Uncertainty: The Element of "Whether" in Weather

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INTRODUCTION

Weather forecasting involves the efficient application of science and technology to predict atmospheric conditions in a given time and place. This has become an integral as well as pivotal aspect of aviation safety. Such a scientific prediction based on the tools of meteorology is not a new phenomenon.

Extreme weather conditions have strongly impacted wars and resulted in the defeat of Napoleon (1812, brutal Russian winters)[1] for example. Other instances where weather has been a major factor in shaping the tide of the wars include, Hitler's invasion of the Soviet Union (1941),[2] the sparing of Kokura city, Nagasaki

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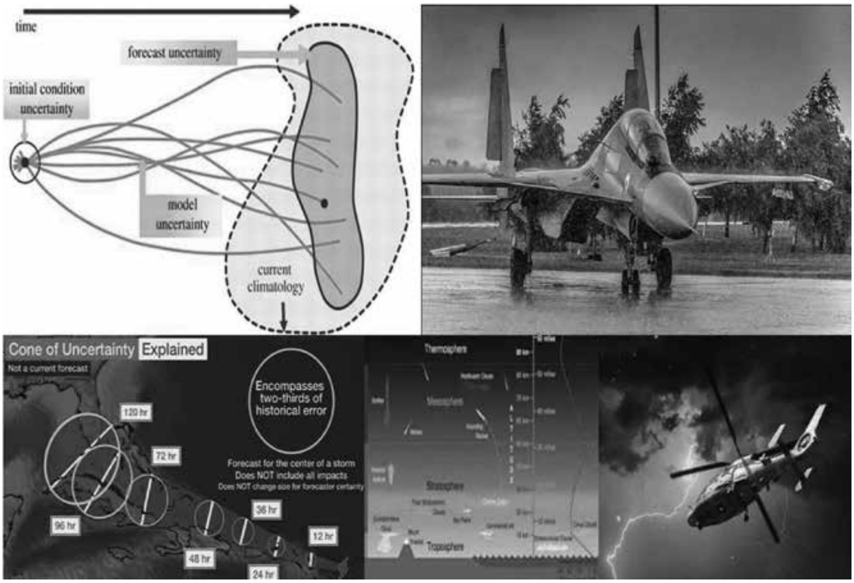
1. A. de Caulaincourt, J. Hanoteau and G. Libaire, *With Napoleon in Russia : the memoirs of General de Caulaincourt, duke of Vicenza*. Dover Publications, 2012, pp. 155, 259.
2. J. Graham Royde-Smith, "Operation Barbarossa", *Encyclopedia Britannica*, October 26, 2022, at https://www.britannica.com/event/Operation-Barbarossa

bombing (1945),[3] destruction of the Spanish Armada (1588),[4] escape from the Long Island (1776),[5] battle of the Bulge (1944-1945),[6] tornado saving Washington (1814),[7] etc., are some of the famous events influenced by weather conditions.



In this article, I will discuss the major factors that affect the weather and how they are implicated in the uncertainties in weather predictions. I will also describe the basic physical laws that govern the atmospheric weather and their consequences in flight operations.

3. https://www.nytimes.com/1995/08/07/world/kokura-japan-bypassed-by-a-bomb.html?smid=url-share
4. H. H. Lamb, "The Weather of 1588 and the Spanish Armada", Weather 1988, 43, pp. 386-395.
5. https://1776history.com/2014/08/31/the-fog-that-saved-an-army/
6. https://apps.dtic.mil/sti/pdfs/ADA121480.pdf
7. https://historicaldigression.com/2012/03/26/a-tornado-saves-washington-during-the-war-of-1812/

IMPORTANCE OF WEATHER FORECASTING IN AVIATION INDUSTRY

Precise weather is critical to aviation, right from the moment an airplane starts its engine until it reaches its finishing line. Accurate weather information not only facilitates the pilots to make informed and efficient route decisions, but also ensures their safety. Weather influences several aspects of flying, such as the pilot's ability to reach a given destination with calculated/remaining fuel, to maintain a safe altitude, forward visibility, etc. Weather conditions such as wind, turbulence, air temperatures, precipitation, pressure, and visibility affect the pilot's ability and the aircraft for successful navigation. For efficient and safe operations at the runway strip and en route phases, pilots require timely and precise information about the in-flight turbulence, icing, and on remarkable conditions such as those generated by thunderstorms or lightning. Hence en route conditions, take-off and destination forecast are paramount towards a safe flying experience.

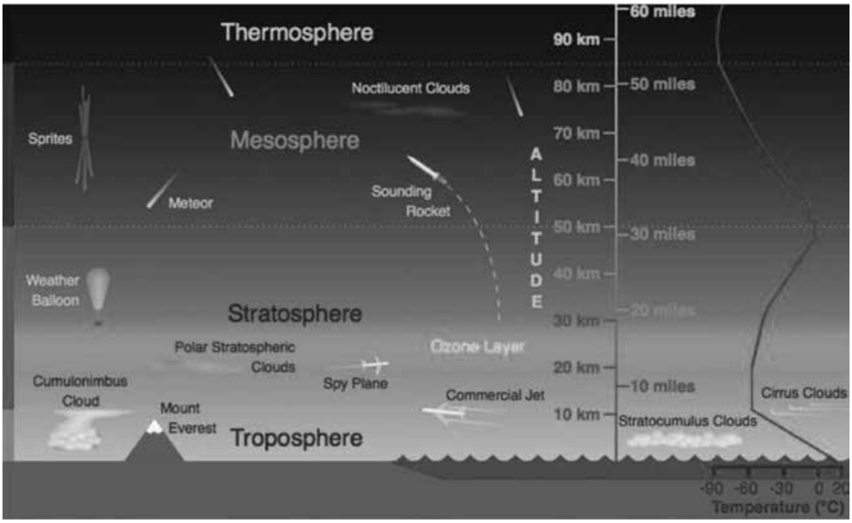
FACTORS REGULATING THE WEATHER CONDITIONS

With great advancement in the sector of science and technology in weather forecasting and meteorological research, new tools have been bestowed that allow a variety of available techniques at one's disposal for better predictions of weather conditions. Technologies pertaining to radar, satellites, advanced computing have tremendously assisted meteorologists across the nations. In the following sentences I will describe the major components that affect the weather conditions, mostly the atmosphere and its related wind scenarios. Since an aircraft operates in the air, understanding the air in the earth's atmosphere is essential towards gaining a better insight on the various attributes of weather forecasting and its implication in aviation territories.

ATMOSPHERE

The layer of gases that envelop the earth is referred to as the "atmosphere", which consists of nitrogen, oxygen, argon, carbon dioxide, and traces of hydrogen, helium, and other "noble" gases (by volume), with some addition of water vapour too. Earth's atmosphere is composed of several layers that have different properties owing to the variations in gaseous compositions, temperatures, and pressures.

Figure 1: Image Displaying the Different Layers of Atmosphere with Relevant Altitudes[8]



Moving upwards from the ground level, these layers are the troposphere, stratosphere, mesosphere, thermosphere, and exosphere. The lowest layer of the atmosphere is the troposphere and extends from the earth's surface to the bottom of the stratosphere. It is noteworthy that the entire weather phenomenon occurs in the troposphere and we humans reside in this layer of the atmosphere. The stratosphere extends from the top of the troposphere to the bottom of the mesosphere. The

8. https://scied.ucar.edu/learning-zone/atmosphere/layers-earths-atmosphere

stratosphere contains the ozone layer and absorbs the ultraviolet radiation that the planet receives from the sun. Next layer is the mesosphere which ranges from 50km to 85km, and the meteors are incinerated in this layer before they reach the surface of the earth. The thermosphere extends from the height of 85km to the base of the exosphere and contains a layer called the ionosphere where the atmosphere is ionised by the solar radiation.

AIR DENSITY, AIR PRESSURE, AIR TEMPERATURE AND HUMIDITY

Interestingly, properties of air in the atmospheric realms influence the control and performance of an aircraft. These include the density, pressure, and humidity. Air has the ability to flow and take the shape of the container in which it is entrapped. Simply put, when the container is heated, pressure increases whereas when the container is cooled, the pressure drops. With this analogy, it is important to understand that at the sea level, the weight of the air is heaviest since it has been compressed by all of the air above it. It is this compression of air that comprises the atmospheric pressure. With an ascending aircraft, the atmospheric pressure and the temperature drops along with a decrease in the oxygen content. At about 12,000 feet, the air pressure is nearly 40 per cent lower compared to what it was at the sea level. This also implies that humans would be breathing 40 per cent less oxygen with the increasing altitude. Therefore, changes in the altitude influence the performance of an aircraft.

One of the important attributes of air is that it can be compressed, and hence the mass of air divided by the volume it occupies comprises the density. The density of the air largely depends on its pressure, temperature, and the water vapour content. Density varies in direct proportion with pressure whereas it is with inverse proportion with temperature. As the altitude increases, the air becomes less dense; in addition, temperature does affect the density where hot air is less dense compared to the air that is relatively cooler. Variation in density affects the aerodynamic conduct of an aircraft. High altitudes, where the density is low, allow the aircraft to fly faster in comparison to low altitudes with greater density. Also with lower air densities, an airplane requires longer runways for take-off and landing, and they are unable to rise as quickly as in the high air density conditions. Moreover the amount of water vapour present in the air constitutes the humidity of the atmosphere. Therefore, on moisture laden days, the air density is less compared to dry days and hence the aircraft needs a longer runway for take-off on damp days than it does on dry day conditions. Additionally, visibility declines with temperatures falling near the "dew point" accompanied with sufficient moisture in the air. Taken together, it is evident that everything that happens in the atmospheric realms is basically a function of temperature and moisture.

WIND

It is imperative to discuss about wind, yet another crucial factor that influences the weather and the aircraft performance. Wind is basically defined as the sustained horizontal movement of air, and which is also caused by the alterations in air pressure. While the engine of an aircraft provides the forward acceleration, it is the wing that makes an aircraft fly. And all this is brought about by the changes in the air flowing above and below the surface of an aircraft. An aircraft is subjected to constantly changing wind velocity during the course of its journey. Strong winds can slow down the groundspeed of an aircraft during landing. However, with an increase in the winds, there occurs an increase in the lift as well. In aerodynamics terms, lift is that force which is responsible for counterbalancing the gravitational force. It is this lift that keeps an aircraft airborne while it moves.

CLOUD

Cloud is an aerosol with a complex visible mass of small liquid droplets and frozen crystals/ice suspended in the atmosphere. When moisture laden air rises upwards, it becomes colder. Cooler air is known to support less amount of water vapour. Hence, in such an upward transition with a gradual decline in temperature, the air can't hold all of the water vapour in itself and therefore a portion of the water vapour condenses to form minute water droplets, forming clouds above the sea level. Since clouds are relatively cooler than the surrounding air, there exists a variable density between the clouds and the surrounding air which eventually generates a kind of cavity/depression/gap in the sky. This further makes a bumpy or a less smooth ride for an aircraft. There are many kinds of clouds (predominantly low, middle, and high) that can produce a bumpy flight, but one among them named cumulonimbus (Cb) needs to be avoided. These are the type of clouds that contain heavy rain, hail, strong winds, lightning, turbulence, and at times tornadoes.

Fogs form rapidly and are quite unpredictable. Under stable conditions with mild winds, fogs can reduce the visibility to dangerous levels. Notably, fogs are considered as "low clouds" and can negatively affect the aircraft visibility in a tremendous way. In addition to cloud and fog, other obstructions of visibility include smoke, heavy precipitation, blowing dust, haze. Lightning and thunderstorm pose the single greatest risk to aircraft operations.

UNCERTAINTY IN WEATHER FORECASTING

Despite a detailed weather forecast issued by a meteorologist, there will always be some kind of uncertainty. The larger question is, why is weather forecasting not 100 per cent accurate? There are several reasons behind this observation. A slight change in the atmospheric state in a given location can have significant consequences over space and time elsewhere. Such a change has famously been named "the butterfly effect" by scientists. Hence the tiniest perturbation in the air and its related atmospheric layers is sufficient enough to dramatically alter the next upcoming sequences in weather phenomenon; and hence such events create a void and uncertainty that gets amplified over time leading to the impairment of the original prediction.

Moreover, weather and climate prediction contain a fraction of uncertainty, because the forecast initial conditions along with its relevant computational representation varies dynamically real time with the changing atmospheric circumstances. Irrespective of new model systems and advancements in the meteorological weather predictions, there will always be some unchangeable level of uncertainty owing to the chaotic nature of the environment.[9]

THE CHAOS THEORY

World renowned meteorologist and scientist Edward Lorenz *did revolutionary work on understanding the reasons behind the challenges for making good/accurate weather forecasts and came up with his scientific revelation called as "The Chaos Theory"*.[10] It's a mathematical theory that delineates the properties/features of a point at which stability proceeds to instability or order moves to disorder. To put it simply, this theory deals with surprises, the unpredictability of events and the non-linearity of living systems. Chaotic patterns are also displayed in nature. Illustrations of chaotic behaviour include ocean currents, air turbulence, blood flow through fractal blood vessels, astronomy, ecosystems, etc. Hence the Chaos

9. Slingo and T. Palmer, "Uncertainty in Weather and Climate Prediction", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 2011; 369: pp. 4751-4767.
10. E. N. Lorenz, "Deterministic Nonperiodic Flow", *Journal of Atmospheric Sciences* 1963; 20: pp. 130-141.

Theory helps to explain the irregularities observed in nature and facilitates a better understanding of turbulence found in all forms.

Weather patterns are an ideal example of Chaos Theory. The dynamic nature of the atmosphere and oceans can give rise to unanticipated tiny aberrations which get amplified over time. Such aberrations can result in the discrepancies in the initial approximation, and this will eventually lead to dramatic changes in the weather forecast which will diverge from the actual weather. In fact, amplified effects of miniscule changes in the present moment can lead to long-term unpredictability, as described in the Chaos Theory. It's crucial to acknowledge that weather is not random, but chaotic. Laws of physics are very well followed by the weather and its associated patterns and phenomena, therefore, every change in the weather has a cause. Since there can be a plethora of possible causes, the challenge remains to recognise all of them. However, if the weather was random, it would be impossible to know the next scenarios. One can predict the weather well when the near future is concerned, but with increasing time there are several other factors added that influence the weather, hence under such circumstances accompanied by slight perturbations, the goal of accurate weather forecasting becomes jeopardised. Weather, being a dynamic system, is extremely sensitive to initial conditions, hence one can never accurately predict the weather with zero chances of uncertainty or surprises.

On the other hand, climate is "average weather" and is not chaotic and usually has better and improvised predictions when compared to weather alone. Nevertheless, talking about short-term forecasts, the predictions are mostly correct. But there can be many underlying reasons for the predictions going wrong at times. These include the amount of initial data collected, ways and methods of its collection and processing, computer error, and above all the very simple truth that mother nature is chaotic and genuinely tough to predict.

CONCLUSION

Weather being a perfect example of chaotic system is highly sensitive to the initial variables/disturbances that can mitigate any robust weather prediction/forecasting model system and technology. Therefore, to expect a 100 per cent accuracy in weather predictions is unreasonable and imprudent. Most importantly, from aviation industry point of view, meteorologists are the backbones guiding and ensuring safe flying environment with respect to weather and enhancing efficient flight operations. Personnel in the weather forecasting sector have to cope up with unwarranted stress, anxiety and backlash when the predictions deviate from the initial forecast. Therefore, it's the moral duty of the users and the leadership to show compassion and understanding that it's not fully in the control of a meteorologist to accurately predict the sequence of events originating by an unknown cause in nature that is highly chaotic and unpredictable. However, extensive research and development needs to be conducted in the field of meteorological sciences towards combating the uncertainties in weather forecasting, thereby leading to the establishment of novel and robust tools for a better scientific approach in this area.