This paper comprises a brief history of the origins and early development of radar meteorology. Therefore, it will cover the time period from a few years before World War II through about the 1970s.

The earliest developments of radar meteorology occurred in England, the United States, and Canada. Among these three nations, however, most of the first discoveries and developments were made in England. With the exception of a few minor details, it is there where the story begins.

Even as early as 1900, Nicola Tesla wrote of the potential for using waves of a frequency from the radio part of the electromagnetic spectrum to detect distant objects. Then, on 11 December 1924, E. V. Appleton and M.A.F. Barnett, two Englishmen, used a radio technique to determine the height of the ionosphere using continuous wave (CW) radio energy. This was the first recorded measurement of the height of the ionosphere using such a method, and it got Appleton a Nobel Prize. However, it was Merle A. Tuve and Gregory Breit (the former of Johns Hopkins University, the latter of the Carnegie Institution), both Americans, who six months later – in July 1925 – did the same thing using pulsed radio energy. This was a simpler and more direct way of doing it.

As the 1930s rolled on, the British sensed that the next world war was coming. They also knew they would be forced to defend themselves against the German onslaught. Knowing they would be outmanned and outgunned, they began to search for solutions of a technological variety. This is where Robert Alexander Watson Watt – a Scottish physicist and then superintendent of the Radio Department at the National Physical Laboratory in England – came into the story. He was asked to investigate the ability of transmitting radio frequency waves of high enough power to boil the blood of German soldiers and pilots, an idea termed the "death ray." Watson Watt had a junior scientific officer – Arnold F. "Skip" Wilkins – do the hard work for him, by giving him the following assignment:

> "Please calculate the amount of radio frequency power which should be radiated to raise the temperature of eight pints of water from 98 degrees F to 105 F at a distance of 5 km and a height of 1 km."

Despite the language changes, Wilkins knew immediately what Watson Watt was asking him to do. The calculations revealed that the English could not currently produce enough power to meet this demand. However, they wondered if perhaps the energy they could produce could be used simply to detect aircraft. After drafting a memo on 12 February 1935 titled "Detection of Aircraft by Radio Methods", Watson Watt set up the Daventry experiment on 26 February 1935. On this crisp, clear, cold, late winter day outside the village of Daventry, he and Wilkins successfully demonstrated the use of radio energy (using the CW signal from a local radio station and pilot R.S. Blucke flying a Heyford bomber) to detect aircraft at distances of several miles in front of a group of British military officials including Air Marshall Sir Hugh Dowding and members of the Tizard Committee (the group will be introduced later). The success of the Daventry experiment, and the work of Watson Watt that followed, would eventually earn this physicist the title "the father of radar." (Note: the word *radar* is actually an acronym that stands for RAdio Detection And Ranging. It was officially coined by U.S. Navy Lieutenant Commanders Samuel M. Tucker and F.R. Furth in November 1940)

After the Daventry experiment, Watson Watt recruited a small number of scientists – among them Welsh physicist Eddie Bowen – to develop the new technology. They first set up in a field outside the village of Orford in the spring of 1935. They would move to Bawdsey Manor, 10 miles south of Orford, by mid-1936, which served as a "main laboratory" for development before the war. This was largely the beginning of the Telecommunications Research Establishment, a name given to the organization that served mostly to develop radar during these early years. The name was selected to be somewhat ambiguous so that it was not obvious that radar technology was being developed. It was during these and the next few years that Bowen, among the other scientists, developed radar to the point where they reduced the wavelength of the energy they could transmit from hundreds of meters to 1.26 meters by 1937, and increased detectable distance from less than 10 miles to more than 100 miles. They also developed the Chain Home Defense System, a network of radar units placed along the southern and eastern British coast, designed for the purpose of detecting incoming German aircraft for the bombing raids they were sure would come during the arriving war. Eddie Bowen was adamant about developing the technology enough to reduce the size of the radar units so that they could fit inside fighter planes so that they wouldn't have to rely on the Chain Home radars when battling German fighters away from the British coast.

As World War II began, the British finally acted on a problem they knew they would face: outgunned and out powered by the German Luftwaffe bombing missions, they needed help. Upon communicating with the Americans, the British would learn that the Americans had also developed some radar technology starting in the mid-1930s, but not to the extent that the British had. The British had come farther along in developing the radar purely out of necessity: they were looking for a way to survive the German attacks during the war, and they knew radar was the answer, but since they lacked either the money or the security to continue to develop it themselves, they had to ask the Americans for help. Therefore they conducted the Tizard Mission, or "The British Technical and Scientific Mission to the United States," from late-August to October 1940. This mission was named after Sir Henry Tizard, an influential Englishman during the early stages of the war who organized the mission and pushed for getting it conducted. The details of the mission consisted of mainly Eddie Bowen personally carrying a small locked chest containing a device called the cavity magnetron, as well as other devices and blueprints for producing and developing these devices. He furtively sailed across the Atlantic Ocean on a Canadian ship called *The Duchess of Richmond*. It landed at Nova Scotia before it went to Washington D.C. He and the package arrived on 9 September 1940. Until showcased and demonstrated, the chest was locked in a safe at the British embassy and it was rumored that only the butler held the key to it for several days. Initially the British hoped to trade one secret for another, but after unsuccessful negotiations, Prime Minister Winston Churchill decided it was more important to share the technology and get help than to barter for a secret from the Americans.

At the heart of the Tizard Mission was the cavity magnetron, invented on 21 February 1940 by John Randall and Henry Boot at the University of Birmingham (England). This funky shaped device, containing six or eight cylinders placed around a central hub, was capable of producing thousands of Watts of power at approximately 10 centimeters, the wavelength of choice at the time. Previous power output was at less than 100 W, so this development was tremendous. Upon demonstration of this device by Eddie Bowen to a number of Americans also working on developing radar, including multi-millionaire investment banker Alfred Loomis, who was on the National Research Defense Committee – Microwave Committee, full speed ahead development of radar technology began in both the United States and England.

Alfred Loomis and Vannevar Bush, a civilian engineer who also advised the Secretary of War Henry Stimson, obtained funding for development of the radar on American soil. They procured $455,000 for the first year of the project, which would be eventually called the Radiation Laboratory and be located at the Massachusetts Institute of Technology. This site was chosen over others after much debate due to the inherent secrecy offered: no one would have thought something so pivotal to winning the war would be developed at a public institution. The initial name chosen for the Radiation Laboratory (common name shortened to "Rad Lab") was the Microwave Laboratory. However, to allay suspicion from the true activities of the lab, it was renamed with the hopes that outsiders would think nuclear physics were being researched there.

The first air-to-air detection using airborne radar occurred in both England and the U.S. on 10 March 1941. The first submarine-from-air detection (called ASV, or air-to-sea-vessel) followed a few weeks later. Such new technologies unarguably aided the Allied powers against mainly the German forces in winning the Battle of the Atlantic, which occurred during mid-1943, in which a majority of German U-boat submarines were destroyed. It is believed that radar technology gave the Allied forces the advantage they needed to win the war.

As far as radar meteorology during the war was considered, there wasn't much to say. The following summarizes the extent of radar meteorology during the war. Detection of meteorological phenomena (i.e., precipitation echoes) did indeed occur. The first detection of precipitation echoes likely occurred in England sometime in late 1940, but it for sure occurred for the first time on 7 February 1941 at the Rad Lab. However, during the war, echoes from meteorological phenomena were regarded as a nuisance or clutter, and were undesirable. Thus little attention was paid to them. The first known U.S. publication from radar meteorology was Bent, 1943: "Radar Echoes from Atmospheric Phenomena". In that publication, Bent described observations made between March 1942 and January 1943. Then, Commander R.H. Maynard of the U.S. Navy introduced the opportunities of radar to the general meteorological community in 1945 by showing scope images of echoes from thunderstorms, cold-frontal showers, and typhoons from 1944 and 1945.

After the war ended, secrecy was no longer important. Thus many new weather radar research groups formed. Included among such groups were the Weather Radar Research Project at MIT, which officially began on 15 February 1946, AW-MET-8 in the All Weather Flying Division of the Air Force which started in December 1945, and Project Stormy Weather, the Canadian research group, which was initially led by J. Stewart Marshall, which formed in 1943.

Now I will discuss some significant developments in radar meteorology during the post-World War II 1940s. Probably the most significant was the work of John Walter Ryde and his wife Dorothy. John was a physicist who worked at the General Electric Research Lab in Wembley, England at the time of the development and his wife was a mathematician, a Cambridge graduate. Using only the works of previous theoreticians, including Rayleigh (1871), Mie (1908), and Gans (1912), together they developed the theory of attenuation and scattering of microwaves, quite a feat for the time. One of the works was called "The attenuation and radar echoes produced at centimetre wavelengths by various meteorological phenomena". Although begun in 1940, it was not published until at least 1946 due to secrecy. They also computed backscatter cross sections by hand since computers weren't really around yet to do such a thing for them. This had to be very difficult. They also used drop-size distribution data from Lenard (1904), Humphreys (1929), and Laws and Parsons (1943) to develop early Z-R relationships. The work of the Rydes was so advanced for their time that many of their peers simply ignored or disbelieved their work. Other papers, such as Wexler and Swingle (1947) and Wexler and Atlas (1963), attempted to disprove their theory, but served only to corroborate it by obtaining the same results. Many good things were said of John Ryde, including the following quote from a biography of him (JSTOR):

> "…Ryde possessed, more than most, the ability to have his feet on the ground and his head in the clouds and as a result could always translate his abstract ideas into practical terms. He was a fortunate possessor of a prodigious memory for anything read or seen…the printer saw far too little of his writing, and the world far too little of his work."

Another significant development was that of the classic Marshall-Palmer drop-size distribution. There were actually three papers published regarding this topic. The first to be published was Wexler and Swingle (1947), in which the authors reported the radar equation for precipitation and plotted a curve of reflectivity, Z, versus rain rate, R. This preceded Marshall et al. (1947), which reported the good correlation between Z and R. However, for some reason (perhaps due to publicity), Marshall and Palmer (1948): "The distribution of raindrops with size", is regarded as the seminal work in the field. Marshall met Walter Palmer while working with the Stormy Weather Group (renamed from Project Stormy Weather) in Ottawa. The classic Z-R relationship from the Marshall-Palmer drop-size distribution is $Z = 200*R^{1.6}$. Other researchers were suspicious of this relationship due to its simplicity, and were compelled to find their own Z-R relationships. Although papers like Twomey (1953), Imai et al. (1955), and Fujiwara (1960, 1965) derived Z-R relationships in which the reflectivity value for a given rain rate differed by up to 38% from that of the Marshall-Palmer Z-R relationship, they all found physical explanations for the differences (such as the location being maritime or continental, at low elevation or high elevation, in warm season or cold season).

Two other significant discoveries in the 1940s were those of bright bands and angel echoes. Many radar meteorologists noted a bright layer of returned power on radar scopes that always seemed to occur near the freezing level of the atmosphere. Upon personally flying into radar bright bands, researchers like Bob Cunningham of MIT and Guy Eon of Canada (who held a sugar scoop outside the cockpit of a Beechcraft as it flew through the bright band) determined that the bright band was indeed composed of dry snow above, wet snow in the middle, and liquid rain below.

Although initially discovered in the 1930s, angel echoes continued to be investigated through the 1940s and really through the 1970s as well. Many early researchers like Watson Watt, S.K. Mitra, P. Syam, and H. Rakshit, noted radar echoes from the clear atmosphere and called them "angel echoes," perhaps due to their heavenly appearance on radar images. Their initial investigations revealed that gradients in the index of refraction (the ratio of the speed of light in a vacuum to the speed of light in air) were the cause of many angel echoes. Later works would support this theory, but expanded the explanation to say that any fluctuation, not necessarily a tight gradient in refractive index, would cause angel echoes. Other types of angel echoes (discrete dots, for example) were discovered. Investigation of those resulted in birds and insects being declared the causes of such echoes.

There were a few more notable events in radar meteorology in the 1940s. One of them was the Thunderstorm Project, conducted in Florida and Ohio in 1946 and 1947. This was the first multiagency field experiment in meteorology in which radar was the key instrument. Thanks to radar, much was learned about the structure and lifecycle of thunderstorms, including the three-stage lifecycle (cumulus, mature, and dissipating stage), as well as the turbulence found at the edges of the buoyant updrafts that gave thunderstorms life. This sort of research spurred further research into the impacts of turbulence from thunderstorms on the aviation community. Coupled with early work from the operational radar networks in the U.S., which were in their infancy stages at the time, there was a dramatic drop off in the number of aircraft crashes caused by turbulence starting in the late 1940s.

The first Weather Radar Conference was held on 14 March 1947 at MIT. Over 90 people from many different agencies, including the Weather Bureau, other universities, nearly every branch of the U.S. Armed Forces, the Canadian Department of National Defense, many airline companies, and many electrical companies attended.

Development of nearly every aspect of radar meteorology accelerated during the 1950s. That acceleration continued for decades. In the remainder of this historical overview, I will highlight some of the more significant developments.

Arguably the single most significant development in radar meteorology in the 1950s (and perhaps ever) was the introduction of "mesoscale" meteorology. In 1951, Myron "Herb" Ligda remarked that he observed a number of radar echoes of a size not previously observed (for example the broad, diffuse echoes associated with warm fronts and the discrete intense echoes associated with cold fronts). These echoes were smaller than the synoptic scale, yet larger than the microscale. He could only think to call the size of these echoes middle, or "meso" scale. It is therefore apparent that the subject of mesoscale meteorology would not exist today if it weren't for radar!

A number of discoveries regarding storm structure and measurement were made in the 1950s and 1960s using radar and Doppler techniques (the Doppler radar era itself came about in the mid-1950s, as will be mentioned shortly). The first discovery of what would be named a "hook echo" from a tornadic thunderstorm occurred on 9 April 1953 in Illinois. Several other such sightings on radar would inspire the formation of the Texas Tornado Warning Network, which rose to prominence after a successful forecast (warning) of a tornado with nearly 30 minutes of lead time in Bryan, Texas on 5 April 1956. This event is discussed in Bigler (1956) and is considered the first event in which radar was used to issue a tornado forecast. Bounded weak echo regions (BWERs) were discovered in tornadic thunderstorms. A thunderstorm that passed near a radar site in southeast England on 9 July 1959 – called the Wokingham storm – was observed to not change its cloud top height or precipitation or mass character for an hour. Although being one, the Wokingham storm was not called a "supercell" until after the Geary, OK storm of 1961, which was the first to be called a supercell at the time. Splitting storms (supercells) were discovered by Walter Hitschfield in 1960. Ralph Donaldson discovered the first mesocyclone detected on radar on 9 August 1968. Michael Krauss is credited with making the first unequivocal observation of a tornado on radar in Brookline, Massachusetts on 9 August 1972. I say unequivocal because at the time of radar observation of the tornado, an MIT student and National Weather Service employees visually confirmed the tornado. It is quite likely, however, that a tornado had been observed on radar at some earlier time, but there was no visual confirmation during the time at which the signature appeared on radar.

The Doppler era of radar meteorology began on 27 May 1953 when by Ian Browne and Peter Barratt procured a Doppler velocity spectrum consistent with a rain shower possessing a 2 m/s downdraft. James Brantley would get their paper regarding this event, which had previously received little attention, much more publicized, especially when he convinced Vaughn Rockney, the man in charge of the operational radar network at the Weather Bureau at the time, that Doppler techniques could be used to detect tornadoes on radar. After applying for, and receiving a grant from Congress, they measured 92 m/s winds in a tornado in El Dorado, KS on 10 June 1958 (not visually confirmed). After the Joint Doppler Operational Project (JDOP) successfully completed in 1979, enough developments and discoveries had been made using Doppler radar that the U.S. government funded the full development of an operational network of Doppler radars in the country. This was the beginning of the NEXt GENeration radar network (NEXRAD), which is still operational today.

The radar equation developed in the work of the Rydes in the 1940s was eventually shown to be imperfect. The Rydes did not verify their own work with experimentation. By the early 1960s, it was apparent that theoretical values of reflectivity were higher than those actually obtained by experimentation. This was caused largely by the assumption in the radar equation from the Rydes' work of a point target, which was true of aircraft. However, meteorological features were not point targets, as they completely filled the radar beam. Therefore, the classic 1962 paper by J. R. Probert-Jones, "The radar equation in meteorology," was written to correct for this inaccuracy.

Finally, the digitization and colorization of radar data and display finally came along in the late 1960s through the 1970s. This enabled the storage of large amounts of archived radar data which would have otherwise been thrown out. Until the late 1960s, the only storage mechanisms for radar data were either from 35 millimeter photographs or from magnetic tape. However, the storage capacity of magnetic tape had been almost fully depleted. The advent of color display in

1974 ushered in a new era of viewing radar using color instead of brightness due to the returned power to the radar. It made the viewing of radar data much easier.

This paper has highlighted some of the most significant developments regarding the origin of radar meteorology. To summarize, radar meteorology was born during World War II when radar echoes from meteorological phenomena were undesirably detected by radars that were intended to be used for aircraft detection and tracking. Radar itself was invented a few years before World War II, mostly by the father of radar, Robert Alexander Watson Watt, and other British scientists, out of necessity for survival of the German onslaught from the war. Radar was initially developed in England, the United States, and Canada. Today we have the subject of mesoscale meteorology, we know that "hook echoes" are frequently associated with tornadoes, we know how to find the freezing level on radar, and we can measure wind velocities both inside and outside precipitation echoes, among other abilities, all thanks to radar meteorology. It is undeniable that radar has significantly advanced the science of meteorology, and we, as meteorologists today, owe a great debt of gratitude to the pioneers who developed this great subject. Without them or radar, we would be years behind where we are now.

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Note: the majority of the citations in this paper were obtained from Atlas et al. (1990), in which they were directly quoted within the narrative. I did not actually read these individual sources, but rather obtained the mention of their use from Atlas et al. (1990). Therefore, none of those works are cited here. Readers can find those citations in the reference list located in Atlas et al. (1990).

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