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

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INTRODUCTION TO PRINCIPLES OF MEASUREMENT AND INSTRUMENTATION - PART 1

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. Till the last section, we have discussed the first two aspects of this course, climate dynamics and climate variability. We had covered various climatological parameters how those parameters show variability in both the temporal scale and the spatial scales, what is the climate dynamics in terms of stability, instability, wind circulation systems, ocean atmospheric dynamics, due to the influence of the heterogeneity, both temporal and spatial, for these climatological parameters. We also looked at anthropogenic variability, due to things like forcings like CO_2, water vapor and feedback like water vapor and how those forcings and feedback can lead to consistent change and trends in the temperature due to perturbations in the energy balance. In the last section, we will discuss methods of measuring these various climatological parameters. So, climate monitoring will be the part that we will be covering over the next few weeks.

So first we will begin by a general introduction to the principles of measurement and instrumentation which is kind of common to all types of instrumentation that is used in the physical and the chemical sciences as well as atmospheric sciences. Though we will focus more on the ideas that are relevant to climatology and meteorology. First, we will define what is an instrument. An instrument is a physical device or system that is used to measure or monitor a physical variable of interest.

I hope that is quite clear. You are creating a system, engineering a system that helps us to measure or monitor a physical variable of interest. Here measure and monitor kind of means two different things. There is a subtle difference between them. For example, a thermometer measures the temperature when you put it in contact with the body or a water bath or something like that.

Monitoring is something that is extra. It is continuously measuring the physical variable of interest. and checking if that physical variable of interest is within a certain expected range or not. For example, if you think of a smoke detector, it is monitoring the presence or absence of smoke in the ambient air continuously and creating an alarm when the extent of smoke it is measuring reaches a critical threshold. A continuous measuring system is basically monitoring and this can be paired with an alarm or a detection system if it goes beyond a certain known threshold.

Such instruments can be as simple as a liquid in glass thermometer, a mercury thermometer of the old days, which is more or less obsolete nowadays, or as complex as a remote sensing weather satellite based instrumentation systems. And we will go over the both ranges during these few lectures. Why do we want to measure things in plant methodology and meteorology? Accurate measurement of present and past climate variable values is vital in the proper understanding and tracking of the changing climate system. While in this class we will not look at how do we measure past climate signals, which is a part of paleoclimatology, here we will be measuring more of the day-to-day current measurement of various climatic variables like CO2 concentration, like surface temperature, like air temperature, like pressure, radiation etc. through ground-based, upper atmospheric or satellite-based instrumentation systems.

These are also important in validation of global and regional climate models. They give us the important data to construct our climate models, also to validate the predictions of the climate. Now, what are the typical parts of an instrument? Now here, this is a generic instrument we are looking at. First part of an instrument is the sensor. You can see the figure of the sensor here.

This sensor is responding to a specific physical parameter that is being measured in a predictable manner. So, you have a physical parameter, say rainfall, and the sensor is measuring the rainfall, say the extent of rainfall in a predictable manner. A simple example, suppose you have a small bucket and that bucket is getting filled by rain that is falling on top of it. At a certain point, the sensor is measuring say the weight if the bucket gains due to the rainfall it collects over a certain period of time. Maybe that is our precipitation measuring device.

So, it is measuring the extent of precipitation by measuring the weight of the accumulated water due to rainfalls. The sensor is usually coupled to a transducer, which is the second part and it is sensor and transducer are usually connected together that converts the sensor response into a more easily measurable value. For example, change in the length of a wire into a voltage difference. You will see such examples, for example, in humidity measurements, where, very interestingly, a hair is often used which increases its length as the air becomes more humid. That length change can be converted into an electrical signal by voltage difference or a signal in, say, stress-strain curve.

So, the sensor measures the variable, a transducer converts that change into a more physically measurable value. An amplifier is used to increase the magnitude of the usually small change produced by the sensor. And this is part of the electrical system or electronic system connected to the transducer. change converted to a voltage or a resistance or a change in deflection due to, by a transducer. That change is usually quite small because we are often measuring small changes in the physical variable.

So, we need an amplifier to amplify that change. It can be a set of pulleys and levers to amplify the deflection. It can be a kind of a voltage or an electronic circuit to amplify the voltage signal. capacitance signal etc. Here the term gain is often used which is the ratio of the output signal amplitude and the input signal amplitude at the amplifier stage.

The ratio of the output signal amplitude to input signal amplitude is called the gain and this is often a important factor in what the amplifier is doing. Very importantly If there are errors, the amplifier can also increase those errors. So, the amplifier circuit has to be very carefully chosen so that random noise, random oscillations in the physical variable being sensed does not get amplified as well. Finally, we have a meter which can be a digital meter or an analog meter which provides the final readout in terms of magnitude. A recording or a data backup device may be attached to the meter or it can send the information directly to a computer as it is very common nowadays.

For a satellite, it can be a backup inside the satellite or a transmission directly to the station where the satellite measurement data is being stored. So, you have the parameter. It will be measured to change in certain physical variable in the sensor state. That variable change is converted to a different variable change that can be more easily measured by the transducer. That variable change is amplified by the amplifier and then recorded by the meter and stored in the recorder.

Now, what makes a good instrument depends on how do we answer a set of questions. For example, how large is the actual response due to the change in the physical variable value? So, the physical variable value changes by a certain amount. The actual response being recorded by the meter, how large is the actual response to that? So, a high resolution instrument can detect very small changes in physical variable value because its response is quite large even for small changes. The second important question is how quickly does the instrument respond to change in the physical variable value? If the variable value changes, what is the time it takes for the sensor and the instrument as a whole to respond to that change and show a concomitant change to the same magnitude? This is very important because if we are doing variable is changing very rapidly with temporal time, then if the instrument response is slow that temporal rate of change will not be measured accurately by that instrument. How reliable are the readings, are the measurements actually correct or not or if they are how close it is to the expected value, actual value of the measured parameters.

And over what range of values does the instrument give reliable readings? This is also very important. So if you think of a simple weight measure, say a simple weighing balance may have a range of say 30 kgs to 100 kgs. If you are putting on a weight that is 1000 kgs, it won't measure it effectively at all. Or if you are putting it on a weight of 10 kgs, it won't be able to measure that. So, the range of values that the instrument gives reliable readings for is also very important.

So, we will discuss these points in terms of certain characteristics which define the instrument response. The first is dynamic range. It is the range between the least and the greatest value of the parameter that can be measured by the instrument. So it is usually given as a ratio. Dynamic range is usually expressed as a ratio between the largest and the smallest values that the instrument can measure.

So suppose you have a pressure sensor. It's easy to understand that. And it can measure up to say, from 0.1 atmospheres to 10 atmospheres. So, its dynamic range is the highest value 10 at the top and the smallest value 0.1 at the bottom 100. So, it gives you the range between the highest value it can measure reliably and the least value it can measure reliably. Another important quantity in this context is the full scale range. which is the greatest value of the parameter that the instrument can detect. So, in this case, the full scale range is 10 atmospheres. So, you are given two points, the dynamic range of the instrument which is 100 and the full scale range is 10 atmospheres, knowing that you can find the lowest possible value that this instrument can measure.

The second important variable that is characterizing an instrument response is its resolution called the instrument resolution. It is the smallest change in a parameter value that is measurable by the instrument. So, it is, it is the, suppose a physical parameter changes by a certain amount delta x. what is the lowest value of delta x change for which the instrument sensor will also, sensor variable will also change and that can be detected through this transducer amplifier circuit. It is often quoted as a percentage of full scale range.

So, if the pressure measuring device has a full scale range of 100 kilopascals and if the resolution is given as 0.1 percent of full scale range, 0.1 percent of Fs, then its resolution is 0.1 percent of 100 kilopascals or 0.1 kilopascals. Any change below 0.1 kilopascals will not be detected. And it is wrong to record the measurements of a such an instrument at values of resolution less than its resolution. So, it can only goes like say 50 kilopascal, 50.1 kilopascals, 50.2 kilopascal, etc. You cannot record 50.15 because its resolution is at 0.1 kilopascal only. That is the resolution. Of course, an instrument with high resolution will detect a much lower amount of change than instrument with coarse resolution.

The third important characteristic is instrument response time. It is a measure of how long the instrument takes to respond by a required amount. This required amount is set to a sudden change in the parameter variable value being sensed. If at time t equal to 0, the parameter value suddenly has a step jump, how long does the instrument take to respond appropriately to a certain level? to that step jump change in its parameter value is the instrument response time. So, a fast responding instrument can quickly give the change in the parameter value, whereas a slow responding instrument will take a long time to respond to a change in the parameter value.

Finally, the process of comparing one instrument with another whose response characteristics are known more accurately in order to know the response characteristic of the first instrument. That process is called calibration. So, we have a new type of instrument. do not know how it responds to the change in physical parameter. We bring in a more well-established instrument whose responses to changes in physical parameter are well known and then based we use the two instruments in parallel to measure the same physical variable changes and see how the first instrument responds and compare it to how the second instrument responds.

And this process helps us to evaluate the response of our first instrument, what we are interested in, and quantify it. And this process is called instrument calibration. The more accurate second instrument is called the calibration standard. And the value of this second instrument is giving is taken to be approximately the same value as that of the physical variable itself. So, it has to be a more accurate, better quality, more sensitive instrument than the first instrument.

Another important parameter is instrument sensitivity and this is related to the instrument response. This is defined as the change in output from the complete instrument. It is sensor, transducer, amplifier all together. Change in output from the complete instrument in response to a unique change in the sensed parameter value. Suppose the sensed parameter value is the temperature and the temperature changes by 1 Kelvin.

From 100 Kelvin to 101 Kelvin. What is the corresponding change in the instrument output? That is, and plotting that looks at the sensitivity of the instrument due to changes in the physical parameter. If y is the instrument output and x is the original sensed parameter variable, then sensitivity is the change in y for unit change in x. So, how much did the output reading change. Output reading can be a voltage signal, for example. So, people who may get confused here, an instrument does not give the actual physical parameter variable as output reading.

It is giving something else. It is a voltage signal, a voltage resistance, a change in the pointer displacement, etc. What we are doing is to trying to characterize this response and connect it with the change in the physical barrier. The first way to do is through calibration. This is a part of the calibration process itself. Here we are saying the calibration helps us to record the change in the output reading of the standard instrument with the change in the output reading of this instrument.

And the standard instrument has already, we know the correlation. So, we can evaluate that this response of our preference, of our new instrument is correlated to this much change in the physical parameter value. And then we can do the ratio, the change in the physical parameter value by change in the instrument response, delta y by delta x or at the limit dy dx, the gradient. And here delta x is the change in the physical parameter value. But how do we know how the physical parameter value is changing? Here the output of the calibration instrument itself becomes the default value changed in the physical parameter.

If the calibrated instrument is saying that the temperature has changed from 100 kelvins to 101 kelvins, then we use that value to record the sensitivity of our instrument. The sense parameter value cannot be directly measured, hence the output y0 obtained from the highly accurate instrument with known output characteristics in calibration standard is used as a stand-in for x. If the change in the instrument output per unit change in the parameter value remains the same throughout its dynamic range, then the instrument has a linear response. That is the gradient dy dx has a single unit value and this has been shown in the right hand top figure. So, this is the test instrument response, this is the standard or calibration standard instrument response.

We see that all our points of what is our instrumental response versus the standard instrumental response fall more or less around the straight line. So, the gradient delta y by delta x or dy by dx is constant even at the lower end of the scale to the higher end of the scale. This is called a linear response. If, however, the instrument output changes on the magnitude of the measured parameter, so the instrument output, how much is coming out of, what is the output signal? That depends on where in the entire scale range we are.

Say at lower values, we have a different dy range. At higher values, we have a different dy range. And this is shown in this plot here. This is kind of a parabolic curve where you are getting higher response near the full scale end of the range and lower response near the bottom scale end of the range. This becomes a non-linear response because dy dx is a function of x also. We will see both linear response systems and non-linear response systems as we continue our discussions in later weeks.

Next comes how to characterize the accuracy of such instruments. Here, an important term is uncertainty, which was previously called errors. Uncertainty is the variability in the output values of an instrument on the repeated measurement of the same physical parameter value. So, we keep the physical parameter value constant and continuously sample it to our instrument. And the variability of the output values obtained under such a condition is called uncertainty.

Uncertainty is of two types, systemic uncertainty, a consistent repeated offset in the measurement as a result of a fixed or regular discrepancy in the instrument response. So, the instrument response has a consistent and repeated offset in the measurement compared to the actual value of the physical variable. This is the result of a fixed or regular discrepancy in the instrument response. So, this is often called a zero error or other things. you have a fixed bias, a fixed error added or subtracted from the actual physical variable value that is being measured that the system is always suffering from.

The calibration process can help quantify the systemic uncertainties and they can be offset in the further post procedure. So, for example, suppose you have a standard weight which weighs 30 kgs and every time you are getting your weighing machine is measuring 32 kg. So, this 2 kg is the systemic uncertainty, a regular fixed discrepancy between what the instrument response is and what the actual value is. Next, you have random uncertainties. Variations in measurements due to statistical fluctuations in either the quantity sense, because the quantity itself may have certain internal fluctuations, or the internal operations of the instrument.

The instrument has a significant internal wiring electricity and there are random processes that kind of skew the result one way or the other way which skew this random answer instrument. Random uncertainties can be quantified. You will see the quantification process in the next class and reduced by using averaging procedures. Because they are random, averaging usually helps to reduce or remove these random uncertainties entirely.

Okay. So, we will stop here today. We will continue the discussion in the next class. Thank you for listening.