Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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WIND MEASUREMENTS TECHNIQUES

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. In the previous week we started our discussion on climate monitoring through various sensors systems. So this week we will continue on that vein and complete many of the in-situ and upper air sensing systems that are used for measuring various climatic and meteorological variables. So today we will start our discussion with measuring an important climatological and meteorological parameter wind speed and wind direction. First we will discuss wind speed and then wind direction. Now wind is a vector and in most instrumentation, the horizontal component is the one that gets measured.That is, the east-west component and the north-south component. As you know, these are called the zonal and the meridional components of wind speed. U is the zonal velocity, which is positive for west to east moving wind. V is the meridional velocity, which is positive for south to north moving win

The magnitude u is the total horizontal wind speed which is square root of u square plus v square. And the direction can also be obtained as tan inverse of v by u with respect to the north. There are two measuring systems, one for measuring wind speed and these are called anemometers and the other for measuring wind direction and these are called wind vanes. Let us discuss the anemometer first. The most common type of anemometer that you may have seen in many places is called the cup anemometer and the picture is on the right.

$$\text{Magnitude } U = \sqrt{u^2 + v^2}\text{ ; Direction } \theta = tan^{-1}\left(\frac{v}{u}\right) \text{ w.r.t North.}$$

As the name suggests, it's made up of three hemispherical crevices or cups that are attached at equal distances from a vertical shaft which is free to rotate. The vertical shaft rotates on a bearing arranged to cause little to no mechanical loading so that even small wind speeds can keep this shaft rotating. One thing to note is the cup arrangement is asymmetric. It is something that we do not see here, but basically they are not symmetrically placed along the 360 degree angle. It is skewed towards one side of the 360 degree angle.

And this is done so that the anemometer always rotates in one direction, even as the wind speed changes from one way to the other. The response characteristic of the anemometer can be deduced. We will not discuss the reduction here. But in general, the angular speed of the shaft in radians per second is proportional the wind speed u minus a constant u0 which is the starting speed of the anemometer. So, what this means is, this is the minimum wind speed that is required for the shaft to start rotating.

Response Characteristic:- $\omega = k(U - U_0)$; ω is the angular speed (rad/s), U_0 is the starting speed of the anemometer (m/s) and U is the wind speed.

So, if u is less than u0, basically omega is 0, alright. So, it is only when u is equal to or greater than u0 that the shaft starts to rotate. Now, there are two different applications. In climatological station, usually larger anemometers are used because these have to be placed in locations and set for many many and need to be robust to even storm speed winds. So, these have a bigger starting speed of using of about 2 meters per second.

So, these anemometers cannot measure wind speeds which are lower than 2 meters per second. However, in micrometeorology, where rapid response is needed, light anemometers with quick response and faster, lower starting speeds are used. These have user of 0.5 meters per second. The response time of these anemometers are also important because wind speeds can change very quickly.

So we need to know how long does the anemometer take to pick up a change that will happen in the wind speed magnitude. The response time is proportional to the inverse of the velocity of the wind. So, higher the wind speed, shorter is the response time, lower the wind speed, longer is the response time. So, suppose you initially have a wind speed of say 5 meters per second and that wind speed changes by 1 meter per second. Then the response time is proportional to 1 by 5.

However, if you had the wind speed of 10 meters per second and that changed by 1 meter to 11 meters per second, then the response time is proportional to 1 by 10. So, how fast it will detect the change in the wind speed much quicker the faster the wind is. It's measured in terms of the response length tau into u. Because tau into u, if you put u in this side, is a constant for a given anemometer. The proportionality constant is itself dependent on the size of the anemometer system itself.

So, for large cup anemometers where u0 is also large, the proportionality constant is around 10 meters. So, tau u is of the order of 10 meters. What this means is tau is proportional to 10 by u for large cup anemometers. Hence, is equal to 10 by u for large cup anemometers where u is in meters per second. Hence, suppose the velocity of the wind at the location is 5 and tau u is 10, then a change in wind speed will approximately take 2 seconds to register.

However, for light anemometers tau u is 2.5 meters. Hence, if the wind speed is 5 meters per second and you have 2.5 as the constant here, then a change in wind speed from 5 meters per second will take 2.5 by 5 or half a second to register.

So, you get a faster response with light cup anemometer. But the trade-off is light cup anometers are relatively fragile and hence they may get damaged mechanically much quicker due to bearing wear, mechanical stresses, etc. The output signal is a voltage proportional to the rotational speed of the shaft. Often the shaft is attached to a very small DC generator which generates a certain electrical signal whose frequency is proportional to the rotational speed of the anemometer shaft. And then that frequency helps us to evaluate the angular frequency omega of the shaft As a result, we can get the wind speed knowing thing.

Another option is a series of electrical pulses. So, this is a digitized format generated at equi-angular sweeps made by the rotating shaft. So, for example, it is possible the switch turns on after one single revolution. So, suppose the shaft is rotating at 50 revolutions per minute. So, it will the switch will turn on 50 times over a minute of duration and from that we know that what the shaft speed is 50 rpm convert it to radians per second and get the wheel velocity.

Another less used option is a sonic anemometer. This is the figure of a sonic anemometer. So, let us try to understand how this works. Here, what we have is a ultrasound emitter, a microphone that emits sound at ultrasound frequencies, 40 to 100 kilohertz. emission of sound comes from this microphone say, it goes here where it is received and also reflected back.

So, the sound hits this receiver where this receiver detects when the sound is hitting this sensor B, but also the sensor B reflects the sound back towards the emitter A. And then the emitter A also has a receiver which detects when the reflected sound comes back to the source. So, here what we are trying to find is the time required for the pulses of ultrasound emitted at 40 to 100 kilohertz to travel forwards and backwards between two fixed transducers. These two are separated by a distance of around 10 to 20 centimeters. Now, and this is kind of the figure.

So, this is kind of open to the atmosphere. So, the wind can move freely through this system. So, suppose now the wind velocity is in this direction. See the wind velocity V here. So, the actual speed of sound will be the speed of sound in still air which is Cs plus the wind velocity V as it moves from A to B.

Alright, now if it moves back towards this side, here the wind velocity will be the speed of sound in still air Cs minus V. So, T1 The time it takes for the sound to move from A to B is the distance L by Cs plus V and T2 is the time required for the reflected sound to move from B to A is L by Cs minus V. You take these two together and you solve for V to get L by 2 into 1 by T1 minus 1 by T2 as the speed of sound. between emission and reception of the direct sound and the reflected sound are accurately detected. This is a way to get the component of the speed of sound in this direction where A and B are oriented.

And what you can do then is have a separate orientation 90 degrees to this to get the other component of wind speed as well. So, sonic anemometer does not only give the magnitude, it can also give the component wise values of the wind speed in the zonal and the meridional direction. And here you can see this in this case that you have one set here, another set here oriented at 90 degrees, so that the zonal and the meridional wind speeds can both be detected and hence we are getting the wind direction as well as the wind speed, which is one of the great advantages of this sonic anemometer. Another advantage of this sonic anemometer is that it can also give the temperature of air. Because the speed of sound in dry air is basically gamma, which is Cp by Cb of air, ideal gas constant of air, temperature of air by the molecular weight of air, which is of the order of 403 into T. T is in Kelvin. So, if the speed of sound is known and you can get the speed of sound by once you know V, you can get the speed of sound from these equations. So, if the speed of sound is known, then you can get the temperature of air at the same point. Important to note that Moist air needs a correction because the speed of sound is not the same for dry air and moist air. Hence a hygrometer is also installed in such devices to have a moisture correction for moisture. Another advantage is measurements can be done very rapidly 5 to 100 hertz rates and hence it is useful to measure turbulent fluctuations in wind.

Sonic Anemometer

- The time required for pulses of ultrasound (40 – 100 KHz) to travel forwards and backwards between two fixed transducers (l = 10-20 cm separation distance) is measured.
- Forward flight time $t_1 = \frac{l}{c_s+v}$; Backward flight time $t_2 = \frac{l}{c_s-v}$;
  Hence wind speed in the given direction: $\boldsymbol{v = 0.5l\left(\frac{1}{t_1} - \frac{1}{t_2}\right)}$ where speed of sound is c_s (m/s) and l is the separation distance in meters.
- Once wind speed is known, c_s can also be determined. But speed of sound $\boldsymbol{c_s = \frac{\gamma RT}{Mw_{air}} \approx 403\,T}$. Thus, knowing c_s, the temperature of air can also be determined.

So you can get also the turbulence that is present in the wind fluctuation that is useful in the meteorological sensing. Also if you remember turbulent fluctuations can be used for rapid meteorological analysis of the wind. So that is the sonic anemometer which is a more sophisticated kind of anemometer that is giving us wind speed, wind direction, temperature of air as well as the turbulent or fluctuating components of the zonal and meridional winds. Next comes direct measurement of wind direction and this is done through wind vanes and this is a typical wind vane that you can see basically it's a kind of a flat vertical plate which is attached to a horizontal arm that is able to rotate on a vertical shaft so again this is often put in con along with the cup anemometer Or on a separate, so these two look to be the same shaft.

That is not true. This is one shaft and this is a second shaft. And the wind vane kind of rotates in the direction in which the wind is blowing. So, unlike a car panometer that always rotates in a single direction, a wind vane rotates in the direction in which the wind is blowing. It basically gives by the dynamic pressure of wind on this plate is half rho, the density of air into u square, the wind speed. which causes a static force on the plate moving it till it is aligned with the wind direction and then it stops moving.

So, you have a flat plate like this and the wind is moving like this, it goes till the plate is parallel to the direction of the motion of the wind, then there is no further force and the wind vane stops moving. and this way the direction of the wind can be determined. Now obviously this can be done manually but in sophisticated systems an automatic wind direction measuring system is installed. It can either be measured using a mechanical switch With multiple contacts distributed evenly around the shaft. So you have a kind of a 360 degree circle.

You have multiple switches. So whenever the shaft moves by a certain angle. Some of the switches get hit. And other switches do not get hit. So, based on what is the last switch that has gotten hit by the movement of the shaft in the wind vane, you can know what is the orientation of the vane and based on that the wind direction is evaluated. Another option is an optical encoder with a digital signal corresponding to the measured angle of the arm with respect to a reference direction.

the arm kind of moves and sweeps a certain angle theta with respect to a certain reference direction say the north direction and the wind vane is oriented at an angle theta with respect to the north then that angle is measured using an optical sensor which gives a digital signal. Another option which I have shown in this figure here is a potentiometer. So this is the direction of the wind vane for example. And this is a circular wire fundamentally with multiple resistances in series.

And this is kind of a short circuit. So, what comes is, suppose this is the positive terminal, this is the negative terminal. So, here the total distance, the current travels up to this point and it kind of moves here and goes out here. If this arrow moves further, then the electrical signal will move further downwards and hence the signal will change, right? The voltage signal will change as there are more resistances on the way for a fixed current. And this kind of gives an idea of the direction in which the wind vane is oriented. It is important to couple wind vane with anemometer readings as in term conditions, wind speeds close to zero, the wind vane simply gives the direction of the previous wind and needs to be discounted.

So, if the speeds are very low, the wind vane does not move at all. So, those measurements have to be discounted and that is why you need to couple an anemometer with a wind vane and has been shown here. Now, we have found the wind direction and wind speed using anemometer and wind waves. Let us not consider sonic anemometers where everything is obtained at once.

Just a typical cup anemometer and a wind wave. How do you evaluate the information there? Now, wind direction is conventionally defined as bearing of a point from which air is blowing. Okay. So, here if you look, the wind is blowing from the northeast direction towards the southwest direction. So, this is a northeasterly wind because it is blowing from the northeast direction. So, here the angle is theta. The opposite, a wind blowing from southwest to northeast is a southwesterly wind. And here the angle is, if you can see, theta plus 180. This theta plus 1. So, this new theta is equal to the old theta plus 1.

So, the direction is very important. So, the zonal west to east velocity component, west to east velocity component for this case is minus u sine theta because it is going in this direction. It is going from east to west. So, it is a negative component. right for this situation here and the meridional south to north velocity component is minus u cos theta south to north so the zonal component west is this way so this component here is on the opposite side so you have the minus side right similarly south to north is this way this is opposite side again so this is again minus u cos theta this is theta this is theta so this is u cos theta this is 90 minus theta so this is sine theta all right so for this wind velocity you can see that the zonal component is minus u sine theta and the meridional component is minus u cos theta and the mean is integral of this over a certain amount of time is this also holding from the other case So, here you can see the theta is now more than 180.

Okay. So, this is 180. This is 90. This is 180. This is 270. So, here theta is basically between 180 and 270. Alright. So, again if you put the values, you will get the correct.

So, here sine theta is negative. So, negative negative cancel, you will get positive u sine theta. And cos theta, is also negative. So, you again get a negative, negative. So, you get a positive value of u cos theta. So, you can do it yourself and see that this formula is valid for all possible cases of evaluating zonal and meridional velocity components.

So, this is the general formula that is applied. So, whatever be the angle theta measured clockwise with respect to the north direction. So, suppose the windmill is measuring the angle theta clockwise from the north direction and u is the cup anemometer based velocity magnitude, then the zonal is minus u sine theta, meridional is minus u cos theta. And the means are this and the average wind direction theta bar is tan inverse of this, all right. So, we will stop here today. In the next class, we will discuss a very important part which is wind measuring radiation. So, thank you for listening.