Supplemental Materials: Analysis of Meteorological Data

(Version 1)

Once the weather data is obtained, readers can analyze it to extract useful information and learn and understand weather. This section offers ideas and examples for some analyses, not meant to be prescriptive but to inspire and encourage readers to brainstorm their own approaches. These methods are intended for analyzing the data collected using their solar-powered weather data recorder after completing the chapters of this book. In the following, we use the phrases "data recorder" and "the solar powered weather station" as described in the chapters 1-9 interchangeably for convenience.

S.1. Calibrating air pressure with local weather stations

Pressure sensors, such as those used in this book, like other sensors, may exhibit systematic errors or offsets, making calibration essential. A reliable reference for calibration is data from an official weather station. Such stations exist in most countries. We will first discuss the use of weather stations for the calibration exercise in the U.S. and then in other countries.

ASOS (NOAA, 1998, Sun et al., 2005), or Automated Surface Observing System, is a network of weather observation stations primarily in the United States, operated by the National Weather Service (NWS), the Federal Aviation Administration (FAA), U.S. Navy, and the Department of Defense (DoD).

ASOS stations provide high-quality, continuous weather observations for public safety, aviation, and meteorological research. They measure parameters such as: temperature – including both air and dew point temperatures; precipitation - rainfall, snowfall, and other types; wind - speed, direction, and gusts; visibility - horizontal visibility, including obstructions like fog or haze; and atmospheric pressure.

ASOS observations are typically reported every 1 minute to 1 hour. With over ~1,000 stations across the United States, located at airports, military bases, and other strategic locations, ASOS data is publicly accessible through platforms like the National Centers for Environmental Information (NCEI) and the National Weather Service.

ASOS data serves diverse purposes, including aviation safety (providing critical runway and local weather conditions), weather forecasting (enhancing accuracy for severe weather predictions), research (supporting meteorology, climatology, and hydrology studies), and climate monitoring (offering long-term observations to understand trends and changes).

Due to its reliability and authoritative nature, ASOS data ensures high-quality standards. Using it as a reference for validating air pressure measurements from a homemade data recorder is a practical and effective approach. It also provides a great opportunity for the users to conduct data quality assessment and calibration against reliable data.

In other countries, there are comparable weather observation networks to the ASOS in the United States. These systems also provide continuous, automated weather monitoring for meteorological research, aviation safety, and public services. Here are some examples from around the world:

Canada: Automated Weather Observation System (AWOS) - Operated by Environment and Climate Change Canada (ECCC) and Nav Canada**.**

United Kingdom: UK Met Office Weather Stations - Operated by the Met Office, these stations offer high-quality weather data for the UK.

Australia: Automatic Weather Stations (AWS) - Managed by the Bureau of Meteorology (BoM).

Japan: Automated Meteorological Data Acquisition System (AMeDAS) - Operated by the Japan Meteorological Agency (JMA).

Germany: DWD Automatic Weather Stations - Operated by the Deutscher Wetterdienst (DWD), Germany's national meteorological service.

India: Automatic Weather Stations (AWS) - Managed by the India Meteorological Department (IMD).

China: National Meteorological Center (NMC) Network - Automated stations operated by the China Meteorological Administration (CMA).

France: Automatic Weather Stations of Météo-France - Operated by Météo-France, the national meteorological service.

Calibration of air pressure data can be done in different ways. But here we will just suggest two methods as examples.

S.1.1 Method 1

This method requires that the user has two data recorders with the air pressure sensor, GPS, and SD-Card as described in the last chapter. One of them is the one deployed at a selected site. The second one is used for calibration. To calibrate the data, the user does not have to use solar power for the second data recorder. Instead, the user should use batteries to power the data recorder so that it can be carried in a car to near an ASOS station, which is often at an airport.

Step 1: Both data recorders with air pressure sensors are placed together at the site where the solar powered weather station is located. The second data recorder is placed at the same vertical level as the solar powered data recorder. Allow the data recorder to record data for a significant number of data points (preferably more than a few hours, if not longer, with the sampling intervals been 1-10 seconds). Please remember always use the GPS time in UTC (there is no need to convert to local time) because all the original standard ASOS data is in UTC. Most likely the two data recorders provide data with similar trends, but their values are offset by a small value. For example, if you are at a coastal city where the elevation is close to the mean sea-level and the mean air pressure from these two data recorders are 1013 mb, and 1014.2 mb. The difference is small (but still significant and must be calibrated or adjusted).

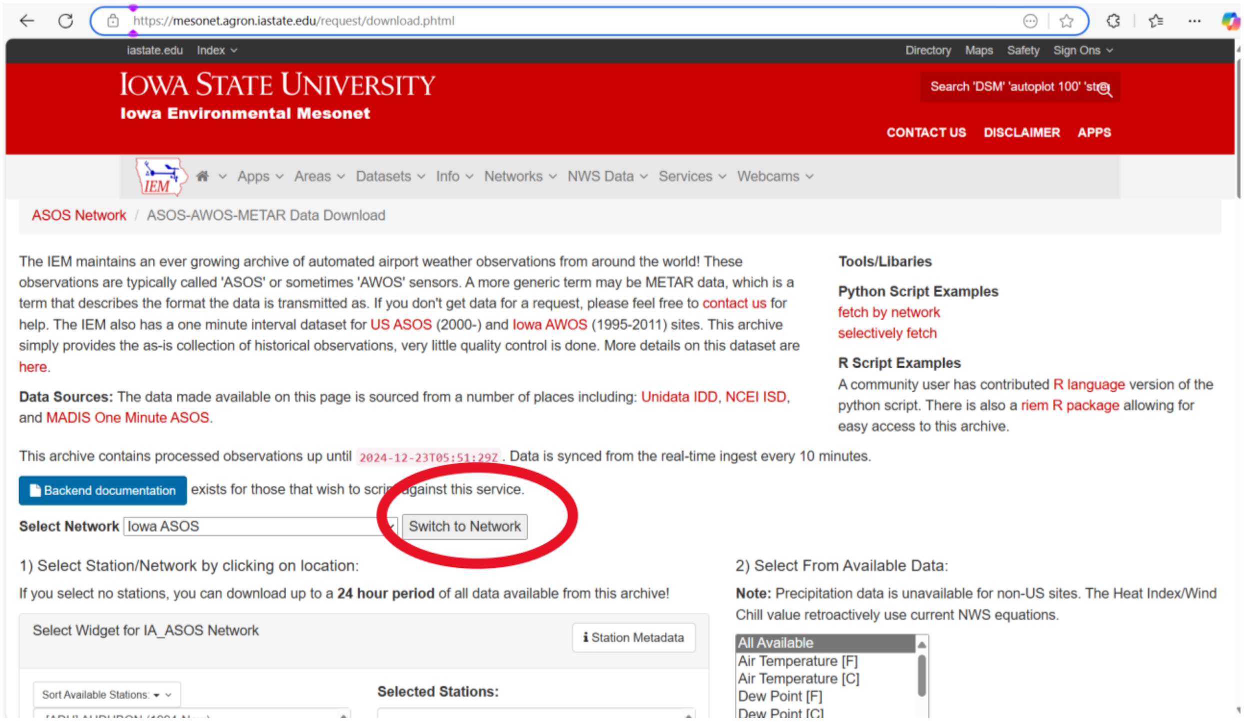


Figure. S1. Web site for ASOS maintained by Iowa State University.

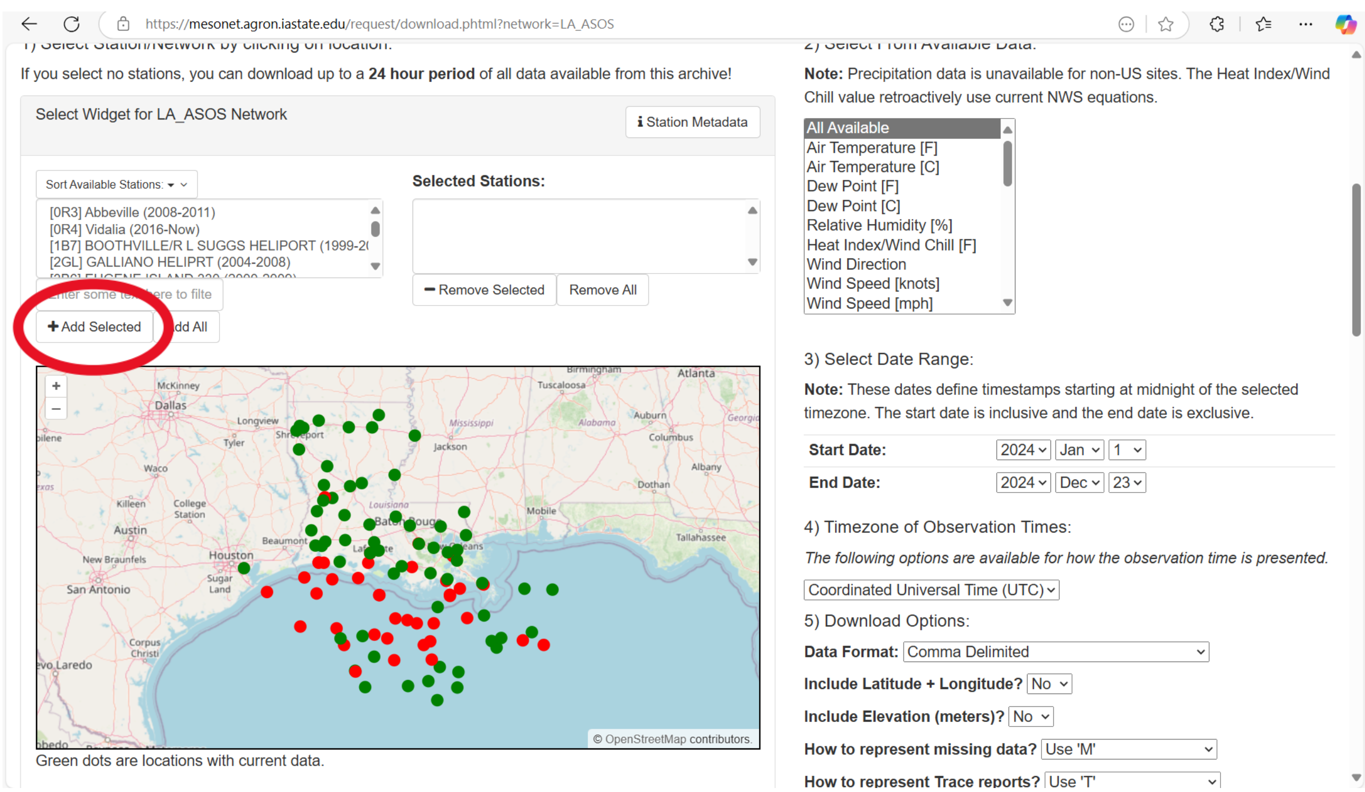


Figure S2. ASOS stations for the State of Louisiana.

Step 2: Before you go to the ASOS station (or a similar local weather station with publicly accessible barometric pressure data) with your second data recorder, check the sensor's height of that particular ASOS by visiting the Iowa State University's web site (for U.S. users) at https://mesonet.agron.iastate.edu/request/download.phtml (Fig. S1). For users outside of the U.S., the users should try to find similar online resources.

Select the State you are in and click the button "Switch to Network". It will then bring up a map showing all ASOS stations in the selected State. Here we use the State of Louisiana as an example (Fig. S2). We chose the ASOS station at Baton Rouge Metropolitan Airport (SID: BTR, Name: BATON ROUGE/RYAN). By zooming in to the map, one can see the location, name, site ID, and data coverage (from 1942 to present, Fig. S3). Select the ASOS station nearest your station with solar powered weather data recorder. In this example, let's say you want to choose the ASOS at Baton Rouge Metropolitan Airport. Find it on the map (Fig. S2). The map may be too small to find the site in the beginning, but you can zoom in if needed (Fig. S3).

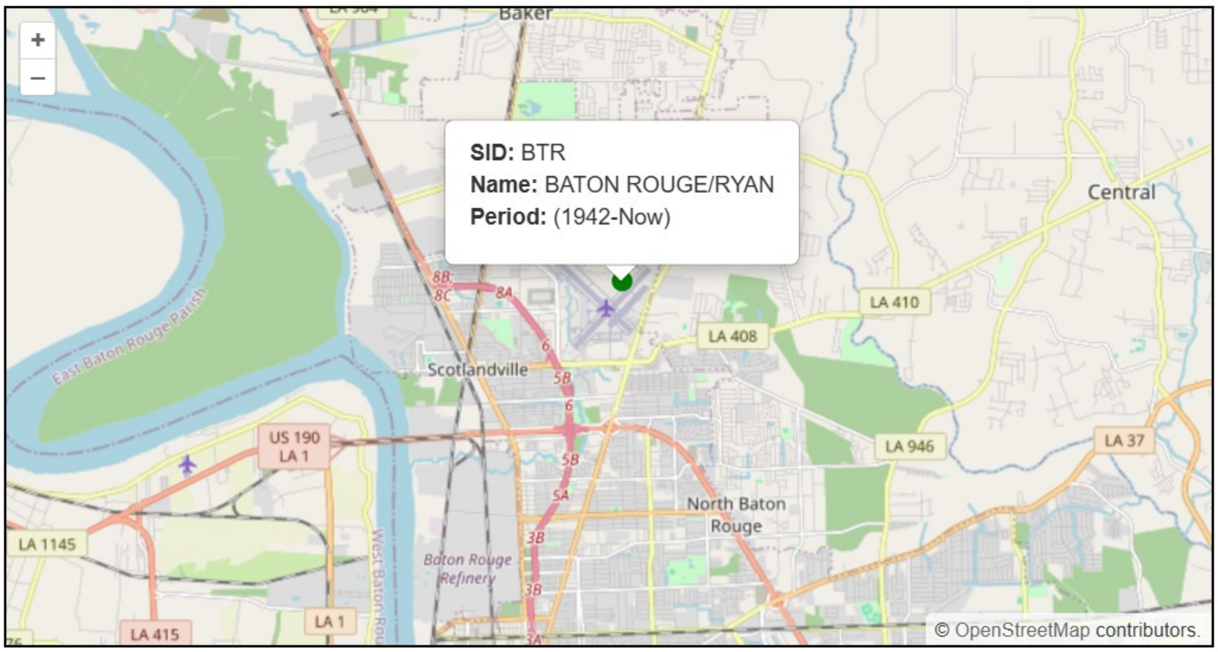


Figure S3. ASOS station at the Baton Rouge Metropolitan Airport (BTR) with data from 1942 to present.

Once you've found the ASOS station, select it and press the button "+Add Selected" as shown in Fig. S4, after which, you will see the selected station as shown on the right panel (Fig. S5). Now you need to select the weather data for calibration use. In our case, we only need to download the air pressure data. But if out of curiosity you would like to download air temperature, dew point temperature, humidity, wind speed, and wind direction, you can select the weather parameters you need (Fig. S6).

Next, you need to select the start and end dates of the data you need to download. In "4) Timezone of Observation Times:" make sure use the default option using UTC. In "5) Download Options:" make sure you also select "Yes" for the "Include Elevation (meters)" option (Fig. S6).

Scroll down a little on the page, and click “Get Data”, you will get the data displayed on a separate web page (Fig. S7). Now you can download the data to a file by right-click the mouse on the page and select “Save as” (Fig. S8). In the data, you should be able to find the elevation of the ASOS station. In this example of the Baton Rouge Metropolitan Airport station, the elevation is 21 meters above sea level (Fig. S7).

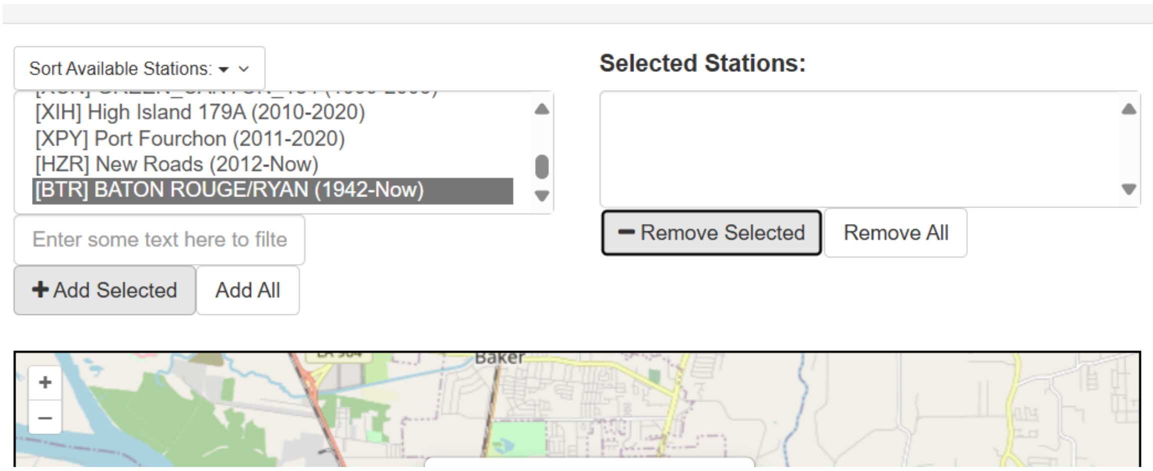


Figure S4. Select the ASOS station you want and click “+Add Selected”.

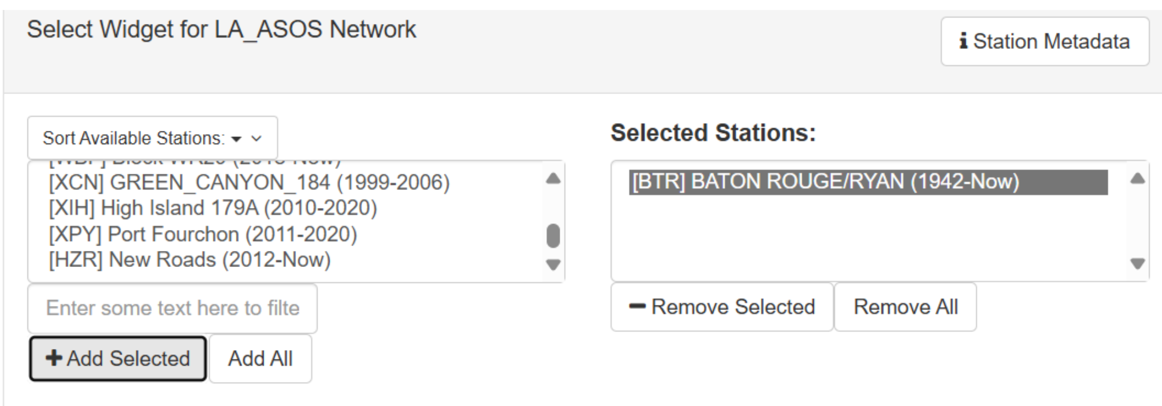


Figure S5. After the selection of the ASOS station.

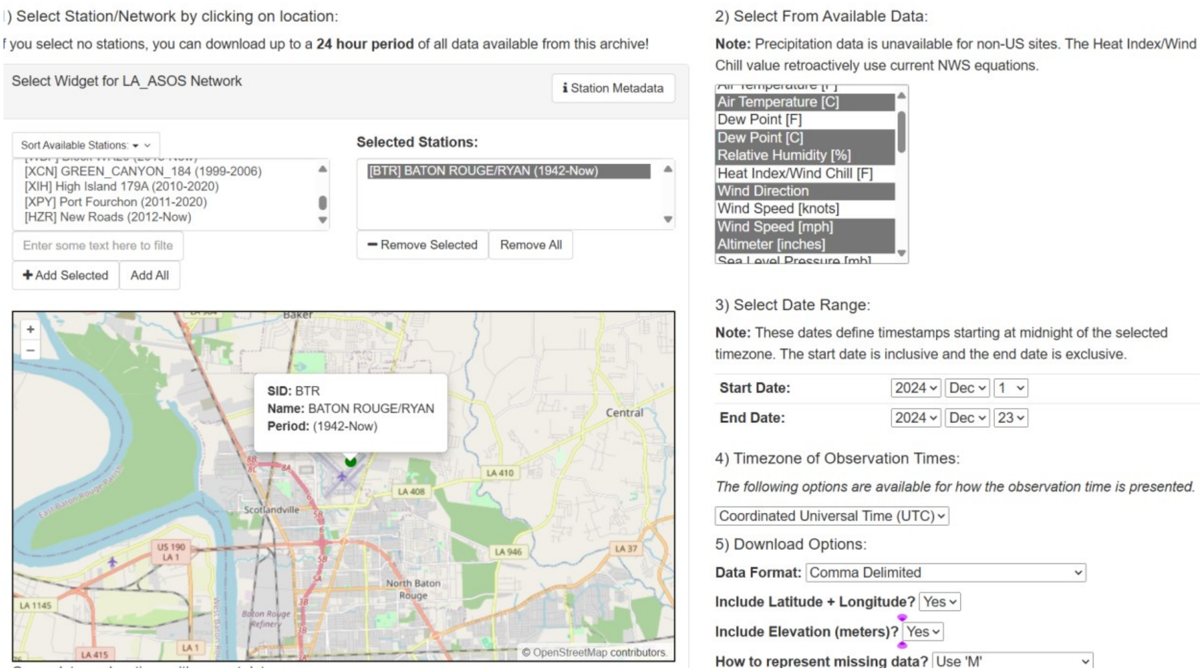
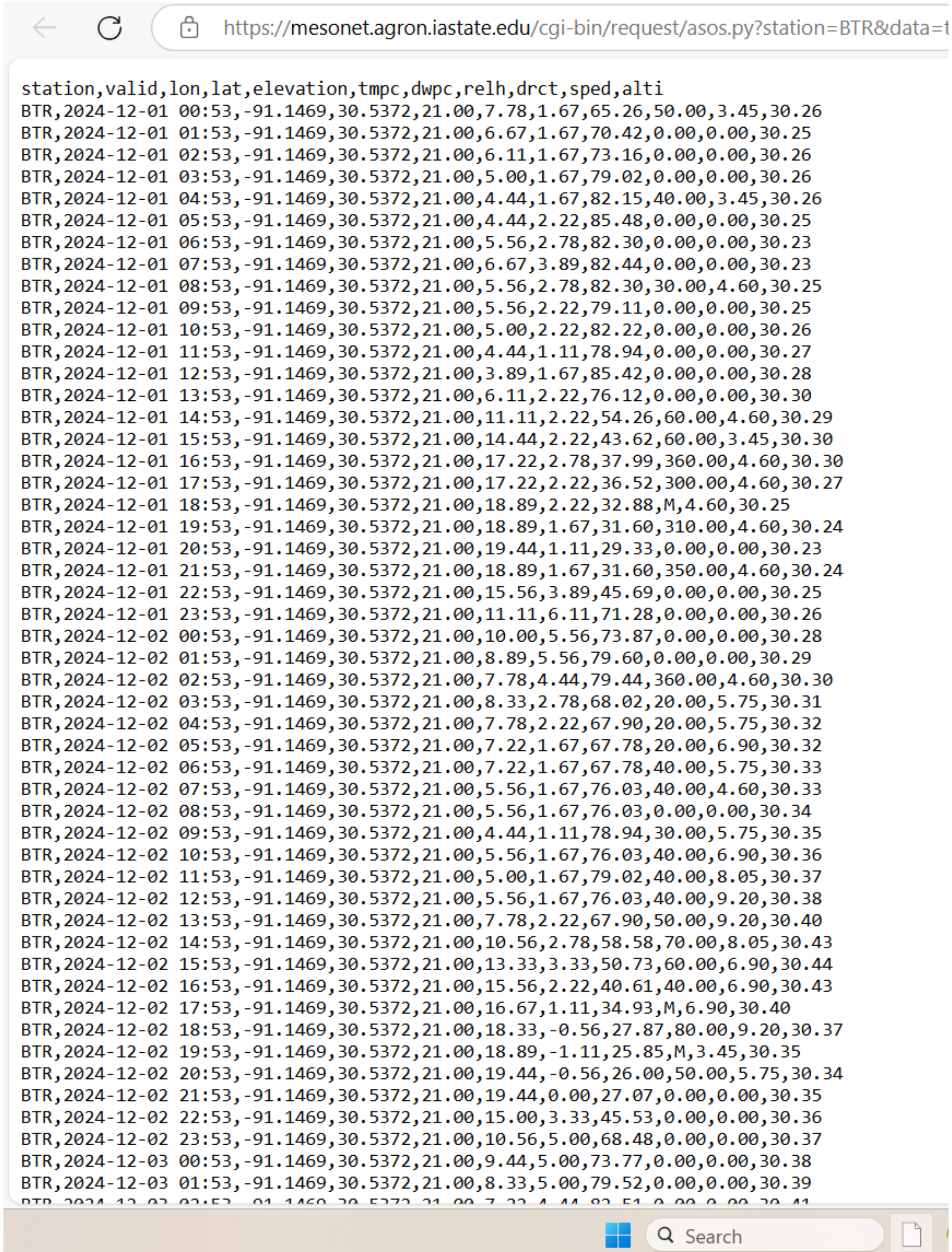


Figure S6. Select the weather data that you want to download.

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station,valid,lon,lat,elevation,tmpc,dwpc,relh,drct,sped,alti
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Figure S7. Selected ASOS data displayed on the web page.

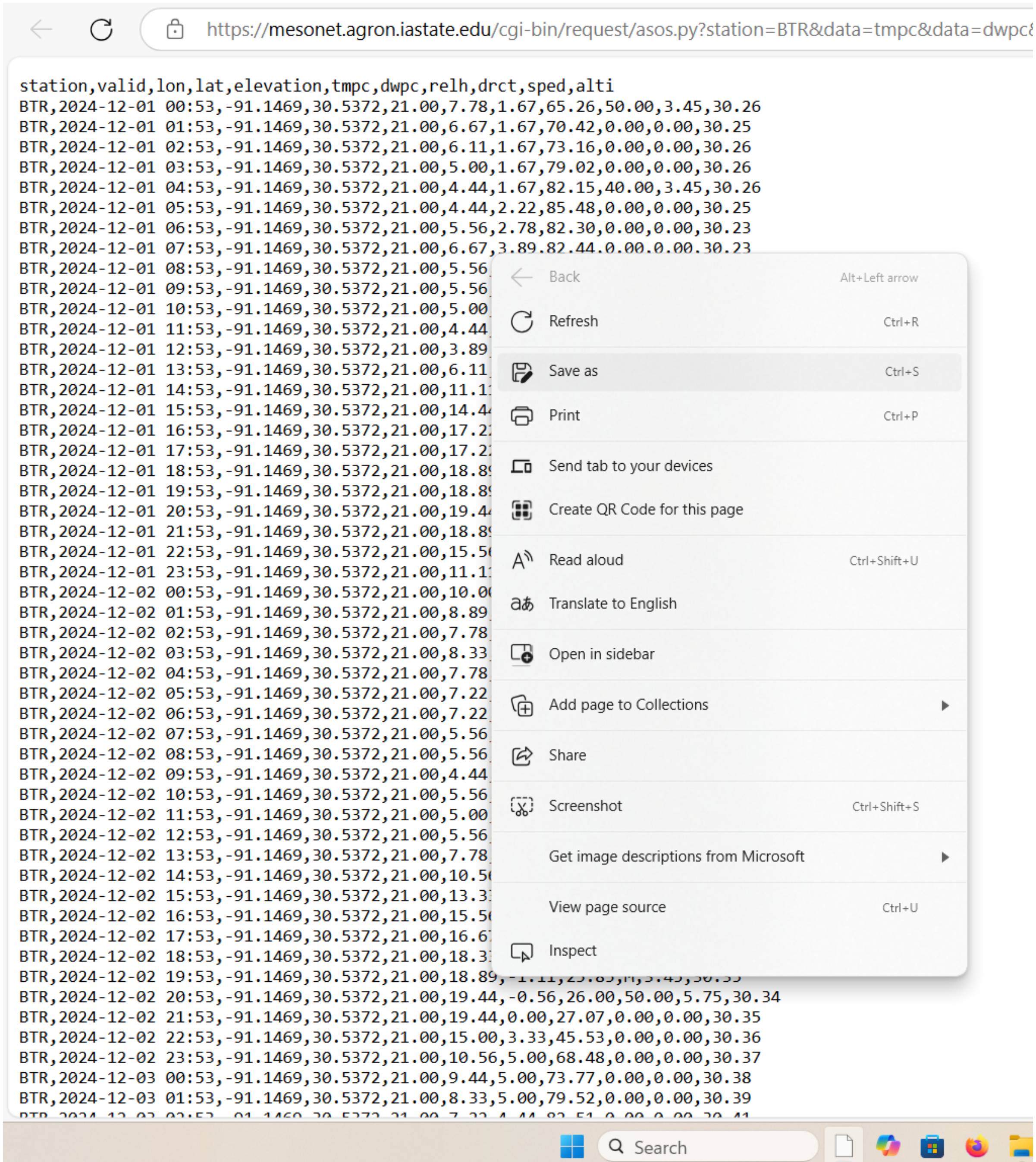

Figure S8. Save the ASOS selected data to a file by right click the mouse and select “Save as”.

Step 3: Take the second data recorder to the ASOS station. You don’t have to be exactly at ASOS station as long as you are at about the same elevation as the ASOS station. For example, you are outside of the airport a couple of miles away from the ASOS station. Record the data for a period inside your vehicle. Make sure you have your solar powered station at its site recording data at the same time (so that you have data from all three sources with a significant number of data points). Assuming you have collected valid data from all three sources, you can now calibrate your air pressure data in Step 4.

Step 4: It should be noted that the ASOS air pressure data is in inch Mercury height (inHg), while the Arduino data recorder gives air pressure data in hectopascal (hPa) or millibar (mb). Before proceeding, you should convert the unit of the ASOS air pressure data into hPa. The conversion coefficient can be found in physics handbooks or online, e.g., https://www.unitconverters.net/pressure-converter.html. At 60 degrees Fahrenheit, 1 inHg = 33.7685 hPa (Fig. S9). This value slightly changes at different air temperatures.

In general, this coefficient of unit conversion can be used for all weather conditions, regardless of the air temperature. The reason is that the change in mercury density with temperature is small and the error can be neglected for our applications. To illustrate, if we choose the conversion value at 32 degrees Fahrenheit, 1 inHg = 33.8638 hPa. The error is less than 0.3%.

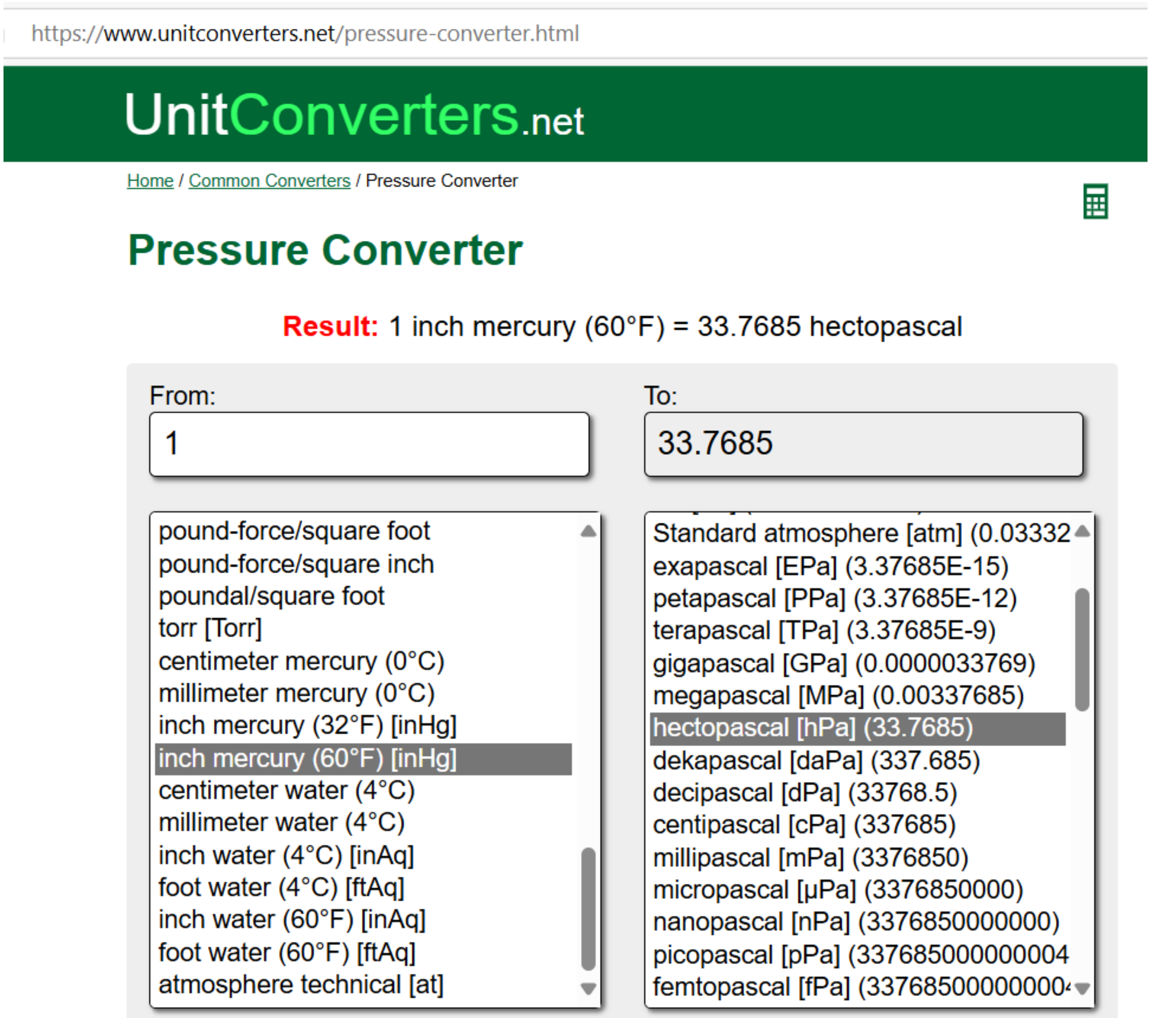

Figure S9. Unit conversion for pressure data.

Step 5: We can now compare the air pressure data among the three sources – the solar powered station, the portable second data recorder, and the ASOS station. You can examine the average value of air pressure from the ASOS station and that from the second recorder during the same period. This difference gives the offset of the second data recorder. This calibrates the second data recorder, which can then be used to calibrate the first data recorder, which is at a different site and possibly different elevation. The calibration process will also provide information on elevation of your station (where the first recorder is deployed).

Now, let's discuss briefly how to convert pressure difference into elevation difference. Converting an air pressure difference into an elevation difference involves the relationship between pressure and altitude in the atmosphere. This is based on the barometric formula, which relates the pressure change to elevation, assuming the atmosphere behaves like a fluid with known properties. The approximate relationship between pressure difference (ΔP) and elevation difference (Δh) under standard atmospheric conditions (1 atmospheric pressure, or air pressure at sea level, which is on average 1013.25 hPa) is:

$$\Delta h \approx \frac{RT}{Mg} \ln\left(\frac{P_1}{P_2}\right) \qquad (S.1)$$

where Δh is elevation difference in meters, P_1 and P_2 are Air pressures at the two elevations (in hectopascals or other consistent units, as long as they use the same unit), R = 287 Joul/(kg Kelvin) is the specific gas constant for dry air, T is the air temperature in Kelvin, M = 0.02896 kg/mol is the molar mass of air, and g=9.80665 m/s^2 is the acceleration due to gravity. Note that the conversions between the temperature in C and in K are:

$$\text{K} = {}^\circ\text{C} + 273.15 \qquad (\text{S}.2)$$

$$^\circ\text{C} = \text{K} - 273.15 \qquad (\text{S}.3)$$

And those between C and F are:

$$^\circ\text{C} = ({}^\circ\text{F} - 32)/1.8 \qquad (\text{S}.4)$$

$$^\circ\text{F} = ({}^\circ\text{C} \times 1.8) + 32 \qquad (\text{S}.5)$$

For small elevation differences (up to a few hundred meters) and assuming standard conditions (T=288.15, P=1013.25 hPa), Equation (S.1) can also be simplified into:

$$\Delta h \approx 8.3\, \Delta P \qquad (S.6)$$

where ΔP is the pressure difference between the two sites. Remember, low air pressure means higher elevation, when other conditions are otherwise identical. As an example, suppose the pressure difference (ΔP) between two locations is 0.02 hPa, using the approximation: Δh=8.3×0.2=1.66 meters.

S.1.2 Method 2

An alternative method is simpler and similar to the above. Instead of using two data recorders, one data recorder is sufficient. We simply record the data at the deployment site with the only data recorder (dataset 1) and then take the recorder and use battery to record data near the ASOS station (dataset 2) to compare with the ASOS data (dataset 3). This still allows the user to compute the elevation difference and the offset. The details are omitted here and left for the users to consider as an exercise. Note that the computations and the formulas given above are all valid for method 2.

S.2. Extratropical cyclones

The data recorded at your station can be used to check the passage of cyclones. While the probability of having a tropical cyclone (tropical storm, hurricane, typhoon) passing through your location may be low, the probability of encountering the influence of extratropical cyclones (Fig. S10) is much higher. For that reason, while the following method also applies to tropical cyclones, we focus on extratropical cyclones.

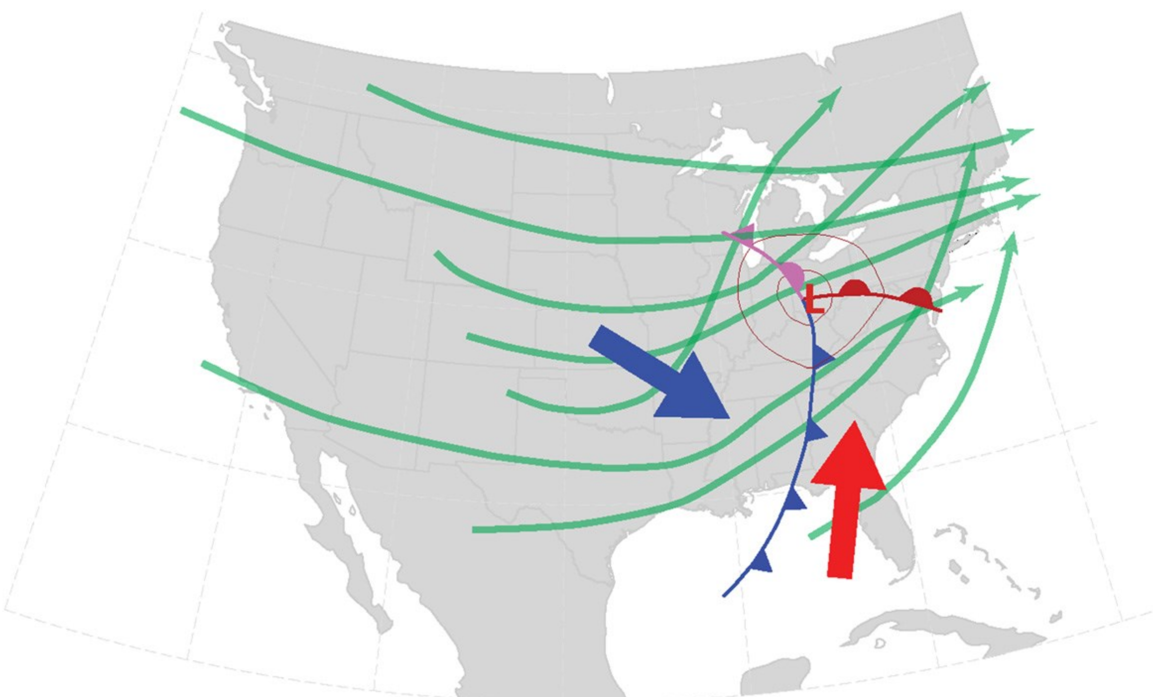

Figure S10. Schematics of an extratropical cyclone and potential tracks and associated fronts. The green lines with arrows are different tracks of extratropical cyclones (from American Meteorological Society). Shown here are also an example of an extratropical cyclone with associated cold and warm fronts and the warm (large red arrow) and cold advections (large blue arrow) of the surface air (from Li, 2024a).

An extratropical cyclone (Scorer, 1997) is a large-scale storm system that forms outside the tropics, typically in the mid-latitudes (30° to 60° latitude). Cyclones can also occur at higher latitudes. Extratropical cyclones form along the boundary between warm and cold air masses, known as the polar front. They are powered by the temperature gradient and the release of potential energy including latent heat as warm air rises and cold air sinks. They typically have a low-pressure center with air spiraling inward counterclockwise in the Northern Hemisphere (clockwise in the Southern Hemisphere). Associated with warm and cold fronts, which bring different types of weather. Much larger than tropical cyclones, with diameters ranging from 1,000 to 2,000 km. The weather associated with extratropical cyclones includes warm fronts with overcast skies, steady precipitation, and rising temperatures; cold fronts with intense, but short-lived precipitation, strong winds, and a sharp drop in temperature; and they can bring heavy rain, snow, or strong winds depending on the season and location. Their lifespan generally lasts a few days to over a week, moving from west to east due to prevailing westerly winds.

Examples of extratropical cyclones include: 1) Nor'easters which are powerful extratropical cyclones along the eastern coast of North America, bringing heavy snow or rain and strong winds. 2) European windstorms, which are intense storms affecting Western Europe, often cause significant wind damage. 3) Bomb cyclones which are certain extratropical cyclones that intensify rapidly through a process called bombogenesis, where pressure drops by at least 24 hPa in 24 hours.

The extratropical cyclones can be identified on weather maps. In the U.S. the following web page provides official weather maps every three hours:

http://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php#nam

These cyclones are driven by differences in temperature and pressure between warm and cold air masses and are often associated with weather fronts. The behavior of air pressure, temperature, dew point temperature, and humidity before, during, and after the passage of an extratropical cyclone can exhibit distinct patterns. Before the cyclone, the air pressure typically decreases as the cyclone approaches. A drop in pressure can be observed in the days leading up to the storm, with a more rapid drop as the cyclone nears. Temperatures generally tend to increase ahead of an extratropical cyclone (the so-called “warm advection”), especially if the cyclone is pulling warm, moist air from a warmer region (like the ocean or southern latitudes). Winds may also pick up, which can enhance the warming effect, depending on the cyclone’s path. Dew point temperatures typically rise as warm, moist air is drawn into the cyclone. The higher the dew point, the more moisture is in the air, which can lead to increased humidity and the potential for precipitation (rain or snow). As the cyclone approaches, humidity increases, especially if it is drawing moist air from a large body of water like the ocean. The relative humidity tends to be high in the days leading up to the storm, as the atmosphere becomes more saturated.

If the cyclone’s center passes the location, as the center (or "eye") of the cyclone passes over, the pressure reaches its lowest point. This is known as the minimum central pressure. The pressure typically drops very quickly as the storm intensifies, often with the most rapid decrease occurring just before the storm reaches its peak intensity. Temperatures typically decrease sharply once the cyclone passes. The central part of the storm usually brings cooler air, especially if the cyclone is pulling in cold air from the north or from higher latitudes. In some cases, sharp temperature drops can occur, especially when the cold front associated with the cyclone moves through the area. The dew point temperature usually reaches its highest level just before or during the storm, as the cyclone draws in significant moisture. There can be a sharp increase in humidity as warm, moist air converges into the cyclone. Relative humidity remains very high during the storm, often approaching 100% as the cyclone pulls moisture from the atmosphere. The air can feel very damp and oppressive, and heavy precipitation often occurs.

Once the storm passes, the pressure begins to rise, often quickly at first, as the storm moves away. The pressure tends to return to normal levels, but may remain a little lower than usual in the immediate aftermath due to lingering disturbances. After the cyclone has passed, temperatures generally start to recover, though they may remain cooler than they were before the storm. The post-cyclone period often sees clearer skies, which can allow temperatures to cool during the night, especially if the system has passed in the cooler season. After the cyclone passes, the dew point temperature typically drops because colder, drier air is often brought in by the storm's cold front.

The dew point may return to more typical levels, or even drop lower than usual, depending on the characteristics of the post-cyclone air mass. Following the passage of the cyclone, the relative humidity generally decreases rapidly as the air clears and dry, cool air is brought in by the storm's cold front. Humidity may remain lower than usual for a period, especially if the storm leaves behind a cooler, drier air mass.

With the above information of the extratropical cyclone weather system, the user can use the homemade data recorder to identify the passage of these cyclones by examining the change in air pressure, temperature, dew point temperature, and wind direction. Perhaps, the easiest approach is when you know such a cyclone is passing through your region, and you can verify that through the official weather maps (like those shown on the web page http://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php#nam), you can then check your data from your solar powered data recorder and verify that the air pressure reached it's minimum as the cyclone's center passed the area (or when it was closest to the site). The time series plot of air pressure will be similar to what we observe when an atmospheric cold front passes the region. This is discussed below.

S.3. Atmospheric cold fronts

The weather changes associated with the passage of a cold front (Hsu, 1988) can be observed in several parameters, including temperature, pressure, wind, humidity, cloud cover, and precipitation. Before the cold front, temperature is typically relatively high, as the air mass ahead of a cold front is usually warm and moist. The air pressure slowly decreases as the cold front approaches. Winds generally blow from the southern quadrants in the Northern Hemisphere, bringing in warm air. The humidity during this stage is generally high, as warm air holds more moisture. We may experience increasing cloudiness. Clouds often begin as high cirrus and progress to lower-level altostratus or nimbostratus as the front approaches. Precipitation may occur as light rain or drizzle may start as the front gets closer, with intensity increasing as the front nears.

During the cold front, temperature usually drops rapidly as the cold air mass replaces the warm air. The air pressure reaches its lowest point just before the front passes, then begins to rise quickly as the front moves through. The wind often shifts abruptly, typically from the southern quadrants to the northern quadrants in the Northern Hemisphere. At the same time, wind speeds increase, sometimes gusty, as the front passes. The humidity decreases, as cold air from the north (polar region) is usually a lot drier. The cloud cover can be heavy, dark clouds (cumulonimbus or towering cumulus) are common. Thunderstorms or intense rain showers are likely during the passage of the front, depending on the strength of the cold front. Precipitation is short-lived but intense rain, sometimes cam occur accompanied by thunderstorms, hail, or even snow in colder seasons.

After the passage of a cold front, temperature further decreases as the cold air mass settles in. At the same time, pressure continues to rise steadily, indicating the arrival of the cooler, more stable air mass. Wind generally comes from the northern quadrants, bringing cooler and drier air. As a result, humidity becomes much lower than before the front, as the cold air is typically drier. The clouds begin to clear, often leaving behind bright blue skies with some lingering cumulus clouds. The precipitation generally stops, though light, scattered showers may persist for a short time if there is lingering instability.

It should be noted that these processes are highly variable, and they depend on the strength of the cold front among many other factors. A strong cold front will bring sharper and more dramatic changes, while a weak cold front may only cause subtle shifts. Strong cold fronts are often associated with severe weather, such as thunderstorms, hail, or even tornadoes, or freezing rains, especially in regions with unstable air masses.

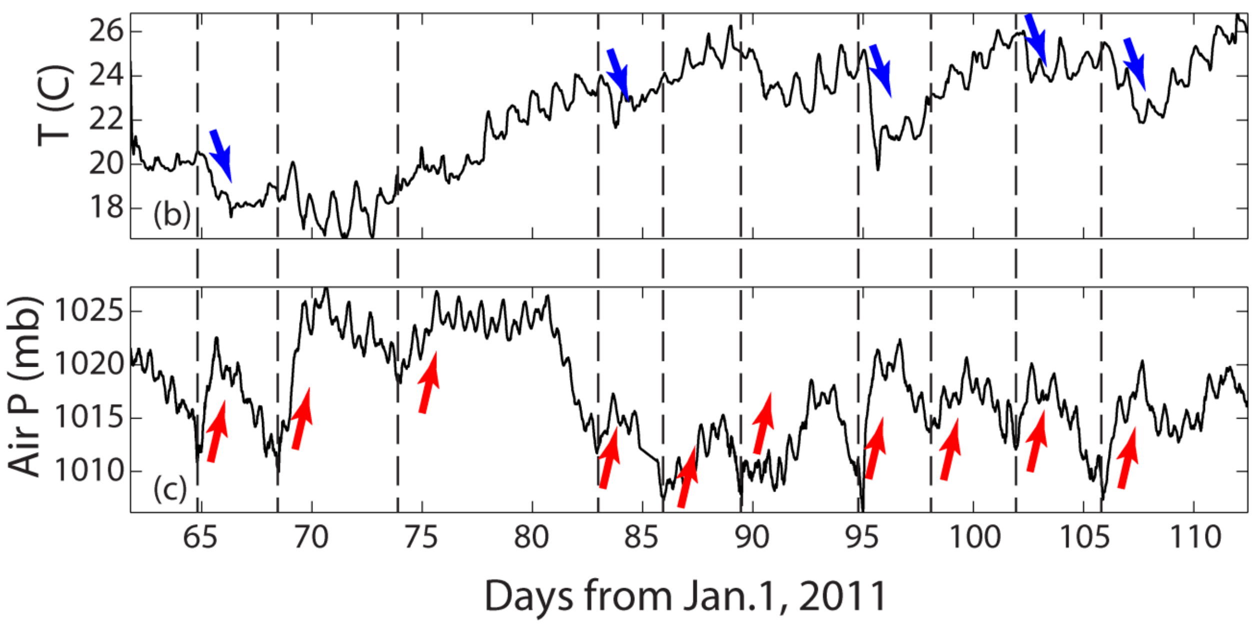

Figure S11. Air pressure and temperature data impacted by cold front passages. The dashed vertical lines indicate the times when cold fronts passaged the region. The change in air pressure and temperature after cold front passages are shown by the red and blue arrows, respectively.

Figure S11 shows an example of timeseries plots of the air temperature and pressure as affected by the cold fronts. The post cold front changes in air temperature and pressure are indicated by the arrows.

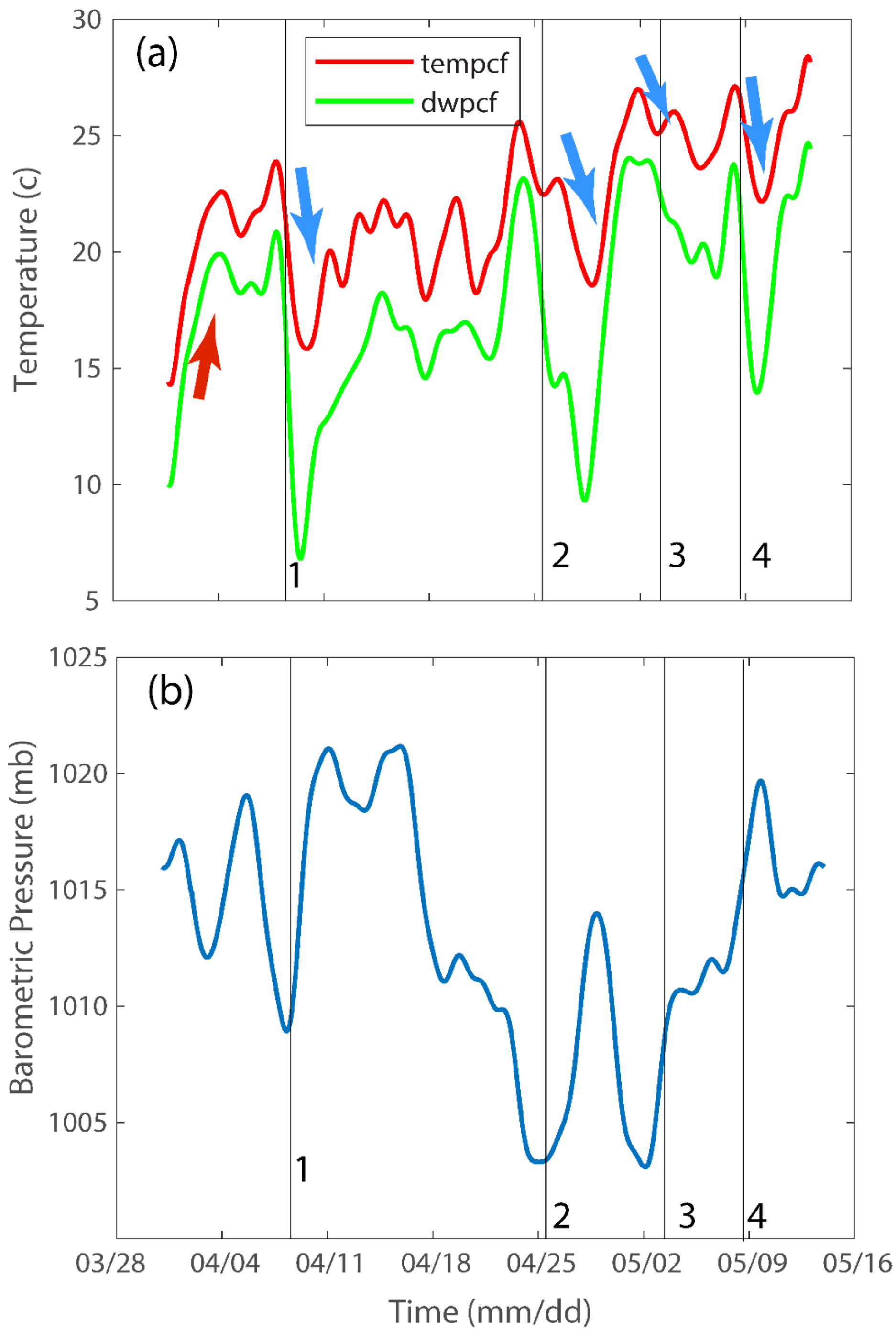

Figure S12. Low pass filtered observations (time series) from an ASOS station (a) Air temperature and dew point temperature. (b) Barometric pressure. The red and blue arrows indicate examples of the effect of warm and cold advections, respectively (from Li, 2024b).

Figure S12 gives more examples of changes in air temperature, dew point temperature and air pressure around the cold front passages (the vertical lines indicate the timing of the cold front passages).

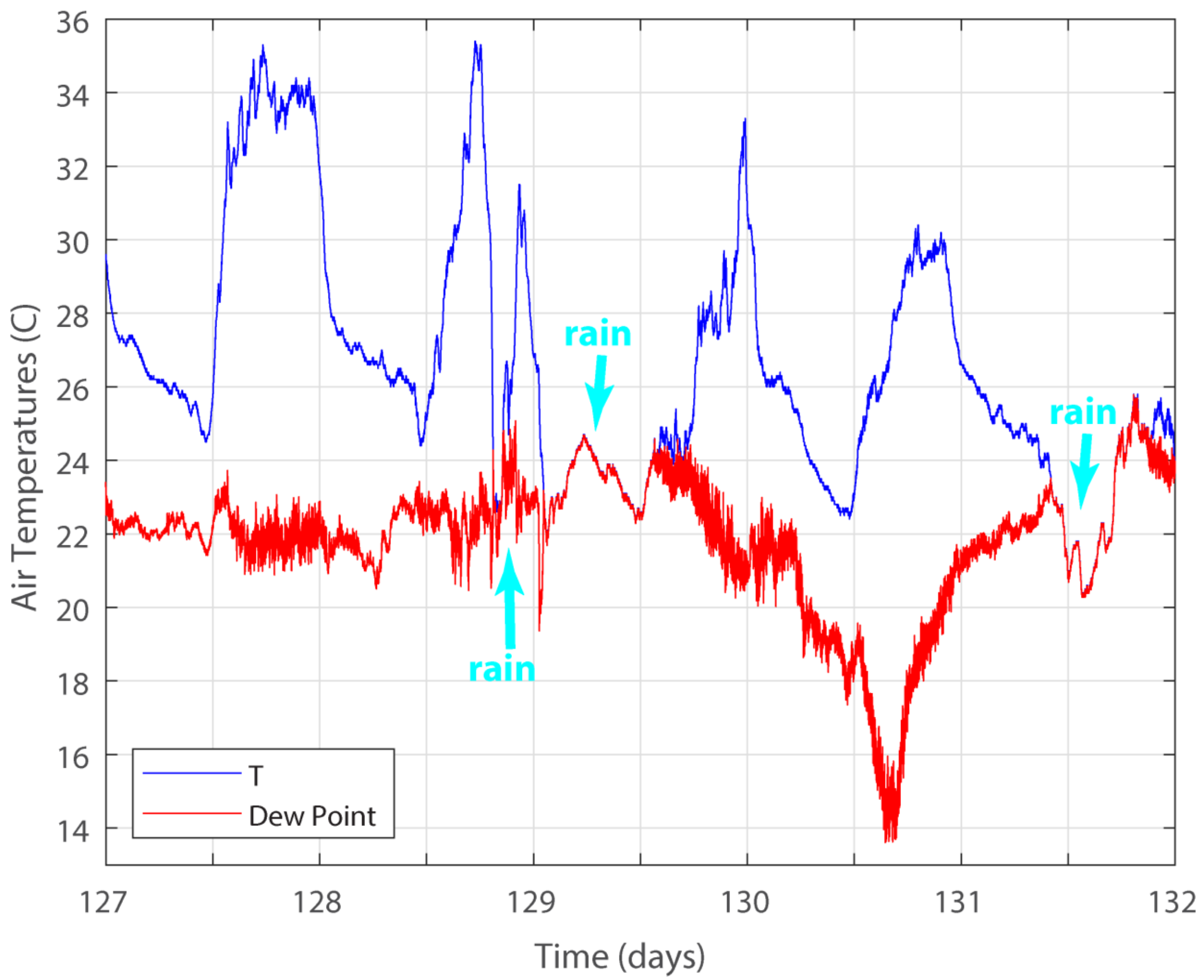

Figure S13. An example of identifying raining events using the data recorded by the solar powered weather data recorder. Data was obtained using one of the author's data recorders based on Arduino as described in the previous chapters. This recorder was deployed at a piling in the Calcasieu Pass in Southern Louisiana for several years at 1 Hz sampling rate (one observation per second). This is a five-day record as an example identifying raining events.

S.4. Rain and fog

When rain or fog occurs, the air will be saturated with moisture and its relative humidity usually will be about 100%. At the same time, the dew point temperature will increase as well. Our data recorders do not record the dew point temperature directly, but it can be calculated from the air temperature and relative humidity. The formula for doing that is as follows:

$$T_d = \frac{b\alpha}{a - \alpha} \qquad (S.7)$$

where $a = 17.271, \mathrm{b} = 237.7$ are the constants for water vapor calculation, T_d is the dew point temperature in Celsius, and α is determined by

$$\alpha = \frac{aT}{b + T} + \ln\left(\frac{h}{100}\right) \qquad (S.8)$$

in which h is humidity and T is air temperature in Celsius.

When rain or heavy fog occurs, the dew point temperature becomes the same as the air temperature and the relative humidity is 100%. By comparing the air temperature with dew point temperature, one can identify events of rain and ground fogs. Figure S13 shows an example of raining events identified this way. The data was obtained using one of the author's data recorders based on Arduino as described in the previous chapters. This recorder was deployed at a piling in the Calcasieu Pass in Southern Louisiana for several years at 1 Hz sampling rate (one observation per second). This is a five-day record as an example identifying raining events. The cyan arrows and letters show these periods when the air temperature and dew point temperature merged together.

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