Climate Monitoring Guide

Planning

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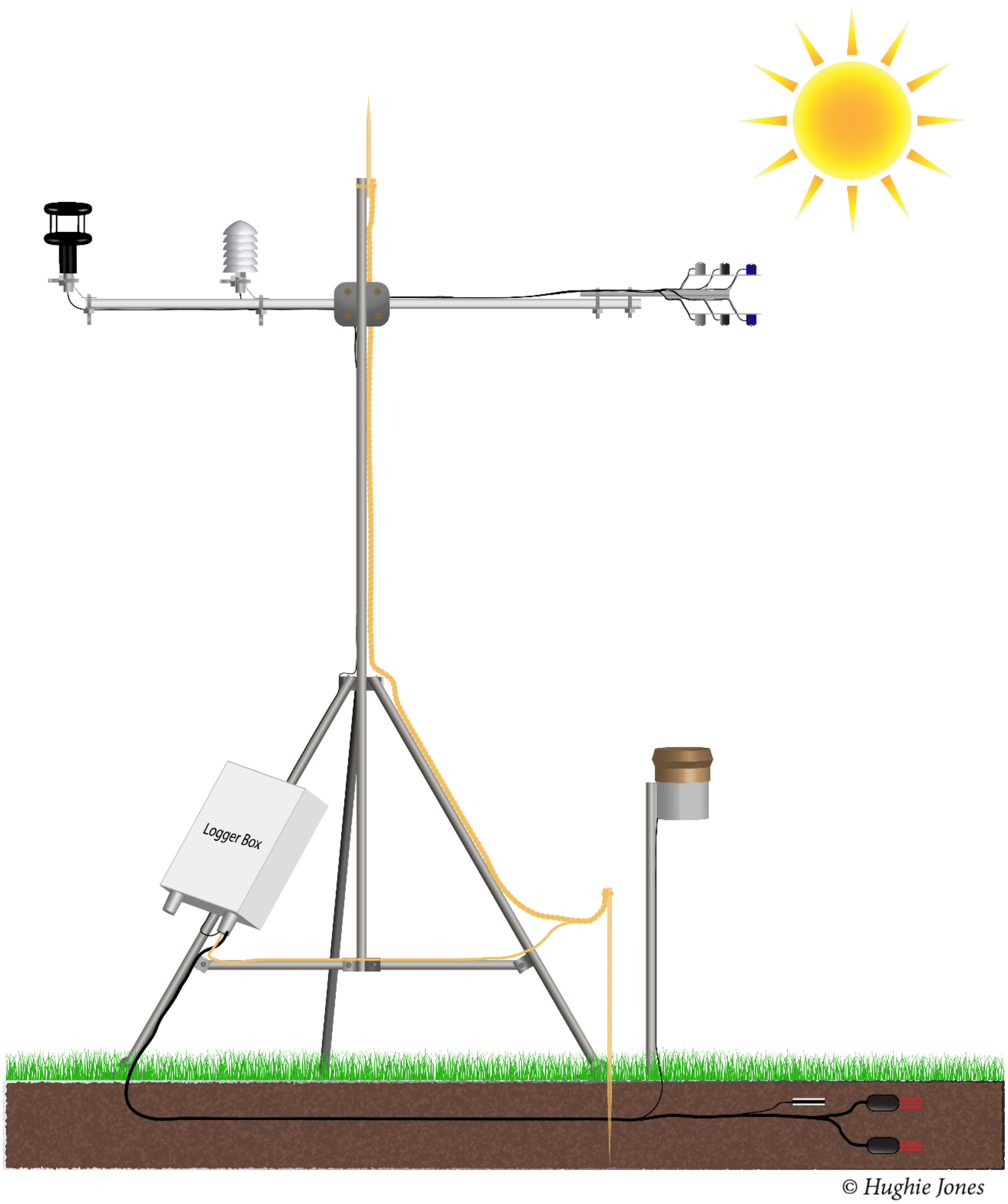

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1 Planning

1.1 Introduction

This section of the guide describes common climate monitoring indicators and sensors available to measure climate indicators. The climate indicators described in this section are common to many climate monitoring projects, yet every project team is required to decide which additional climate indicators are crucial for their specific climate monitoring objectives. In general, all project teams should focus on answering these core questions (why, what, where, when, how?):

- Why – **why** are we measuring climate?
- What – **what** should be measured?
- Where – **where** will climate monitoring occur?
- When – **when** will measurements occur (e.g., summer; winter; year-round; day and night)?
- How – **how** will climate indicators be measured?

The questions listed above should be discussed, answered, and constantly referred to throughout all phases of a climate monitoring project.

1.2 Climate indicators

For simplicity, the climate station in this guide will comprise common climate indicators measured at climate stations (

Table 1 and **Fig. 1**). In general, essential climate monitoring focuses on various key components of the environment (defined in Section 1.3), more specifically:

Radiative inputs and outputs

- Shortwave radiation (i.e., solar radiation)
- Longwave radiation (i.e., thermal radiation)
- Photosynthetically active radiation

Hydrological cycle

- Atmospheric humidity (e.g., relative humidity, vapour density, vapour pressure deficit)
- Precipitation (e.g., rainfall, snowfall)
- Soil moisture (e.g., volumetric water content)

Atmospheric motion

- Wind speed
- Wind direction

Heat energy

- Air temperature
- Soil temperature
- Soil heat flux density

Table 1. Climate variable chosen for measurement with common abbreviations and scientific units.

Climate indicator name	Common abbreviation	Units
Air temperature	T_a	Kelvin (k) or Celsius (°C)
Precipitation	P	mm
Relative humidity	RH	%
Wind speed	u	m s^{-1}
Wind direction		Degrees (°)
Incoming shortwave radiation	S_d	Watts (W) m^{-2}
Outgoing shortwave radiation	S_u	W m^{-2}
Incoming longwave radiation	L_d	W m^{-2}
Outgoing longwave radiation	L_u	W m^{-2}
Incoming photosynthetically active radiation (PAR)	Q_d	μmol m^{-2} s^{-1}
Outgoing PAR radiation	Q_u	μmol m^{-2} s^{-1}
Soil temperature	T_s	Kelvin (k) or Celsius (°C)
Soil water content (gravimetric and volumetric)	θ	%
Soil heat flux density	G	W m^{-2}

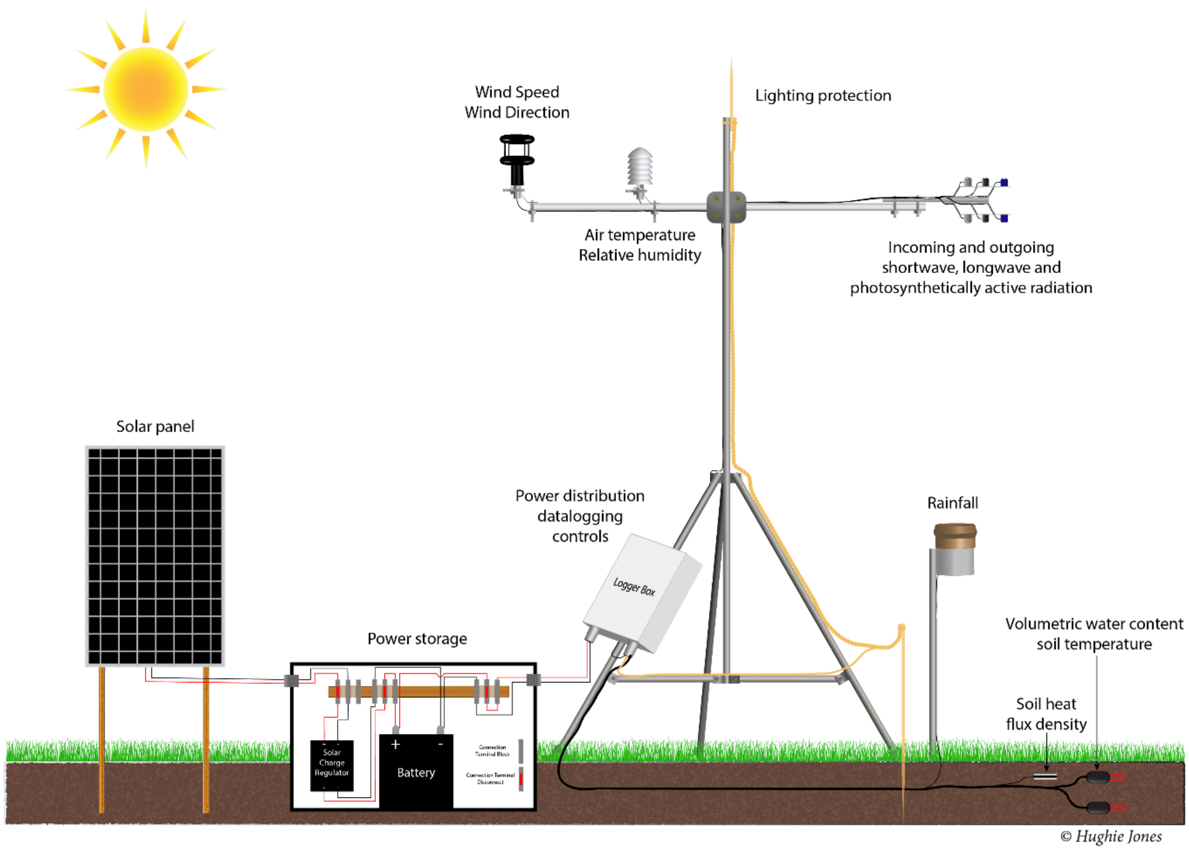


Fig. 1. Illustration of a climate monitoring station powered by an off-grid solar/battery system. The climate variables measured at this station include wind speed, wind direction, air temperature, precipitation, soil heat flux density, volumetric water content, soil temperature, relative humidity, shortwave radiation (incoming and outgoing), longwave radiation (incoming and outgoing) and photosynthetically active radiation (incoming and outgoing).

1.3 Climate sensors

Sensors are devices which measure a change in the physical environment and quantify the change with particular units and scale. Sensors are classified into two different categories, analog and digital. Dataloggers provide power, excitation to sensors and measure electrical signals produced by sensors. In general, both analog and digital sensors are wired directly into a datalogger, unless wireless sensors are used.

Analog sensor – produce a continuous (i.e., infinite number of values) output signal (e.g., voltages) which changes in proportion to changes in the physical environment (e.g., temperature, humidity, radiation).

Digital sensor – produce a discrete (i.e., finite number of values) output signal, using an analog-to-digital signal converter (ADC), which change in a step-wise manner in proportion to the changes in the physical environment (e.g., temperature, humidity, radiation).

1.3.1 Air temperature

Air temperature (T_a) is defined as the average kinetic energy contained in air and typically has units of Kelvin (K) or Celsius (ºC) (where K = 273.15 + ºC). T_a is a standard climate indicator, measured using various sensors (**Table 2** and **Fig. 2**).

Table 2. List of various sensors used to measure T_a.

Sensor type	Examples
Fine-wire thermocouple	https://www.omega.ca/en/resources/thermocouple-types
Resistance temperature detectors	https://www.omega.ca/en/resources/rtd
Thermistor	https://www.campbellsci.ca/109-l

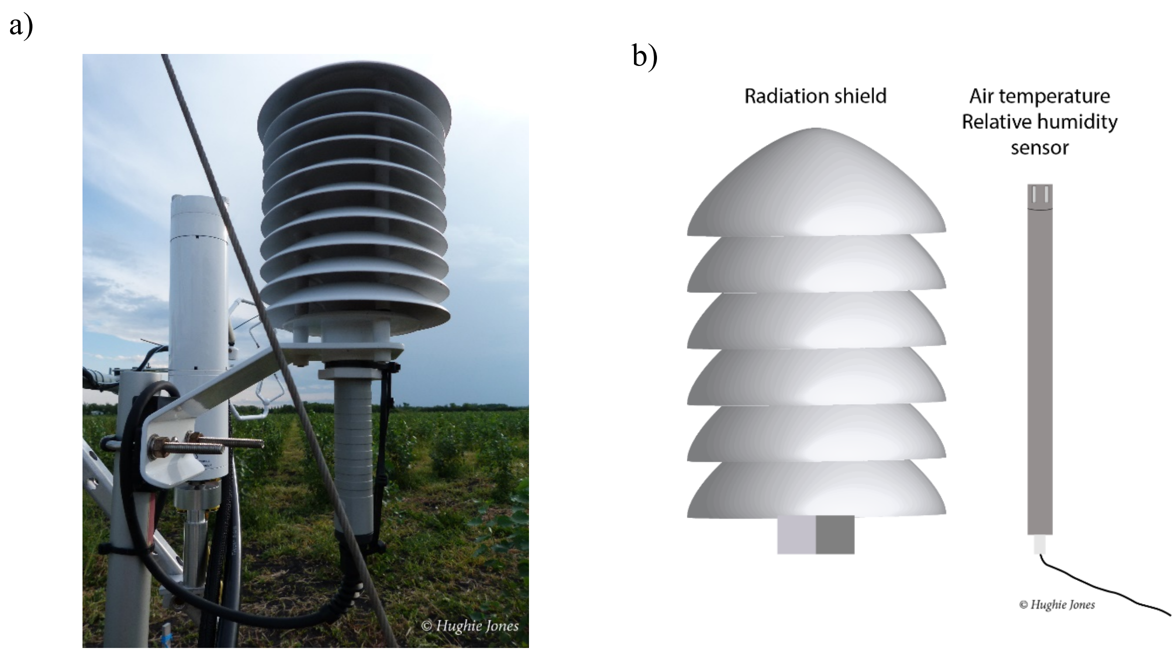


Fig. 2. Panel a) is a picture of a radiation shield with an air temperature and relative humidity sensor extending from the bottom of the shield. Panel b) is an illustration of a radiation shield and the air temperature and humidity sensor side by side, as they would appear separate from one another. The illustration in panel b) is used in **Fig. 1**.

1.3.2 Precipitation

Precipitation (P) is the process by which water vapor in the atmosphere returns to earth as a solid (e.g., snow, hail) or liquid (e.g., rainfall) and is typically measured as depth of liquid with units of millimeters (mm). P is a standard climate indicator which is measured using various sensors, depending on its state of matter (e.g., liquid vs solid) (**Table 3** and **Fig. 3**). In situations where P comes in both liquid and solid-state, multiple sensors are typically required.

Table 3. List of various sensors used to measure *P*.

Sensor type	Examples	State of matter
Tipping-bucket rain gauge	https://texaselectronics.com/products/rain-gauges/rain-gauge-tr-525m-metric.html	Liquid
Snow pillow	http://geonor.com/live/products/weather-instruments/fluidless-snow-pillow-snow-water-equivalent-monitoring/	Solid
Snow water equivalent	https://www.campbellsci.ca/cs725?gclid=CjwKCAjwkJj6BRA-EiwA0ZVPVsbigYtCiSbm65GGXFtmoWXCIY9pAbhlXS8H5UzDTksbJDY-i2nL5hoCRQAQAvD_BwE	Solid

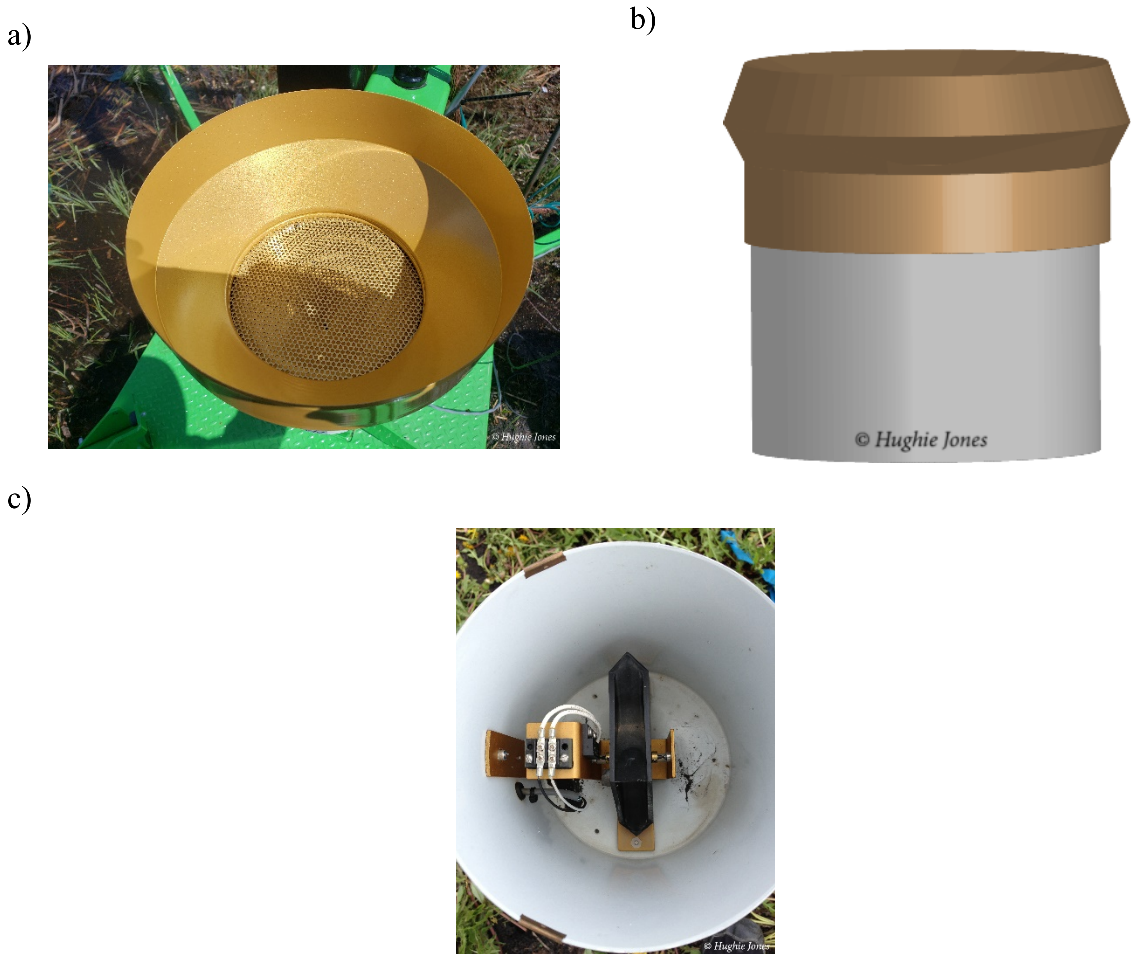


Fig. 3. Panel a) is a picture of a tipping bucket rain-gauge, with a debris screen. Panel b) is an illustration of a tipping bucket rain-gauge, as seen in **Fig. 1**. Panel c) is an overhead view of a tipping bucket rain-gauge with the rainfall catcher and debris screen removed, which shows the tipping bucket and associated electronics.

1.3.3 Humidity

Humidity is the quantity of water vapour in the atmosphere. Humidity is often expressed as:

- Water vapour density (ρ_a), gravimetric density (g m^{-3}) or molar density (μmol m^{-3})
- Vapour pressure (VP), with units of pressure (kPa).
- Relative humidity,

Humidity is also expressed in terms of atmospheric dryness, as relative humidity (RH) or vapour pressure deficit (VPD). The most common humidity sensors used on climate research are capacitive humidity sensors and infrared gas analyzers (**Table 4** and **Fig. 4**).

Table 4. List of various sensors used to measure humidity.

Sensor type	Examples	
Capacitive humidity sensors	https://www.vaisala.com/en/products/instruments-sensors-and-other-measurement-devices/instruments-industrial-measurements/hmp113	https://www.digikey.ca/en/products/detail/te-connectivity-measurement-specialties/HPP805C031/760154
Infrared gas analyzers	https://www.licor.com/env/products/gas_analysis/LI-830_LI-850/	

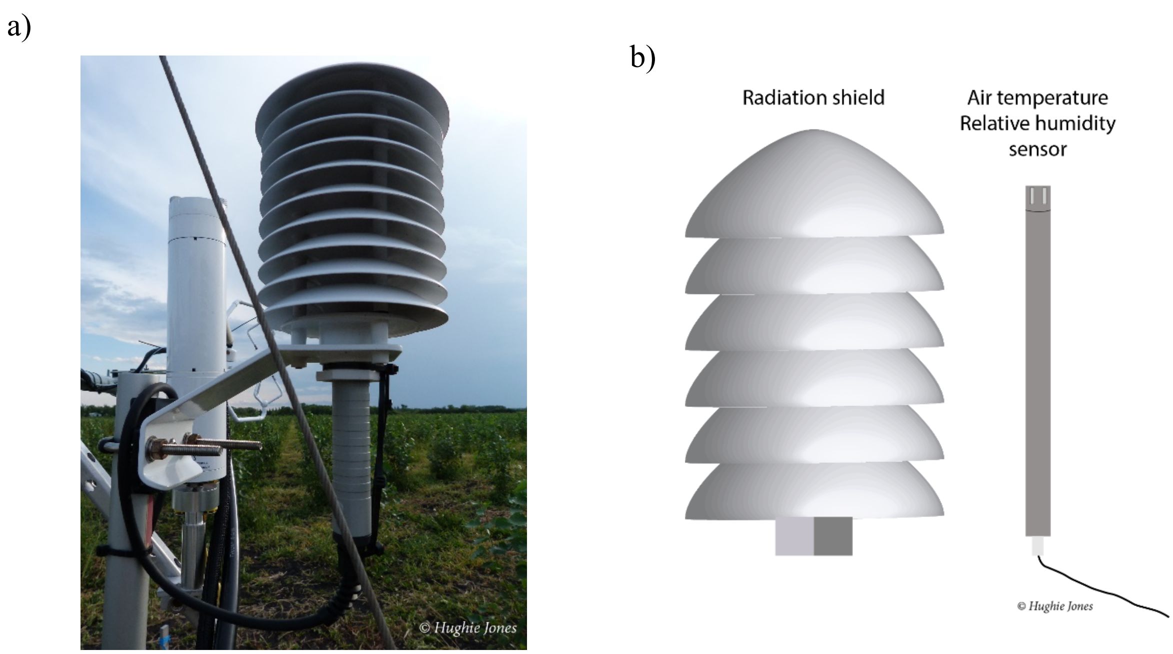


Fig. 4. Panel a) is a picture of a radiation shield with an air temperature and relative humidity sensor extending from the bottom of the shield. Panel b) is an illustration of a radiation shield and the air temperature and humidity sensor side by side, as they would appear separate from one another. The illustration in panel b) is used in **Fig. 1**.

1.3.4 Windspeed and direction

Horizontal wind speed and direction are often measured simultaneously using one instrument (e.g., sonic anemometer). Wind speed is defined as the air velocity of the atmosphere, measured in meters (m) per second (s) ($m\ s^{-1}$). Wind speed can be measured in 3 dimensions (horizontal, cross-wind and vertical), yet the horizontal component is measured most often at standard climate stations.

In climatology, wind direction (measured in degrees; ^{o}) is defined as the direction from which the air is flowing from, not the direction from which the air is flowing toward. For example, if the wind is flowing towards your position directly from the west the wind direction is equal to 270^o (See **Fig. 5** for another example). Horizontal wind speed and direction are commonly measured using either mechanical sensors or digital sonic anemometers (**Table 5** and **Fig. 6**).

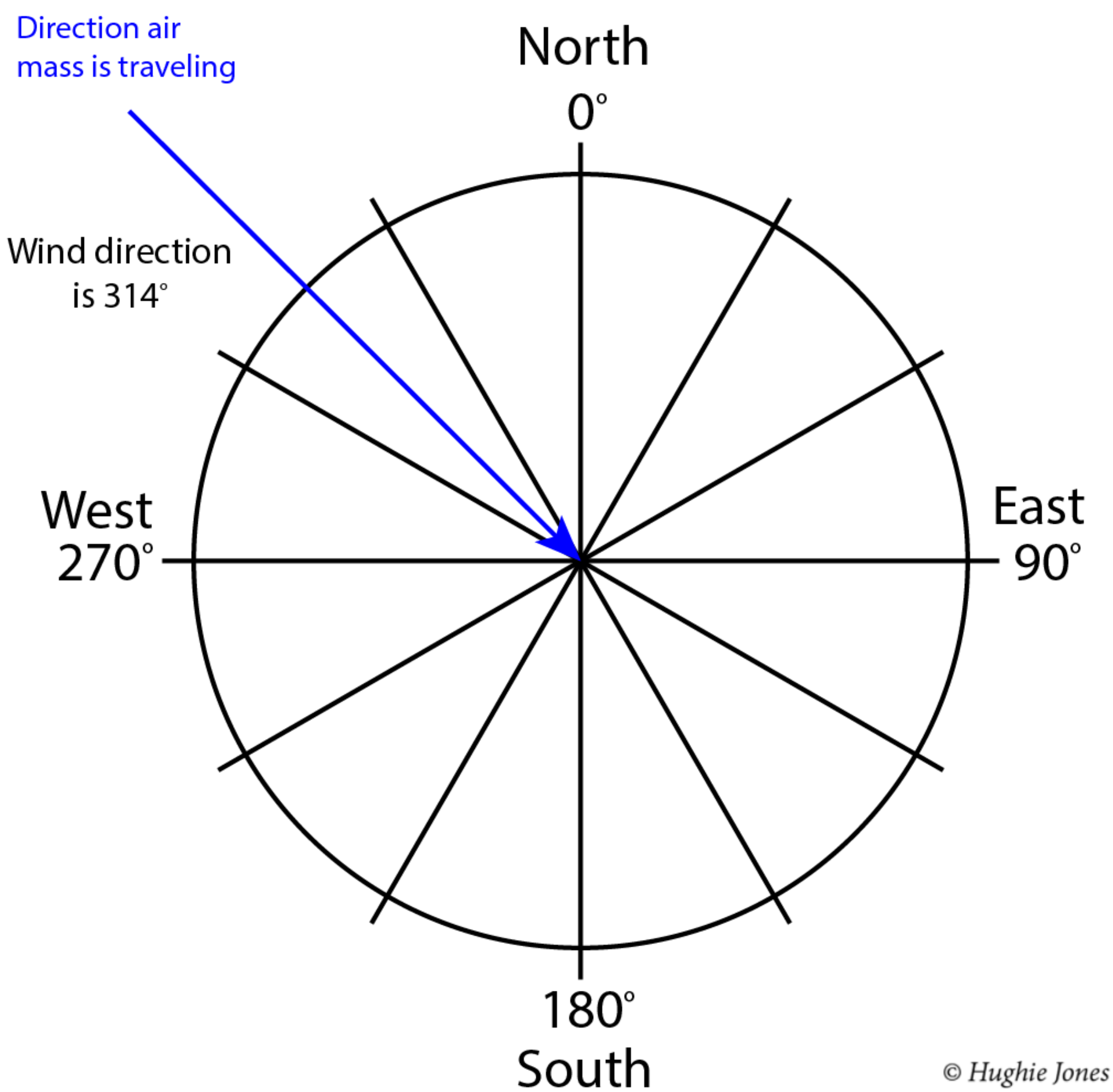


Fig. 5. Illustration of directionality convention for wind direction measurement in climatology.

Table 5. List of various wind speed and direction sensors.

Sensor type	Examples
Mechanical wind sensor	http://www.youngusa.com/products/7/5.html
Sonic anemometers	http://www.gillinstruments.com/products/anemometer/windsonic.htm

a) b)

Fig. 6. Panels a) is a picture of a sonic anemometer used to measure wind speed and direction. Panel b) is an illustration of a sonic anemometer, as seen in **Fig. 1**.

1.3.5 Shortwave and longwave radiation

Shortwave radiation (*S*) (i.e., sunlight or solar radiation) and longwave radiation (*L*) (i.e., terrestrial radiation or thermal radiation) are fundamental climate indicators used to quantify the radiation balance of earth surface.

Shortwave radiation - Incoming shortwave radiation ($S_{incoming}$) from the sun is measured using an upward-facing (facing the sky) pyranometer and outgoing (or reflected) shortwave radiation ($S_{outgoing}$) is measured using a downward-facing (facing the earth's surface) pyranometer (**Table 6** and **Fig. 7**).

Longwave radiation - Incoming longwave radiation emitted from the sky ($L_{incoming}$) is measured using an upward-facing (facing the sky) pyrgeometers and longwave radiation emitted from the earth surface ($L_{outgoing}$) is measured using a downward-facing (facing the earth's surface) pyrgeometer (**Table 6** and **Fig. 7**).

Net radiation - Sometimes, sensors for measuring $S_{incoming}$, $S_{outgoing}$, $L_{incoming}$, $L_{outgoing}$ are combined into a single unit called a net radiometer, which allows the calculation of net radiation (R_n; $R_n = [S_{incoming} - S_{outgoing}] + [L_{incoming}, L_{outgoing}]$) (**Table 6** and **Fig. 7**).

The units for shortwave, longwave and net radiation are watts (W) per meter squared (m^{-2}) (W m^{-2}).

Table 6. List of sensors used to measure shortwave and longwave radiation.

Sensor type	Examples	Additional information
Pyranometer	https://www.campbellsci.com/cs320	https://www.campbellsci.com/blog/pyranometers-need-to-know
Pyrgeometer	https://www.apogeeinstruments.com/pyrgeometers/	
Net radiometer	https://www.apogeeinstruments.com/net-radiometer/ https://www.kippzonen.com/Product/85/CNR4-Net-Radiometer#.X07Eq4tlCUk	

a) b)

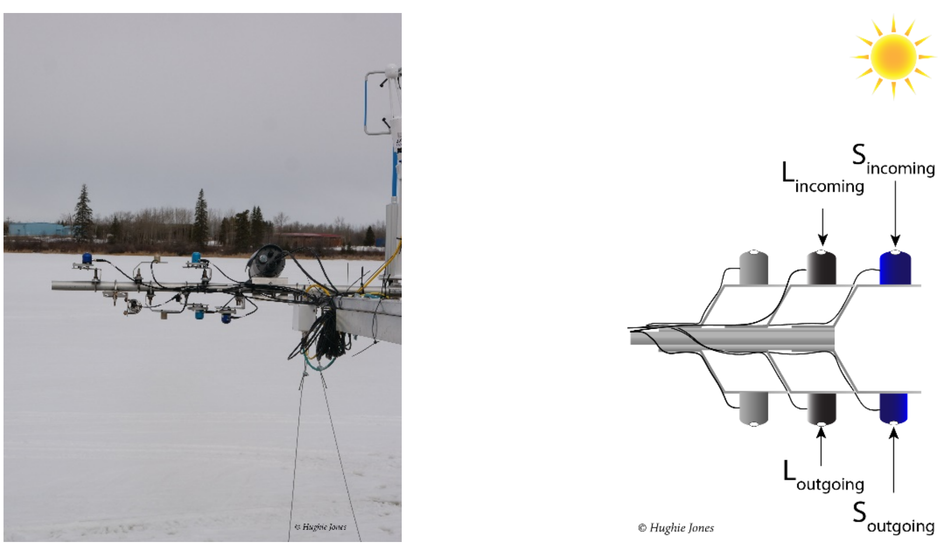


Fig. 7. Panels a) is a picture of pyranometers and pyrgeometers used to measure shortwave and longwave radiation, respectively. The upward facing sensors measure incoming radiation and the downward facing sensors measure outgoing radiation. Panel b) is an illustration of a pyranometers and pyrgeometers, as seen in **Fig. 1**.

1.3.6 Photosynthetically active radiation

Photosynthetically active radiation (PAR) is radiation that can be utilized by plants for photosynthesis (400 – 700 nm; nm is nanometers) and is a fundamental climate indicator used in climate monitoring to understand plant and ecosystem growth and productivity. PAR is measured as photosynthetic flux density (PPFD) and has units of micromoles (μmol) per meter squared (m^{-2}) per second (s^{-1}) ($\mu mol\ m^{-2}\ s^{-1}$). In outdoor conditions, incoming PPFD ($PPFD_{incoming}$) from the sun is measured using an upward-facing (facing the sky) quantum sensor and outgoing (or reflected) PPFD ($PPFD_{outgoing}$) is measured using a downward-facing (facing the earth's surface) quantum sensor (**Table 7** and **Fig. 8**). Analog and digital quantum sensors are commonly available.

Table 7. List of sensors used to measure shortwave and longwave radiation.

Sensor type	Examples
Full-spectrum quantum sensor	https://www.apogeeinstruments.com/full-spectrum-quantum-sensor/
Quantum sensor	https://www.apogeeinstruments.com/original-quantum-sensor/

a) b)

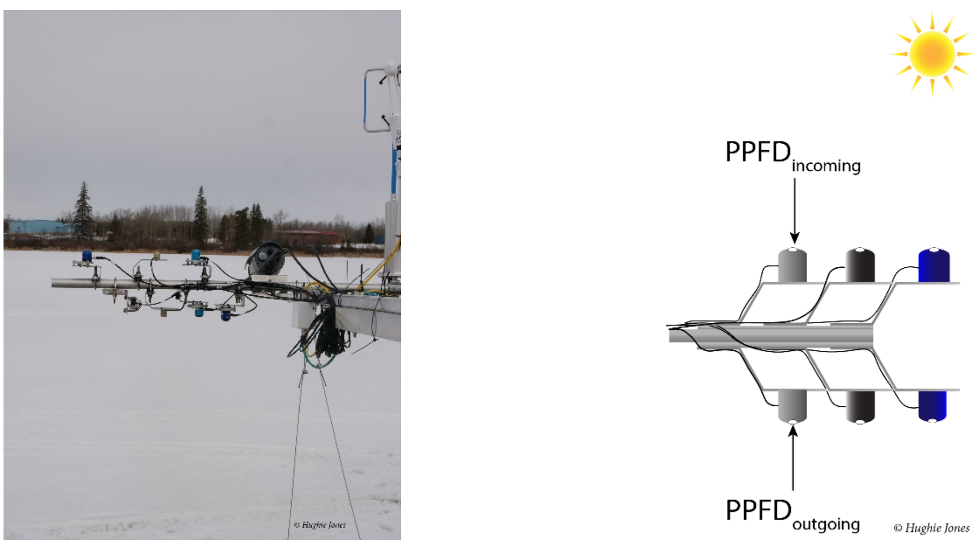


Fig. 8. Panels a) is a picture of a quantum sensors used to measure as photosynthetic flux density (PPFD). The upward facing sensors measure incoming PPFD and the downward facing sensors measure PPFD. Panel b) is an illustration of quantum sensors, as seen in **Fig. 1**.

1.3.7 Soil temperature

Soil temperature (T_s) is defined as the average kinetic energy contained in soil and is often measured at various depths (e.g., 0, 5, 10, 20, 50, 100 cm) depending on your study question. T_s typically has units of Kelvin (K) or Celcius (°C) (where K = 273.15 to ºC). T_s is measured using thermistors attached to a datalogger. Surface temperature is often measured using an infrared thermometer (**Table 8**).

Table 8. List of various sensors used to measure soil temperature.

Sensor type	Examples
Thermistor	https://www.campbellsci.ca/109-l
Infrared radiometer	https://www.apogeeinstruments.com/infraredradiometer/

1.3.8 Soil water content (gravimetric and volumetric)

Soil water content (θ) is expressed gravimetrically (θ_g) or volumetrically (θ_v). θ_g has units of gram per gram (g g^{-1}) and θ_v has units of volume per volume expressed as meters cubed per meters cubed (m^{-3} m^{-3}). θ_g is measured by physically sampling soil at various depths and processing the soil gathered in the laboratory using well established protocols (https://labmodules.soilweb.ca/gravimetric-soil-water-content/) and is an important step required to calibrate sensors which measure θ_v. Sensors that measure θ_v are appealing for climate studies because they operate continuously in the soil. θ_v is typically measured using a time domain reflectometer (TDR) sensor (

Table 9 and

a) b)

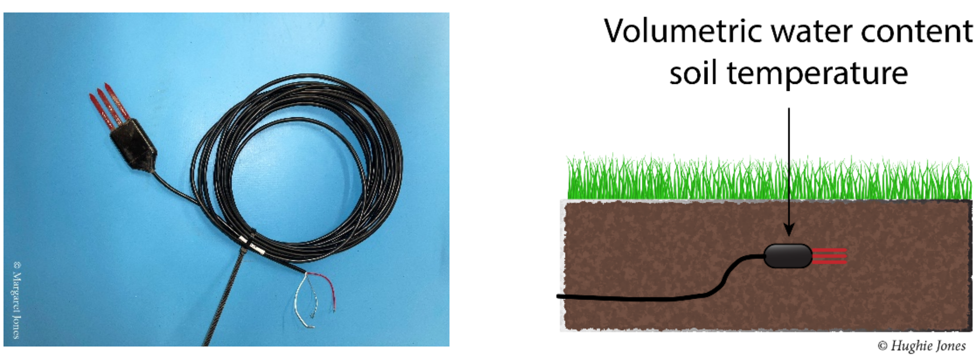


Fig. 9. Panel a) shows a volumetric water content and soil temperature sensor and panel b) is an illustration of the same sensor installed in soil.

Table 9. Common sensor to measure volumetric water content.

Sensor type	Examples
Time domain reflectometer (TDR) sensor	https://www.metergroup.com/environment/articles/measurement-volume-meter-volumetric-water-content-sensors/

a) b)

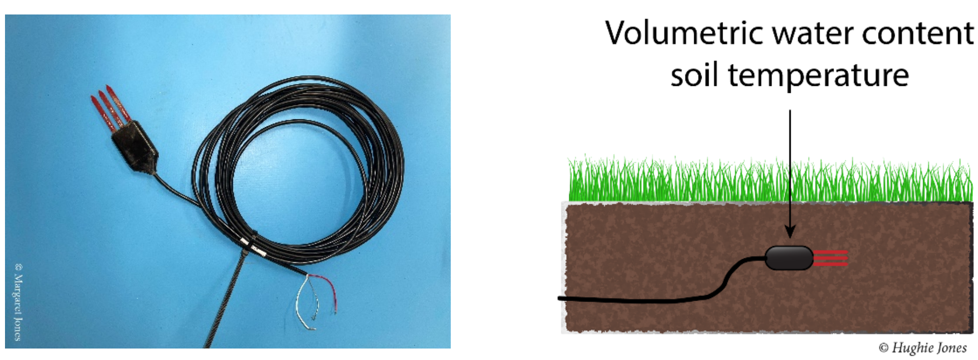


Fig. 9. Panels a) is a picture of time-domain reflectometer used to measure volumetric water content. The sensor also has a thermistor to measure soil temperature. Panel b) is an illustration of the sensor, in-situ, as seen in **Fig. 1**.

1.3.9 Soil heat flux density

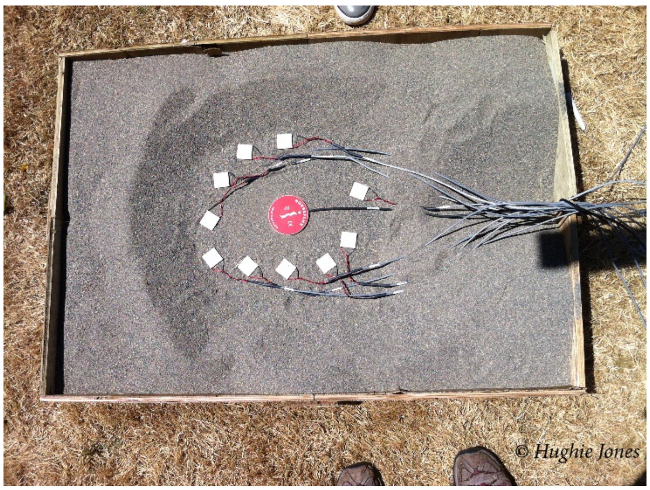
Soil heat flux density (*G*) is the flow (i.e., flux) of heat energy, typically in the vertical direction, either away from the soil surface (downward flow; typically, during the daytime) or toward the soil surface (upward flow; typically, during the nighttime) through a cross section area. The unit of *G* are watts (W) per meter squared (m^{-2}) (W m^{-2}). *G* is typically measured using a heat flux sensor or Peltier cooler module that has been calibrated in comparison to a heat flux sensor (**Table 10** and **Fig. 10**).

Table 10. List of various sensors used to measure soil heat flux density.

Sensor type	Examples

Heat flux sensor	https://www.hukseflux.com/products/heat-flux-sensors/heat-flux-meters/hfp01-heat-flux-sensor
Peltier cooler module	https://tetech.com/product/hp-127-1-0-1-3-71/

a)



b)

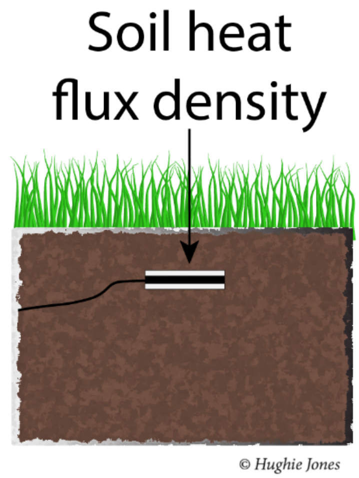


Fig. 10. Panels a) is a picture of Peltier cooler module used to measure soil heat flux density. Panel b) is an illustration of the sensor, as seen in **Fig. 1**.

A complete list of sensors chosen to measure the climate indicators discussed above is show in **Table 11**.

1.4 Project sensor list

Table 11. List of commercially available sensors to monitor variables discussed in Section 1.2.

Variable name	Common abbreviation	Units	Chosen sensor
Air temperature	T_a	Kelvin (k) or Celsius (°C)	https://www.campbellsci.ca/hmp60
Water vapour density	ρ_a	%	https://www.campbellsci.ca/hmp60
Precipitation	P	mm	https://www.campbellsci.com/te525 mm-l
Wind speed	u	m s^{-1}	http://gillinstruments.com/products/a nemometer/windsonic.htm
Wind direction		Degrees (°)	http://gillinstruments.com/products/a nemometer/windsonic.htm
Incoming shortwave radiation	S_d	Watts (W) m^{-2}	https://www.campbellsci.com/cs320
Outgoing shortwave radiation	S_u	W m^{-2}	https://www.campbellsci.com/cs320
Incoming longwave radiation	L_d	W m^{-2}	https://www.apogeeinstruments.com/ sl-510-ss-pyrgeometer-upward-looking/
Outgoing longwave radiation	L_u	W m^{-2}	https://www.apogeeinstruments.com/ sl-610-ss-pyrgeometer-downward-looking/
Incoming photosynthetically active (PAR) radiation	Q_d	μmol m^{-2} s^{-1}	https://www.apogeeinstruments.com/ full-spectrum-quantum-sensor/
Outgoing PAR radiation	Q_u	μmol m^{-2} s^{-1}	https://www.apogeeinstruments.com/ full-spectrum-quantum-sensor/
Soil temperature	T_s	Kelvin (k) or Celsius (°C)	https://www.campbellsci.com/107

Soil water content (gravimetric and volumetric)	θ	%	
Soil heat flux density	G	W m^{-2}	https://tetech.com/product/hp-127-1-0-1-3-71/