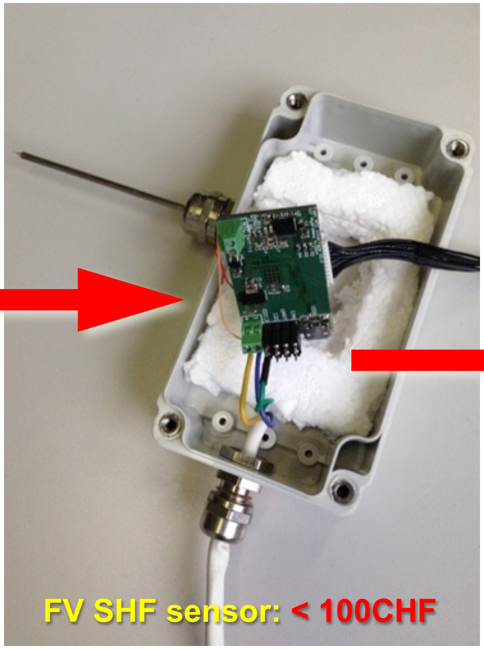
Reference sensors use Eddy Covariance (EC) method: $H_{EC} = \rho c_p <w'T'>$ [Wm^{-2}]

Here: Measurement principle based on
free convective scaling – flux variance (FV) method:
Albertson et al. 1995, Water Resour. Research *

$$H_{FV} = \sigma_T^{3/2} T_a^{-1/2} \rho c_p C_1^{-3/2} (\kappa g z)^{1/2}$$

Measurement of turbulent heat fluxes





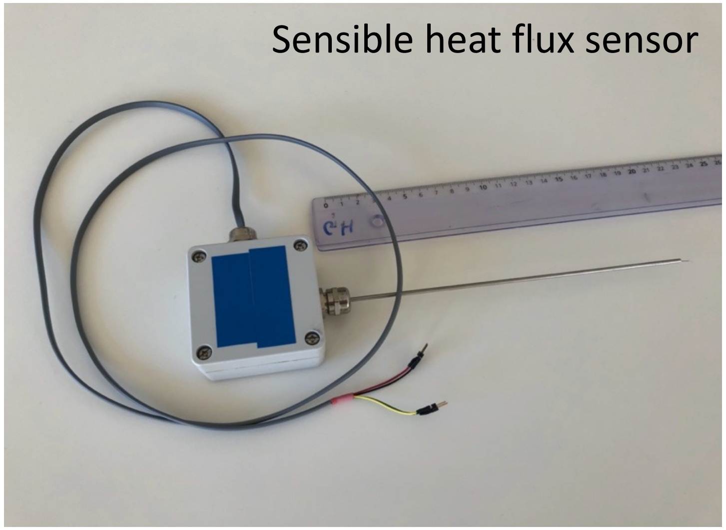
* https://doi.org/10.1029/94WR02978

Flux variance method for convective scaling

$$H_{FV} = \sigma_T^{3/2} T_a^{-1/2} \rho c_p C_1^{-3/2} (\kappa g z)^{1/2}$$

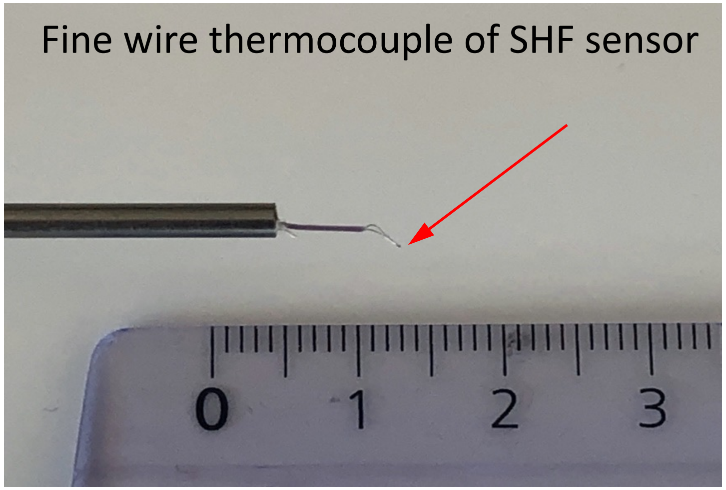
Albertson et al. 1995, Water Resources Research

H_{FV} = sensible heat flux from flux variance [W m^{-2}]
σ_T = **standard deviation** of air temp. (T_a) over meas. period [K]*
T_a = mean air temperature over sampling period [K] (1min)
$\rho(T_a)$ = density of the air 1.15 [kg m^{-3}]*
$c_p(T_a)$ = heat capacity of air 1005 [J kg^{-1} K^{-1}]
C_1 = empirical constant equal to 0.97 [--]
κ = von Karman's constant (0.4) [--]
g = gravitational acceleration 9.81 [m s^{-2}]
z = measurement height [m], here: 1m



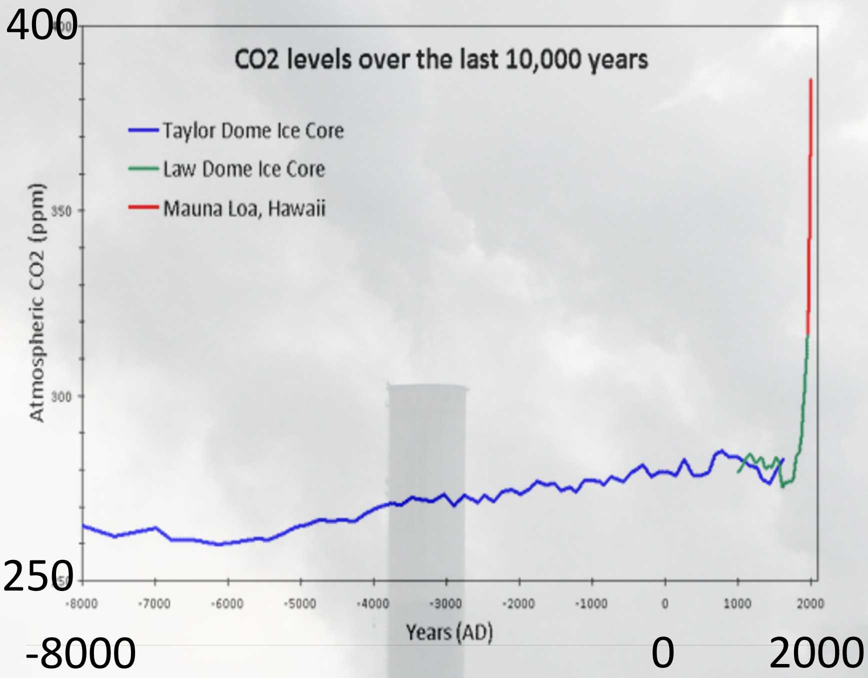
Requirement: Fast response temperature sensor.

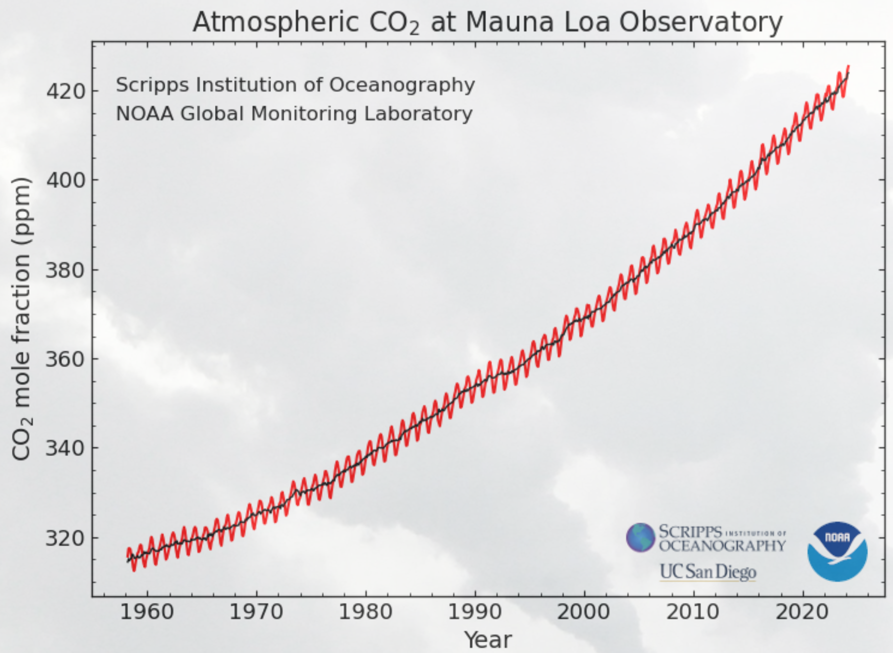
Here: thermocouple, TC (cold wire)
SH flux sensor specifications & characteristics:
TC Type E (Chromel-Constantan)
Wire diameter: 0.08 mm
Response time in still air: 0.1s
Sampling frequency: 20Hz continuous
Sampling interval/period: 1min



* For P = 950hPa, Ta = 12˚C, moist air RH = 30%
* For std and var given in [K], no need to add 273.15K, since std(T) of 1°C = std(T) of 1K (and not 274.14K !!)

Carbon dioxide (CO_2) measurements





Atmospheric pre- / historic CO_2 concentration

March 2024:	**425.38 ppm**
March 2023:	**420.99 ppm**

Last updated: Apr 05, 2024

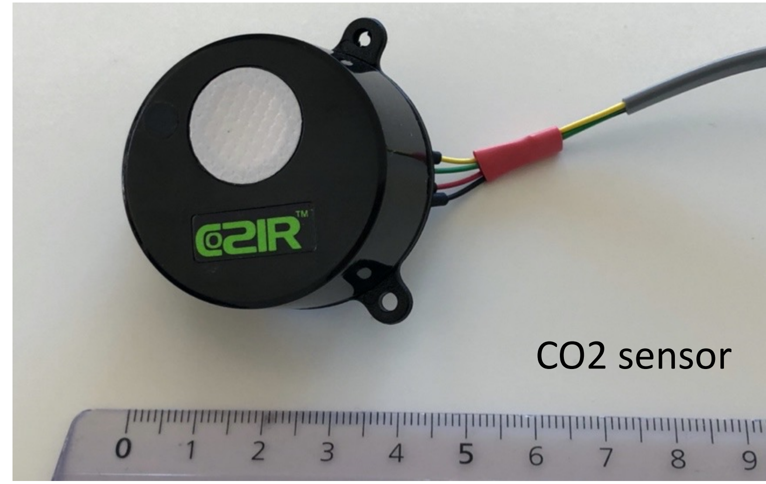
CO2 Sensor specifications and spectral absorption

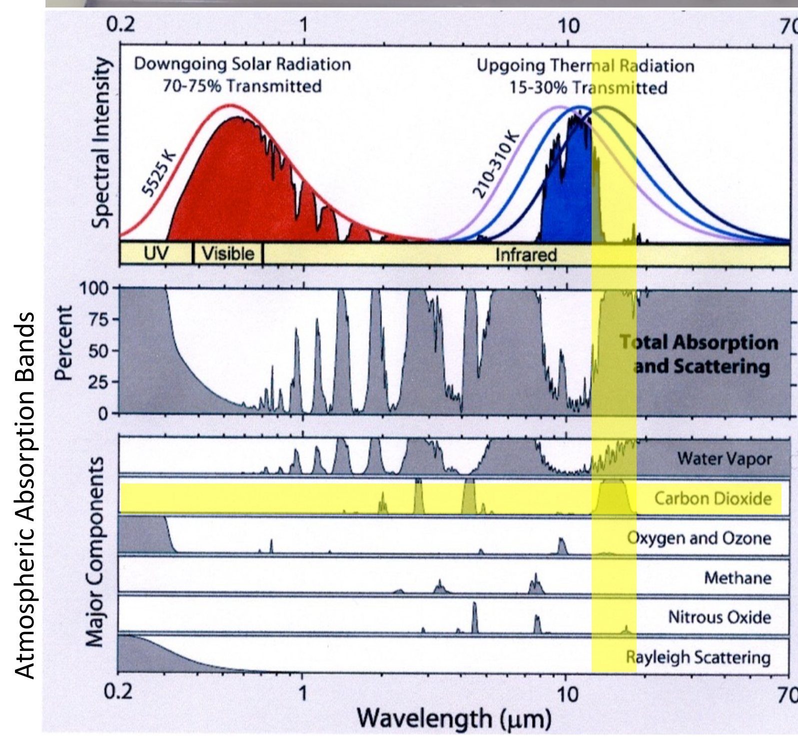
Low power (3.5mW), high performance non-dispersive infra-red (NDIR) CO_2 sensor based on IR LED detector technology; measurement range of 0-5000 ppm

Specifications

General Performance	
Warm-up Time	< 10s. 1.2 secs to first reading.
Operating Conditions	0°C to 50°C (Standard) -25°C to 55°C (Extended range) 0 to 95% RH, non-condensing
Recommended Storage	-30°C to +70°C
CO2 Measurement	
Sensing Method	Non-dispersive infrared (NDIR) absorption Patented Gold-plated optics Patented Solid-state source and detector
Sample Method	Diffusion
Measurement Range	0-2000ppm, 0-5000ppm, 0-1%
Accuracy	±50 ppm +/- 3% of reading[1]
Calibration	Autocalibration[6]
Non Linearity	< 1% of FS
Pressure Dependence	0.13% of reading per mm Hg in normal atmospheric conditions.
Operating Pressure Range	950 mbar to 1050 mbar[2]
Response Time	30 secs to 3 mins (Configurable via filter type and application)[3] Reading refreshed twice per second.[3]

Temperature & Humidity Measurement[5] Optional Temperature and Humidity sensor (only available as digital output)		
Sensing Method	Humidity: Capacitive Temperature: Bandgap	
Measurement Range	-25 to +55 °C 0 to 95% RH	
Resolution	0.08 °C 0.08% RH	
Absolute Accuracy[5]	+/- 1 °C +/- 3% RH +/- 2 °C +/- 5% RH	0°C to 55°C. 20°C to 55°C. over the full temperature range. over the full temperature range.
Repeatability	+/- 0.1 °C +/- 0.1 % RH	

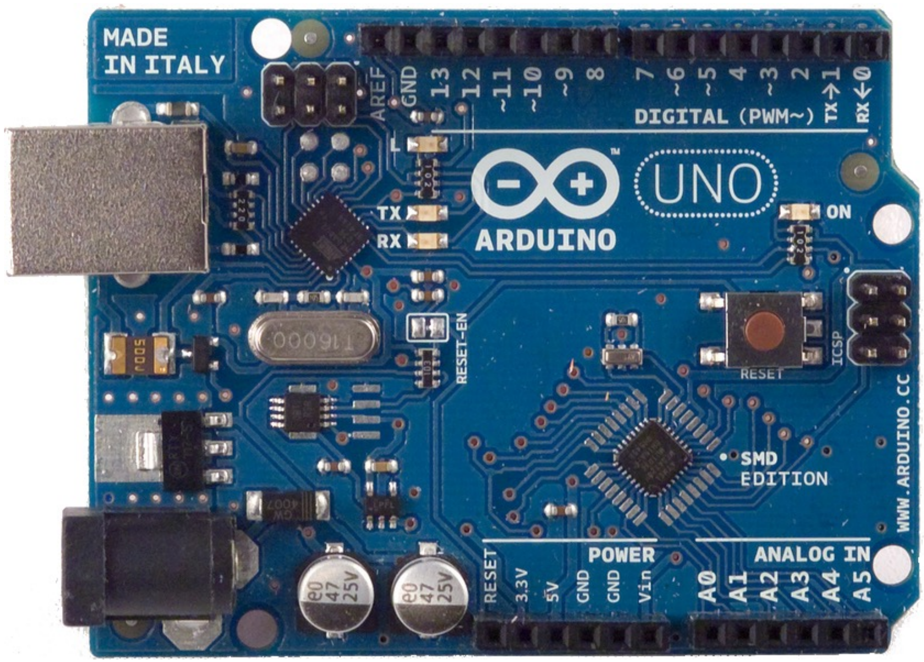


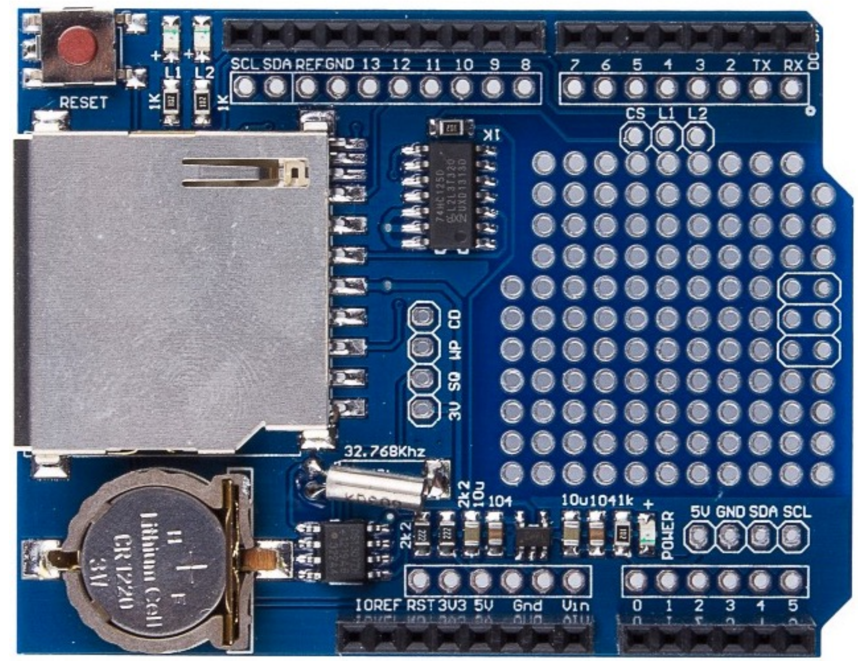


Arduino-based data logging system

Arduino UNO

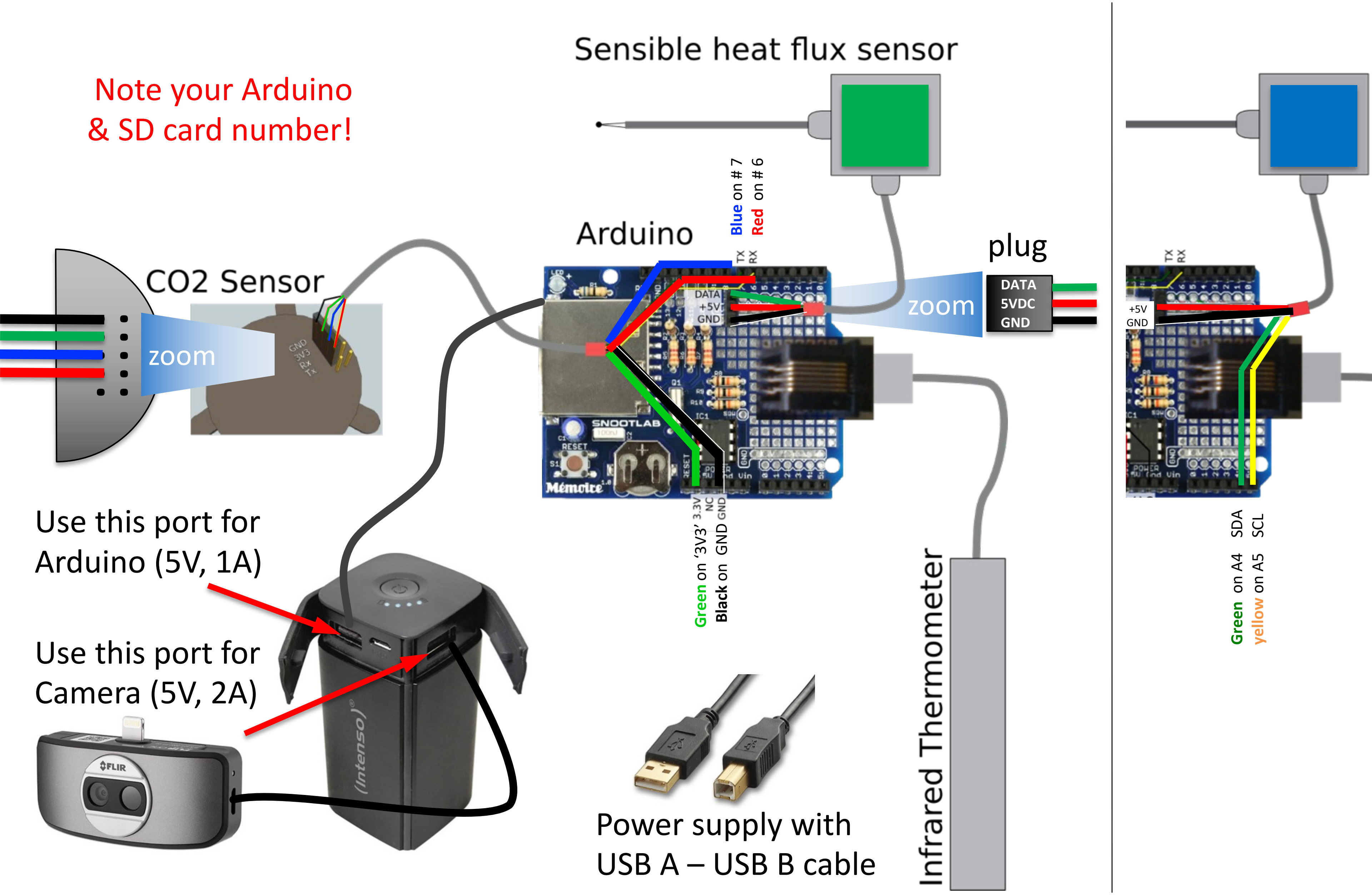
logging shield with real time clock and (micro-) SD card





Please download and install Arduino IDE 2.3.2 (or 1.8.19) on your laptop

Wiring scheme



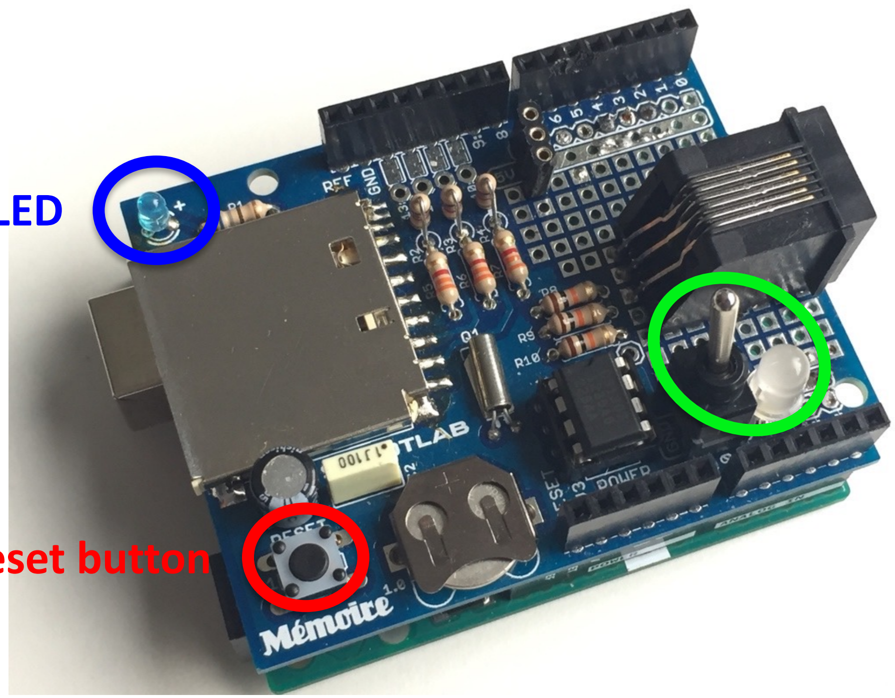
Data files from logger

Filename ddHHMMSS.csv e.g., 27151239.csv where dd is the day of the month

CO2 sensor | **IR sensor** | **SHF sensor**

Unix time [s], date, Temp [degC], RH [%], CO2 [ppm], IRTemp [degC], AmbientTemp [degC], SHFTemp [degC], SHFVar [1x10-4 degC^2]
1460472165, 2016/4/12 14:42:45, 24.90, 33.70, 669, 24.91, 24.54
1460472170, 2016/4/12 14:42:50, 24.90, 33.70, 664, nan, 24.54
1460472175, 2016/4/12 14:42:55, 24.90, 33.70, 685, 24.85, 24.54
1460472180, 2016/4/12 14:43:0, 25.00, 33.70, 673, 25.04, 24.54, 19.818, 955.216
1460472185, 2016/4/12 14:43:5, 24.90, 33.70, 676, 24.79, 24.54

Be careful, the sensor gives the temperature variance (σ^2) in [$1x10^{-4}$ °C^2]. In the SHF equation, you need the standard deviation (σ) to the power of 1.5



Data logger (Arduino) operation

- First, make sure the SD card is present. Connect all sensors, then power the Arduino, while the tip switch is turned “OFF”. The program takes the following measurements:
  CO_2 and IRS: sampling at 5s, SHF: sampling at 20Hz, output at 60s. Writing on SD card: 60s.

- If all works fine, the large LED on the SD shield is green; in case of a problem, it turns red.
  During measurements, the small LED is blinking blue.
  (During code compilation the blue LED is on continuously).

- A new file is created each time the tip switch is pushed to the “ON” position. Then, measurement/logging starts without any other action from the user (green LED indicates measurement and data writing in progress). In case of red LED (indicates error mode), push the RESET button (this also creates a new file).

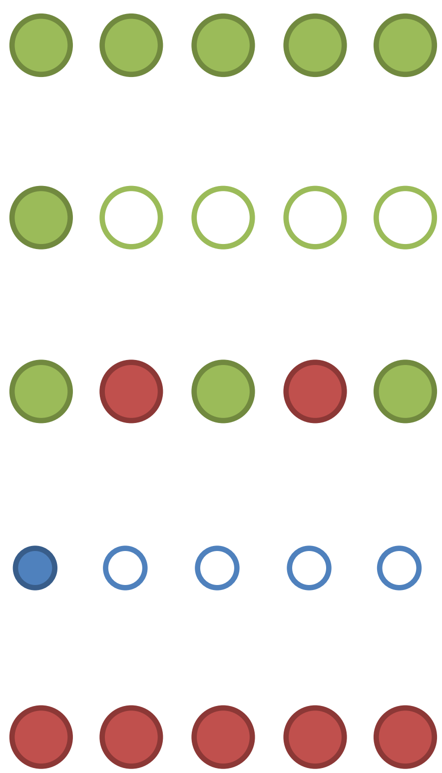
- For logging data of a new experiment, it is best to operate the switch: (OFF: LED off, and ON: LED green). This creates a new time-stamped file (ddHHMMSS.csv) on the SD card.

- Removing the SD card from the shield and putting it back does not automatically reset the Arduino. The logger will not be able to log again on the same file. Reset the logger (power off/on or push the RESET button).

- Note: the SD card may already have some test files written to it (you can ignore them).

LED signals

1s 2s 3s 4s 5s — Time in [seconds]



Normal operation

Normal operation but turned off

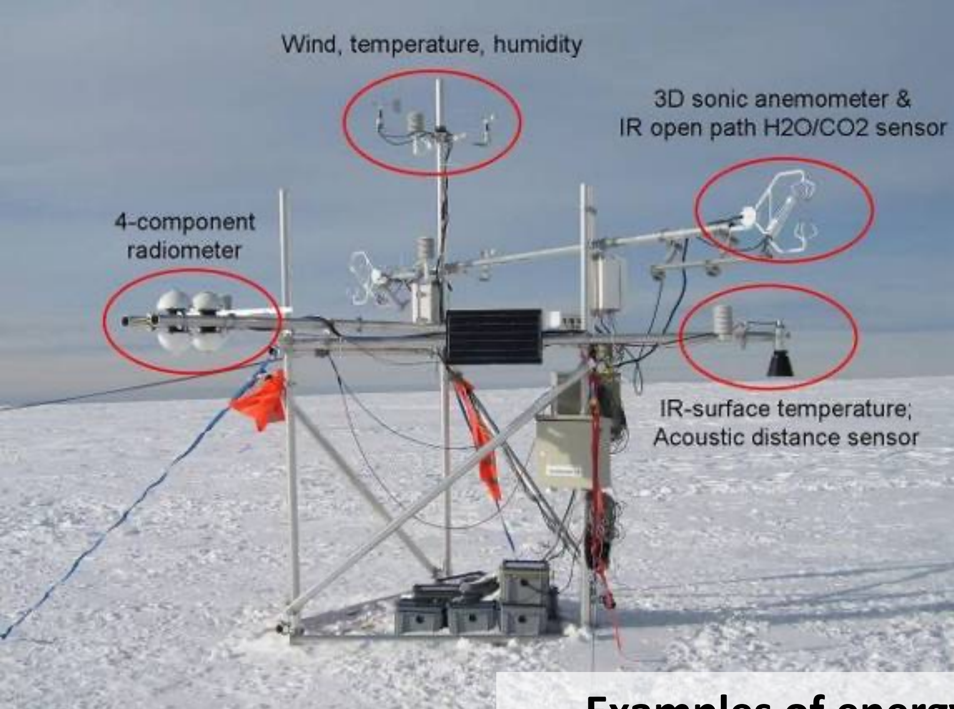
Writing data to SD (every 30 seconds)

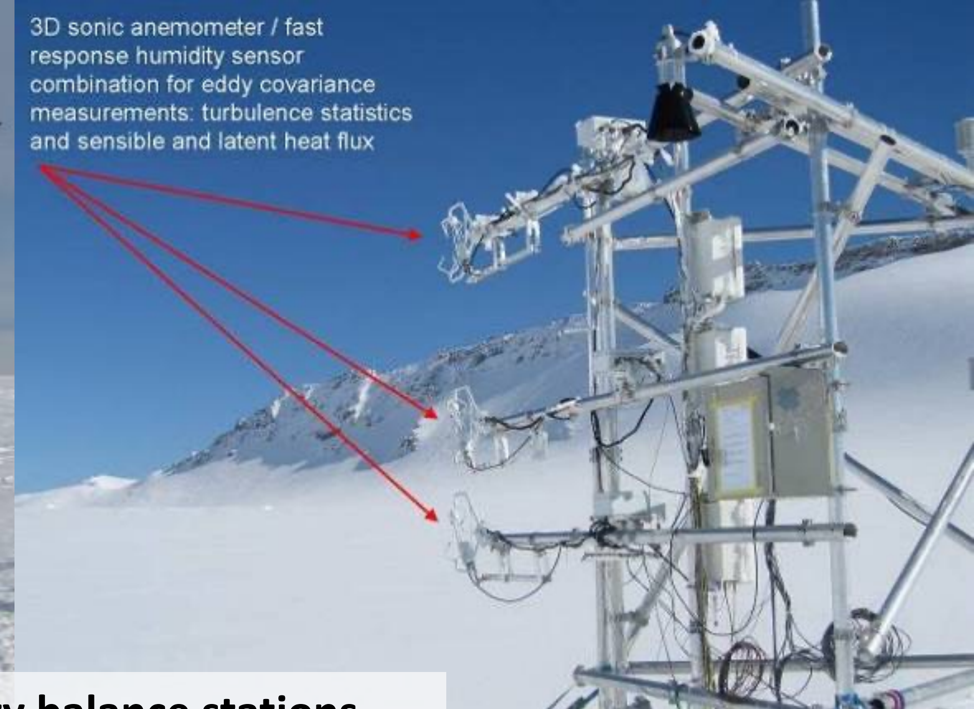
Measure all sensors

ERROR -> Turn OFF -> disconnect power and wait 15s

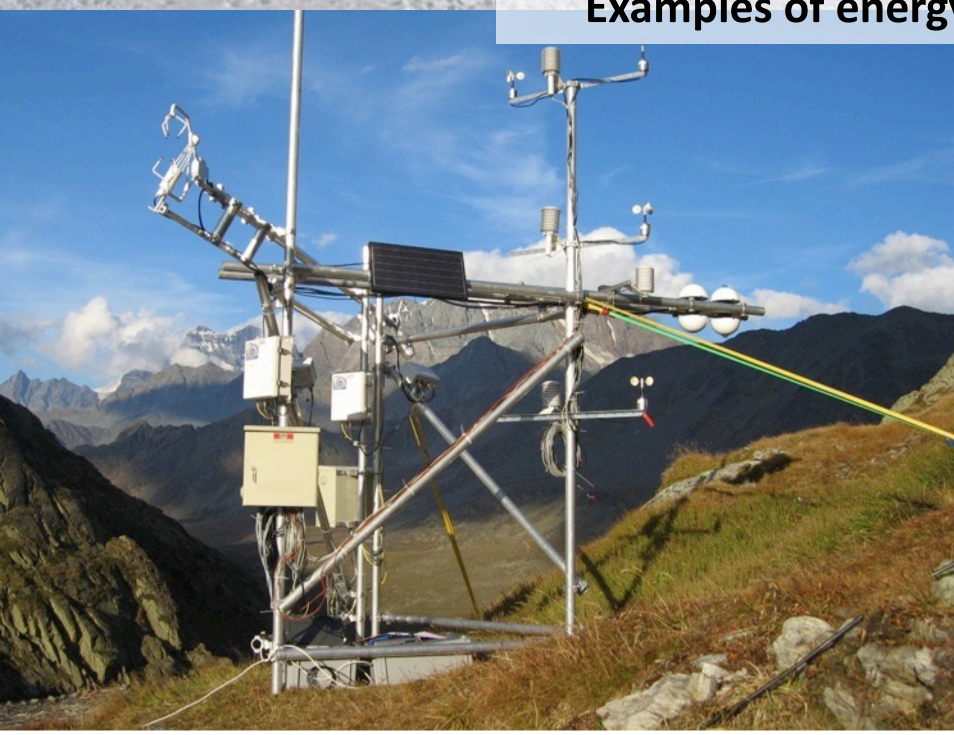
Taking notes: field book / measurement protocol

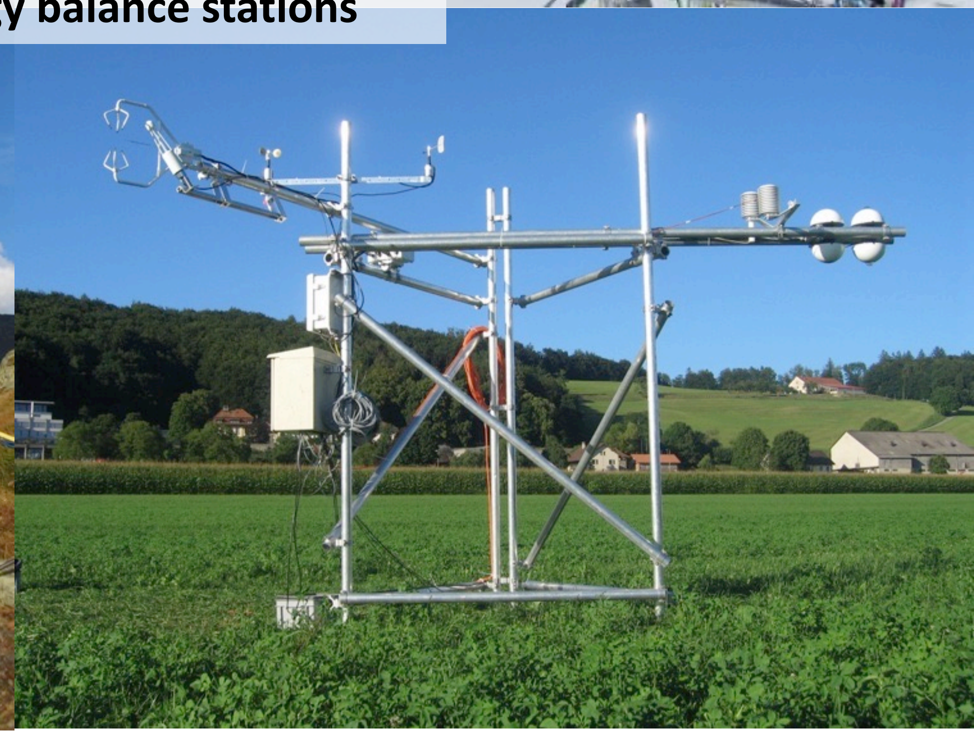
- Note the number of your Arduino data logger and SD card.
- Note where, when, and what you measure to identify events or different experiments in recorded output files. Match with corresponding time stamps.
- Note if conditions change during data acquisition, e.g. cloudiness, wind speed, etc.
- For transportation, it is best to leave the Arduino, power bank, and sensors in the provided box.
- Before starting with the experiments, check system functionality and measurements using the Arduino "Serial Monitor".
- Before you start measuring, read the instructions for each experiment.
- Whenever possible, fix sensors to the pole during measurements (not hand-held).
- For SHF and CO_2 measurements, note the sensor height (above ground), for IRS and IRC the approximate distance to the target (to know the footprint area given the FOV of the sensor).
- Heat flux measurements should last at least 10 min per site.
- IR temperature and CO_2 measurements last at least 5 min per site.





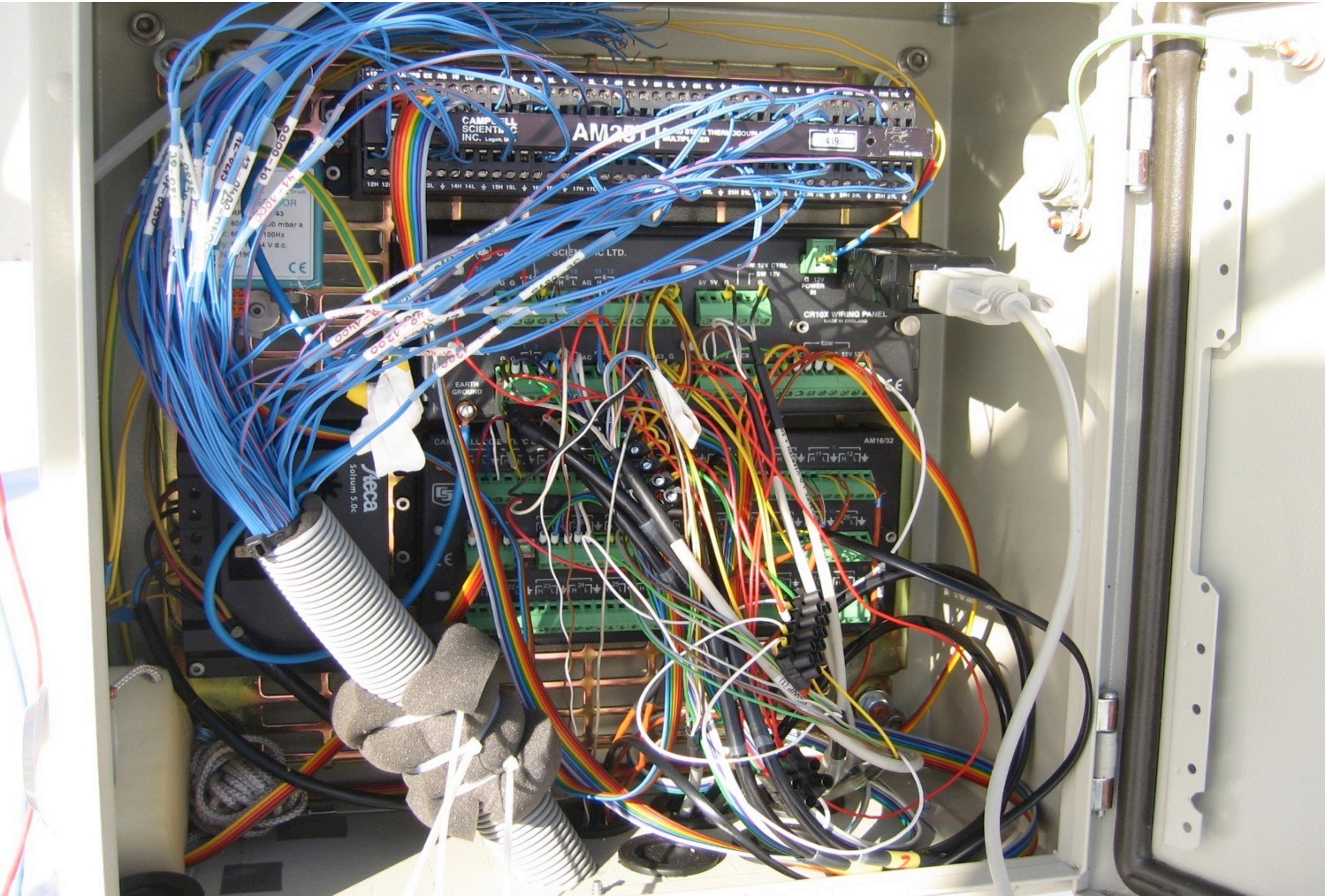
Examples of energy balance stations





Measurement errors: weather conditions

Measurement errors: mismanipulation



Precaution and Safety instructions

Wear mask
Disinfect hands
Keep distance

- **Handle all equipment (sensors) with great care (some components are very fragile: e.g., TC tip, cable connections)**
- **Protect sensors from rain/water**
- **Do not touch white membrane of CO_2 sensor**

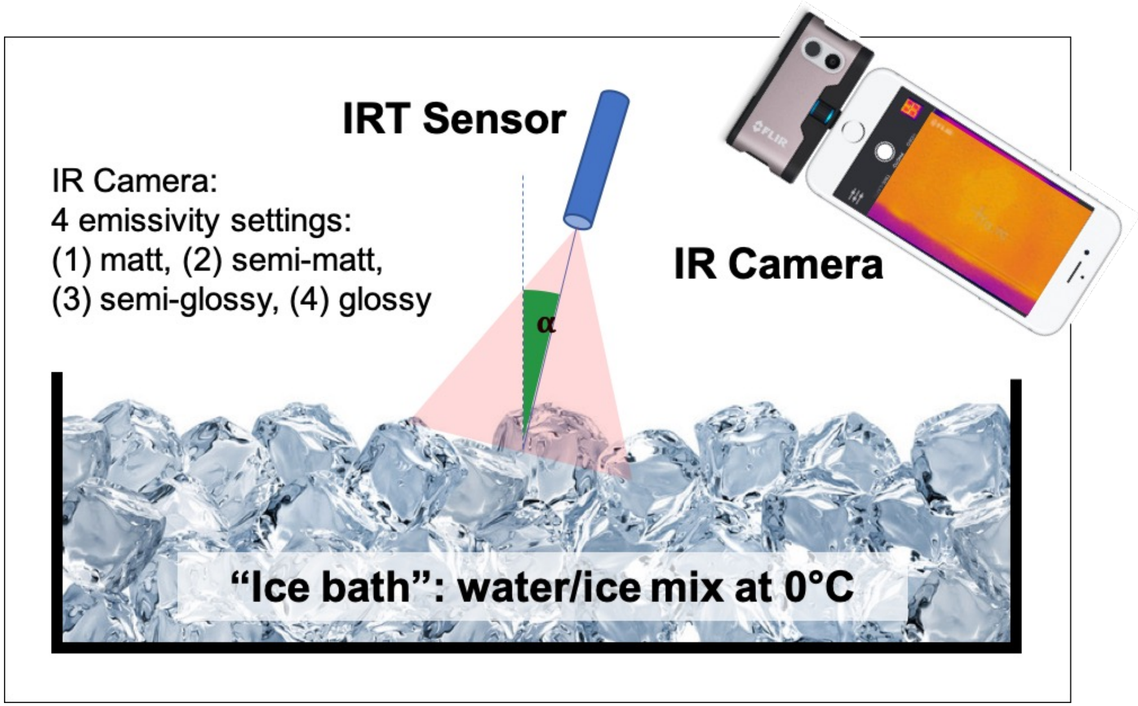
Measurement instructions (1)

(1) IR surface temperature, Ts, using IR sensor (IRS) and/or IR camera (IRC)

(a) Indoor:

1. <u>Ice bath</u>: A plastic box is filled with a mixture of crushed ice and water. IRS and IRC are oriented towards the ice surface at a small zenith angle (to reduce direct thermal reflection). Take care that the instrument field of view contains nothing else than the ice water mixture; avoid contributions from box walls and from your hand, ideally use a support to hold the sensors.

   Using the IRS, measure Ts of the ice/water mix over a few minutes. Measure Ts of the ice-water mix with the IRC held at a zenith angle of about 20° for all 4 FlirOne pre-set emissivities; later compute the IRS intrinsic emissivity, and the 4 IRC emissivity values assuming an emissivity of the ice/water mixture of 0.98, a room temperature of 23°C, and an emissivity of 0.95 of the surrounding.



Note: in **all other** experiments, the IRC pre-set emissivity "**matt**" should be used.

Measurement instructions (2)

(1) IR surface temperature, Ts, using IR sensor (IRS) and/or IR camera (IRC)

(a) Indoor:

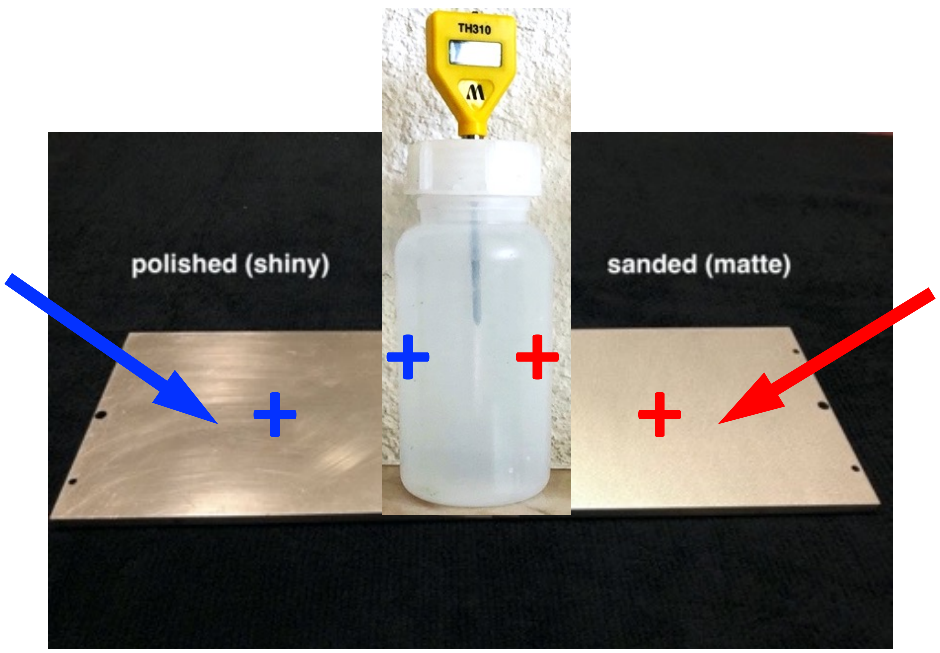
2. PE bottles: Using the IRC, measure Ts of the 3 PE bottles; Place the camera such that all 3 bottles are in the FOV; place the 3 target pointers on the center of each bottle. Record the corresponding thermometer reading. Assume a value of 0.95 as emissivity of the PE bottles. Present all measurements in a table and discuss the results and especially the observed differences (if any). Which factors may be responsible for potential differences?

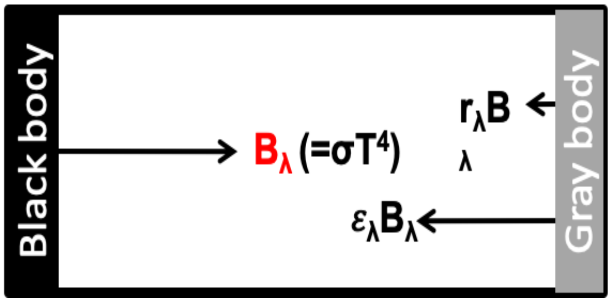
Measurement instructions (3)

(1) IR surface temperature, Ts, using IR sensor (IRS) and/or IR camera (IRC)

(a) Indoor:

3. Reflection: An object of known temperature (here a PE bottle filled with warm water) is placed at the center of an aluminum plate, which has a polished and a sanded surface. Using the IRC, take an IR picture including the bottle and the polished side of the plate, placing the camera target pointers one on the plate and one on the bottle (see blue arrow and sign). Take another picture including the bottle and the matt side of the plate, (pointers at equivalent positions (see red arrow and sign). Present, explain and interpret the images and measured apparent temperatures; what can be said about the texture and emissivity of the surface material?





Emissivity of different materials

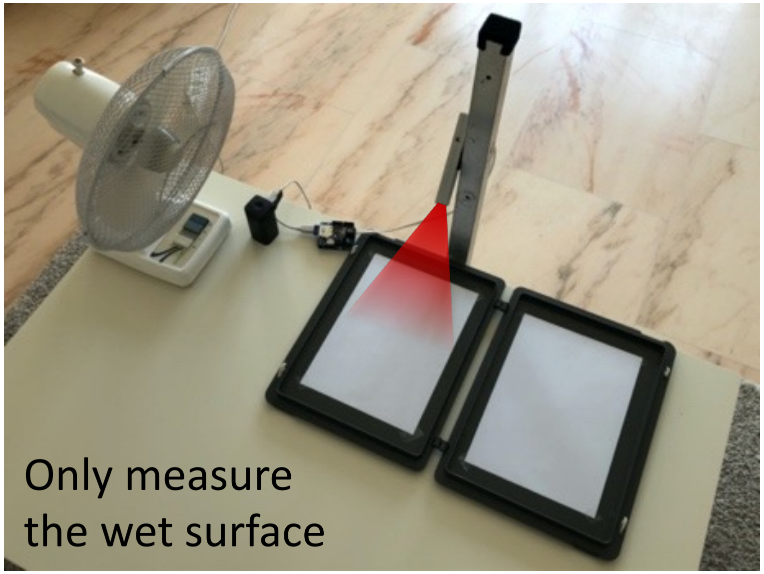
Material	Emissivity
Aluminum foil	0.03
Aluminum, anodized	0.90
Glass	0.95
Concrete	0.91
Water	0.97

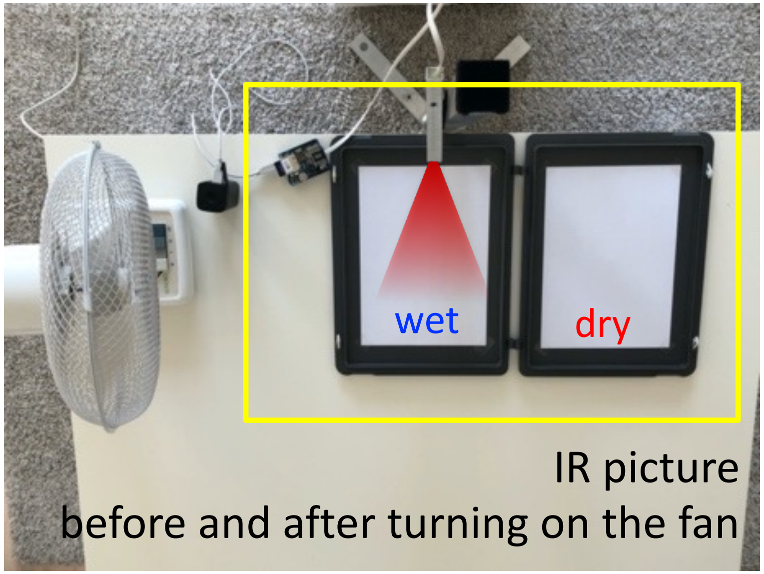
Measurement instructions (4)

(1) IR surface temperature, Ts, using IR sensor (IRS) and/or IR camera (IRC)

(a) Indoor:

4. Evaporation: Place the IRS such that the surface labeled “wet” is in its field of view as indicated in the Figure below. Using the IRC, take a picture including both designated surfaces. Start the fan and the measurements. After 1 min moisten the corresponding surface with ethanol at room temperature using an aerosol diffuser. A few seconds later, take a picture with the **IRC** including both designated surfaces. Continue measuring the designated wet area exposed to the air flow using the IRS until the surface is dry. Plot the time evolution of Ts of the wet area. Compare, discuss, and interpret the results, illustrate with the IR photos taken.





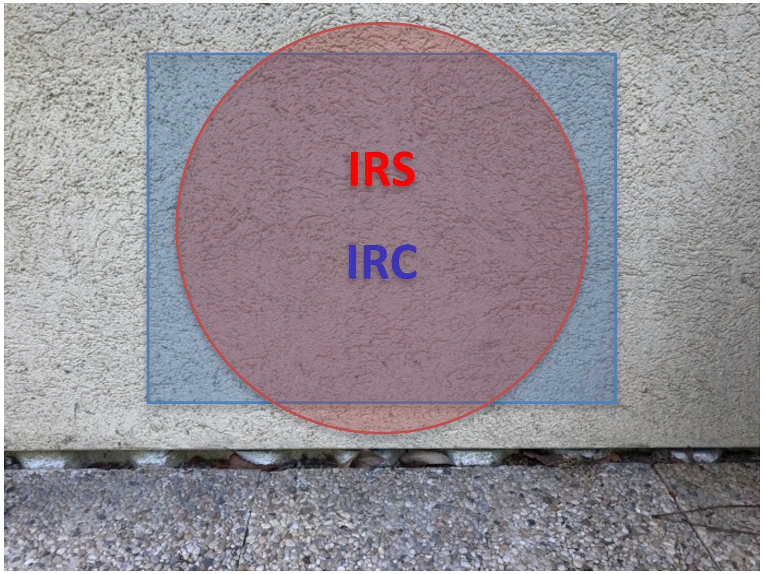
Measurement instructions (5)

(1) IR surface temperature, Ts, using IR sensor (IRS) and/or IR camera (IRC)

(b) Outdoor:

1. Façade temperature: Using the IRS and the IRC, measure the façade temperature of the GR building at the N, E, S, W façades (or at least sun-exposed and shaded) on the same façade material, preferably the concrete base (not the metal). Try targeting the same area with the two sensors. Present, compare, and discuss the results.

   If possible, measure a sun-exposed façade of different color but same material and orientation. Discuss the results.



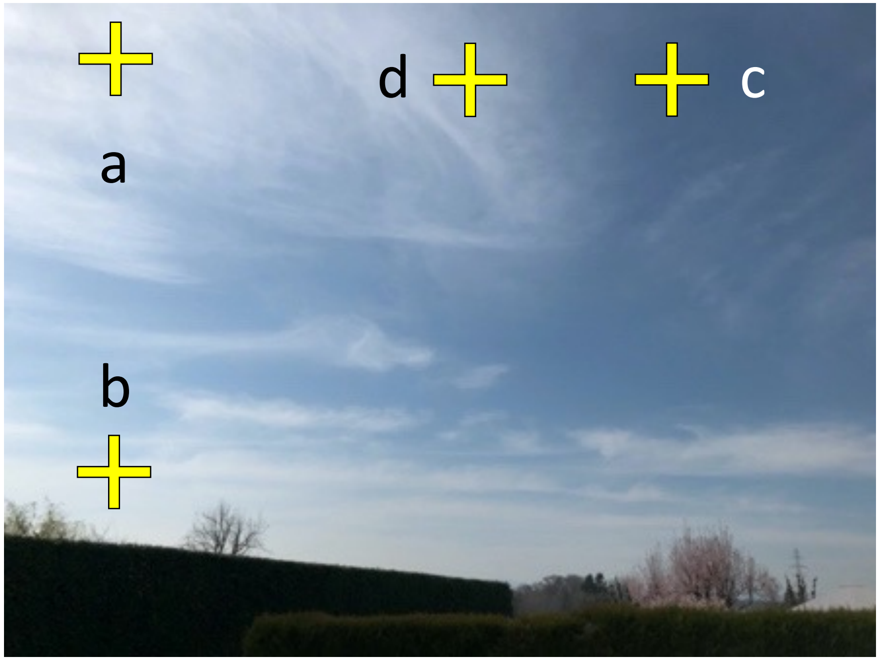
Measurement instructions (6)

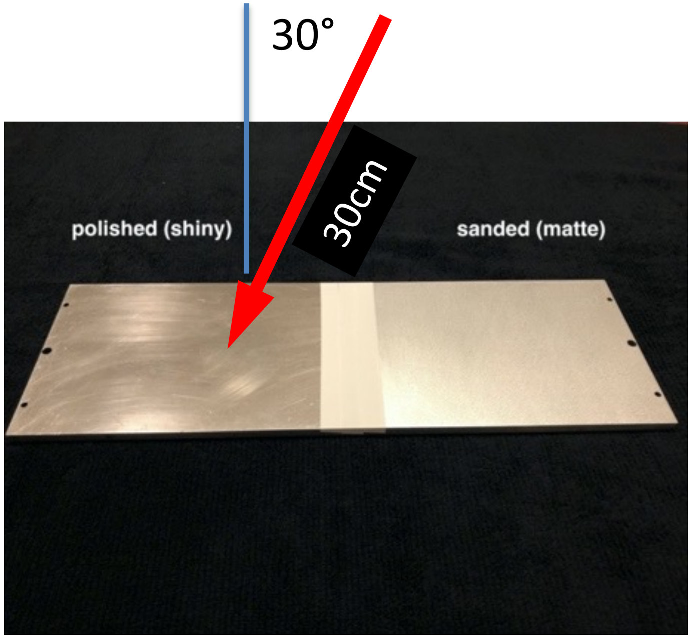
(1) IR surface temperature, Ts, using IR sensor (IRS) and/or IR camera (IRC)

(b) Outdoor:

2. Sky temperature: Using the IRC, measure Ts of the sky (a) vertically, not directly into the sun (not during rain), (b) just above the horizon; compare and discuss the results. Depending on the meteorological situation, target the blue sky (c), and a cloud (d), both at the same elevation angle; compare and discuss the results.

3. Using the IRC and the aluminum plate (polished side) from 1-a-3, measure the surface of the alu plate from a distance of about 20 cm and a zenith angle of about 30°. Discuss and interpret the results.





Measurement instructions (7)

(2) CO_2 concentration, c(CO_2)

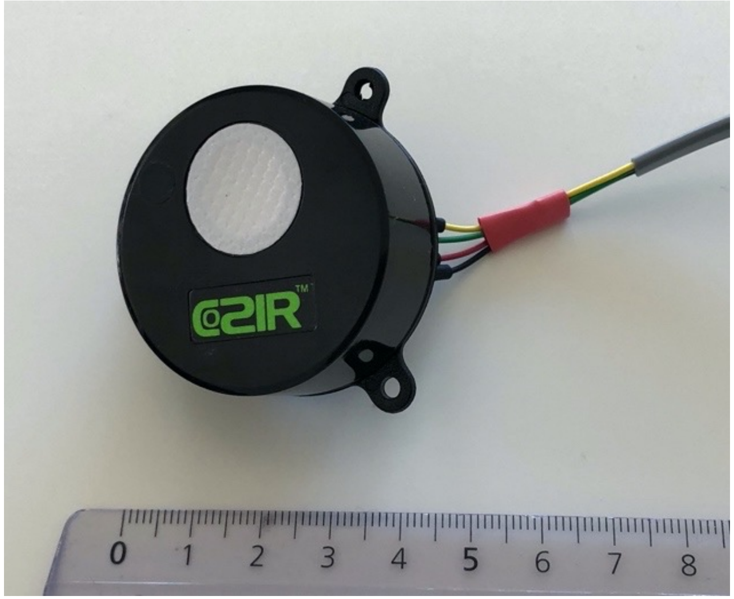
a. Measure c(CO_2) in the lab, i.e., TP room for at least 5min. Present and discuss the results.

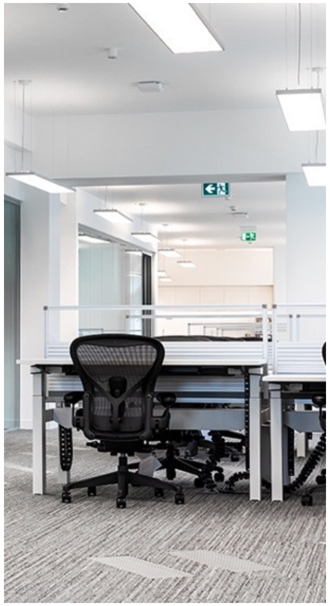
b. Measure c(CO_2) outdoors at a site far from potential CO_2 sources. Present and discuss the results.

c. Measure c(CO_2) of exhaled air and try to determine the sensor response time:

Place the CO_2 sensor in an empty zip-lock plastic bag and close it except for 1cm length. Insert a straw and blow air until bag is filled with exhaled air. Wait 1 min, then take the sensor out of the bag and measure for at least another 3 min.

d. Using the measurements of (c), try calculating (estimating) the response time of the sensor. Compare your result to the sensor specifications. Compare the max. concentration measured to the typical CO_2 concentration of human respirated (exhaled) air.



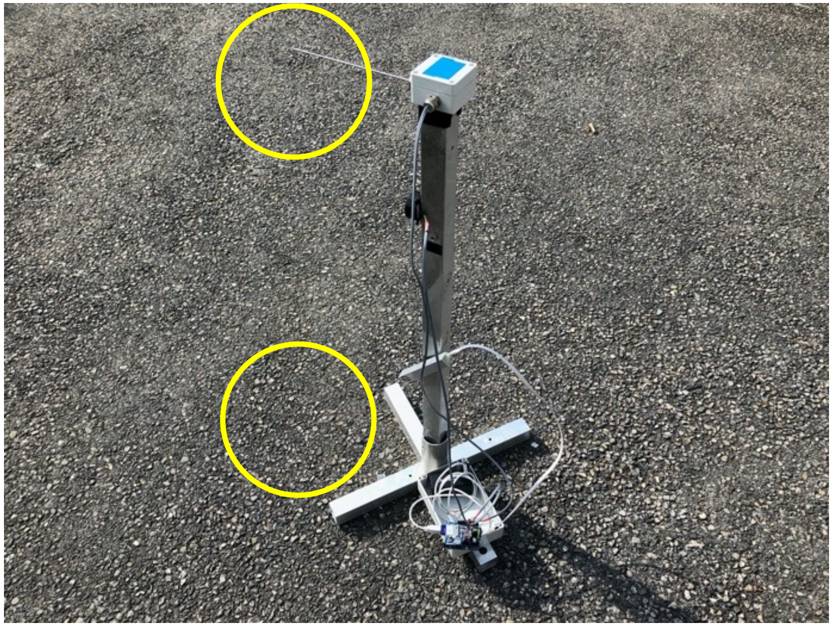


Measurement instructions (8)

(3) Sensible heat flux, SHF

a. Measure the air temperature variance over horizontal surfaces of (a) short grass and (b) asphalt, concrete, or tile, both sun-exposed if possible. The sensor tip points into the direction the wind is coming from. Do not stand upwind of sensor (or very close). Select a homogeneous and sufficiently large fetch (footprint area) without obstacles as a function of the wind direction. Using the air temperature variance data, calculate the SHF at both sites and compare and discuss the results.

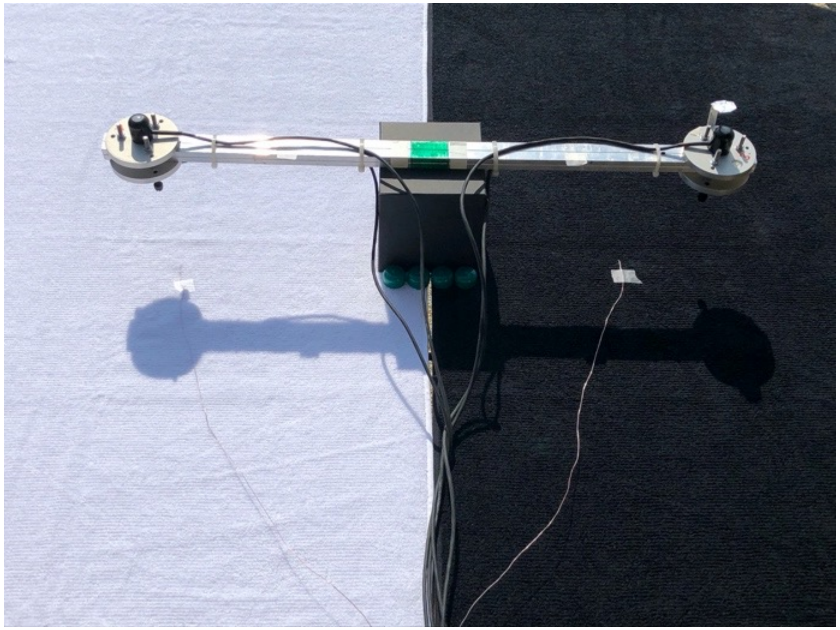
b. Using the IRS, measure Ts at the same locations (where the sensible heat flux is measured). Pay attention of the IRS footprint.



Measurement instructions (9)

(4) Solar radiation, albedo and surface temperature

a. Inspect the albedo experiment (pyranometers). Using the IRC, measure the surface temperature of the dark and bright surface. Radiation and surface temperature data will be provided at the end of the lab course day. Present and discuss the data set (provided as csv file).



Information for report writing

One report per group of 3 people as during the lab session (TP).

Format: **one** pdf submitted per email to hendrik.huwald@epfl.ch

Make sure you copy your co-authors for information.

Deadline: See Moodle: http://moodle.epfl.ch/course/view.php?id=13910

If applicable, (additional) data will be posted on Moodle shortly after the TP session, e.g., SW radiation/temp data

Evaluation criteria: "3C"

Complete: Report includes all elements indicated in the guidelines (next slide).
Correct: The results, analysis and discussion/conclusion are correct, concise and coherent
Clear: Figures, tables, layout, and argumentation are clear, well explained, pertinent, and easy to understand

Each requested report element is graded [$1 \leq x \leq 6$] and the mean is computed. Missing elements are graded 1.

Report guidelines

- **Front page**: course title, names of group members, name of teacher, date of lab session, number of Arduino and SD card used.
- **Include:** page numbers (not counting the front page). **Do not include:** table of contents, list of figures, list of tables, appendix.
- **Introduction:** (max. 2 pages, including figures)
  a) Weather conditions of the day and during outdoor work, (e.g., sun, clouds, wind, rain, humidity, surface conditions, etc.) and how they may impact the measurements; antecedent conditions: was it sunny/rainy the entire day? Suitable figure/s showing the evolution of relevant variables during the day may be useful.
  b) Situation map, any suitable map of your choice, e.g., Gmaps, SwissTopo, Campus Map, indicating locations, and annotated with type of measurements performed, map source, scale, orientation (North direction), and a legend explaining any symbols used.
- **Description of experiments:** as short/concise as possible, preceding the analysis and results of an experiment. Mention information relevant for the analysis and interpretation, e.g., where and how sensors are placed and oriented, distances, etc.
- **Presentation of results:** Calculate, plot, visualize, compare, and aggregate results using suitable graphs, figures, tables, and text of your choice. Make smart choices to present results in a concise, complete, and clear way.
- **Discussion:**
  a) Analysis and interpretation of results, conclusions.
  b) Discussion of errors and uncertainty arising from sensors (accuracy, resolution, response time, etc. refer to sensor specs), locations, surrounding, methodology, manipulation, data reliability, representativeness, and plausibility.
- **Summary and synthesis** of all experiments, connecting results and conclusions (max. 1 page).

Typically, reports consist of 10-12 pages (excl. front page, incl. all other above-mentioned elements and figures), but this is only indicative.

It is important that the following elements are clearly presented and understood:

- Difference between emissivity and albedo
- Difference between SW and LW and their physical processes (emission, absorption, reflection, transmission, refraction, scattering)
- Difference between sensible and latent heat flux

Bad weather alternatives

SHF:
Place the sensor indoors over a table and over a hotplate, create some random turbulence
Measure the surface temperature of both surfaces with the IRC
Lab hotplate: set to 50°C, SHF sensor 30cm above surface

SW:
Setup the experiment indoors next to the window