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

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Lecture 63

UPPER AIR MEASUREMENTS

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. Today we will discuss how do we measure climatological and meteorological variables in the upper atmosphere through in-situ instrumentation. These are upper air measurements and the primary method are balloon carried in-situ probes which are called radiosondes. Radiosondes are balloon carrying measuring probes that return data by radio and hence that's why it's called a radiosonde instrument. These provide vital information about the atmosphere's vertical structure. All the measurement methods we have discussed earlier, they provide information only at the ground level.

However, For proper climatological modeling, we also need measurements of the various layers of troposphere and stratosphere and how they vary. And this information about the atmosphere's vertical structure and the dynamics thereof are obtained by radioscience. Typical measurements are obtained for temperature, humidity, pressure, radiative flux, etc. Balloon carriage sensors are routinely used in today's world and are launched from thousands of meteorological and climatological sites on a daily basis.

So it's a continuous and continuing operation from multiple weather station sites that continue to give a detailed vertical atmosphere profile of the Earth's climate and weather from multiple places on the planet. While temperature, pressure and humidity can be measured directly, wind speeds are indirectly inferred from the location and ascent data of the balloons. Then, once these measurements are made, these are telemeter that is transmitted to a ground station by a radio transmitter. One of the critical components of a radiosonde instrument package is the sounding balloon, the balloon that is carrying the radiosonde. These are typically latex balloons of mass between 200 grams and 1000 grams and is inflated with light gases like helium or hydrogen that allows free lift.

So, a helium being lighter than air and hydrogen being lighter than air, these balloons once filled with these two gases can easily move up into the upper atmosphere at a certain ascent rate that is determined by the buoyancy that is present for that balloon. The balloon rises and eventually bursts due to pressure differential caused material strain. So as the pressure of the atmosphere falls with altitude, the balloon starts to expand outwards to maintain pressure equilibrium. This causes increasing strain in the latex material and eventually it bursts. The burst height depends on the balloon weight as well as the payload weight.

So for a given payload weight, the burst height will increase with the weight of the balloon. So heavier is the balloon, longer is it able to move up in the atmosphere without bursting. So if you want to go really high up, you need a heavier balloon. And if you want to stay limited, say within the troposphere, a lighter balloon would do. After bursting, the radiosonde package descends by a parachute.

This is primarily a safety precaution as we don't want any person or property to get hurt by fast moving instruments falling down from the sky. Because these packages are usually not recovered and considered to be disposable. The measurement is made during the ascent stage and not during the descent stage. So when the radiosonde package is moving up through the balloon, only then the measurements are made. Helium being inert is the preferred gas.

But nowadays, helium is becoming increasingly costly because of supply problems. And hence, in many cases, hydrogen is also used despite the fact that increased handling care is needed because hydrogen is inflammable. Now that we have discussed how the balloon is like, let's take a look at the measuring system. The radiosonde is a very old measuring system that has been around since 1930s. So in early classical radiosonde instruments, obviously analog systems were used, but these have more recently been supplanted by digital technology.

This figure here is a picture of a classic radiosonde that is used in the 1940s to 1960s by United Kingdom. These are called Mark II radiosondes. In this, we have a pressure sensor which is an aneroid capsule. So, you remember the aneroid barometers we discussed. So, we have an aneroid capsule pressure sensor.

Temperature is measured using a bimetallic strip. So, a thermocouple or a small bimetallic based temperature sensor and humidity is measured using a mechanical hygrometer material. So, it may be a hair or a gold bitters material. cloth and other materials which are hydroscopic in nature. And all of these sensors have in common is that there is a mechanical change that happens because of the change in the variable.

So, the bimetallic strip will bend due to the presence of temperature differential. Aneroid capsule parameters will also have a mechanical deformation due to the presence of pressure differences and the material that is measuring humidity will expand or contract because of the change in humidity. So, the mechanical changes in these sensors modulate the frequency of an audio oscillator. So there is an audio oscillator which is connected to these mechanical sensors and the mechanical changes in the sensors, deformation of these sensors for example, modulates the frequency of the audio oscillator through an inductor in system. And this frequency modulation is transmitted to an antenna based radio transmitter.

So here you can see how the system works. You have the various meteorological sensors, pressure, temperature, humidity, etc. There may be a multiplexing switch. So, which can quickly switch between one sensor to another. And here you have the audio frequency oscillator

So, the mechanical deformation of one of these sensors to which the switch is connecting to modulates the frequency of the oscillator here. And this through an inductor system is converted into a radio frequency oscillator that goes into a transmission through a transmitter to an antenna, ok. However, modern radiosondes use semiconductor based data acquisition system and we will discuss this subsequently connected to radio transmission systems. So, classical radiosaurs use sensors where a certain type of mechanical deformation occurred due to the variability of the parameter that is being measured. That mechanical change in the sensors change the frequency, that is what called modulation means, changes the frequency of an audio oscillator through an inductor system and this frequency modulation was transmitted by an antenna based radio transmission.

However, nowadays you will have an analog to digital converter and then the digital signal is stored and processed in an onboarding, onboard semiconductor chip, a microcomputer and then that is transmitted to an audio frequency and this will come across later, just a few minutes later. All radiosonde need a battery's power supply, which is currently we use alkaline and lithium batteries. In the olden times, maybe lead acid batteries were also used. And you also need an efficient radio transmission and receiving system so that very little power is consumed and the radio transmission signal remains strong even over long distances. So, as it ascends high up in the atmosphere, the distance increases, but you have to have a strong radio signal that can be received.

So, you need a battery power supply and an efficient radio transmission and receiving system. Current measurement requirements of a radiosonde is quite stringent because it is measuring over the multiple layers of the atmosphere. So, temperatures it should be able to measure is between 40 degree centigrade near the sea level to minus 60 degree centigrade towards the top of the troposphere and at an accuracy of plus minus 0.5 degree centigrade. Pressures, similarly it should be measuring between 1000 hectopascals to 20 hectopascals, so sea level to the top of the troposphere or close to the center of the stratosphere.

So, here there is a significant change in pressure from near sea level to extremely high altitudes and this has to be measured with an accuracy of plus minus 1 hectopascal. And relative humidity can change from 0 to 100 entirely. Okay. Because it becomes very dry at the upper atmospheres as the air becomes cold and the accuracy will be less than plus minus 5 percent.

Okay. So, the key challenge is to have these ranges and accuracies reliably sensed by the various radiothon transmitters, sensors for them to be reliably transmitted via radio waves through an efficient transmission and receiving system. What kind of pressure sensors are usually used? Usually there are two types of pressure sensors used either together or simultaneously and often simultaneously may be used because the range of pressures is quite high. So either you use a series of aneroid capsules with temperature compensation program built in, say using a microcomputer, for the wide temperature variation that is encountered. The transducer converts the mechanical change into capacitance or inductance variation, and this capacitance or inductance variation is transmitted through frequency modulation of an audio signal as a radio transmission. So, you have a series of analyte capsules with built-in temperature compensation program in a microcomputer for example, in order to correct for the large temperature variations encountered during its ascent phase.

The mechanical change is converted to a change in capacitance or inductance that in change changes into a frequency modulation that is transmitted via the radio signal. Alternatively, we use something called hypsometer, which I have not discussed previously. And this is very important, specifically used in various radiosonde measurements of pressure. This measures pressure by determining the boiling point temperature for liquid at that given pressure. So, let us understand this idea.

We know water boils exactly at 100 degree centigrade at 1 atmosphere. However, if you go up high in the mountain, the water will boil at a lower temperature, say at 95 degree centigrade. And the reason is the pressure has decreased from 1 atmosphere to say 0.8 atmospheres, like that. So, given a certain ambient pressure, there is a constant temperature at which a liquid will boil.

And if you know the temperature at which the liquid is boiling, you can infer the pressure based on the phase change diagram for that liquid which is usually well evaluated. Given that, suppose you carry up a little bit of liquid, it may be water or it may be a low boiling liquid as well like say a alcohol type of a thing, ok. At various pressures as the sensor attends, you periodically heat the liquids and measure the temperature at which it starts boiling. When once you measure the temperature, based on the temperature, boiling temperature at that certain altitude, you can infer the pressure using the pressure temperature phase change diagram for that liquid. you can estimate the pressure based on the PT diagram of phase change for the screen without needing any correction.

Higher sensitivities at lower pressures encountered at high altitudes. So, this is especially useful at high altitudes where pressure falloff is quite high because you are getting better sensitivities there. So, this hypsometer becomes more and more sensitive And better estimates the pressure as the pressure falls to low values compared to near 1 atmosphere. So, unlike an aneroid capsule which has a problem with sensitivity at low pressures, a hypsometer is better at measuring changes when the pressure is already quite low.

So, high altitude sensors. And a low boiling point liquid can be used like a chlorofluorocarbon or an alcohol as I said to avoid a large heating power requirement. Because you know you have to heat the liquid electronically or on a periodic basis to measure the pressure. So that drains energy. So a small amount of liquid, low boiling liquid is often used. However, here we have taken a picture of a small hypsometer with a resistive heater element which contains water inside.

So, these are the two ways of measuring pressure. Then comes the measurement of temperature, humidity and wind. And this is kind of a picture, a blown out picture of a radiosonde system. So, this is the entire radiosonde box. So, the sensor shields, you need a shielding around it to prevent say moisture from entering and causing damage to the instrument for example.

You have a GPS antenna. This gives a location of the radiosonde. We will see why the location data is important. Inside you have the pressure sensor. Here it is probably an aneroid barometer that is being used. This is the temperature and humidity sensor.

We will discuss this here quickly. This is a camera. This may or may not be used to record an optical image of the ascent system. This is a GPS. So, this is a GPS module. This is connected to the antenna here to basically track the location.

This section is the radio receiver. So, the radio transmitter and the radio receiver system. This is the transmitter and this is the receiver that you have in your station to receive the radio signal. This is the entire setup. Now temperature is measured using a fine wire tungsten based resistance thermometer. So we have discussed resistance thermometers before.

So tungsten based resistance thermometer is often preferred because tungsten has a very stable temperature range as we have discussed earlier in our classes. Often however a capacitance based temperature sensor is also used. It is just another type of temperature sensor where change in temperature causes a change in capacitance. The sensor, whatever be the method used, the sensor is periodically heated so that the wet bulb saturation effects are minimized. So, because it becomes cold, water vapor tends to collect on the surface of the temperature sensor B.

So, when it is not measuring, you may periodically heat it quickly to evaporate the water and then let it come down to a stable temperature and then measure the temperature. That way, dry bulb temperature can be more easily measured. Humidity is measured using, again, we prefer non-mechanical means for the digital sensors that are used nowadays in radiosondes. We use a humicap, which is a humidity-based sensitive capacitor or a resistance-based high grister. So, either humicaps are used where changes in humidity cause a change in capacitance.

We discussed humicaps before or high gristers where change in humidity causes a change in resistance. The radio navigation systems or GPS systems, whichever is used, provide exact location of the package in space and time. Wind speeds above the surface can be determined by successive position changes of the radiosonde. So because the balloon is being carried passively by the wind, you know the rate of ascent because of the buoyancy effect. Any other changes of the balloon's location in the zonal or the meridional direction is due to the presence of zonal and meridional winds.

And knowing the weight of the radiosonde, you can calculate and the speed at which the displacement of the radiosonde is happening, you can calculate the wind velocity. That is that the balloon and the radiosonde instrument package is exposed to during its ascent period. So, that way wind speeds can be inferred based on the location data of the radiosonde during its ascent stages. Next, we come to the data transmission part. So, we have sensed it So, all of the electronic sensors nowadays used causes a change in the electrical output either which eventually is converted into a voltage change.

Even if resistance is changing, capacitance is changing, through a suitable converter, we eventually get a voltage signal from radiosonde, from any electronic instruments nowadays. And these electrical outputs from the radiosonde transducers has to be converted to radio transmitter. So, that is the main task. One way to do that is to arrange an oscillator to vary with the parameter sense and supply the oscillator frequency to modulate the radiosonde transmission frequency. So, suppose when there is no measurement, the oscillator is oscillating at a certain frequency.

Now, when a measurement is made and a voltage signal is generated, that voltage signal frequency is added to the added or somehow combined with the oscillator frequency to modulate its oscillator frequency. So, during sensing there is a change in the frequency of this oscillator. This can be done for multiple sensors. A multiplexing switch is therefore needed for the multiple sensors. Care is to be taken that the range of frequencies obtained from each sensor is non-overlapping.

So, this is very important. So, if you go back to this figure, you have multiple sensors and these sensors create a voltage signal in this case that is changing the audio, the frequency of this oscillator. How do we know which sensor is being activated? If the frequency change is at different ranges for the different sensors, so that this may be 1 to 20 kilohertz, this may be 30 to 40 kilohertz, this may be 50 to 60 kilohertz. Then we know, knowing at what range the frequency has been altered, which sensor was activated and which variable we are measuring. So this is a very important point. Care is to be taken that the range of frequencies obtained is non-overlapping.

Modern radio sounds use analog to digital converters coupled with an onboard microcomputer to digitize and control inputs from the multiple sensors. The digitized information is sent over radio channel via a modem. So, modern radio sounds instead of having this oscillator that is changing in frequency and having an analog signal sent, it converts the signal into a digital form using an ADC converter which we discussed earlier in the class. There is an onboard microcomputer to digitize and control the inputs from these multiple sensors. And there is a pre-programmed system by which that onboard computer directs which sensor to get the digitized data from.

The radio frequency for the transmitter is called the carrier wave. So, the base wave and the sensor signal is added as a modulation to the carrier wave. That is what we were speaking of as either a modulation of amplitude. So, the change can be changed in the amplitude of this wave, audio wave or a modulation of the frequency, the rate at which the waves are moving up and down.

Okay. or simply a repeated on-off of the waveform itself. So, if it is a pulse data, maybe the pulse creates a stock of the basic signal and the next pulse creates a on of the basic signal. So, how many times the signal has been turned off and turned on gives an input of the pulse, the number of pulses per second and that gives an idea of the required variable. So, it can either be a change in frequency of the transmitter audio, change in amplitude of the transmitted audio or a on-off nature of the transmitter audio. Once generated, the radio frequency is supplied to an antenna. The transmission distance ranges from 50 to 100 kilometers, but line of sight is required.

So, usual transmission is entirely possible for a very large distances 50 to 100 kilometers that is sufficient for measurements of stratosphere and tropospheric vertical measurements. However, line of sight is required. So, if the instrument has moved so far that it has gone beyond the horizon and there is no line of sight between the receiving station and the radiosonde, then you would not be able to get the signal. So this is the arrangement. So you have the various sensors, analog to digital converter, which is sent into a digital computer or microcomputer.

The location data is coming from the GPS. Then the digital to modem tone generator, the modem converts the digital signal into an audio tone. which is added as a change in the radio frequency and then is transmitted to the antenna. Merged with any other measurement data and position data by a small digital computer, the data stream generator is passed to a modem to convert a digital sequence into two different audio tones for radio transmission. These digital tones are converted back to data values at the receiver end.

Now, what are some of the uncertainties and we will close with that. Typically, one of the uncertainties is the response time. The radiosonde, I will change the spelling, there is a mistake here, typically ascend at the rate of 5 meters per second. The response time of 5 seconds implies, so if the response time of a sensor is 5 seconds, then the sensor signal is only sensing over a distance where the instrument has moved by 25 meters. So, there is a vertical smoothing of 25 meters if the sensor response time is 5 seconds.

Suppose it takes 5 seconds for the sensor to equilibrate to a new value. Alright. In that 5 seconds, there is radius of the ascended 25 meters. So, the next sensing must be at 25 meters later. in the height. So, you have a vertical smoothing of the variable at a resolution of 25 meters.

However, if the response time is 100 seconds, then you have a vertical smoothing of 500 meters. So, only the average value over this smoothing length can be measured by the radiosonde measurement and this is very much dependent on the response time. Hence, a first fast response sensor gives a much more resolved profile of a vertical variable say temperature, pressure or humidity than a slow response radiosonde sensor. Usually temperature and pressure responses are quite quick and hence you are getting better resolutions there. But relative humidity sensors have a long response time because the system itself needs to get water into the system or water evaporated out of the system and that takes a little bit of time.

So, relative humidity measurements have lower resolution than temperature and pressure measure in radiosonde by their very nature. Other uncertainties in radiosonde measurements include errors due to radiation. So the temperature bulk of the temperature sensor is exposed to solar radiation as it is ascending. So it is getting heated by direct sunlight and that is adding an additional heating source rather than the heat from the ambient air itself.

So, this can be modeled. So, assuming you have a spherical bead, so this may be a thermistor or a thermocouple whatever, a spherical temperature sensor bead at a certain temperature T, the air temperature is T ambient, this sensor is attached to a radiosonde which is rising at a speed w in the vertical direction, the diameter is d and the solar radiation that is incident on it is S. Also, the reflectivity of this sensor to sunlight, shortwave which is alpha, kinematic viscosity of air is nu, thermal conductivity of air is K. If this is so, we can show by modeling and we have not shown it here that temperature differential is basically 0.735 S * 1 minus alpha by K * nu by W to the power 0.6 D to the power 0.4.

$$\Delta T = 0.735\frac{S(1-\alpha)}{k}\left(\frac{\nu}{w}\right)^{0.6} d^{0.4}$$

So, this is the overestimation of the temperature sensor because of the excess heat that is coming through shortwave radiation coming from the sun that is it is absorbed. Clearly, if reflectivity is 1, it is reflecting everything back, then this becomes 0. So, this is internally consistent. Of course, as the solar wattage increases, the delta T will also increase. And you can see here, for a case of a 1000 watt per meter square system, solar wattage and for different sensor diameters from 1 millimeter to 5 millimeter for example, and different ascent speeds, so this is 3 meter per second ascent speed, 5 meter per second ascent speed and 8 meter per second ascent speeds, you are getting a radiation error ranging from around say at 1 millimeter case 0.5 degree centigrade to a 5 millimeter case So, 0.2 for a fast ascent, to a 5 millimeter case it goes to 0.5. If the ascent is slow, there is a greater amount of error. So, you are getting at slower ascent, you are getting 0.5 at 1 millimeter diameter only, at slower ascent at 5 millimeter diameter bit you are getting over 1 degree centigrade of temperature correction.

So, what this means is, That bigger is the sensor diameter, greater is the radiation correction that is needed. Slower is the ascent, greater is the radiation correction that is needed. So, small beads and if the radio sound is rising fast, we will have much lower temperature error. So, other errors include wet bulbing error. This is induced when the radiosonde passes through a cloud resulting in condensation of the temperature sensor.

The subsequent evaporation gives aeronautical reading. We have already discussed that how many radiosondes have an inbuilt heater to heat up the thermal sensor periodically to avoid this problem. The other is location error. If the radiosonde gets displaced significantly in the horizontal direction due to winds, then it is not measuring the vertical profile of the station or at a certain location vertically up. It is finding points over a large spread of geographic location. Then analyzing that data becomes difficult and it may induce a significant amount of errors.

So, that, so tracking data of radiosonde is critical in order to analyze how much location error has happened and how to compensate for it. So, with that we will close our discussion of radiosonde and the theory part. The last class of this week will have a small tutorial session where we will look at several numerical problems that we can solve readily on the various concepts of measurement technology that we have covered in the last few lectures this week and the week before. Thank you for listening and see you again in the next class.