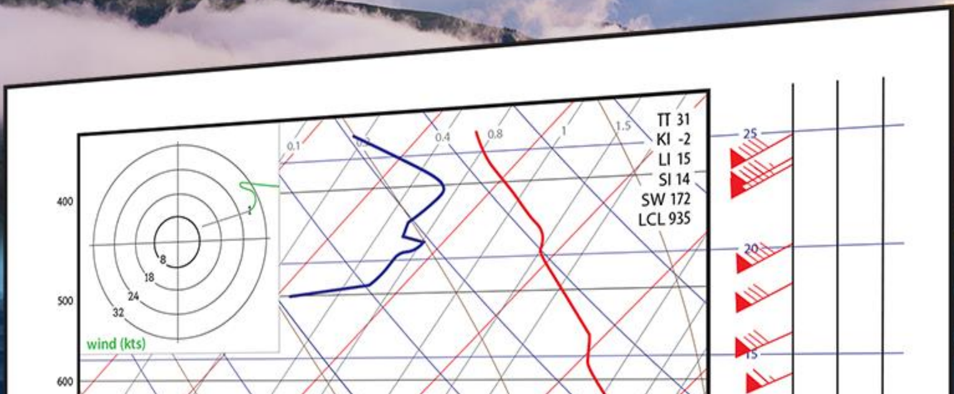
The Skew-T log (p) and Me

A Primer for Pilots



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“The Skew-T log (p) diagram is the best kept secret in aviation if you know how to unlock its secrets. Learn the basic principles and concepts of weather by learning how to interpret the Skew-T diagram.”

- Dr. Scott Dennstaedt

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Preface

When I was learning to fly in the mid-1990s, I quickly discovered that the Federal Aviation Administration (FAA) was not a huge proponent of the Skew-T log (p) diagram. This is not likely on purpose. It is more likely due to the oversight of its intrinsic value to pilots. In fact, as a budding pilot, I was astounded that the non-regulatory guidance contained in the Aeronautical Information Manual (AIM), and various FAA handbooks and advisory circulars did not make any mention of it. In fact, only the Glider Flying Handbook (FAA-H-8083-13A) gave it an honorable mention in the glossary, simply defining it as a thermodynamic diagram and nothing more.

As a meteorologist for over 40 years and certified flight instructor (CFI) for over 25 years, this is still quite a disappointment. Nevertheless, the FAA is making some attempt to rectify their actions based on the Aviation Weather Services Advisory Circular AC 00-45H, Change 2 that states in the revision memorandum issued in November 2016:

> *"The experience of listening to a weather briefing over a phone while trying to write down pertinent weather information becomes less tolerable when the reports are easily obtainable on a home computer, tablet computer, or even a smart phone. To see weather along your route using a graphic of plotted weather reports combined with radar and satellite is preferable to trying to mentally visualize a picture from verbalized reports. Although most of the traditional weather products, which rolled off the teletype and facsimile machines decades ago, are still available, some are being phased out by the National Weather Service (NWS) in favor of new, Web-based weather information."*

I could not agree more.

Given the critical nature of weather I aimed to set the bar higher for general aviation pilots. To that end, I co-authored a book entitled, Pilot Weather: From Solo to the Airlines with Doug Morris who is a Boeing 787 captain for Air Canada. This book was officially published in October 2018 and readers frequently commented that they wanted to see more information to learn more about the Skew-T log (p) diagram. Given the nature of this complex diagram, I felt that it deserved its own text which you are reading now.

Yes, the dialogue can be a bit challenging to learn how to properly utilize the Skew-T log (p) diagram. Even though you may not completely understand an adiabatic process or what the saturation mixing ratio tells you, there are still many basic applications that almost any pilot can master with just a few hours of education that this book provides. For those that really want to master the Skew-T log (p) diagram, I recommend that you read each section more than once to unlock its deep, and perhaps dark secrets. Spoiler alert…there is quite a bit more weather education contained between the covers of this book than you might imagine. One thing is clear: many pilots attempt to learn the Skew-T log (p) diagram on their own without reading a formal text such as this. That's the best way to end up in a compromising situation in flight. Since I began teaching pilots how to use this diagram in the late 1990s, it became obvious that pilots were poor at interpreting what they saw, especially those without any formal training. The result is that bad assumptions trickle into their briefing with no one to look over their shoulders. Moreover, some pilots have said bizarre things like:

> "*There's never been an accident because the pilot failed to consult the Skew-T.*"

This is likely because some pilots do not want to take the time to learn how to effectively use the Skew-T log (p) diagram and are envious of those who do make the time to learn and unlock its secrets. If you are reading this book, congratulations! You have taken the first step to a long yet rewarding journey. It seems quite common to hear a pilot to incorrectly compare a Skew-T log (p) diagram with a vertical route profile such as the one found in my EZWxBrief progressive web app (see ezwxbrief.com). It is as if they believe the Skew-T is some kind of "primary" source of data. For example, here is a common comment that shows a deep misunderstanding of the differences between the two when referring to a specific application's vertical route profile:

> *"I thought they [vertical route profiles] used soundings as their base engine, but I guess not. I'd rather everything be based off soundings."*

Both the vertical route profile and the Skew-T log (p) diagram are specific visualization tools that do overlap and draw their base data from similar sources (e.g., numerical weather prediction models). While forecast wind speed and direction at any segment point along the route is like the wind forecast depicted on the Skew-T log (p) diagram, it is hard to easily quantify the actual lapse rates on a vertical route profile. Also, you cannot "lift a parcel" of air on a vertical route profile to determine the presence of moist instability or derive other useful thermodynamic parameters such as Convective Available Potential Energy (CAPE) or Lifted Index (LI).

Lastly, it is hard to quantify uncertainty on a vertical route profile since these vertical profiles often make undocumented assumptions about the altitude of where clouds exist. Knowing just how quickly the temperature and dewpoint diverge (as we will explore later) is key to knowing how certain we are of where the tops of a stratiform cloud deck may be located. Consequently, it is still important to learn how to use the Skew-T, given that it has other features that a vertical route profile cannot offer.

You will find that the Skew-T log (p) diagram is the centerpiece for discussion in this book, but to get a better appreciation on how to utilize the diagram, this text dives deeply into some of the basic principles of weather that pilots attempt to avoid or have never been properly taught. Therefore, be prepared for a well-rounded education in weather. Furthermore, if you want to do a deeper dive, I am available for personalized one-on-one online training as well.

Since I began to introduce this amazing tool to general aviation pilots in the late 1990s, it is refreshing to see that the Skew-T log (p) Diagram has become important guidance to a subset of pilots when making critical operational decisions. As you wind your way through this text, consider the fact that you may never take advantage of all its capabilities, but if you invest the time, I am sure it will enhance your preflight briefing in a way that few other tools can. Who knows…you may even become a Skew-T junkie?

Please let me know your thoughts.

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Why the Skew-T?

In a nutshell, it's a great tool to learn about weather. No, I don't mean to learn what weather has occurred, is occurring, or is expected to occur at a particular time and location. Yes, it will provide that kind of useful information, but it is also a tool to learn the basic principles and building blocks of weather. Since I first began teaching pilots to use the Skew-T log (p) diagram back in the late 1990s, I found that I could use it as a canvas to teach pilots about what causes the formation of clouds, fog, icing, turbulence, and thunderstorms, just to name a few. In other words, my students need to understand these basic principles of weather first, before understanding how to use the Skew-T log (p) diagram for their preflight weather planning and analysis. Instead of typing out "Skew-T log (p)" for each reference, in this text I will just refer to this simply as the "Skew-T" or "Skew-T diagram" unless otherwise needed.

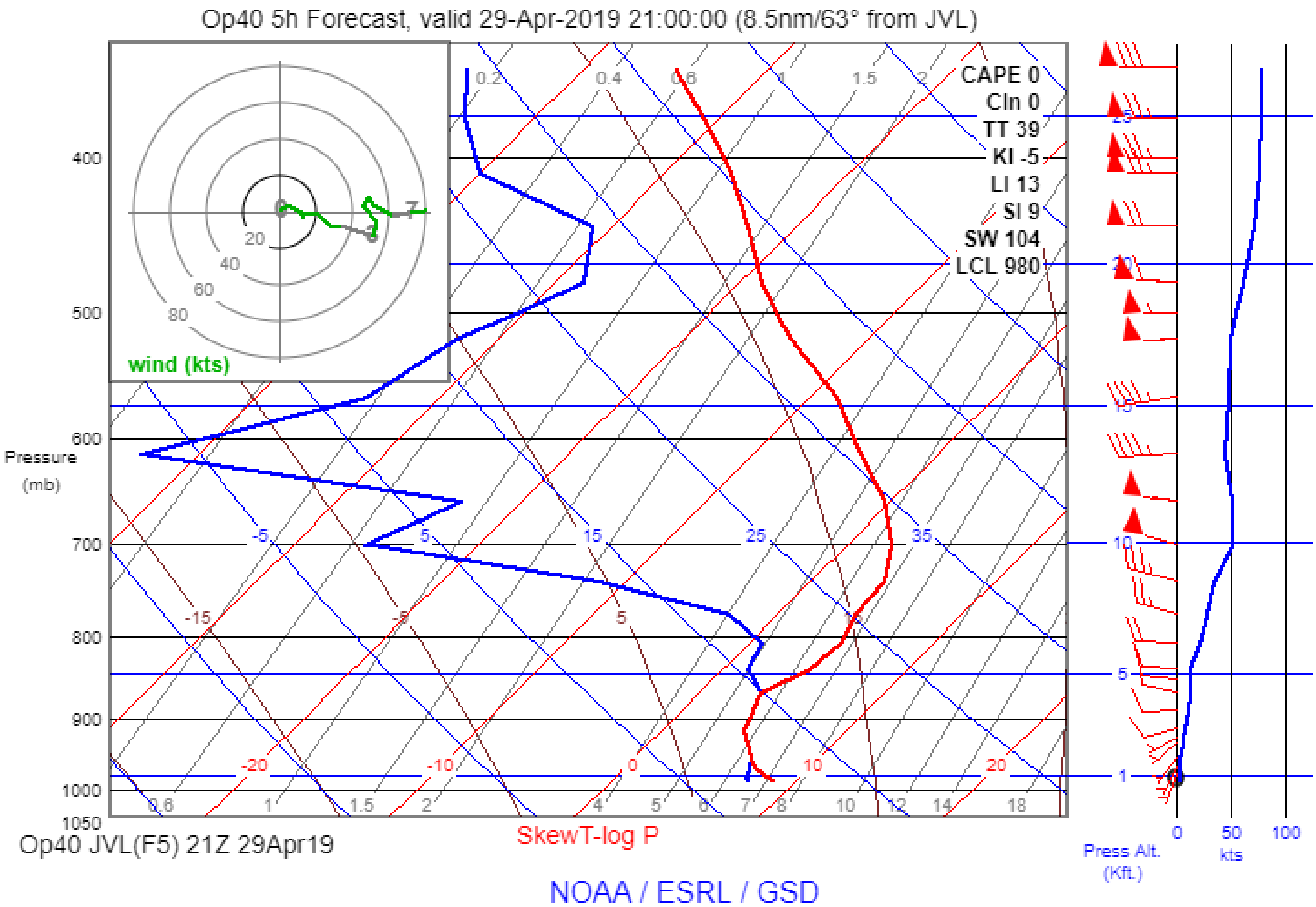

__Fig. 1:__ Temperature, dewpoint temperature and wind plotted on a Skew-T log (p) diagram.

First and foremost, using the Skew-T like the one shown above (Fig. 1) is not for everyone. Certainly, any pilot can be taught how to extract some basic information such as finding the height of the lowest freezing level, or determining the current or future winds aloft at cruise altitude over a particular location. Simple applications like these require a dearth of knowledge about the diagram and can be taught to just about any pilot in a short period of time. However, some of the more complex techniques such as finding the tops of a cumuliform cloud deck, or the potential for trapped lee waves, or the possibility of supercooled large drop (SLD) icing will require a substantial amount of knowledge and practice as well as a good grasp of the basic principles of weather, also known as meteorology.

Key points –

"The Skew-T is also a tool to learn the basic principles and building blocks of weather."

"You need to understand the basic principles of weather first, before understanding how to use the Skew-T log (p) diagram for your preflight weather planning and analysis."

Valid times

When using any weather observations, forecasts, or analyses, it is of utmost importance that you check and recheck the valid time of that guidance before using it. Failure to do so may result in weather you did not anticipate, leading to an unpleasant outcome once you are airborne. Weather depictions overlaid on charts and maps and other textual observations and forecasts may be valid over a range of time (e.g., accumulated precipitation forecasts), or they may be valid at a single time. The latter is typically the case for a Skew-T diagram.

General aviation pilots prefer local time even though most observations and forecasts throughout the world use Coordinated Universal Time (UTC) which is the successor of Greenwich Mean Time (GMT). Where did Zulu come from? The military and the North Atlantic Treaty Organization (NATO) assigned each time zone throughout the world a single phonetic letter. There are 24 time zones with the International Date Line utilizing two phonetic letters, namely “M/Mike” and “Y/Yankee.” The letter “J” was reserved for the local time of the observer. And the letter “Z” for “Zulu” was assigned the time zone at the Prime Meridian. In a nutshell, Zulu time is the time at the Prime Meridian that runs through Greenwich, England. This represents zero degrees longitude in both hemispheres.

Sometimes it’s easier to compromise

You might be wondering why UTC is the abbreviation for Coordinated Universal Time. Simply put, nothing is ever easy. The acronym came about as a compromise between English and French speakers: Coordinated Universal Time would be abbreviated by scientists in the U.S. as CUT, and the French name, Temps Universel Coordonné, would be TUC. Of course, scientists compromised, and UTC was born. It is interesting to note that a number of proposals in recent years have been made to replace UTC with a new system that would eliminate for leap seconds. A decision whether to remove them altogether has been deferred until 2023.

Aviation centric or not, most weather products throughout the world in the form of observations and forecasts depict the valid time in UTC (or Zulu). Therefore, to keep it simple, Zulu time will be used exclusively throughout this text unless otherwise necessary. For example, 1400 UTC will be abbreviated as 14Z, and 0000 UTC will be abbreviated as 00Z.

The Earth system

As you learn how to utilize the Skew-T diagram in your preflight briefing, for better or for worse, you will undoubtedly be exposed to the basic principles of meteorology. This is a good thing. Meteorology is the study of the physical state of the atmosphere driven by the sun. Therefore, the atmosphere of the earth is a heat engine transporting energy from the warm surface to cooler locations. This is done both vertically and horizontally (pole to equator). While both the vertical and horizontal nature of heat transport are extremely important to weather forecasting, the primary topic we will discuss in this text is related to the vertical transport of energy.

Shortwave radiation coming directly from the sun is absorbed primarily at the earth's surface, not by the atmosphere it passes through. Some of that incoming solar radiation is reflected to space by clouds, snow cover and large bodies of water such as the oceans. That is referred to as the earth's albedo. The atmosphere acts like a fluid, which distributes heat by motion systems on all space and time scales. Longwave radiation escapes to outer space which acts as the heat sink. Some of that long wave radiation is absorbed by the atmosphere through the help of greenhouse gases which is the key to making this planet habitable.

Outgoing radiation is key

The atmosphere for which we live and breathe is called the troposphere. It receives most of its energy not by the incoming solar radiation as is usually taught but is absorbed by the outgoing long wave radiation. In other words, the atmosphere is inefficient in absorbing the primary wavelengths of energy emitted by the sun but is a sponge when it comes to those wavelengths in that outgoing long wave radiation emitted by Earth.

It will become readily apparent while reading this text that Mother Nature abhors extremes. This imbalance in the atmosphere creates a temperature difference which, in turn, creates pressure differences (gradients), which drive the wind and circulations in the atmosphere. The Skew-T is just a way to visualize the result of this intricate interaction over this complex planet.

This Skew-T primer will not teach you to become a meteorologist so you can forecast the weather. However, to master the Skew-T, you will need to learn more meteorology than you were likely taught during your primary training. This is akin to learning how to play a musical instrument. You may learn enough to play the piano, guitar, or violin very well, but you may never feel comfortable enough to write a line of original music.

Writing music takes a special talent, creativity, and a lot more effort. The same is true for meteorology. You should be able to learn enough meteorology to read the diagram well but may never use the diagram along with other meteorological guidance to forecast the weather.

The good news is that you do not have to be a budding meteorologist to leverage the power the Skew-T diagram has to offer. But it is imperative to have a solid foundation to avoid the wrong interpretation. The primary goal of this book is to give you that foundation so you can continue to learn to integrate this diagram into your preflight planning toolbox.

Key points –

"The atmosphere acts like a fluid, which distributes heat by motion systems on all space and time scales."

"Mother Nature abhors extremes. This imbalance in the atmosphere creates a temperature difference which, in turn, creates pressure differences (gradients), which drive the wind and circulations in the atmosphere. The Skew-T is just a way to visualize the result of this intricate interaction over this complex planet."

The big weather picture

The key to a good preflight briefing is understanding the big weather picture or what a meteorologist calls the "synoptic weather overview." While it can be valuable to view a series of Skew-Ts along your proposed route of flight to gain a sense of the weather at those points, it can be difficult, if not fundamentally impossible to ascertain what is driving the weather by simply using an evenly spaced series of Skew-T diagrams.

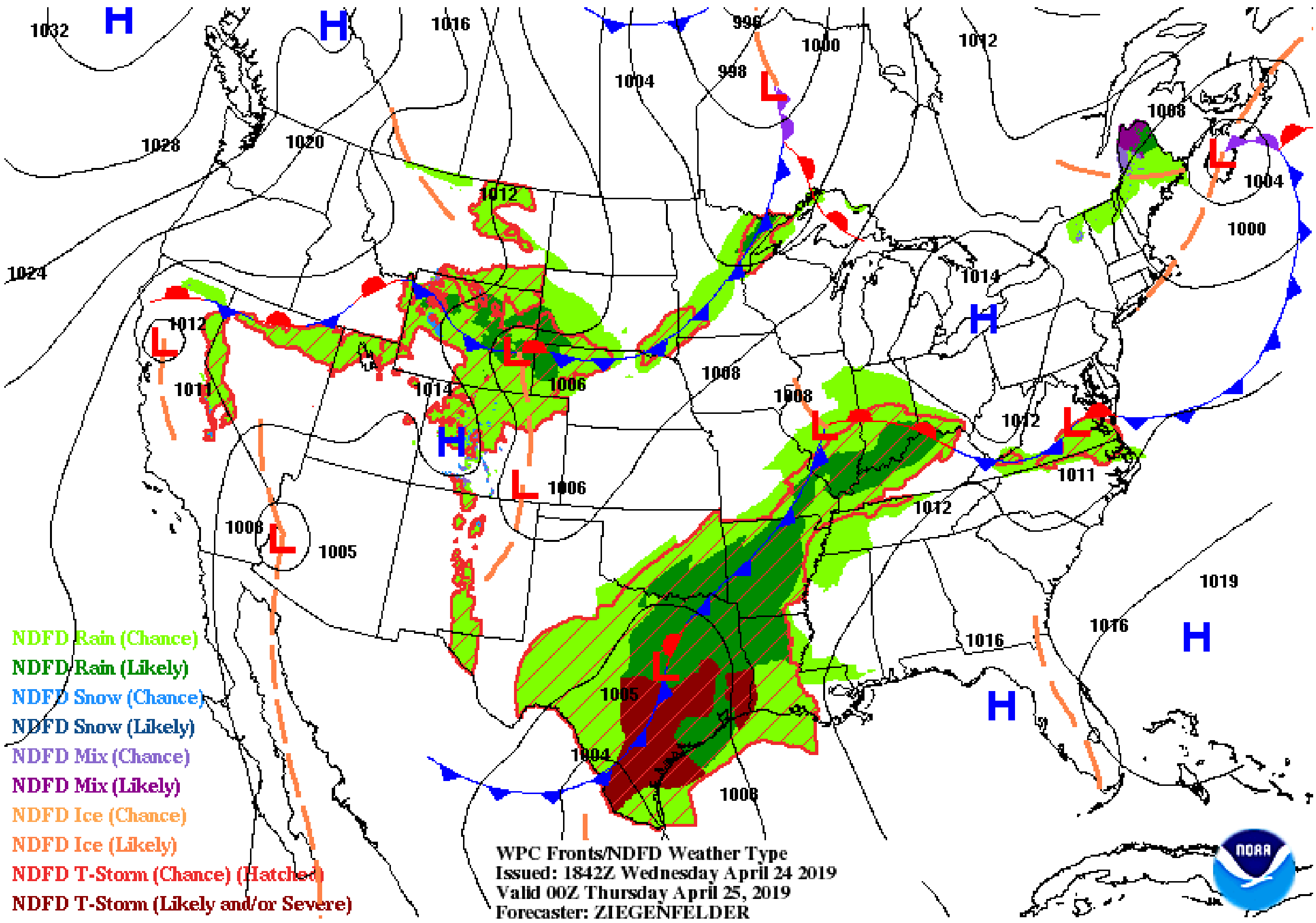

Fig. 2: *Use a prog chart issued by the Weather Prediction Center (WPC) to get a grasp of the big weather picture. Visit https://www.wpc.ncep.noaa.gov or use the EZWxBrief static weather imagery.*

More than just reading progs

Understanding the big weather picture is more than just evaluating what is occurring at the surface. Surface analysis or prognostic charts (referred to as "prog" charts) aim to depict the evolution of major weather systems over the next several days, but only tell a small part of the overall weather story. Upper air charts called constant pressure charts can help you complete that story and identify the magnitude of these major weather systems.

Even so, if the Skew-T diagrams all along the route appear to look similar, then it is very likely you will experience the same weather (good or bad) at your departure and destination airports and at all points in between. For example, if a strong cold front moved through your route laying down a widespread stratocumulus cloud deck (to be covered later) then you will see the same stratocumulus signature depicted on each location you chose along your proposed route. On the other hand, if the Skew-Ts look drastically different at some point along the route, then it is time to evaluate what might be driving that difference (e.g., a cold front). If it is the latter case, you should plan to understand the big weather picture by studying the prog charts like the one shown above (Fig. 2) that is issued by highly trained meteorologists at the Weather Prediction Center (WPC) located in College Park, Maryland.

Key points –

"It can be difficult, if not fundamentally impossible to ascertain what is driving the weather by simply using an evenly spaced series of Skew-T diagrams."

"If the Skew-Ts look drastically different at some point along the route, then it is time to evaluate what might be driving that difference (e.g., a cold front)."

Drill down tool

The Skew-T is a graph that provides a point observation or point forecast. It is not designed to give you big picture weather guidance as discussed above. As such, it should be used strictly as a drill down tool to help you better understand the details of the weather at a particular time and location. Therefore, it is best used to augment your briefing to fill in the gaps in both time and space for important weather guidance that is harder to decipher or extract using the typical low resolution weather observations and forecasts.

For example, after the passage of a strong cold front, you look at the satellite image and notice that there is a solid and expansive cloud deck along your proposed route. Let's assume there are no recent pilot weather reports (PIREPs) in the immediate area that would be relevant, and you would like to know the altitude you may break out to be on top of this overcast cloud deck. The Skew-T diagram is an excellent tool to help determine the tops of that overcast stratiform cloud deck for planning purposes.

Practice makes perfect

Pilot weather reports (PIREPs) are often a good way to practice using the Skew-T diagram. For example, when there's a recent report from a pilot that climbed through a stratus deck and reported the altitude of the tops, it's always a good practice to pull up a Skew-T analysis in that area and attempt to corroborate the pilot reported tops to what you see in the diagram. Or perhaps the pilot or crew reported airframe ice climbing through that layer. Pulling a forecast sounding analysis for that location and time might better illuminate how an icing signature may look on the diagram. In the end, exercises such as this can help with your interpretation skills using the Skew-T.

Is there an advantage by choosing several points along your route of flight to get a sense of what to expect while en route? That's a common question from pilots who are trying hard to get the most from the diagram. While picking a bunch of equidistant points along a proposed route of flight may illuminate a common theme when the weather is tranquil and homogeneous, doing so is like driving down the highway while looking only through a drinking straw. Nobody would ever do this since it is unsafe. The data rendered on a Skew-T diagram is an extremely narrow view of the weather and it is not uncommon that 50 miles on either side of your route can make a huge difference between a flight that is benign and one that is fraught with serious adverse weather. Be sure to always consult the big weather picture.

Key points –

"It is best to use the Skew-T to augment your briefing to fill in the gaps in both time and space of important guidance that is harder to decipher or extract using the typical weather observations and forecasts."

"The data rendered on a Skew-T diagram is an extremely narrow view of the weather."

The base diagram

The Skew-T is one of several thermodynamic diagrams available and is designed to aid in the interpretation of the vertical structure of temperature and humidity in the atmosphere and used widely throughout the world meteorological community. It has the property that equal areas on the diagram represent equal amounts of energy. When temperature, humidity and wind are plotted on the diagram, this enables the calculation of a wide range of atmospheric processes to be carried out graphically. Going back many decades, shown below (Fig. 3) is an example of the original coordinate system of the Skew-T log (p) diagram.

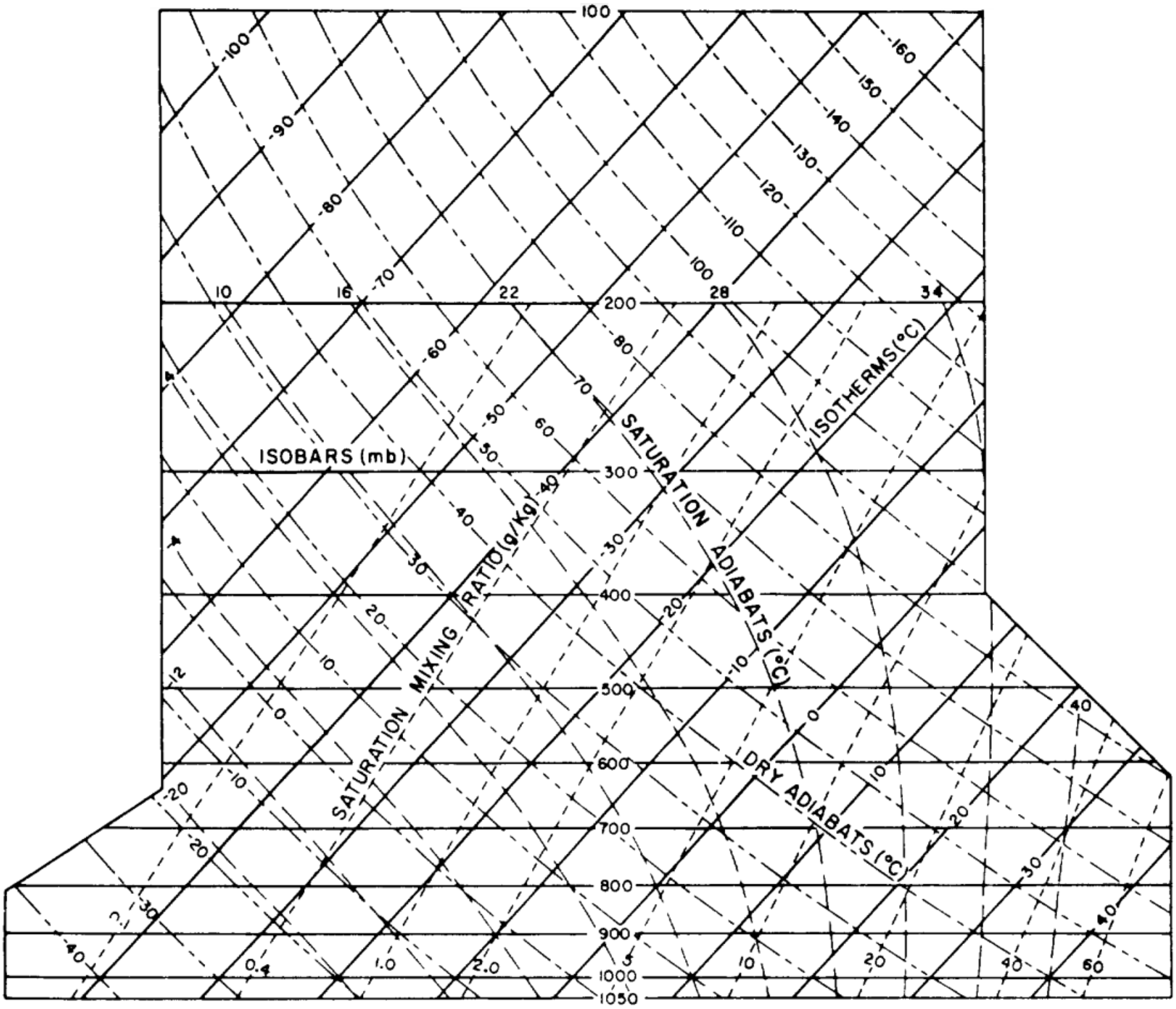

Fig. 3: *Original coordinate system of the Skew-T log (p) diagram without a hodograph.*

There are four basic thermodynamic diagrams used by meteorologists, including the Stüve, Tephigram, Emagram, and the Skew-T log (p) diagram. You may also hear the term "pseudo-adiabatic diagram" used as well. All these thermodynamic charts are "pseudo-adiabatic diagrams," in that they are derived by assuming that the latent heat of condensation (to be discussed later) is used to heat the air, and that condensed moisture falls out immediately.

All four present the same information and physical relationships and show isobars, isotherms, pressure altitude, dry-adiabats, saturation (moist) adiabats, and saturation mixing ratio lines. They differ only in the arrangement of these coordinates. The coordinate system of the Skew-T was first suggested by N. Herlofson, a Norwegian meteorologist. However, if you are a purist, the Tephigram is regarded as near perfect for strict thermodynamic calculations. In short, each type of thermodynamic diagram has its own "twist." To avoid getting bogged down in the differences, we'll exclusively focus on the Skew-T in this text, given that it is also the most referenced of the diagrams in U.S. aviation today. From time to time, though, you may run across one of these other thermodynamic diagrams online or in other books on the subject.

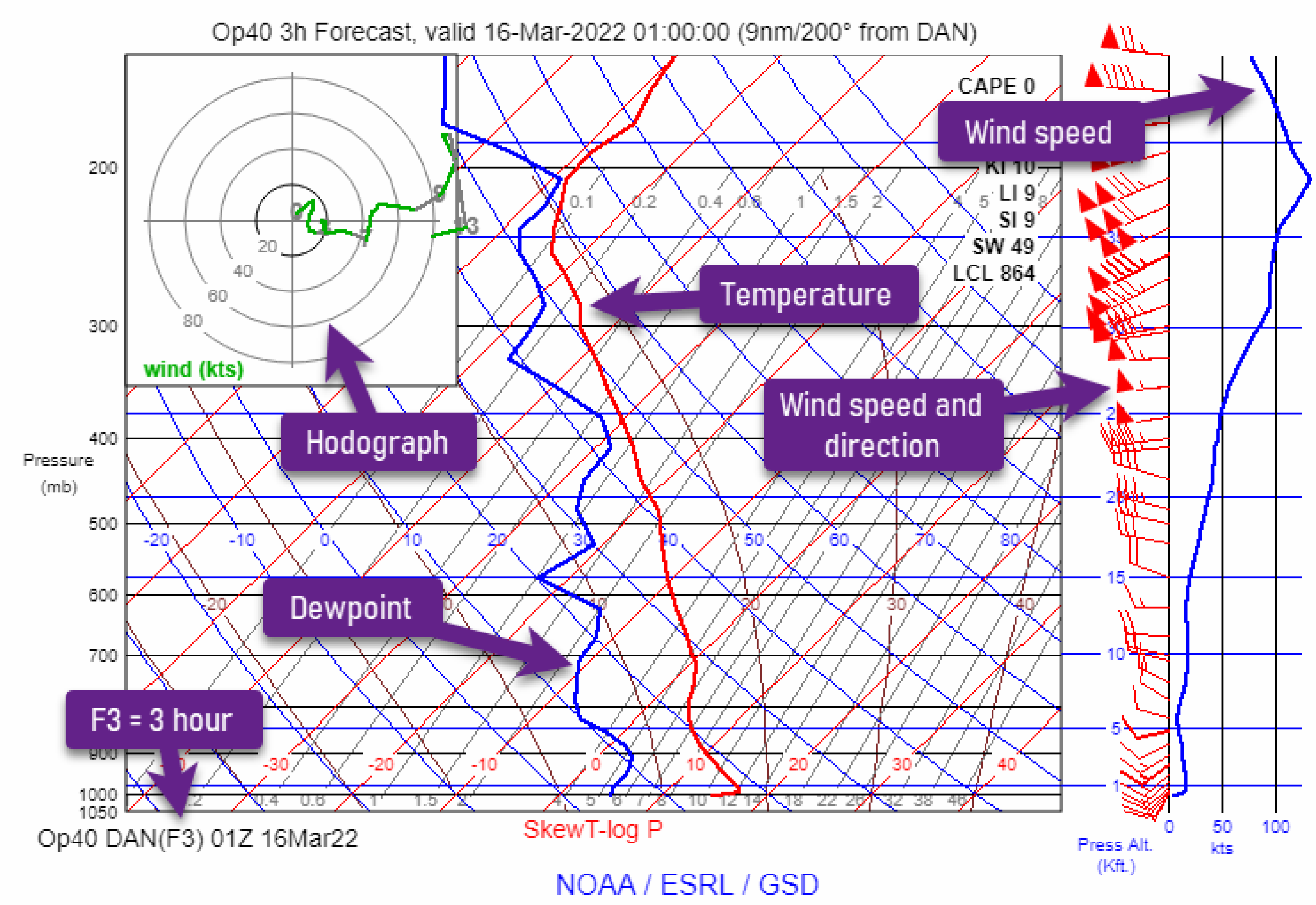

Fig. 4: A 3-hour forecast sounding (F3) for Danville, Virginia from the Rapid Refresh (RAP) model.

Thermodynamic diagrams are considered nomograms. That is, they are diagrams having lines that show the solutions to a set of equations, in this case, thermodynamic equations. The base diagram describes the thermodynamic laws of nature and their physical relationships. You do not have to plot the base diagram and the base diagram never changes. Think about this as a sophisticated form of graph paper. By the way, the bull's-eye diagram in the upper-left corner of the Skew-T shown above is called a hodograph. This portion of the diagram depicts environmental wind shear, which influences thunderstorm evolution and severity. This does not have much value to pilots, so we will only touch on this briefly in a later section.

On the Skew-T diagram above (Fig. 4), meteorologists plot environmental temperature shown in red and environmental dewpoint shown in blue. Also plotted on the right side of the diagram are wind speed and wind direction in red using standard wind barbs (in knots). Additionally, a graphical presentation of wind velocity is depicted in blue. All three of these parameters, namely, temperature, dewpoint and wind are plotted as a function of pressure or altitude.

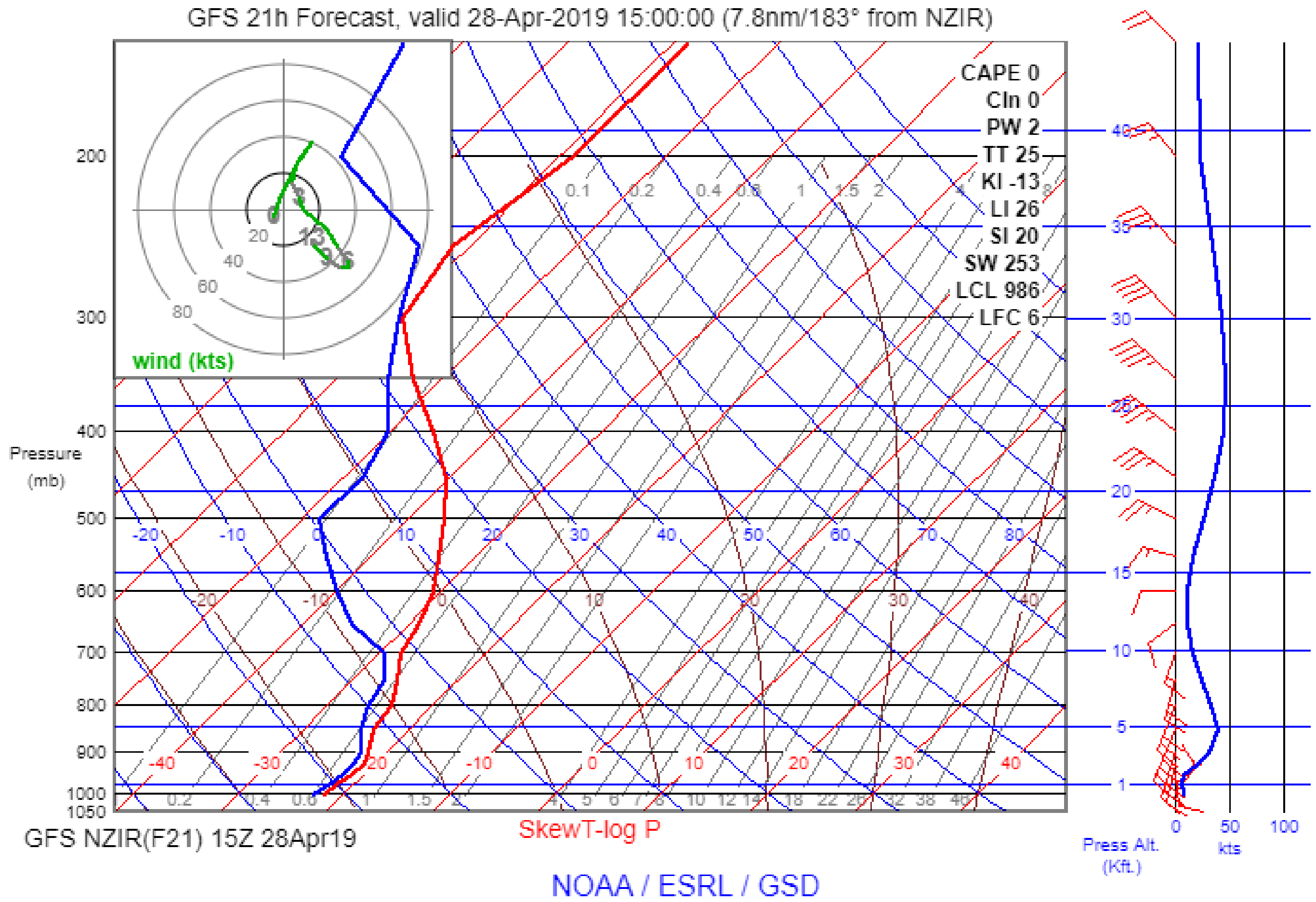

Fig. 5: A 21-hour forecast sounding from the Global Forecast System model near McMurdo Station in Antarctica (NZIR).

The temperature, dewpoint temperature and wind data plotted on a Skew-T diagram can come from multiple sources, which we will explore in more detail later. This includes data generated by a weather balloon, also known as a radiosonde, depicting observed environmental data and data from a numerical weather prediction model depicting analysis or forecast data. While it is nice to view the actual radiosonde sounding data, it is the forecast that concerns many pilots. For example, the Skew-T shown above (Fig. 4) depicts forecast weather conditions near the Danville Regional 13 Airport (KDAN) with a 3-hour lead time denoted by F3. It is important to reiterate that this is not data from a weather balloon (radiosonde). Instead, it is a forecast of temperature, dewpoint temperature and wind from a numerical weather prediction model called the Rapid Refresh (RAP) model. We'll discuss these numerical weather prediction models later and how they fit into the overall picture, but unlike a radiosonde which is released at very specific locations twice a day, forecast model data depicted on a Skew-T diagram (called a forecast sounding) can be plotted at hourly intervals *near* just about any airport in the United States—or even the world—depending on the model utilized. For example, the Skew-T diagram above (Fig. 5) is a forecast sounding with a 21-hour lead time (F21) near McMurdo Station in Antarctica.

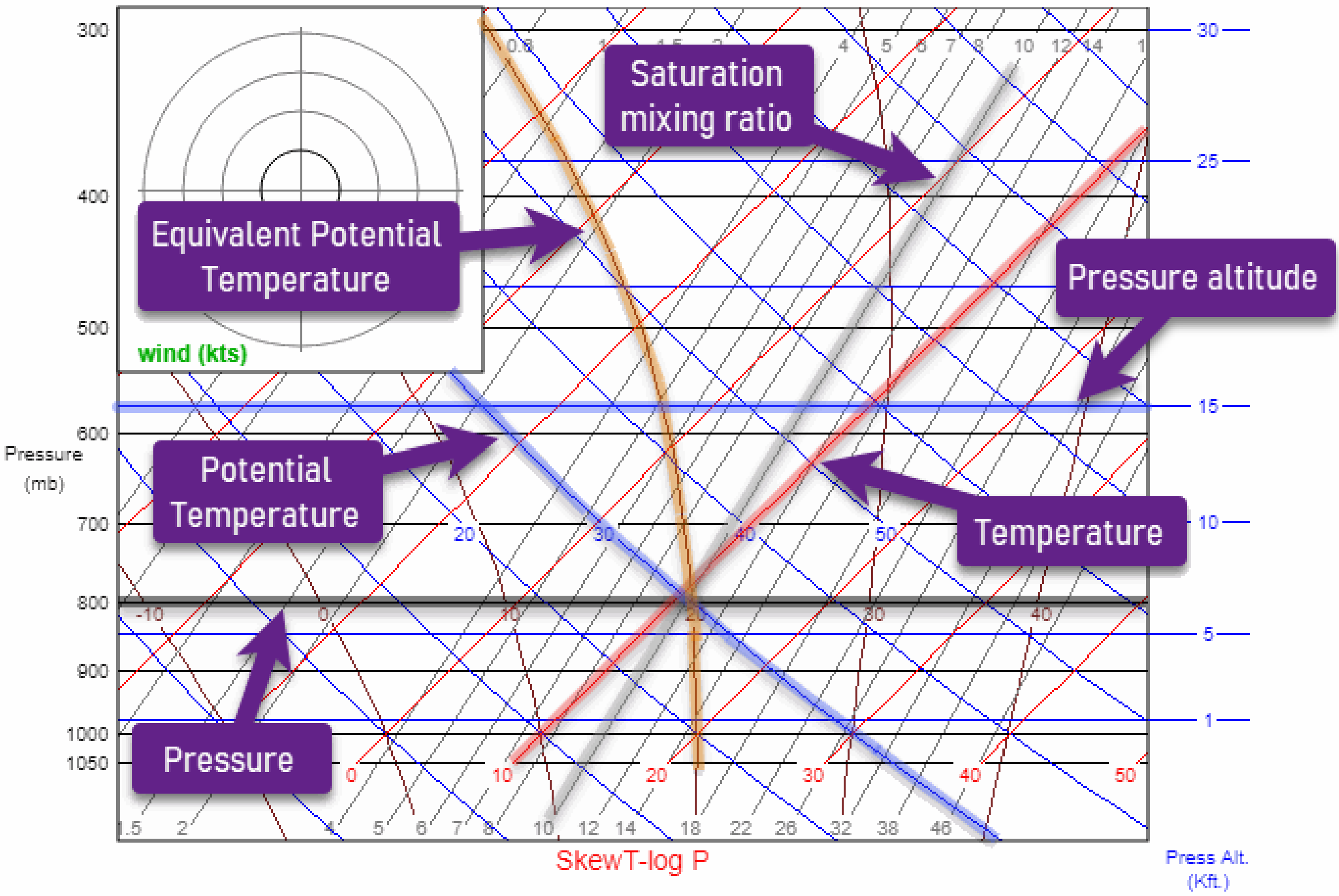

Fig. 6: *Five principal quantities found on the Skew-T log (p) diagram plus pressure altitude.*

Let's zoom in on the Skew-T diagram for the moment as shown above (Fig. 6). You will notice that there are a total of six different reference lines on this base diagram. That is common. You may find that some websites or apps might use a "simplified" version of the Skew-T that has less than six reference lines—and still, others might utilize more than six reference lines. It is also common to see pressure altitude represented in kilometers on some diagrams.

There are five principal quantities indicated by constant value lines: pressure (black), temperature (red), potential temperature (θ) (blue), saturation mixing ratio (gray), and equivalent potential temperature (θ_e) (brown) for saturated air. The sixth reference line on the chart is the pressure altitude (also blue). Yes, many of these terms are likely unfamiliar to the average pilot. Not to worry, all these important terms will be defined and explained later.

Each constant value line on the base diagram is typically coded in some fashion. In some instances, the lines are color-coded as they are in the diagram above, and others may use line type or line thickness to distinguish between the various lines. Unfortunately, there are no industry standards, so this largely depends on the website or application (or app) you are using.

Temperature (represented in degrees Celsius) is depicted on the **abscissa** (X-axis) and shown in red with warmer temperatures at the right and colder temperatures on the left. Pressure (represented logarithmically in millibars) is depicted on the **ordinate** (Y-axis) and shown in black with higher pressures at the bottom and lower pressures at the top. And for those millibar-challenged pilots, pressure (represented in thousands of feet) is depicted in blue, also on the Y-axis. From these two variables of temperature and pressure, three different equations can be solved to represent three other lines on this diagram. First, let's take a closer look at the three lines just introduced.

The red lines that are slanted or "skewed" at a 45-degree angle are the lines of constant temperature also called isotherms, hence the name "Skew-T" diagram. The 10-, 20- and 30-degree Celsius isotherms are highlighted below (Fig. 7).

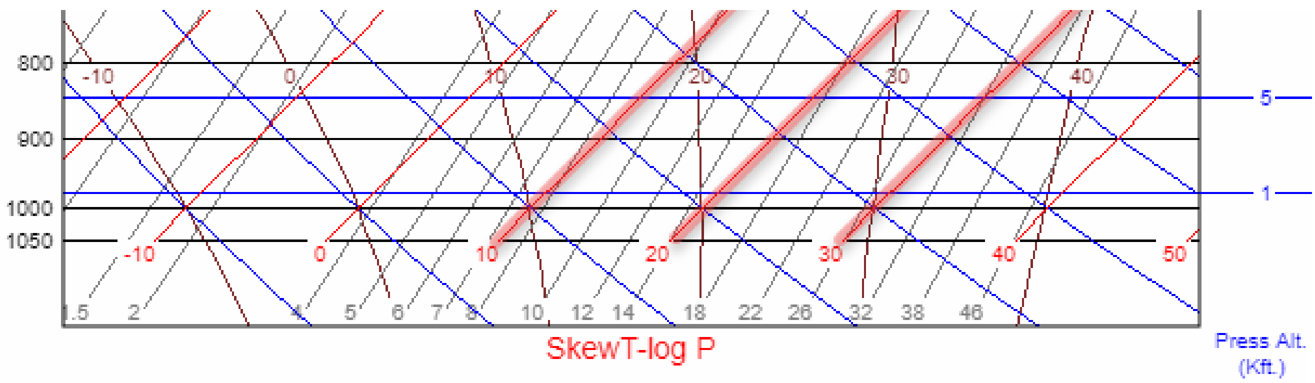

Fig. 7: *Temperature reference lines or isotherms in degrees Celsius (°C) highlighted on the base Skew-T diagram.*

Why are the isotherms skewed? Arguably, the reason they are skewed is primarily for convenience and utility. That is, meteorologists desire to have a diagram on which:

a) The important lines are straight rather than curved.

b) The angle between moist and dry adiabats (to be discussed later) and isotherms is large enough to facilitate estimates of the stability.

c) The ratio of area on the chart to thermodynamic energy is the same over the whole diagram.

d) An entire sounding to levels inside the stratosphere can be easily plotted.

e) The vertical in the atmosphere approximates the vertical coordinate of the diagram.

Next, the black horizontal lines are the lines of constant pressure, also called isobars, which are represented in millibars. For reference, the 1,000, 900, and 800 mb isobars are highlighted below (Fig. 8). While hectopascals (hPa) is used in meteorology, most weather forecasts quote atmospheric pressure in millibars instead.

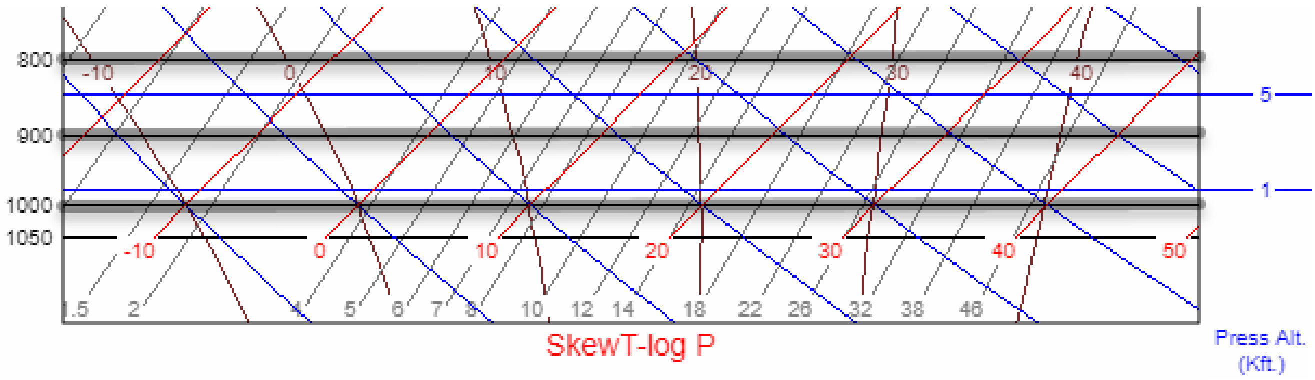

Fig. 8. *Pressure reference lines or isobars in millibars (mb) highlighted on the base Skew-T diagram.*

Notice that on the Skew-T diagram, pressure surfaces are at a greater distance from each other as pressure decreases (altitude increases). In the dark gray highlighted area shown below (Fig. 9), each pressure slice has the same 100 mb top-to-bottom pressure difference (900 to 800 mb, 700 to 600 mb, and 500 to 400 mb), but you can easily see the altitude spread is over a greater depth with increasing altitude. This is because the atmosphere is said to be compressible under its own weight; that is, lower layers are compressed more than the upper layers. As a result, atmospheric pressure, and air density both decrease exponentially with height. This illustrates the logarithmic or log (p) nature of pressure with altitude. From the discussion above, now you know why it is called a Skew-T log (p) diagram. The temperature reference lines or isotherms in degrees Celsius are skewed at a 45° angle and pressure in millibars is represented on a logarithmic scale.

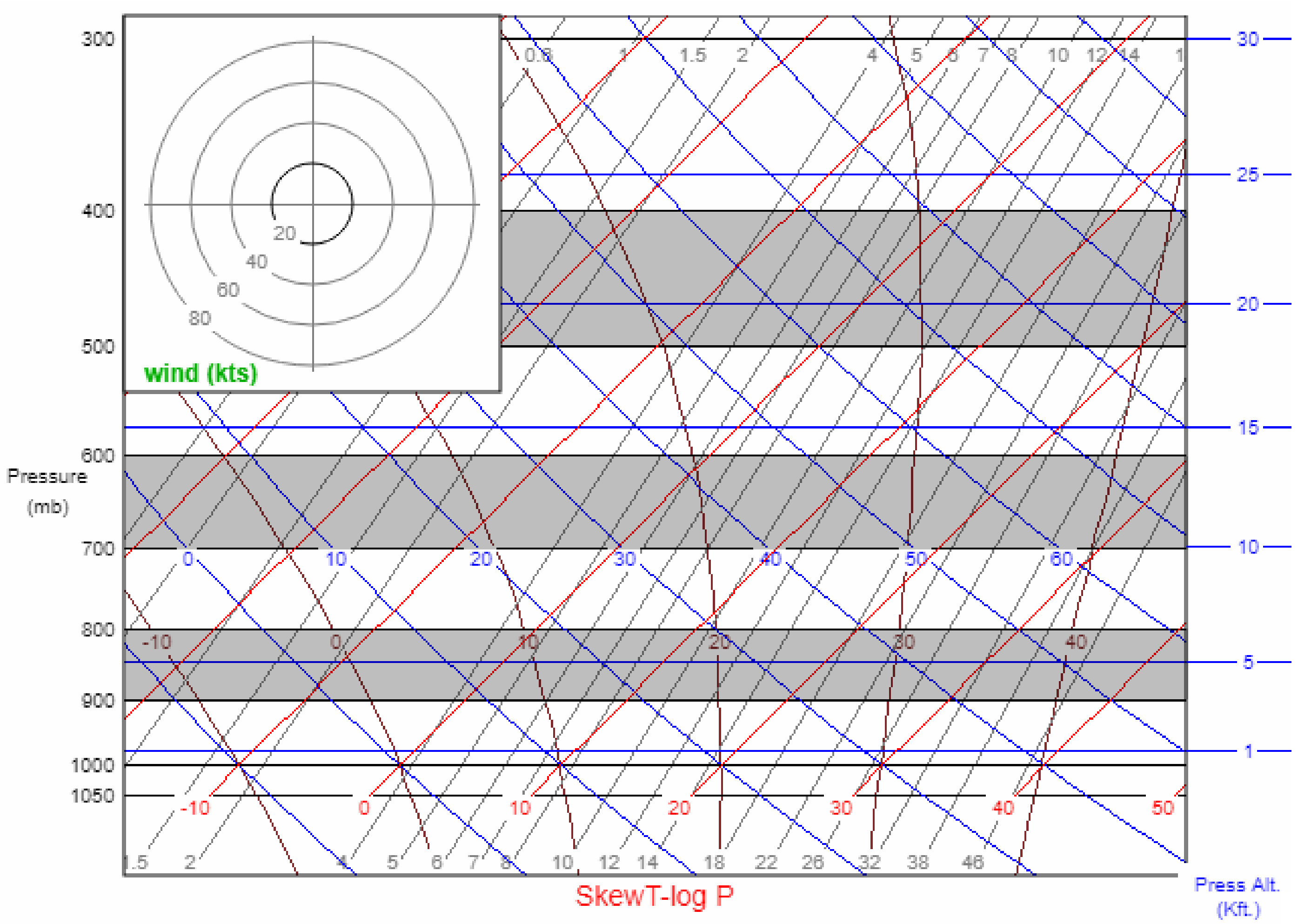

Fig. 9: *The logarithmic nature of pressure due to atmospheric compression.*

Lastly, the blue horizontal lines are the lines of constant height that represent pressure altitude in thousands of feet. Remember that pressure altitude is the resulting altitude on your digital or analog altimeter in the cockpit when the altimeter setting is adjusted to 29.92" Hg (1,013.2 mb). This setting is equivalent to the atmospheric pressure at mean sea level (MSL) in the international standard atmosphere (ISA).

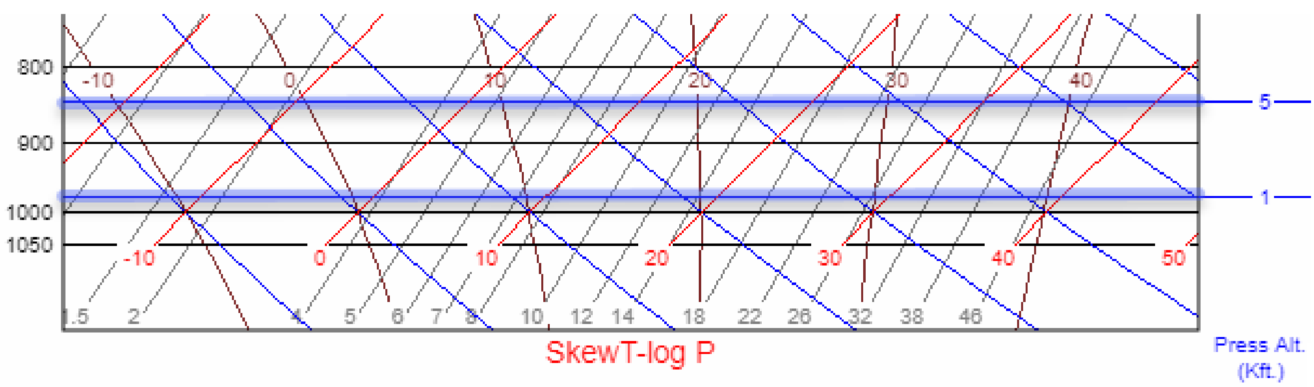

Fig. 10: *Pressure altitude reference lines in thousands of feet (Kft) highlighted on the base Skew-T diagram.*

For reference, the 1,000-foot and 5,000-foot heights are highlighted above (Fig. 10). Note that this is pressure altitude, not true altitude, height above mean sea level (MSL), or height above ground level (AGL). Other than extreme weather situations, mean sea level height and pressure altitude are close enough that the difference isn't significant. In this text, all altitudes are assumed to be pressure altitude or mean sea level height unless otherwise noted as AGL.

Both the skewed version of the Tephigram and the Skew-T have most of these advantages, but the latter is preferred because its isobars are parallel, which makes it easier to quickly estimate pressure altitudes, something pilots appreciate more than using pressure in millibars.

Let's take a moment to review what we have discussed so far. The Skew-T log (p) diagram depicts the temperature, dewpoint, and wind as a function of pressure or altitude. Plotting data from a radiosonde observation depicts the measured temperature, measured dewpoint, and measured wind as a function of pressure or altitude. The same kind of data could also come from the output of a numerical weather prediction model to represent the current or future state of temperature, dewpoint temperature, and wind. Pressure and pressure altitude are depicted on the Y-axis as horizontal and parallel black and blue lines, respectively. Lastly, the temperature is depicted on the X-axis, represented by red lines skewed at a 45-degree angle.

Up to this point, we have tackled three of the six reference lines on the base Skew-T diagram. In the end, a thermodynamic chart such as the Skew-T represents a point observation or forecast over a particular location at a specific time. Given that it describes a very narrow view of the atmosphere, it is best served as a tool to "drill down" and uncover important details not easily discovered on other maps, charts, or forecast guidance that are more likely to provide a much broader scale overview in time and space.

In the remainder of this text, you will learn techniques of how to use the Skew-T diagram to quantify and describe the potential for adverse weather elements such as airframe icing, turbulence, and thunderstorms, just to name a few. Before this can be achieved, we need to first delve into the basic properties of the atmosphere that often dictate what adverse weather is the most probable. Note that some of the following dialogue will be complex and challenging for many pilots but is necessary to fully appreciate the complexity of all that Mother Nature has to offer.

Key points –

“The temperature, dewpoint temperature and wind data plotted on a Skew-T diagram can come from multiple sources. This includes data generated by a weather balloon, also known as a radiosonde, depicting observed environmental data and data from a numerical weather prediction model depicting analysis or forecast data.”

“There are five principal quantities indicated by constant value lines: pressure, temperature, potential temperature (θ), saturation mixing ratio, and equivalent potential temperature (θ_e) for saturated air.”

“The base diagram describes the thermodynamic laws of nature and their physical relationships.”

“In the end, a thermodynamic chart such as the Skew-T represents a point observation or forecast over a particular location at a specific time.”

Internet data resources

There are dozens of online resources that provide access to these thermodynamic diagrams. The primary resource for Skew-T diagrams utilized in throughout this text can be found at **https://rucsoundings.noaa.gov**. This interactive tool was created and is maintained by developers at the National Oceanic and Atmospheric Administration (NOAA) Global Systems Division (GSD) of the Earth System Research Laboratory (ESRL). More about this interactive sounding tool will be discussed later. A simple Internet search and search on the Apple's App Store or Google's Play Store will reveal many websites and apps that provide access to these diagrams. Nevertheless, listed below are a few websites that are worth mentioning. There are dozens of others. Please note that for some of the website's access to these diagrams may require selecting a point on a forecast model map to show the forecast sounding at that location.

- https://www.spc.noaa.gov/exper/soundings (radiosonde)
- http://weather.rap.ucar.edu/upper (radiosonde)
- http://weather.uwyo.edu/upperair/sounding.html (radiosonde)
- https://vortex.plymouth.edu/mapwall/upperair/raob_conus.html (radiosonde)
- https://vortex.plymouth.edu/mapwall/upperair/raob_conus.html (radiosonde)
- https://vortex.plymouth.edu/myowxp/fx/fxsnd-conus.html (forecast soundings only)
- https://skewtlogpro.com (app) (forecast soundings only)
- http://www.twisterdata.com (forecast soundings only through map selection)
- https://www.tropicaltidbits.com/analysis/models (forecast soundings through map selection)
- https://ezwxbrief.com (distributes soundings through the interactive NOAA soundings site).

Key point –

"The primary resource for Skew-T diagrams utilized in throughout this text can be found at https://rucsoundings.noaa.gov."

Basic properties of air

Before we get knee-deep into explaining how to use the Skew-T diagram, it is extremely important to review the basic properties of the atmopshere. In fact, understanding what causes icing, turbulence and convection is very highly dependent on these basic principles.

Air is simply of a mixture of many gases. The three major constituents of "average" air near the surface are nitrogen (76.9 percent), oxygen (20.7 percent) and water vapor (1.4 percent) (Eagleman, 1980). The relative concentrations of nitrogen and oxygen are actually quite uniform with height for a considerable distance above the earth. In other words, the same *percentage* of nitrogen exists at 30,000 feet as it does at 1,000 feet. Water vapor, on the other hand, varies quite a bit in the atmosphere, especially with height. It rapidly decreases with height and is almost exclusively confined to the lowest 50,000 feet.

While the relative concentrations of nitrogen and oxygen are uniform with height, the atmospheric pressure and density of air decreases quite rapidly with increasing altitude as mentioned earlier. In fact, it decreases exponentially with height and is where the log (p) reference of the diagram gets its name. Because of this characteristic, we say that the atmosphere is compressible on itself and has higher pressure and density near the surface. Similarly, the altimeter used in most aircraft is an instrument that directly measures atmospheric pressure and displays that pressure as a function of height or altitude. Due to nonstandard temperature, pressure, and density (differences in moisture), pilots are required to update their altimeters to the local settings based on surface observations before they depart and during their flight. In the U.S. the altimeter is set to 29.92" Hg when flying at or above Flight Level 180 (18,000 feet MSL).

A common reference

There are many references to height used by both meteorologists and pilots. This includes mean sea level height (MSL), true altitude, pressure altitude and above ground level (AGL).

The density of air is determined by the masses of atoms and molecules and the amount of space between them. It is calculated by the mass of air divided by the volume and represented as kilograms per cubic meter (kg/m^3). In other words, density tells us how much matter is occupying a given space or volume. As the temperature of the air is increased, the kinetic energy (activity or motion of the atoms and molecules in the volume of air) also increases. As shown in the depiction below (Fig. 11, right), the added energy causes the molecules to spread further apart which, in turn, decreases the density of that warmer air. Conversely, as the kinetic energy is decreased by lowering the temperature, this slows down the motion of the molecules, allowing them to crowd closer together and air density subsequently increases as shown below (Fig. 11, left). **This leads us to the property that warm air is always less dense than cold air at a given static air pressure.**

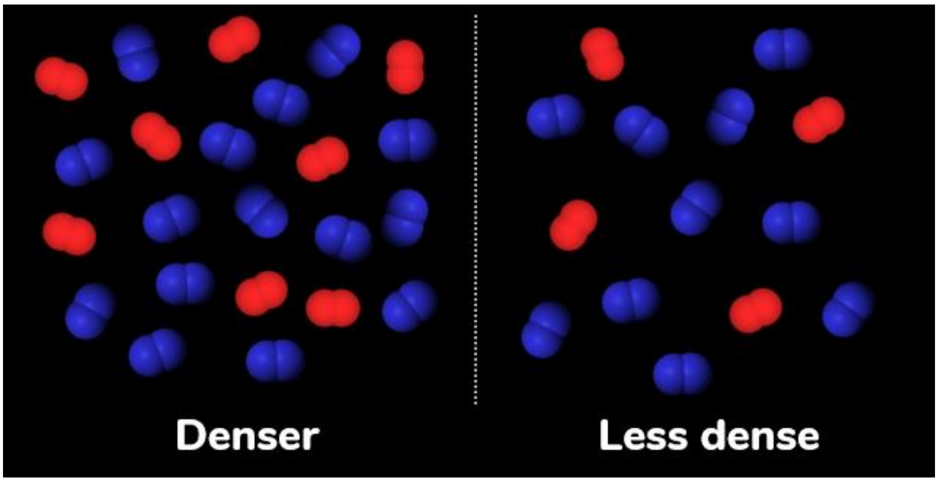

Fig. 11: *Oxygen (red) and nitrogen (blue) molecules with cold, dense air on left and warm, less dense air on right.*

A perfect example

A hot air balloon is an excellent example of about how increasing the temperature of air will decrease the density and make the hot air balloon "lighter than air."

Water vapor is an especially important gas in the atmosphere for a variety of reasons. Not only is it the most important greenhouse gas, but it also stores much of the energy in the form of latent heat in our atmosphere (we will see this later when condensation and deposition are discussed). Of course, this is released at some later time to produce the most significant weather events on our planet. The density of air is also affected, to a lesser extent, by the amount or mass of water vapor in a given volume of air. Water vapor is a relatively light gas when compared to nitrogen and oxygen molecules. Thus, as shown below (Fig. 12), increasing the water vapor within a volume of air causes it to displace the heavier nitrogen and oxygen molecules. The molecular weight of water vapor (H_2O) is approximately 18. Both nitrogen and oxygen occur in the atmosphere in molecular form as N_2 and O_2 and have a molecular weight of approximately 28 and 32, respectively. Other trace gases such as argon and carbon dioxide account for less than 1 percent of the total volume.

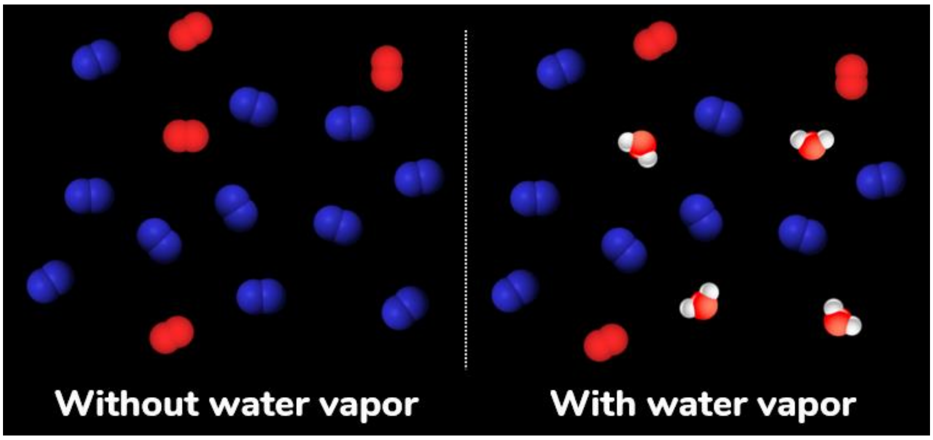

Fig. 12: *Adding water vapor (red and white) decreases the density by displacing heavier nitrogen (blue) and oxygen (red) molecules.*

When water vapor increases within a volume of air, the amount of oxygen and nitrogen decrease per unit volume and the mixture becomes lighter or less dense. **This leads us to the property that moist air or air with more water vapor is always less dense than dry air or air with less water vapor given the same temperature and static air pressure.**

The wedding dance

Imagine you are attending a wedding reception and the DJ calls all adults to join the bride and groom on the dance floor. The dance floor is crowded with people movin' and groovin' to the music. Next, the DJ asks all children to come join them. Since the dance floor is full already, the smaller children will force some of the larger adults to be displaced off the dance floor. The same thing occurs in the atmosphere; as the number of lighter water vapor molecule increase in the mixture, those will displace the heavier oxygen and nitrogen molecules making the mixture of air lighter or less dense.

When you think of a fluid, you probably think of a liquid. A fluid is simply anything that can flow. This includes liquids such as water or mercury at room temperature, but gases are fluids, too. More importantly, two fluids with different densities tend to stay separated. This occurs when motor oil is mixed with water, for instance. The oil rises to the top since it is less dense than water. A similar thing happens when two air masses of differing densities are forced to mix. For example, when warmer, less dense air is introduced within a cooler air mass, the warmer air will be lighter and will tend to rise within that cooler air. In fact, it only takes a few degrees difference between the two air masses to generate enough of a density discontinuity to stay separated. This property is known as buoyancy. Essentially, buoyancy is an upward force exerted by the differences in pressure, driven by differences in air density—in this case, air density. In the end, buoyancy in the atmosphere is a term used to compare the relative density differences of air. This leads us to the property that less dense air is more buoyant and will tend to rise, while more dense air is less buoyant and will tend to sink.

A familiar example

Even a student pilot understands the buoyancy concept very well. Prior to a flight, it is important to always sump the fuel tanks to be sure any impurities such as water is removed. Even though water and avgas appear to be very similar in density, water is denser than avgas and will separate and sink to the bottom of the tank so it can be properly sumped and removed before flight.

Key points –

"Understanding what causes icing, turbulence and convection is very highly dependent on the fundamental properties of air."

"Warm air is always less dense than cold air at a given static air pressure."

"Moist air or air with more water vapor is always less dense than dry air or air with less water vapor given the same temperature and static air pressure."

"Less dense air is more buoyant and will tend to rise, while more dense air is less buoyant and will tend to sink."

Relative humidity and saturation

One of the key reasons why pilots learn to use the Skew-T is to determine the location and altitude of clouds, especially during the cold season when airframe icing is more likely to occur. How to determine the presence or absence of clouds solely based on a Skew-T depends on how to properly recognize when the atmosphere is saturated. Knowing whether the air is saturated can be incredibly easy to determine for warm stratiform-type clouds, or incredibly difficult for cumuliform clouds or cold stratiform-type clouds. This depends on many factors that will be discussed soon, but the first important concept to learn is how to measure or forecast the quantity of water vapor in the atmosphere.

What is relative humidity? As mentioned earlier, the earth's atmosphere is composed of mainly molecular nitrogen (N_2) and molecular oxygen (O_2). What about water vapor? In the presence of nitrogen and oxygen, water vapor is considered a trace gas. Even as a trace gas, it has a vital role and is responsible for two-thirds of the greenhouse effect. Most importantly, it is responsible for formation of clouds and precipitation which is vital to our existence. While this is not usually covered in the pilot's primary training, it is also responsible for one-sixth of the energy transport from the earth's surface into the atmosphere. This is done via evapotranspiration of water at the ground (storing energy through the latent heat of fusion and vaporization) and ultimately resulting in condensation and freezing in the atmosphere that produces cloud formation and the release of that stored energy. As we will see later, the release of latent heat is vital for the formation of deep, moist convection and thunderstorms and plays a significant role in the production of airframe icing.

The amount of water vapor can be quantified in a several ways. A common approach is to measure the exact amount of water vapor by counting the number of water vapor molecules per volume or per mass of air. This simply describes the *absolute* amount of water vapor, and therefore, is referred to as absolute humidity. Perhaps the most common scale familiar to pilots and the general population is relative humidity. You have probably heard your local broadcast meteorologist mention the *relativity* humidity during their segment. But you probably have never heard them mention the *absolute* humidity.

This is because relative humidity has distinct advantages over absolute measures of water vapor in the atmosphere. We know that relative humidity is expressed as a percentage, usually in a range between 0% (totally void of water vapor) and 100% (saturation). An absolute scale, on the other hand, must be much wider because the amount of water molecules at a given location decreases from the surface to the top of the troposphere or tropopause (~36,000 feet) by roughly a factor of 10,000. More importantly, cloud formation through condensation or deposition is controlled by relative humidity, not by absolute humidity.

A tale of two cities

Imagine being at Key West, Florida on a winter day and the surface temperature is a balmy 78°F with a relative humidity of 60 percent. On that same day in International Falls, Minnesota the temperature is a chilly 14°F, but the relative humidity is 100%. Which of these two environments contain more water vapor? Even though the relative humidity is higher in Minnesota, the amount of water vapor in the atmosphere is significantly less than at Key West if you were to compare the absolute humidity.

Relative humidity is defined as the ratio of the actual amount of water molecules to the amount of water molecules when saturation is reached. Saturation is a common term for many applications but is often fraught with misconception when applied to the atmosphere. For example, when a rag or sponge is saturated, it can no longer hold any more liquid water. On the other hand, it is incorrect to say that when the air is saturated, it can no longer "hold" any more moisture (i.e., water vapor). That's because nitrogen and oxygen molecules do not have any holding capacity for water vapor any more than they have a holding capacity for carbon dioxide or other trace gases. To be clear, relative humidity is only used in the context of water vapor.

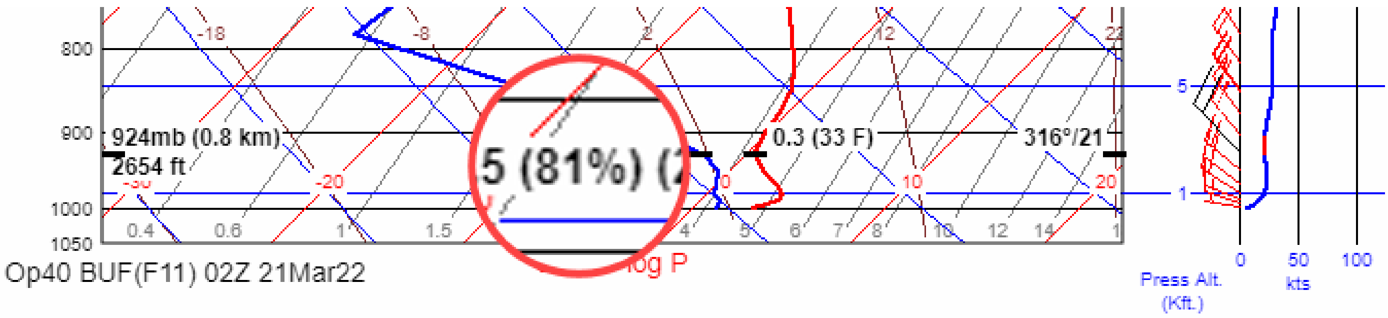

Fig 13: *NOAA's interactive soundings tool automatically calculates the relative humidity for the altitude selected.*

Surface observations (METARs) do not provide the relative humidity directly; only the temperature and dewpoint are provided. Unfortunately, it is not a simple back-of-the-envelope calculation, however. When an observation is decoded, some weather applications will calculate the relative humidity for you. Nevertheless, using NOAA's interactive soundings tool (to be discussed in greater detail later) you can move your cursor up and down over the diagram and it will calculate and display the relativity humidity at the altitude where your cursor is positioned as shown above (Fig. 13).

Keep in mind that this is the relative humidity with respect to liquid water. At colder subfreezing temperatures, the air may be saturated with respect to ice (water in the solid state) even though the relative humidity as described above may only be 80%. For example, in the forecast sounding below (Fig. 14), notice that the relative humidity is calculated to be 82% at FL300. However, given a temperature of -25.7°C at this altitude, the atmosphere is most likely *saturated* with respect to ice even though the temperature and dewpoint are not equal.

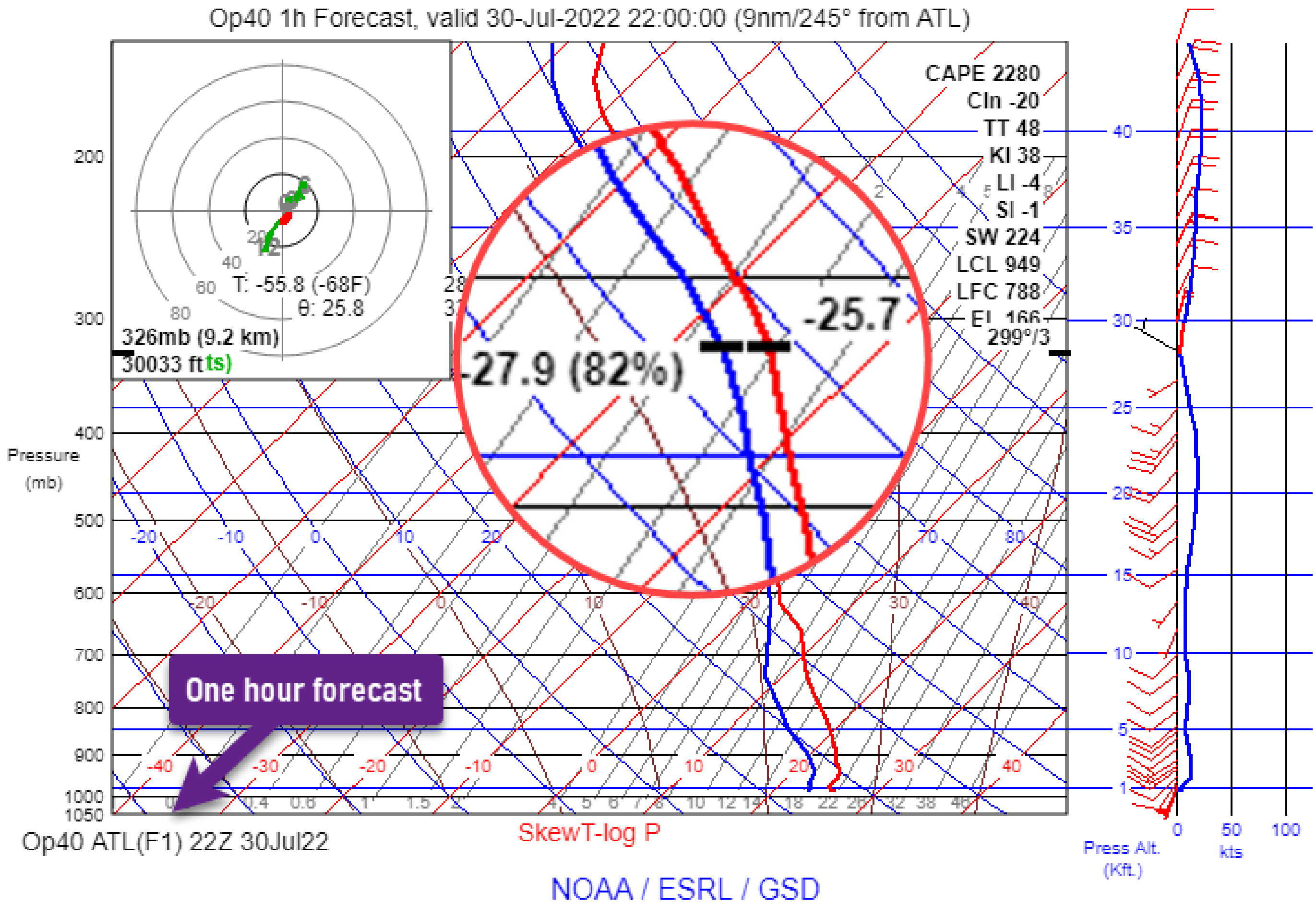

Fig 14: *In this 1-hour forecast sounding (F1) near the Hartsfield - Jackson Atlanta International Airport (KATL) the conditions are likely saturated with respect to ice at 30,000 feet even though the relative humidity is only 82%.*

If you ask a meteorologist to describe saturation, they will likely use the expression "dynamic equilibrium" in their definition. To better understand saturation, let's do a brief thought experiment. Consider an open container of water sitting on your kitchen counter. If you were to leave your house and return two weeks later, do you expect the level of the water in the open container to increase, decrease or stay the same upon your return? Of course, the water level decreases. Why? Simply put, there is a net *evaporation* of liquid water. In other words, while you were gone there was more liquid water evaporating from the surface of the liquid than there was water vapor condensing back into the liquid state (yes, both evaporation and condensation are occurring in this situation). In this case, there isn't an equilibrium, so saturation does not occur.

Now, let's do the same thought experiment, but instead of the container being left open, let's put a lid on it. What do you expect the level of water to be upon your return after two weeks? In this case, the water level in the container will be nearly the same as when you left. After you cap the container, the liquid begins to evaporate into the air between the surface of the water and the lid. At some point, the air in the container reaches saturation. That is, the number of molecules of water leaving the liquid state to become vapor is the same as the number of water vapor molecules condensing back onto the surface of the water. Therefore, the water level stays the same in the capped container because dynamic equilibrium is reached. The water vapor in this case is said to be saturated with respect to liquid water and the relative humidity reaches 100% in the air above the water's surface.

The science behind it

In liquid form (e.g., a cup of water), the amount of water molecules varies only slightly with temperature and pressure. On the other hand, the amount of water vapor molecules immediately above the surface of the liquid varies quite a bit and is highly dependent on temperature (and pressure). Warmer air is less dense which allows for a higher concentration of vapor. Said another way, the flux of water molecules that move out of the liquid state into the vapor state is nearly constant, whereas the flux from the vapor state into the liquid state increases with the amount of water molecules in the vapor state. Dynamic equilibrium is a fancy way of saying that these two opposite fluxes are the same so that the net between evaporation and condensation is zero.

Water molecules in liquid form in such a container are in constant motion. In their motion, they exhibit energy and collide with each other as well as the walls of the container itself. Some of these molecules gain enough energy during a collision to leave the surface of the water and enter the vapor space above it. **This is evaporation.** At the same time, water molecules in the vapor phase just above the water's surface are also in constant motion, and sometimes one of them stores energy and enters the liquid below. **This is condensation.** This becomes a continuous exchange of water molecules between the liquid in the container and the vapor space above the surface.

We can do the same thought experiment with an ice cube in your freezer. If you keep the ice at a temperature colder than 0°C, then it will remain frozen. Let's say you leave that ice cube in the freezer for a period of six months. Do you believe the ice cube will have grown, remained the same size, or decreased in size? After six months in a frost-free freezer, the ice cube will likely have decreased in size. Why? This is like the open container of water, except the process is much slower due to the colder temperature in the freezer. Essentially, a molecule of solid water (ice) will leave the solid state to become water vapor, even at these colder temperatures. **This is sublimation.**

Phases changes of water

Water naturally occurs in the atmosphere in a vapor, liquid, and solid state. When it moves between these various states, we say it is changing its phase. Phase changes include evaporation (liquid to vapor), condensation (vapor to liquid), freezing (liquid to solid), melting (solid to liquid), sublimation (solid to vapor), and deposition (vapor to solid). Any time a change of phase occurs, water must either store energy or release energy in the form of heat. Often you may hear the term latent heat of condensation when water vapor condenses. This phase change is what drives deep, moist convection that leads to dangerous convective turbulence.

At the same time, water vapor will deposit on the ice cube to become solid. This is deposition. In a frost-free freezer there will be a slow, but sure, net sublimation so the ice cube will get smaller with time. This is also why snow in colder climates can disappear without melting. Now this must be applied to the atmosphere where liquid (or solid) water is not in a container, but in tiny droplets and ice crystals suspended in the atmosphere. This will be covered later as it relates to airframe ice.

Preserve hailstones in the freezer?

Imagine a severe thunderstorm moves over your house that dumps hailstones in your yard the size of a golf ball or tennis ball. You bravely run outside and quickly scoop up a few hailstones and pop them in your freezer so you can impress your friends and relatives over the next several months. Will they last that long? Certainly, they won't *melt* in the freezer. However, hailstones have a lot of air pockets and over a couple months in the freezer, you will find that those hailstones are now quite small and will eventually disappear due to rapid sublimation over time and your friends and relatives will not be all that impressed. Don't ask me how I know this!

Key points –

“One of the key reasons why pilots learn to use the Skew-T is to determine the location and altitude of clouds, especially during the cold season when airframe icing is more likely to occur.”

“Water vapor is said to be saturated with respect to liquid water and the relative humidity reaches 100% in the air above the water’s surface.”

“Relative humidity has distinct advantages over absolute measures of water vapor in the atmosphere.”

About Scott

Dr. Scott Dennstaedt was born in Baltimore, Maryland. He grew up and attended grade school in Linthicum, Maryland about two miles from what was named Friendship International Airport. As the airport grew in popularity, it was renamed Baltimore/Washington International Airport in 1973. Living near an airport with a lot of aircraft flying overhead, Scott has always had a love for aviation and flying.

Throughout grade school, Scott has always been fascinated by weather. To that end, Scott attended the University of Maryland at College Park (UMCP) to earn a bachelor's degree in Physical/Atmospheric Science where he also participated in a work-study program at the National Weather Service (NWS). After college, Scott was hired as a research meteorologist for the NWS working in the Development Division at the National Meteorological Center (NMC) in Camp Springs, Maryland (now the National Centers for Environmental Prediction in College Park, Maryland).

He left government service after five years to pursue a career as a software engineer for several aerospace giants that included McDonnell Douglas and Northrop Grumman. During that time Scott helped build various real-time software systems for weather radar, air traffic control, airport surveillance radar, air defense and even helped develop the software for a Level D flight simulator for a Beech 1900D. He received his Master of Science degree at University of Maryland, University College in Computer Systems Management in the early 1990s.

In the mid-1990s, Scott decided to pursue his love for aviation and earn a private pilot's certificate and instrument rating. While he never intended to instruct, he purchased a Turbo Arrow IV and earned his commercial pilot certificate and became a part-time instrument flight instructor. During the time he was honing his stick and rudder skills as a pilot and flight instructor, he quickly realized that certificated pilots had a very poor foundation in weather knowledge. He was able to marry up his love for aviation and meteorology and began to teach pilots at all experience levels how to minimize their exposure to adverse weather.

In 2001, Scott was instrumental in helping the Cirrus Owners and Pilots Association (COPA) to develop their pilot proficiency program (CPPP). Moreover, Scott also helped to develop the proficiency program for the Cessna Advance Aircraft Club (CAAC). That experience led Scott to build several different weekend weather workshops for pilots that focused on increasing a pilot's weather acuity beyond the basics received during primary training. Ironically, the first workshop he held in 2002 was an "Introduction to the Skew-T log (p) Diagram" where four pilots paid to attend the half-day program at a small general aviation airport in Fort Meade, Maryland. In addition to doing thousands of hours of flight instruction, Scott toured the United States and Canada holding several other weekend workshops over the next 15 years.

Scott has also written over 250 articles published in various aviation magazines to include IFR, IFR Refresher, Plane & Pilot, Twin & Turbine, Contrails, Flying, and Aviation Consumer just to name a few. In 2006, Scott relocated to Charlotte, North Carolina and built a complementary training website called AvWxWorkshops.com. This subscription-based website offered a growing library of online content as well as an Internet briefing tool he called the Internet Weather Brief Roadmap.

In 2018, Scott was accepted in the doctoral program at the University of North Carolina at Charlotte (UNCC). His dissertation was focused on studying how pilots consume weather guidance to prevent VFR into IMC accidents using a route-based approach and personal weather minimums. In March 2021, he successfully defended his dissertation, and his doctorate degree was conferred on May 13, 2021. Scott was please to graduate with a Ph.D. in Infrastructures & Environmental Systems (INES) and proudly finished his study with a 4.0 GPA.

The result of three years of research spawned a new subscription-based progressive web app (PWA) for general aviation pilots called **EZWxBrief** (**https://ezwxbrief.com**). This new app went live on April 7, 2021, and replaced his popular website, AvWxWorkshops.com. Today he continues to expand the capabilities of EZWxBrief and remains committed to offer personalized online weather training to pilots at all experience levels in the U.S. and Canada.

On March 1, 2022, Scott began offering a live stream broadcast called **The Daily EZ Weather Brief.** This live broadcast was created to fill a significant void in the quest for a national level general aviation-targeted weather overview like the early morning "A.M. Weather" morning news program that ran from 1978 to 1995 on PBS member stations throughout the U.S. The goal of **The Daily EZ Weather Brief** program is to provide general aviation pilots with a 10-to-15-minute synopsis of today's aviation weather impacts across the conterminous U.S. and southern Canada using high-resolution weather guidance. It is available live each weekday morning on the EZWxBrief YouTube channel at **https://youtube.com/avwxworkshops**. If you miss the live program, it is recorded and available shortly after the broadcast ends.

Scott is married to his very supportive wife of nearly four decades with three adult children and is a now enjoying the benefits of being a cool grandfather.