

ASSIMILATING THOR:
HOW AIRMEN INTEGRATE WEATHER PREDICTION

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APPROVAL

The undersigned certify this thesis meets master's-level standards of research, argumentation, and expression.

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DISCLAIMER

The conclusions and opinions expressed in this document are those of the author. They do not reflect the official position of the US Government, Department of Defense, the United States Air Force, or Air University.

ABOUT THE AUTHOR

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Mark married his high school sweetheart and together they raised a daughter (a preacher's wife) and are raising a son (a high school sophomore) and caring for a homebound parent.

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While many people contributed to this project, special recognition goes to Donald May, Air Force Weather Agency historian and a one-man research wrecking crew. What's right is to the credit of those who helped; what's wrong is mine alone.

To my family: thank you for your patience, support, and timely motivation.

ABSTRACT

Aircraft performance increases parallel increases in weather prediction capabilities. When prop wash gave way to jet thrust, weather prediction capabilities both benefited from greater fields of data obtained from air- and space-based weather surveillance and required those data to improve flying safety at the edge of the performance envelope. Later, combat reliability demanded “all weather” airplanes, and those advanced designs benefited from computers which enabled atmospheric modeling to develop into a real-time weather prediction tool. Finally, the interdisciplinary nature of stealth technology paralleled stochastic (vice deterministic) ensemble computer modeling techniques derived from disciplines as diverse as biology, economics, and theoretical physics. The needs of the aviation community changed, and the weather community responded to those needs. Despite these links, the interaction between operational airmen and weather prediction appears surface-deep and may benefit from a more systematic integration.

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Introduction

And therefore I say: 'Know the enemy, know yourself; your victory will never be endangered. Know the ground, know the weather; your victory will then be total.'

-- 孙子 (commonly rendered Sun Tzu)

Too many weathermen whine 'pilots don't listen to us' or cry out 'we are important!' That is not this paper's purpose. The United States Air Force retains meteorologists because they contribute to the fight. A commander, pilot, or decision maker may elect to forego or to ignore a briefed weather forecast. These same people can get stuck in a rut. 'We've always done it this way' can never excuse ineffectiveness or inefficiency, despite its popularity as a first line of defense when an outsider or novice challenges a policy or practice. Every commander, pilot, or decision maker must be open to examine the reason for every policy and practice, holding back no sacred cows or pet projects. The United States may stand astride the planet as a colossus of military might unparalleled in the history of man, but to assume this colossus is mightier than Ozymandias' statue is to trumpet the worst kind of hubris.

This paper exists to examine how airmen have integrated weather prediction, particularly in flying operations.¹ Are weather forecasts just another item on a preflight checklist? Do flight planners consult meteorologists while setting launch and recovery times, establishing flight routes, and weaponeering? Or is meteorology as integrated as intelligence into aviation operations? These three levels do not represent two extremes and a middle point, but they do frame a useful scale of integration. This paper will describe the link between aviation capabilities and meteorological capabilities, will argue growing aviation capabilities drove the need for better and more accurate weather prediction, and will assert advances in meteorological science had a salutary effect on aviation capabilities. To establish the link, the paper will sketch major aviation technology advances and parallel contemporary weather prediction advances, then show

¹ Space and time restrict this paper's scope to the Air Force and her forebears, and to the tactical-operational level. There is much to be said about integration of weather prediction at the strategic, operational, and tactical levels of war and peace in all military branches, but it will not be said herein.

their interrelationship. Ultimately, this paper finds evidence the integration of weather prediction into aviation operations has been inconsistent and unimaginative.

The introduction and chapter one provide a road map and a foundation. Diving into the meat of the work, chapter two recalls the origin of aviation and its earliest years. Inventors and visionaries heaved heavier-than-air heaps into the heavens, hoping for fame and fortune. Daredevil aviators risked life and limb to discover the cutting edge of technology, striving to wrest from the birds their sovereign domain. Brilliant scientists and engineers ratcheted back just enough to make flying feasible to a risk-conscious military and developed aircraft like the Martin NBS-1 bomber and the Curtiss JN-4 “Jenny” trainer. The beloved Jenny is an archetype of early military aviation, and serves as the first chapter’s congenial host. Weather prediction, the guest, actually had been extant for millennia in the form of what is now classified as climatology, though the distinctive science of meteorology was still relatively young at the time of the Jenny. The farmer’s almanacs used historical weather data to predict future conditions, but new techniques, resting on the theoretical physics of atmospheric dynamics, held much promise.²

The third chapter examines the immediate post-World War II aviation and weather studies world. From the matriarchal wood and fabric Jenny of the interwar period sprung fast, powerful, all-metal war birds such as the Boeing B-17 “Flying Fortress” and the North American Aviation P-51 “Mustang.” The Mustang was a demanding airplane, and, like her sisters, demanded much more from the weatherman than a glance to the sky and a page from the Old Farmer’s Almanac. Happily, the turn-of-the-century promise of scientific meteorology found fulfillment during the interwar period. Meteorology became a pinnacle of interdisciplinary study in physics, geology, and mathematics, and the brightest minds in the best schools attempted the summit. Brilliant men like Vilhelm Bjerknes and his son Jacob, Carl-Gustaf Rossby, and the wunderkind Sverre Petterssen advanced weather prediction from its American roots in the nineteenth century to a level of precision unimagined as the Wright brothers sampled wind speeds on the breezy slopes of Kill Devil Hills. That precision is only marginally

² The distinction between the two weather prediction concepts of climatology and meteorology is crucial, though often blurred in early writings. Climatology is the purview of statisticians, while meteorology is the purview of theorists and mathematicians. Subsequent chapters provide more detail on the differences.

better today. As proof, Petterssen's singular influence on Group Captain James M. Stagg's D-day weather forecast remains the Holy Grail of integration of weather prediction into military operations.

Ground forces were not the only beneficiary of improved weather support. The aviation weather service responded to the demands of advanced aircraft like the Flying Fortress and the Mustang by replacing a glance to the sky with examination of large-scale charts plotted from timely observations of weather at the surface and aloft, and replacing the Old Farmer with prognostications based less on historical averages and more on math- and physics-based models of the movement of atmospheric gasses across varying geographical features, which modified both in a fascinating open feedback loop.³

The fourth chapter opens the gaping maw of the jet intake. Fourth-generation fighters like the Lockheed Martin F-16 "Fighting Falcon" and massive cargo haulers like the mammoth Lockheed C-5 "Galaxy" demanded even more from the weatherman. Terms like all-weather became more important than high-ceiling or high-mach, though ceiling, speed, range, and payload increased an order of magnitude over the best aircraft of World War II. Computers helped not only with the design of fourth-generation fighters and impossibly-large transports, but also with their operation – the F-16, or "Viper" as her pilots call her, is not designed to be aerodynamically stable at subsonic speeds, and thus requires near-constant computer-actuated control surface adjustments to maintain controlled flight. Similarly dependent on computers, the Galaxy has an automated fault detection and analysis system which gathers data from over 800 sensors to alert crewmembers to problems with the aircraft.

Computers also helped boost the science of weather prediction into the jet age. The meteorological framework of physics, geography, and mathematics established in the interwar period and honed during World War II found its limit in the speed at which humans could perform complex computations. In physics and mathematics, the application of relatively stagnant fluid dynamics to the manic 'fluid' of atmospheric gases demanded computational speeds an order of magnitude greater than the best calculators

³ For example, an imaginary parcel of air with a given temperature and humidity will become warmer and drier as it moves down a hillside, and thus will cause faster evaporation of the pond at the foot of the hill. The parcel of air is changed by the geography, and the geography is likewise changed, though less dramatically, by the parcel of air.

of World War II. In geography, observation of the atmosphere and the earth from the air and from space widened the aperture of data so as to overexpose humans to the panoply of information coming in at flabbergasting volumes. Chapter 4's basic inquiry is this: If computers can fly a fighter jet, can they combine all this weather data into a coherent atmospheric model?

The fifth chapter beckons in the new millennium with a fifth-generation fighter jet, the Lockheed Martin/Boeing F-22 "Raptor," and another key enabler – the controversial KC-X air refueling tanker. With advances like integrated intelligence collection and distribution systems, enhanced crew and airframe protection systems, readiness for technology upgrades, engines tuned for super-efficiency or super-cruise, special avionics, and ruggedized stealth (Raptor only), these multi-function platforms fuse scientific disciplines to achieve synergistic effects.

Unfortunately, advances in weather prediction were not as ground-breaking. The revolutionary benefit of interdisciplinary confluence had taken place early in the twentieth century, and subsequent cooperation, while beneficial, did not result in the dramatic innovations of that era. Nevertheless, chaos, complexity, and uncertainty (as those terms relate to math and physics) introduced a willingness to examine old forecast delivery methodologies. In place of the deterministic weather forecasts of today, where a meteorologist makes a go/no-go recommendation by specifying future atmospheric parameters, the acceptance of probability-based forecasts for tropical storms suggests a meteorologist might present in a similar graphic the range of weather conditions anticipated by parallel but independent chaotic, complex, and uncertainty-friendly computer-generated atmospheric models – and rest the decision squarely on the shoulders of those commanders, pilots, and decision makers most entrusted to make the go/no-go call.

Increases in early aircraft performance demanded weather prediction capabilities increase from a glance to the sky and a peek at an almanac to a synoptic and scientific evaluation. When prop wash gave way to jet thrust, weather prediction capabilities both benefited from greater fields of data obtained from air- and space-based weather surveillance and required those data to improve flying safety at the edge of the performance envelope. Combat reliability demanded "all weather" airplanes, and those

advanced designs benefited from computers which also enabled atmospheric modeling to develop into a real-time weather prediction tool. Finally, the interdisciplinary nature of stealth technology paralleled stochastic, not deterministic, ensemble computer modeling techniques derived from disciplines as diverse as biology, economics, and theoretical physics. In each case, the needs of the aviation community changed; each time, the weather community responded to those needs. Across time and especially today, however, the linkage between operators and weathermen appears to reflect only surface-deep changes, suggesting the efficacy of air power would benefit from a deeper and more systematic integration.

The integration of weather prediction into military aviation operations appears to have changed but little in the century after the Wright brothers first flew, despite dramatic leaps in both the aviation and weather fields. Three changes could improve integration, multiplying combat capability for the United States Air Force. The first, a shift to briefing weather as probabilistic versus deterministic, requires little to implement and could have a dramatic and immediate positive impact. The second change, enabling weather-sensor-to-shooter, would require investment of a significant portion of the weather community budget to implement, but could similarly have a dramatic and immediate positive impact. The third change, broadening the jobs open to military weather officers to include, as an initial test, the Air Operations Center Strategy Division Chief, requires a small pen-and-ink change to an existing publication, but a significant change in senior leaders' willingness to raise the glass ceiling further than they have already in allowing space and missile and intelligence officers to get their noses in the strategy tent.

The author does not expect the reader to become a weather integration zealot; rather, the reader should gain a fresh perspective on the value of the supporting elements of the United States Air Force, and, perhaps, a renewed appreciation for the humble, long-suffering, and oft-neglected weatherman.

Chapter 1

Background

The time is approaching for the conquest of the air... when more real horrors will awe the uplooker, the very heavens themselves will become a new theatre of war, and weather will again assert a fresh influence over the strife of mankind.

-- Richard Bentley

Medieval Climatology to Enlightenment Meteorology

Welcome to a world before atmospheric physics and weather maps. Climatology, the study of weather patterns, reigned. Meteorology, the study of atmospheric elements and interactions to establish predictive laws, appeared much later. Pre-Enlightenment, meteorology and climatology were synonyms. By the end of the Enlightenment, meteorology and climatology had assumed their modern distinctive meanings, and continued to advance at relatively equal paces. Then, in the twentieth century, the rapid growth of meteorology and the stagnation of climatology reflected aviation's significant influence. Figure 1 depicts this bifurcation and increasing differentiation.

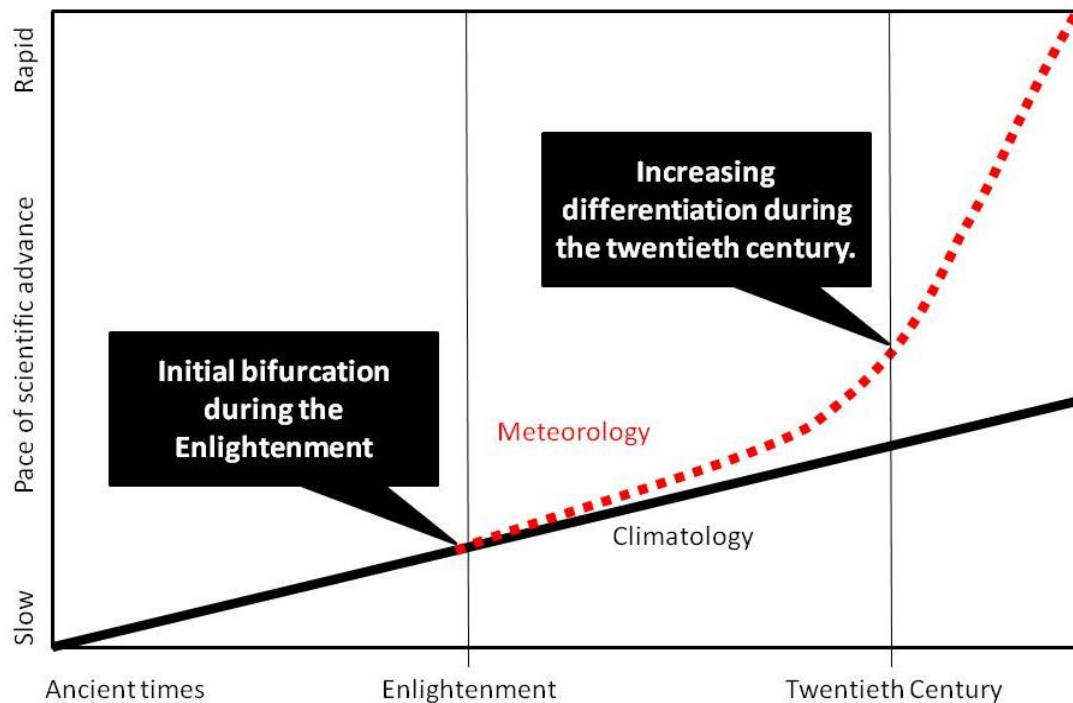


Figure 1. Division of meteorology and climatology.

Source: Figure by author.

Weather conditions have interested mankind since before recorded history. As weather often presented survival challenges in pre-modern times, foreknowledge of weather events often gave an advantage to the clan best able to augur their occurrence. Certainly by the time hunter-gatherers settled into societies centered on cultivation, the prediction of frosts and the duration and frequency of rain and drought became as important as security from beasts and opposing tribes. A reliable source of ancient stories shows attention to weather was ingrained in the public. The author of Proverbs drew on this commonality: “whoso boasteth himself of a false gift is like clouds and wind without rain”; and “the north wind driveth away rain: so doth an angry countenance a backbiting tongue.”¹ Later, in the New Testament, John records Jesus saying, “when it is evening, ye say, it will be fair weather: for the sky is red. And in the morning, it will be foul weather today: for the sky is red and lowering. O ye hypocrites, ye can discern the face of the sky; but can ye not discern the signs of the times?”² These examples help reframe modern perceptions which see weather prediction as a matter of personal convenience and societal interest, rather than as a matter of personal and societal survival, as had been the case for ten millennia.

For thousands of years, the cultivation process established nearly universal patterns of human behavior and settlement. The cycle of sowing and reaping formed a common backdrop for cultures with little else in common. The majority of able-bodied people, counting from 10,000 years ago until the early 1900s, were involved in farming. Whether along the Euphrates, the Nile, the Amazon, or the Volga, plants grow the same way – and around the globe, and for thousands of years, people could find common ground by creating analogies for unfamiliar concepts using familiar terms related to sowing and reaping. As a result, the experience of thousands of years has been concentrated into stories told against the common background of the farm, and for farmers the weather has always been of central importance.³

¹ Proverbs 24:14 and 23. Holy Bible, King James Version.

² Matthew 16:2-3. Holy Bible, King James Version

³ Clarence F. Wells, “Weather and Warfare: The Military Uses of Meteorological Data.” *Army Ordnance* 16, no. 92 (September-October 1935): 101-105.

In the fifth century B.C., Indian state grain storehouses used standardized rain gauges to enable taxation based on predicted harvests.⁴ Aristotle, one of the brightest of all ancient scholars, in 350 BC wrote *Meteorologica*, a general earth sciences treatise which was the first scientific work to discern the water cycle.⁵ The ninth century Arab scientist Al-Kindi conducted field experiments proving the atmosphere contained significant amounts of water vapor.⁶ His Persian neighbor Abū Ḥanīfā Dīnawarī systematically recorded the effect of weather on agriculture in the region.⁷ Within a century, Levant forecasters and farmers began working together to plan crop growth and rotation schedules tied to the seasons.⁸ The thermometer appeared soon afterward, though its origins are broadly contested. Wind measurements, however, are by acclamation credited to Leone Battista Alberti, who developed the first anemometer *circa* 1450.⁹ Other instruments followed, allowing weather observations to become more objective and thus more suited for scientific study. With the invention of the barometer in 1643, the weather station of the past became typical of the weather station of today.¹⁰

Increasingly well-equipped diarists at universities in Europe began recording daily weather observations in the late fifteenth century. In some locations over 500 years of reasonably objective and reliable historical weather data exists.¹¹ By the middle seventeenth century, Ferdinando II de Medici established the first network of ten weather

⁴ D.D. Kosambi, *The Culture and Civilization of Ancient India in Historical Outline* (New Delhi: Vikas Publishing House, 1982).

⁵ Aristotle, *Meteorology*, trans. E.W. Webster (Adelaide, Australia: The University of Adelaide Library, 2007), <http://etext.library.adelaide.edu.au/a/aristotle/meteorology/> (accessed 22 March 2010).

⁶ Douglas M. Dunlop, *Arab Civilization to 1500 A.D.*, (New York, NY: Praeger, 1971), 223ff and Plinio Prioreschi, "Al-Kindi, A Precursor Of The Scientific Revolution," *Journal of the International Society for the History of Islamic Medicine* 1, no. 2 (October 2002): 17-19, also available online at <http://www.ishimj.net/ishimj/ishimj2.htm> (accessed 22 March 2010).

⁷ Toufic Fahd, "Botany and Agriculture," in *Encyclopedia of the History of Arabic Science*, Vol. 3, eds. Rashed Roshdi and Régis Morelon (New York, NY: Routledge, 1996), 813-52.

⁸ Zohor Idrisi, *The Muslim Agricultural Revolution and its Influence on Europe*, Foundation for Science Technology and Civilisation (FSTC) occasional paper (Manchester, England: FSTC, June 2005), also available online at <http://www.muslimheritage.com/uploads/AgricultureRevolution2.pdf> (accessed 22 March 2010).

⁹ W.E. Knowles Middleton, *Invention of the Meteorological Instruments* (Baltimore, MD: Johns Hopkins Press, 1969).

¹⁰ Today's weather station measures precipitation, temperature, wind speed and direction, and barometric pressure. Machines have achieved limited but improving success in replacing the subjective human in evaluating other weather features.

¹¹ Christian Pfister et al., "Daily Weather Observations in Sixteenth-Century Europe," *Climatic Change* 43, no. 1 (September 1999): 111-50, also available online at <http://www.springerlink.com/content/m1j5m4315021q681/> (accessed 22 March 2010).

observing sites which sent weather data to Florence at specified intervals.¹² Grand empirical weather studies reached their apex when George Hadley presented his three-cell theory of global wind circulation in 1735; this theory still holds sway among all reputable climatologists and meteorologists.¹³

While empirical climatological studies continue to the present day, Daniel Bernoulli's 1738 treatise on hydrodynamics applied the laws of physics to the atmosphere and enabled the theoretical study of meteorology.¹⁴ Bernoulli's theories opened weather science to physicists and mathematicians and gradually relegated the climatological studies of farmers and statisticians to a useful though uninspiring backwater. The field of meteorology was open, but progress was slow over the next two hundred years. In time, however, the echoing shouts of "contact!" not only ignited the fuel-air mixture in the aeroplane's carburetor but also lit a fire under the meteorological scientists.

A Review the Impact of Weather on War

Richard Bentley, president of England's Royal Meteorological Society, was in 1907 the first English academic to address systematically and exhaustively the impact of weather on war.¹⁵ He identified 362 specific historic events where weather influenced military operations on land or sea. Most of the events rightfully belong in the realm of meteorological concern, including rainfall, hail, snow, fog, cold, heat, thunderstorms, and contrary winds; but the earthquakes, comets, and eclipses he cited are today events which belong in other scientific realms.

Noting the impact of rainfall, Bentley recalled the massacre of Roman legions by German skirmishers at Lippe in 9 A.D. In sodden Westphalia, under heavy rains, wagons, cavalry, and legionaries foundered while attempting standard movements. Bentley compared this defeat to the English loss to the Zulus at Isandlwana under similar

¹² Raymond S. Bradley and Philip D. Jones, *Climate Since A.D. 1500* (New York, NY: Routledge, 1992), 144.

¹³ George Hadley, "Concerning the Cause of the General Trade Winds," *Philosophical Transactions* 39 (1735): 58-62.

¹⁴ Daniel Bernoulli and Johann Bernoulli, *Hydrodynamics and Hydraulics*, trans. Thomas Carmody (Mineola, NY: Dover Publications, 2004). Originally published in Latin in 1738.

¹⁵ Unless separately cited, this section follows Richard Bentley, "Weather in War-Time," *Quarterly Journal of the Royal Meteorological Society* 33, no. 142 (April 1907): 81-138.

weather conditions.¹⁶ The gales off Iceland earned credit for the destruction of the Spanish Armada in 1588, as Philip II claimed, “I sent the Armada against men, not God's winds and waves.” The loss of the city of Namur, southeast of Brussels, in 1692 was due to a heavy rainfall which prevented English soldiers from engaging the French army besieging the city.¹⁷ John Churchill earned Bentley's praise for choosing the weather for battle: “the great Duke of Marlborough seldom neglected an opportunity, and succeeded in the dangerous operation of crossing a river like the Scheldt in the presence of an active enemy in 1708 by choosing his weather. The day the Duke's army crossed, a dense fog masked the preparations until the last moment, and the French were unprepared and unconscious of the movement until too late to arrest it.” Bentley noted with approval artificial fog in the form of smoke screens was two centuries later a common nautical tactic.

Napoleon Bonaparte's early defeat in Italy, at Caldiero in 1796, came about because the Austrian cannon were already sited in their defensive positions, while French guns found movement impossible over rain-soaked fields. In February 1807, the *Grande Armée* swept into Poland to mop up Prussian and Russian forces, but was stymied not by an opposing army but by bitter cold and blinding snow near Preussisch Eylau.¹⁸ Fairfax Downey, a biographer and military historian, asserted in 1974 that Eylau laid the groundwork which “seated the meteorologist high in every military council.”¹⁹ After Napoleon's Russian campaign, in which weather played a significant though not decisive part, the great artillerist found himself disarmed by steady rainfall at the battle of the Katzbach in Silesia in 1813 and again at Waterloo.²⁰ Bentley recorded two engagements involving Confederate general Robert E. Lee and rainfall. The first, in May 1863, saw heavy rains cause the Rappahannock River to rise too swiftly to allow Lee to smite

¹⁶ Making Bentley's point that weather often escapes the notice of historians, the *Oxford Companion to Military History* omits reference to weather conditions in the Zulu campaign. Richard Holmes, ed., *The Oxford Companion to Military History* (New York, NY: Oxford University Press, 2001), 1021-22.

¹⁷ Namur fell to the Germans in WWI due to a fog that allowed the Germans to site their guns without opposition. Robert DeCourcy Ward, “The War and the Weather during the First Three Months of the Fighting,” *Popular Science Monthly* 85, no. 36 (December 1914): 612.

¹⁸ Fog obscured the advancing French from the Prussians at the battle at Jena; the same fog at Auerstadt later that day caused the King of Prussia to underestimate the French force, to his demise.

¹⁹ Fairfax Downey, “When the Great, White Cold Walked at Eylau,” *Army* (Mar 1974), 46-49.

²⁰ Marshal MacDonald commanded the French during the meeting engagement at Katzbach, but Napoleon's established pattern of warfare formed the critical weather vulnerability in both battles.

Joseph Hooker's retreating Yanks; the second, two months later, saw Lee suffer from sodden immobility as he attempted to extricate the Southerners from their graveyard at Gettysburg.

As Bentley closed his address, he emphasized the benefit of military training in all weather conditions. Bentley cited the diary of Sir William Hosto, who with his frigate sank 218 enemy ships and controlled the Adriatic despite being outnumbered by 10 larger enemy warships and a number of smaller combat vessels. Hosto wrote, "the enemy are afraid of the weather and are badly manned; we are well manned and do not care a rap about the weather." Bentley did not attribute Hosto's statement to imprudence; rather, he concluded, "such was the magnificent result of English naval training during war-time - and which incidentally emphasizes the value of preparation and practice in times of peace."

Weather influenced some of history's most portentous events.²¹ Naval storms resulted in the destruction of Xerxes' hordes as they approached Europe and rescued England from the Spanish Armada. Rain, snow, and cold, as much as the power of his opponents, collapsed the French empire under the first Napoleon. These examples stood ready to illumine those who would employ the airplane in combat, and to counsel consultation early and often with those cognizant of weather's unique perturbations. Anticipating the significant impact of weather on nascent aviation operations, Bentley wrote, "the use of dirigible balloons or air-ships in the future, while it indicates another phase in which the weather will play an important part, is so large a subject that it is best not to touch upon it [in this work]." Today, a century later, few air power advisors, theorists, or advocates should follow Bentley's advice.

²¹ This Western-centric thesis omits such Oriental weather disasters as the "Divine Wind," a typhoon which in 1281 wrecked the 4,000 ship Mongol fleet seeking a landing point for an invasion of Japan.

Chapter 2

If Man Were Meant to Fly, He'd Have Wings

Camilo [Cienfuegos], no measurer of danger, used it as a diversion, played with it; he lured it, he toyed with it and he managed it; in his mentality as a guerrilla no cloud could delay or alter a plan.

*-- Ernesto "Che" Guevara, Guerrilla Warfare,
on why his mentor died in an airplane crash*

How Did This All Start?

The giant leap from lighter-than-air to heavier-than-air flight began as a series of small steps taken by pioneers around the globe, but it was at Kitty Hawk at the dawn of the twentieth century where the penultimate step challenging the birds for sovereignty in the air domain took place. Wilbur and Orville Wright were bicycle manufacturers and inventors looking for a place to perform manned glider experiments. Octave Chanute recommended they look along the Atlantic coast due to the regular sea breezes and flat, sandy terrain. After analyzing available climatological data and consulting with the meteorologist at the Bureau's Kitty Hawk weather station, the Wrights found at Kill Devil Hills, near Kitty Hawk, North Carolina, a site well suited for their experiments.¹ Three years later, this site witnessed the birth of the airplane.

The airplane was an ugly baby. With a 40-foot wingspan and a weight of over 600 pounds, the Wright Flyer's specifications belied its ungainly aspect.² Accomplishing what is accredited to be the first heavier-than-air flight on 17 December 1903, Orville took the beast on a 12-second, 120-foot hop into a 20 knot headwind at a blistering 7 miles per hour. Wilbur followed with a 175-foot launch, and Orville finished the day's experiments with a 200-foot flight. None of these flights achieved an altitude greater

¹ Marvin W. McFarland, ed. *The Papers of Wilbur and Orville Wright, including the Chanute-Wright Letters and other papers of Octave Chanute* (New York, NY: McGraw-Hill, 1953).

² McFarland, *The Papers of Wilbur and Orville Wright*, 394-97 and 1183 and plates 60 and 63-78 and James Tobin, *To Conquer the Air: The Wright Brothers and the Great Race for Flight* (New York, NY: Simon & Schuster, 2004), 159.

than 10 feet above ground level.³ Back in the shop over the next two years, the Wright brothers modified their aircraft to improve stability and control, eventually staging six flights near Dayton, Ohio, ranging from 17 to 38 minutes aloft and covering 11 to 24 miles, between 26 September and 5 October 1905.⁴ With much interest but little money, the Wright brothers proposed the War Department purchase a purpose-built airplane, the 1909 Military Flyer. Smaller but faster, the Military Flyer met the Army Signal Corps' requirement that the aircraft be able to carry two people at 40 miles per hour for 125 miles.⁵ On 2 August 1909, the date the Signal Corps bought the Military Flyer, American military aviation came into being.⁶

The Curtiss JN-4 Jenny, the Matriarchal Hostess

Crafted by artisans from wood, canvas, and a lacquer called dope, with an engine harnessing as much power as a modern suburbanite's pleasure boat, the Curtiss JN-4 "Jenny" was a swan compared to the Wright's ugly duckling. In its time, it was as far removed from the Wright Flyer as any modern aircraft is from the wood and fabric aircraft of World War I. The Jenny, a biplane built as a training aircraft for the United States Army, found enough operational missions to warrant the title of the "backbone of American post-war aviation" and was the most famous American World War I aircraft.⁷ A 90 horsepower V8 engine gave it a top speed of 75 miles per hour and a ceiling of 6,500 feet with a maximum takeoff weight of nearly a ton.⁸ The Jenny had roughly the same dimensions as the Wright Flyer, but few other cosmetic similarities. The biplane tractor design carried over, as did the engineering and structural concepts which governed airflow over the wing and kept weight low. As horsepower per pound increased, raw power enabled flight characteristics explosively greater than those of only five years

³ Carroll F. Gray, "The First Five Flights: The Slope and the Winds of Big Kill Devil Hill – The First Flight Reconsidered," *WW1 AERO – The Journal of the Early Aeroplane*, August 2002, 28, also available online at <http://www.thewrightbrothers.org/fivefirstflights.html> (accessed 22 March 2010).

⁴ The Dayton Metropolitan Library retains a document showing the duration, distance, and witnesses to each of the long flights undertaken between September and October 1905. <http://home.dayton.lib.oh.us/archives/WBcollection/wbexhibit.html> (accessed 22 March 2010).

⁵ James C. Fahey, *U.S. Army Aircraft (Heavier than Air) 1908-1946: The Ships and Aircraft of the United States Fleet* (New York, NY: Ships and Aircraft, 1946).

⁶ Fred E.C. Gulic and Spencer Dunmore, *On Great White Wings* (Shrewsbury, England: AirLife Publishing Ltd., 2001).

⁷ Enzo Angelucci, *Great Aeroplanes of the World*, (London, England: Hamlyn, 1973), 44.

⁸ David Donald, ed. *The Encyclopedia of World Aircraft* (London: Aerospace Publishing, 1997).

previous. Weight increased three-fold, speed increased by a factor of four, and the ceiling increased from a rooftop to over a mile high.

The Jenny, introduced before World War I, represented engineering advanced enough to persist through the conflict. Designers took this engineering and developed aircraft for other wartime functions, including bombing from the air. The Martin NBS-1 bomber, procured in greater numbers during the interwar period than any other Army bomber, provides a good example of the advance in combat radius from the days before the Great War. Slightly more naval bombers saw production, but their designs complied with restrictions induced by their requirement to be launched from carriers or to be carried by ships, hoisted into the sea, and launched and recovered as floatplanes. The NBS-1 was the standard land-based bomber for a decade beginning in 1920, and became the standard against which other designs competed.⁹ William “Billy” Mitchell made history, and enemies, when he used NBS-1 bombers to sink the German battleship *Ostfriesland* on 21 July 1921.¹⁰ Similar to the Wright Flyer and the Jenny, the NBS-1 was a biplane made of wood and fabric, but had two engines and two rudders.¹¹ The NBS-1 doubled the Jenny’s dimensions – nearly 43 feet long with a wingspan over 74 feet, and carried double the crew, with four on board. Other comparisons show exponential increases: engines producing a total of 840 horsepower granted a maximum takeoff weight of six tons, with a speed and ceiling measurably better than the Jenny. Most impressive was the NBS-1’s range, at 400 miles able to fly from Dayton, Ohio, to Montgomery, Alabama, without stopping for gas. A combat radius of over 200 miles meant the NBS-1 could take off from Kitty Hawk, bomb Atlantic City, and return home to rearm.¹²

⁹ National Museum of the United States Air Force, “Martin MB-2 Fact Sheet,” National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2415> and “Martin NBS-1 Fact Sheet,” <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2416> (accessed 22 March 2010).

¹⁰ William “Billy” Mitchell, *Winged Defense* (Tuscaloosa, AL: Fire Ant Press, 2009), 45-46 and 66-73.

¹¹ National Museum of the United States Air Force, “Martin NBS-1 Fact Sheet,” National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2416> (accessed 22 March 2010).

¹² National Museum of the United States Air Force, “Martin NBS-1 Fact Sheet,” National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2416> (accessed 22 March 2010).

Despite these dramatic increases in aviation capabilities, just to fly was a daredevil feat – pilots risked life and limb every takeoff. Part of the risk was connected to equipment, because structural and engine failures were common. As the heavier-than-air flying machine set speed and altitude records, the laws of physics became increasingly a part of risk calculations. Falling from 10 feet with a thousand square feet of canvas did not give gravity's cumulative pull time to accrue a deadly descent rate, but falling from 6,000 feet did. Similarly, a crash landing at seven miles per hour presented a much different assault on human physiology than a crash landing at 100 miles per hour. In addition to these risks, weather risks became more notable. Weather conditions, though fickle, are unlikely to change unexpectedly during a flight measured in hundreds of feet of range, tens of feet in altitude, and tens of seconds in duration. However, flights of hundreds of miles, thousands of feet aloft, and lasting hours rather than minutes compel greater attention to weather factors impacting structural components, engines, and physics.

Nascent Scientific Meteorology, the Welcome Guest

Recalling the bifurcation and differentiation of meteorology from chapter one, these advances in aviation lit a fire under the meteorologists. While the transition to the Jenny from the Wright Flyer took only a dozen years, the field of meteorology opened by Daniel Bernoulli in 1738 still lagged behind climatology both in the scientific world and in the aeries of military power. The parallels between the quick advance from the Wright Flyer to the Jenny and the slow advance from pre-Bernoulli climatology to World War I-era meteorology began just over a century before the first military aircraft purchase.

Military aviation's heightened need for a weather service has deep roots in the early nineteenth century Army. Captain Meriwether Lewis, as ordered by President Thomas Jefferson, recorded weather observations on his trek across the Continental Divide to the Pacific and back from 1804 to 1806.¹³ Army Surgeon General Doctor Joseph Lovell, building on earlier studies showing the possible influence of weather and climate on illness and disease, ordered Army surgeons in 1818 “to keep a diary of the

¹³ Unless separately cited, the following seven paragraphs follow Fuller. John F. Fuller, *Thor's Legions: Weather Support to the U.S. Air Force and Army, 1937-1987* (Boston, MA: American Meteorological Association, 1990), 1-15.

weather, and to note everything of importance relative to the medical topography of his station, the climate, diseases prevalent in the vicinity.” By 1853, the medical corps recorded twice-daily weather reports from 97 locations from shore to shore and border to border. The advent of the telegraph allowed civilian weather observers to report daily, making them timelier than military weather observers, which reported data at three-month intervals set for seasonal medical study. Joseph Henry, first Smithsonian Institution secretary, established in 1849 a civilian weather network of 150 stations telegraphing data daily for study by the Smithsonian.¹⁴

All this data, whether collected seasonally or daily, gave scientists a body of evidence which promised to convert Bernoulli’s theories into laws enabling weather prediction. In the 1830s, academics William Redfield and James Espy used archived weather observations to debate the structure of storm systems, refining them from straight-line gusts to enormous whirlpools to inflowing winds moving obliquely into a low pressure center.¹⁵ By 1841, Elias Loomis presented the first known theory of frontal zones after carefully analyzing maps covered by plots of weather data.¹⁶ It was Espy’s able lobby, however, that caught the attention of Congress and won him an appointment to study the weather across the United States. In his first annual report in 1843, Espy cited storm movement trends and declared it “highly desirable to surround storms and keep them constantly in view from their beginning to their end,” concluding, “may not some of them even reach the shores of Europe?”¹⁷

Across the Atlantic a decade later, an unexpected mid-nineteenth century Black Sea storm threw Emperor Napoleon III’s Crimean war plans into disarray. Napoleon called on Urbain Leverrier, the leading French academic of the era, to study the event. Familiar with the work of the Americans, Leverrier determined the storm could have

¹⁴ Frank Rives Millikan, “Joseph Henry: Father of the Weather Service,” historical study, The Joseph Henry Papers Project (Washington, D.C.: Smithsonian Institution, 1997).

¹⁵ “A Chronological Outline of the History of Meteorology in the United States of North America,” *Monthly Weather Review* 37, no. 3 (March 1909): 88-89.

¹⁶ Loomis’ frontal zone concept did not gain traction until the Norwegian school expanded it after World War I. David M. Schultz, “Perspectives on Fred Sanders’s Research on Cold Fronts,” paper submitted to the Fred Sanders Symposium September 2003 (Norman, OK: Cooperative Institute for Mesoscale Meteorological Studies, 2 September 2003, revised 7 September 2006), 5, also available online at <http://www.cimms.ou.edu/~schultz/sanders/sanders.pdf> (accessed 22 March 2010).

¹⁷ James P. Espy, *First Report on Meteorology, Made to the Surgeon General, U.S. Army* (Washington, D.C.: Public Printer, 1843), 1-4.

been tracked and predicted using telegraphed weather data from existing European weather observing networks. With the efficiency of dictatorial authority, the Paris Observatory began issuing storm warnings less than a year later, in February 1855. Within two years, all of Europe had adopted the French model. Advances on the Continent inspired Englishman Robert FitzRoy to produce in 1860 the first synoptic weather charts, defined as weather maps plotted and analyzed on a regular, daily basis over an extended geographical area. Figure 2 is an early French example. FitzRoy also coined the term “weather forecast” and published the first daily weather forecast in 1860.

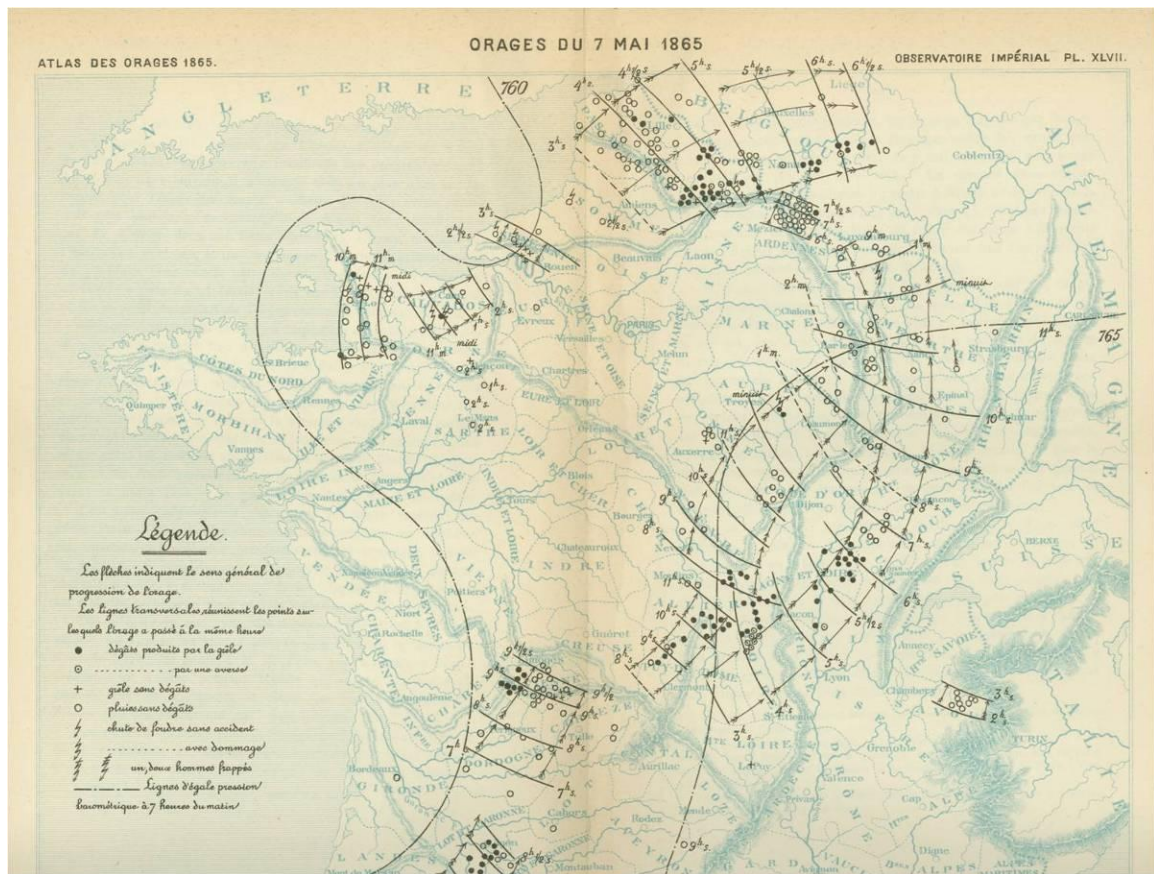


Figure 2. One of the world’s first weather maps. Commissioned by Napoleon III. Source: NOAA Photo Library, <http://www.photolib.noaa.gov/>¹⁸

The spread of national weather services in Europe, Turkey, and India reinvigorated efforts by advocates of the same in the United States. Congress, largely occupied with the Civil War and its aftershocks, took no action until prompted by Wisconsin congressman Halbert Paine. Congressman Paine received an earnest letter and

¹⁸ NOAA Photo Library, <http://www.photolib.noaa.gov/> (accessed 12 January 2010).

detailed study from the Quaker Renaissance man Professor Increase Lapham which claimed significant economic benefit would accrue to shipping firms across the Great Lakes if the United States would adopt a storm warning service on the European model. Congressman Paine, recently freed from the ivory tower of *academe*, was familiar with Loomis' work on storm structure and became a vocal and coherent advocate of a national weather service, on an experimental basis at first.¹⁹ Colonel Albert Myer, head of the shoestring Army Signal Service, snatched the bait before Henry at the Smithsonian could work up a proposal, promising the federal government, via the widespread patchwork of forts, posts, and camps across the North, the South, and the unsettled West, could do the job more cheaply than a civilian agency. On 9 February 1871, President Ulysses Grant signed a joint resolution which read, in part: "*Be it resolved by the Senate and House of representatives of the United States of American in Congress assembled, That the Secretary of War be, and he hereby is, authorized and required to provide for taking meteorological observations at the military stations in the interior of the continent and at other points in the States and Territories of the United States, and for giving notice on the northern lakes and on the seacoast, by magnetic telegraph and marine signals, of the approach and force of storms.*" As desired by Myer, the secretary of war gave the job to his Signal Service.

Myer's *coup* did not engender universal support. Professor Cleveland Abbe, the respected director of the Cincinnati Astronomical Observatory, had since 1869 published a daily weather map based on observations from cities in the Midwest. Abbe did not believe soldiers had the requisite intelligence to perform weather observing or forecasting duties. He had written an open letter months before the 1871 joint resolution claiming the "meteorological observations of the Army have generally proved themselves very unreliable" and concluding, "I am specially of opinion that the money would do more toward effecting good results if it goes through the hands of meteorologists than through the hands of Army officers."

Admitting his Signal Service soldiers knew little about meteorology, Myer sought counsel from the nation's most respected meteorologists on how to organize, train, and

¹⁹ In addition to Fuller, see also Karl Larew, *Meteorology in the U.S. Signal Corps, 1870-1960*, Signal Corps Historical Division study (Washington, D.C.: Signal Corps Historical Division, 1960), 4.

equip for the new mission. One result was the weather training school at Fort Whipple, Virginia, which functioned until Congressional belt-tightening strangled it in 1886.²⁰ Myer's best decision was to hire Lapham, who promptly issued the first Signal Corps Great Lakes storm warning the same day. In poor health, Lapham served only six months with the Signal Corps, presenting Myer with another crisis of credibility. Despite Abbe's early opposition, Myer was able to convince the professor to leave his position at the Cincinnati Observatory and take the position of Chief Forecaster and Scientist of the Signal Service. Abbe's lengthy service, from 1871 to 1913, cemented the confidence of the nation in her new weather forecasting service, warmly nestled in its military nest.

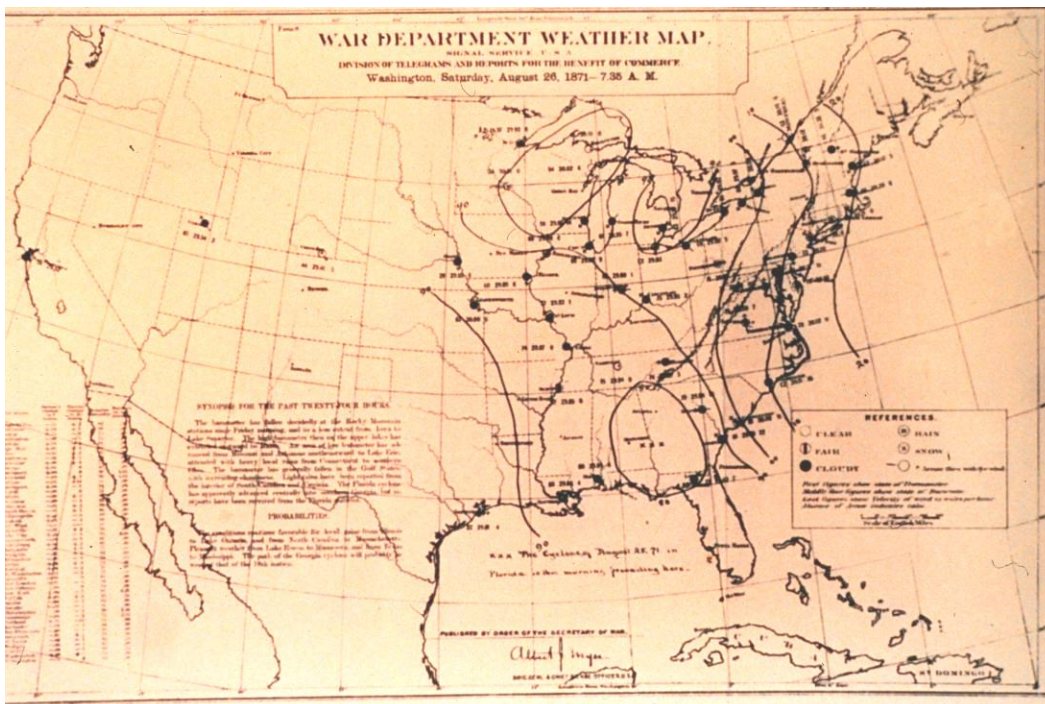


Figure 3. One of the first Signal Service weather maps. Analysis by Increase Lapham. Source: NOAA Photo Library, <http://www.photolib.noaa.gov/>²¹

²⁰ Fort Whipple, the school's home, is now named after Myer. After the weather school closed, Brigadier General William Hazen, who took over after Myer's death, successfully lobbied high schools and colleges to make meteorology a part of their curricula. Larew, *Meteorology in the U.S. Signal Corps*, 16.

²¹ NOAA Photo Library, <http://www.photolib.noaa.gov/> (accessed 12 January 2010).

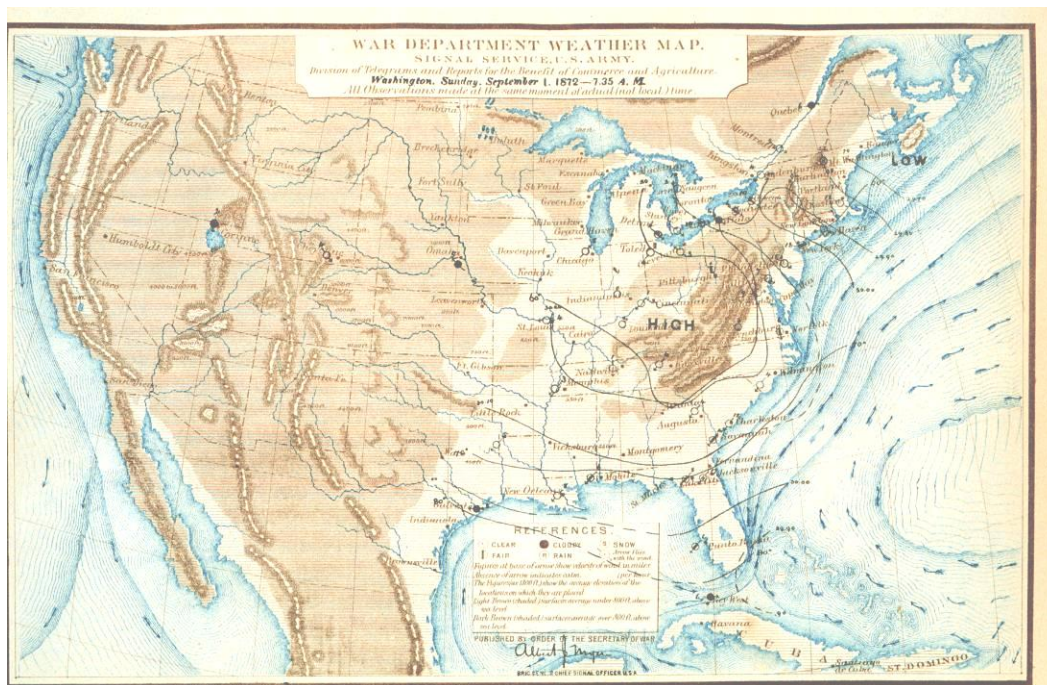


Figure 4. Early analysis by Cleveland Abbe, Lapham's successor.
Source: NOAA Photo Library, <http://www.photolib.noaa.gov/>²²

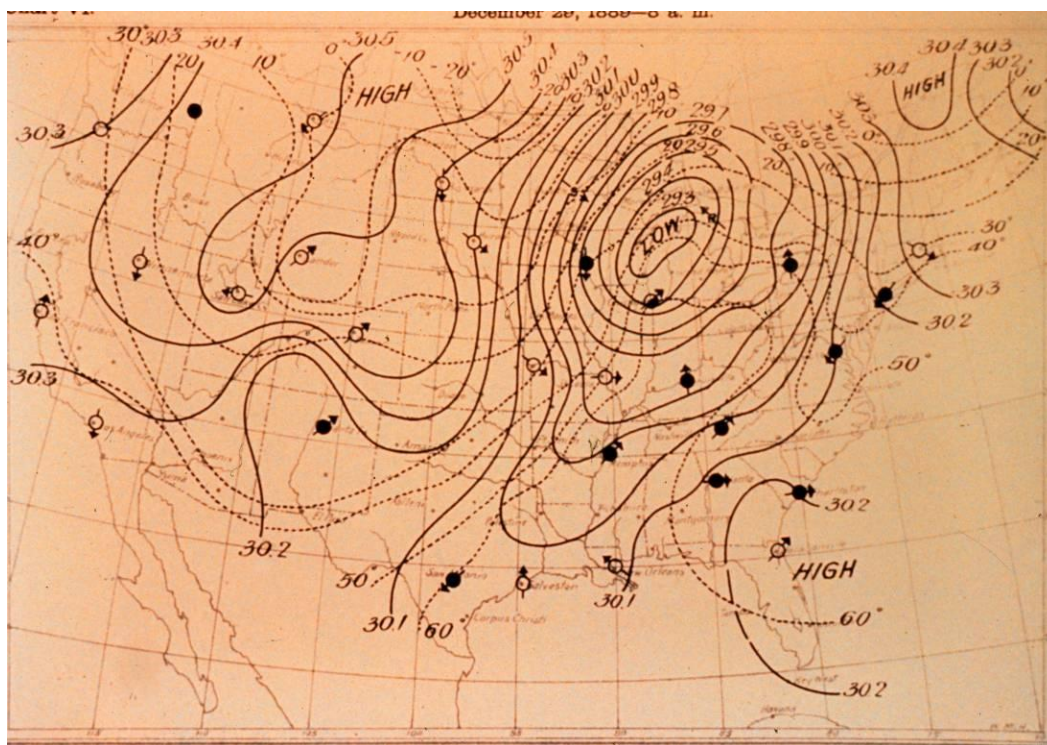


Figure 5. The result of a decade of practice and scientific advance; Abbe *et al.*
Source: NOAA Photo Library, <http://www.photolib.noaa.gov/>²³

²² NOAA Photo Library, <http://www.photolib.noaa.gov/> (accessed 12 January 2010).

The early successes of Myer resulted in a growing Signal Corps weather service. From 24 Army weather stations in 1870, the service grew to 55 in 1871, 93 in 1873, and 224 in 1878.²⁴ The forecasting staff grew as well, and by 1873, Myer's Signal Service prepared an average of 35 weather bulletins and 60 weather maps each day. "Under Myer's aplomb and leadership," Air Weather Service historian John Fuller wrote, the Signal Service became a world leader in furnishing weather support for the public's benefit. Weather service soon became the Signal Service's biggest task, and expansion was so great that it soon crowded other agencies such as the Corps of Engineers almost totally out of the field." Myer sponsored regulations to require Navy ships to report weather conditions and sponsored balloon ascents and established weather stations at Mount Washington and Pike's Peak to gather weather data in the upper atmosphere. At the First International Congress of Meteorology at Vienna in September 1873, Myer proposed all nations take an observation at a specified time, to be collected and published. The resulting Bulletin of International Simultaneous Observations, Fuller gushed, "was as fine a piece of international cooperation as any."

Despite all this growth, war-fighting technology grew still faster. Signal Corps historian Karl Larew noted the imbalance between the war fighter's requirements and the meteorologist's capabilities. "In strictly military meteorology," Larew claimed, "the advancement of ordnance and ballistics caused an increased need for weather information on the part of gunners." The Signal Corps began in 1892 to equip gunnery ranges with weather instruments, which "helped increase the accuracy and rate of artillery fire." Regarding military aviation, however, meteorological needs remained urgent. "The early airplanes," Larew lamented, "were largely at the mercy of the elements."²⁵ These concerns grew more pressing as Europe prepared for war.

As World War I raged, however, the young science of meteorology had many acolytes but few eyeing military use. Among the few was Harvard's Robert DeCourcy Ward, who systematically cataloged weather's influence during the war for the

²³ NOAA Photo Library, <http://www.photolib.noaa.gov/> (accessed 12 January 2010).

²⁴ In addition to Fuller, see also Larew, *Meteorology in the U.S. Signal Corps*, 9.

²⁵ Larew, *Meteorology in the U.S. Signal Corps*, 24-25.

periodicals *Popular Science* and *The Journal of Geography*.²⁶ As he began his reports, he recited now-familiar meteorological credenda: “The weather factor in war is not a joke. It is a perfectly serious subject for study on the part of military and naval strategists. It must be taken into account in laying out a campaign or in organizing troops for a battle. To disregard the weather factor in warfare is almost, if not sometimes quite as serious an omission as to forget to provide food, or clothing, or ammunition. The weather has, time and again, turned the scale, for victory or for defeat.” Ward was prescient of Hitler’s folly in World War II, for the “terrible winter retreat of Napoleon’s Grand Army from Moscow furnishes a tragic but wonderfully vivid illustration of the strength of Russia’s two invincible generals, January and February, who, if the scene of the present war [World War I] should be transferred into Russia during the winter, would again be found fighting on the side of the Czar,” or, in the case of World War II, on the side of Comrade Stalin.

Where Bentley praised military commanders who took advantage of weather conditions favorable to their operations, Ward found two separate classes of weather influences. The first Ward termed accidental or unexpected, and characterized as part of Clausewitz’s fog and friction of war. The second class he cited as being “perfectly normal and natural for the particular region and season in which they occurred, but the army was not prepared for them because of the ignorance, or lack of foresight, or over-confidence, or haste, on the part of the commanding officers.” Ward, a celebrated climatologist, considered the wise commander to be one who would take care “to know, in advance, the general climate of the war zone; to be prepared for the special weather conditions which are reasonably to be expected at this or that season; to have as accurate a knowledge as possible of the probability of occurrence of severe cold; of sudden thaws; of heavy rains; of great heat; of high winds; of deep snows – this is a very essential element in planning a campaign or in organizing a single engagement.” The reader

²⁶ Unless separately cited, the following 12 paragraphs follow Ward. Robert DeCourcy Ward, “The War and the Weather during the First Three Months of the Fighting,” *Popular Science Monthly* 85, no. 36 (December 1914): 604-13; Ward, “The European Winter and the War,” *The Journal of Geography* 13, no. 6 (February 1915): 169-71 and no. 7 (March 1915): 208-15 and Vol. 14, no. 3 (November 1915): 71-76 and no. 10 (June 1916): 373-84 and Vol. 15, no. 3 (November 1916): 79-86 and no. 8 (April 1917): 245-51 and Vol. 16, no. 2 (October 1917): 47-51 and no. 3 (November 1917): 86-90 and no. 8 (April 1918): 291-300 and “Weather Controls Over the Fighting in the Italian War Zone,” *The Scientific Monthly* 6, no. 7 (February 1918): 97-105 and no. 19 (April 1918): 289-304 and Vol. 7, no. 1 (July 1918): 24-33.

should note Ward's emphasis is on climatology, the statistical and empirical study, not meteorology, the theoretical study to determine predictive laws.

In a slight nod to meteorology, Ward's second divergence from Bentley was his acknowledgement of the growing understanding of storm movement advanced by Loomis, Espy, and Leverrier. In his detailed narrative of the first three months of the war, Ward observed the expected autumn rains "come in connection with storms that drift in from the Atlantic Ocean, and pass eastward, across the Channel and the North Sea." Conversely, Ward noted, "in the northeast, the Germans seem to have been surprised by the setting in of cold weather in the first half of October, and, not having heavy clothing, they are reported to have suffered severely. The Russians, on the other hand, were well protected.... It is not unlikely that the Germans, even if they were distinctly victorious in this zone, would think of penetrating far into Russia, to face, as did Napoleon, the might of Generals January and February." Ward showed no bias, finding along the Western Front the "warning chill" of September "seemed to arouse all the commanders to a sudden realization of the unpreparedness of their troops for a winter campaign."

Ward's distinctive break from Bentley was his willingness to apply weather to aviation. "It is hardly necessary to point out," opined Ward, "that in the matter of aeroplanes and airships modern warfare is far more dependent upon weather conditions than it ever was." Ward concluded from early wartime evidence aerial reconnaissance, observation, and spotting duties required fair weather, and forecasted weather could allow early warning of Zeppelin attacks on London. The lack of weather data from England, which had been shared with the world before the war, complicated German aerial attack planning, however. Ward also noted, though indirectly, weather information is of sufficient value to warrant its protection by warring states, and even went so far as to speculate about German spies who risked their lives to transmit the data surreptitiously.

Ward's second installment began with a climatology-based characterization of the war zone by climatic region. Swiftly, though, he returned to descriptions tinged with Bernoulli-influenced atmospheric dynamics in describing how, as storms passed, "the wind-vanes of central Europe turn, with characteristic regularity, from south-east through south to west." Writing his third installment in March 1915, he noted melting snow in warm weather "has been accompanied by an immediate slackening of military operations,

owing to the difficulty of transportation. Every cold spell has stimulated military movements. Whenever the curve of temperature has gone up the curve of military activity has gone down, and whenever the curve of temperature has gone down the curve of military activity has gone up.” Observing the double-edged sword of weather, Ward wrote regarding aviation “the German aeroplane which dropped a bomb over Dover in late December ‘escaped in the mist’ from the British aeroplanes which pursued it. In the Christmas day aerial raid by the British upon Cuxhaven the atmosphere was so thick that it was difficult for the airmen to achieve their purpose. It is obvious that a fog gives aviators their best chance of safety, but, on the other hand, they cannot pick out their targets. In the German air raid of Jan. 19 a mist prevented the airmen from aiming their bombs with accuracy, and also prevented effective pursuit of and successful shooting at the invaders.”

Writing for the June 1915 publication, Ward reported how an early thaw prevented Paul von Hindenburg from fully springing his Russian trap. The forces which were to form the northern “jaw” found mobility nigh-impossible in the muddy morass approaching Petrograd, allowing a third of the Russian force not only to escape through the gap, but also to counterattack the pursuing German army corps when the frozen lakes under the German supply lines also thawed. Regarding aviation, Ward found it significant “every important German air raid during the winter occurred at the time of a fog, apparently accurately forecasted by the German meteorological war service.” Ward also bore witness to a precursor to military meteorology, the Chemical Downwind Message. “A new and curious emphasis upon the importance of weather controls in modern warfare,” Ward asserted, “comes in the report that the wind which, on one occasion, had been carrying the deadly asphyxiating gases used by the Germans towards the Allies’ trenches, suddenly changed, blowing these same gases back to the German lines, and forcing the men to flee for their lives.”

By September 1915, Ward’s perspective on weather through the bitter winter allowed him to acknowledge commanders on both sides had not been surprised by the cold, despite his earlier condemnation of the Germans in the east and all commanders in the west. He patted himself on the back for predicting increased Zeppelin raids during the favorable weather of late spring and summer, while admitting often good weather on

the Continent and poor weather over the British Isles was a recipe for German bombing success and English air patrol failure. Ward noted Zeppelins wore new paint schemes to help them blend in when flying under an overcast sky, “a good illustration of man’s adaptation of his own inventions to the meteorological environment in which they are used.” He closed his autumn installment with a lengthy description of the German military meteorological service, noting the early change from a scientific and descriptive function to an operational and predictive function, significantly enhanced in importance by the German use of gas warfare along the western front, where the prevailing winds were westerly, in the face of the attacking Germans. Ward reluctantly praised the enemy prognosticators for their accuracy, finding “reports of but two cases in which the Germans were themselves forced to retreat before their own gases, owing to a change in the wind.”

As Ward penned his subsequent installment in March 1916, he found laudatory the gradual acceptance by commanders of the importance of weather prediction on tactical and operational military plans. Ward cited a Swiss daily: “*Le Temps*, on Dec. 26, reported ‘the wind is blowing from the east, which will permit the enemy to use asphyxiating gases. It is, then, the most elementary prudence for us to be ready with masks, and to man the batteries.’ This is a significant statement: a forecast of a probable hostile attack because the wind was favorable for the use of gas.” Ward again bowed to the skill of enemy forecasters, citing how few were the reports the German gas attacks were foiled by unpredicted wind shifts. He found cause for condemnation of “military experts” in climatology in the Dardanelles campaign, whose predictions in early October of “three months of good weather ahead” not only left troops ill-prepared for a hot and dry October and November and a wet and cold December, but also contributed significantly to noncombat losses during the retreat from Gallipoli. Of particular interest to the historian is Ward’s novel addition of a section entitled “The War in the Air” to this and subsequent reports, a prescient acknowledgement of the intrinsic connection between combat in the air and weather conditions in this domain.

As the winter of 1916 settled in, Ward shifted from a focus on weather effects on tactical operations to operational and strategic levels. He noted the Zeppelin campaign became less predictable by wind direction forecasts and more predictable based on the

use of the barometer to ascertain the interplay of the storm systems proposed in the mid-nineteenth century. Ward attributed this change to technological advances. “It appears, more and more emphatically,” claimed Ward, “that the Germans have made a very careful study of weather conditions before starting their Zeppelin raids, and it also seems as if, with their new super-Zeppelins, they are becoming somewhat more independent of wind and weather.” Ward quoted a “distinguished European aviator” who claimed “favorable weather conditions are no longer necessary when flights are undertaken, but that the men go up ‘when they have to’, without regard to the weather. While this is to a certain extent true, it must not be taken too literally. Thus, on the western front, we note that rain and thunderstorms and low clouds and bad weather frequently interfered with air work.” This connection between the airplane and the weather, though tenuous this near to aviation’s infancy, grew stronger as aviation grew more mature.

Ward described a new German tactic in his spring 1917 article – the use of a hose to spew poisonous gas on the Russians in Carpathia, like a fireman might use a hose to douse a fire. The failure of this device due to unfavorable winds highlighted weather forecasting incapacities at the tactical level. Dramatic advances in meteorology, which at this point in the war had brought it to a level of respectability and influence nearing that of climatology, had not yet driven military leaders to establish a weather service capable of influence at the cutting edge of small-unit ground warfare. In the fall 1917 installment, Ward confirmed the continuing primacy of climatologists in planning at the operational and strategic levels of war. “Proper attention to meteorological conditions,” Ward asserted, “often enables an army to take advantage of the favorable spells for its more extended movements. This the Germans seem frequently to have done.” But Ward saw gains for meteorologists as well, observing “storm weather, with high winds, is obviously less and less of an obstacle to war flying.” Ward found evidence in dispatches from the front lines of German aviators using clouds as cover, and suggested this tactic “adds emphasis to a study of cloud types, and their conditions of formation, on the part of our aviators.” In again praising the German meteorologists for their accuracy, Ward concludes “it is clear, as it has been since the war began, that the German military meteorological service has been doing good forecasting.”

Ward, writing in the hopeful spring of 1918, followed the triumphant tones of *New York Times* war correspondent Philip Gibbs in praise of the dogfaces in the trenches at Passchendaele, by lauding the aviators “who flew under conditions formerly regarded as prohibitive.”²⁷ He expounded weather conditions considered unfavorable for flying “now no longer act as a deterrent, although they render the task of the aviators infinitely harder,” and observed “the superdirigible may now be considered practically weather-proof. Its vastly increased speed has put at its disposal a dynamic lifting or depressing force which in amount almost rivals the total lift of the gas. Easily compensating the ordinary fluctuations of the gas lift, due to barometric conditions and changes in temperature, it resists far more formidable agencies like rising or descending air currents, impact of rain or hail, and even weighting of the hull with water or snow.” While the specific technological advances were lost on Ward the climatologist, the newer dirigibles clearly enabled operations increasingly independent of weather conditions.

Ward’s lengthy serial completed, his summative articles in *The Scientific Monthly* offer immediate insights to the interaction between the conduct of war and the prediction of weather. He found by “means of daily weather forecasts, such as are now being made by the expert meteorologists on all the war fronts, the military commanders are often able to plan operations in such a way as to take advantage of weather conditions favorable to their purposes, and, at least to some extent, to guard against those conditions which are hostile.” In contrast with this hopeful promise of meteorology, Ward devoted the balance of the first half of his summary to the controls of weather from a climatology perspective, citing deviations from means of temperature, rainfall, and snowfall as of greatest import. He did admit an increase in meteorological personnel associated with specialized tactical units, finding in the German gas regiments a number of weather observers who have “made very careful study of wind and weather before launching such gas attacks, and their success, in a large majority of cases, shows how well their weather forecasts were made.” The practice of fielding military meteorologists with tactical units whose missions are significantly influenced by weather is mirrored today by Air Force

²⁷ Philip Gibbs, “Mud the Chief Enemy as British Advanced.” *New York Times*, 12 October 1917.

meteorologists, who deploy in significant numbers with Army aviation units at the brigade level and below.²⁸

Fighter and bomber wings were among the specialized tactical units whose personnel included military meteorologists. However, a survey of World War I aviation memoirs reveals a cavalier attitude toward aerodrome weather personnel, when they are mentioned at all.²⁹ While meteorologists found employment and voice at strategic and sometimes operational levels of war, little evidence exists of regulations or procedures dictating anything but an informal weather check before taking to the air. The manual provided with the Jenny is typical, including 35 “hints on flying,” only two of which mention weather phenomena. Pilots should consider the effect of a head or tail wind on glide slope, said hint 13, and hint 15 recommended a long, straight glide to the landing zone to allow the pilot “a fine chance to judge distance and wind.”³⁰

In the years after the war, the drawdown did not leave military weather units untouched. In his history of the military weather service, Larew found interwar leaders divided weather support requests into those requiring current weather observations, like those of the Coast and Field Artillery, and those requiring increasingly more resource-intensive weather forecasting services, like the Air Service. “The sharp increases in the weather budget are to be explained by the increasing support rendered the Air Service,” claimed Larew, and found in the late 1920’s and 1930’s a military weather service “so identified with the Air Corps as to lead to serious questions concerning the location of proper responsibility for weather support.”³¹

²⁸ Major Barbara Costa, Air Force Personnel Center Chief of Weather Officer Assignments, observed that 36 percent of Air Force Weather officers serve in Army support billets, and that this figure has held consistent for over 20 years. Interviewed by the author, 15 April 2010.

²⁹ Cecil Lewis’ *Sagittarius Rising* infers one conversation via telephone with a weatherman. In *Flying Fury*, Major James T.B. McCudden included two weather anecdotes, but omitted the meteorologist. Ernst Udet epitomized the autodidactic nature of weather briefings in his two references in *Ace of the Iron Cross*: “And in the mornings, when I rise, my first look is skyward. What is the flying weather like?” (p. 73) and “The blue of the sky shows through only in spots. ‘Good weather for balloon attacks,’ I say to myself.” (p. 81). Captain Eddie V. Rickenbacker obtained his weather briefings from personal observation, or occasionally from his orderly, according to his autobiographical *Fighting the Flying Circus*. Lt. Col. William A. Bishop, in *Winged Warfare*, frequently cites weather conditions but never an aerodrome meteorologist. For a less prominent but no less valuable memoir which discusses weather extensively, see John Edward Tenant, *In the Clouds Above Baghdad, Being the Records of an Air Commander* (London: Cecil Palmer, 1920).

³⁰ Kevin Holcomb, “Curtiss JN-4D - Specifications & Operating Instructions,” Holcomb’s Aerodrome, http://www.airminded.net/jenny/jn4_spec.html (accessed 2 December 2009).

³¹ Larew, *Meteorology in the U.S. Army Signal Corps*, 38-41.

Writing in 1926, Thomas Reed noted the link between aviation technology and meteorological advances.³² Reed found the “design and construction of airplanes in the few years since the development of the theory of flight have vastly outpaced the development of surface organizations. The war, of course, was responsible for this. Military needs forced the one and provided for the other only so far as they were indispensable to military operations. The safety of men and machines was incidental, not paramount.” Reed cited the attention mariners gave meteorology, and stated “meteorology inherits a position far more consequential than any it ever held as an adjunct to water navigation, even in the palmiest days of the wind-jammers.” His delight at the establishment of a national Weather Bureau was founded in his claim that air commerce depends on a reliable network of weather observing stations combined with accurate and timely weather forecasts and warnings.

The end of the war did not serve, however, to increase the influence of meteorology over climatology in all military circles. F.E. Edgecomb, writing in 1928 for an artillery organization interested in atmospheric conditions and their impacts on target acquisition and, more importantly to the artillerist, on weapon flight, characterized weather information as either statistical or current.³³ Statistical information, or climatological information, was of little use to the artilleryman, according to Edgecomb. What the artilleryman valued, however, was accurate current measurement of weather conditions at the surface and aloft, and Edgecomb detailed in seven close pages schema to gather and analyze pertinent weather elements. His omission of predictive, scientific meteorology was purposeful – he cited Loomis, indicating his awareness of the mature science of frontal system prediction, but refused to admit the value of predicting the weather conditions so crucial to artillery fire success.

Contrasting Edgecomb’s snub, his contemporary, L.G. Garbett, superintendent of the British Navy’s weather office, found value and promise in weather prediction.³⁴ Garbett saw in the rapid development of guns, torpedoes, and aircraft a need for deeper

³² Thomas R. Reed, “Meteorology—An Aid to Aviation.” *The Military Engineer* 18, no. 102 (November-December 1926): 476-79.

³³ Captain F.E. Edgecomb, “Meteorology for Artillery,” *Coastal Artillery Journal* 69, no. 3 (September 1928): 203-11.

³⁴ Commander L.G. Garbett, R.N. (ret), “Meteorology & the Fighting Services,” *Journal of the Royal United Service Institution* 73, no. 492 (November 1928): 700-15.

understanding of weather than climatology afforded. “Once we are in a position to calculate or forecast the course of the weather,” opined Garbett, “we can adjust ourselves to it by selecting the most favourable time for an operation. The weather, therefore, must always be to the fighting services a factor of immense importance; in aerial warfare it is the dominating factor.” The value of meteorological study in peacetime remains great, he asserted, because of the impact on training, on trials of new technologies, and the advancement of the science as a multiplier of wartime capabilities. The advent of carrier-based aircraft linked advances in technology to advances in meteorology, as accurate forecasts of winds at the surface and aloft are necessary to enable accurate navigation, without which aircraft would be unlikely to rendezvous with the carrier absent landmarks. Garbett’s experience in the fleet gave him credibility when he asserted, however important climatology may be, “weather forecasting is entirely dependent on maps, and the weather map or synoptic chart, as it is now called, is the foundation on which much of the science of meteorology rests.” Garbett summarized the slow progress of meteorology since Bernoulli, in contrast with the quick advance of aviation since the Wright Flyer, when he wrote:

Weather forecasting was until recently to a large extent empirical, but knowledge of the processes at work in the atmosphere has advanced greatly since the war, and with this advance of knowledge meteorologists are able to an increasing degree to make scientific as opposed to empirical forecasts.

Meteorology is a young science, still in the course of development, but I hope that I may have succeeded in showing you how important it is. I would again submit to you that training, armament and courage may well be equal, but that a superiority in the application of Meteorology, like a superiority in any other secondary feature of equipment, might indeed become a decisive factor.³⁵

Garbett expressed in his recognition of the synoptic weather map the fundamental challenge which faces meteorologists even today – insufficient data. At the time, expanding data coverage over larger areas was of greatest concern; today, meteorologists question if datum is inherently insufficient. Chapter Four explores this concern in greater detail.

³⁵ Garbett, “Meteorology & the Fighting Services,” 711-12.

Clarence Wells also spoke on issues contemporary to the inter-war period.³⁶ To him, weather forecasting began with accurate climatology which established “the typical or normal condition of the atmosphere which would exist if there were no disturbances or local influences,” then modified the norm to account for disturbances in the form of high or low pressure systems, then further modified the result to account for “local influence such as land and sea breezes, presence of large bodies of warm water, mountains, etc.” Writing seven years after Garbett, that Wells took for granted the existence of a daily, national weather forecast shows how quickly the exceptional became run-of-the-mill: “In time of peace in the United States we do not have to worry greatly over the weather for we have the Weather Bureau to make our observations and forecasts and all that we have to do is to turn to the daily paper and we have our weather forecasts before [us].”

In his extraordinary 1935 weather prediction tutorial, Signal Corps meteorologist W.H. Wenstrom foresaw increased weather forecasting requirements driven by aviation missions and capabilities.³⁷ Wenstrom concluded “the next war will see plenty of bad-weather flying on military missions. All this will mean that the Air Corps should have current weather data – ceiling, state of sky, precipitation, visibility, surface winds, and the like – from dozens of stations arranged in fairly close networks. It will need also frequent reports on upper winds, probably up to higher altitudes than those flown regularly at present. And needless to say, it will depend heavily on accurate weather forecasting.”³⁸ Wenstrom heard the winds of war blowing across both oceans and augured with eerie prescience “the next war for ‘Uncle Sam’ is likely to come whether he wants it or not, in the form of a sudden and unwarranted attack by a power that believes in aggression for the sake of territory and prestige. When that time comes, we shall appreciate the emergency value of all the technical preparations that we can make in comparative leisure now.”³⁹

³⁶ Clarence F. Wells, “Weather and Warfare: The Military Uses of Meteorological Data,” *Army Ordnance* 16, no. 92 (September-October 1935): 101-105.

³⁷ Wenstrom’s 19 pages on weather forecasting principles, including 10 figures, would hold up in any college of meteorology, and could suffice as a manual for training enlisted members and officers in weather theory and application. First Lt. W.H. Wenstrom, “Modern Meteorology,” *The Signal Corps Bulletin* 22, no. 85 (July-August 1935): 8-27.

³⁸ Wenstrom, “Modern Meteorology,” 24.

³⁹ Wenstrom, “Modern Meteorology,” 27.

Summary

Three questions stand at the end of each chapter, in light of the thesis that aviation advances drive weather prediction advances, and subsequent weather predictions seem irregularly integrated into aviation operations. First, did aviation advances between the Wright's first flight and the end of World War I demand more from meteorologists? Second, did weather prediction advance to meet the needs of aviation? Third, did the aviation community improve integration of weather prediction during the decade and a half since Kitty Hawk?

The first section in the chapter detailed aviation's exponential advance from the Wright Flyer to the Jenny and the NBS-1. Increases in flight range, altitude, and duration were most demanding of improved weather prediction. Modern and contemporary writers confirmed aviation's increasing demands on the weather service. Therefore, aviation advances surely demanded more from meteorologists.

The second section in the chapter summarized the slow march of weather science, even while prodded by air-enabled combat in World War I, from a field exclusively statistical and empirical to a field increasingly influenced by Bernoulli's fluid dynamics theories. Governments and other agencies developed weather observing networks reporting daily, which enabled production of large-scale synoptic weather maps scientists used to surround storm systems, follow them, and autopsy them to determine what laws govern their growth and death. These advances allowed weather prediction to move from statements of the climatic mean to accurate forecasts of future conditions based on variations from the mean extrapolated from interactions in atmospheric and geographic elements governed by the laws of physics, not the laws of statistics.⁴⁰ Not only did these advances improve forecasting at the earth's surface, but increased observation and study of the upper atmosphere also improved predictions of conditions far above the ground. Therefore, weather prediction surely advanced to meet the needs of aviation.

Finally, did the aviation community improve integration of improved weather prediction? For a study as limited in scope as this, the answer rests on inference rather

⁴⁰ Signal Service weather forecasts verified at 77% accuracy, based on an official Army audit. See Fuller, *Thor's Legions*, 4, footnote 37.

than missing or well-hidden historical data.⁴¹ At the outset of military aviation, such neglect is no condemnation. Early in the aviation era, the Wright brothers took sufficient consideration of the weather by consulting climate data to determine the site for flights and observing current conditions at the beginning of each flight. As noted earlier, pilots obtained weather briefings at their discretion. However, surveyed memoirs recorded the presence of meteorologists at their aerodromes, and some cited receiving weather updates from them. This *ad hoc* process, while not systematic, did show an improvement over the autodidactic traditions of the earliest aviators, and was likely sufficient because other risks far outweighed weather risks during the time when nascent technology killed the unlucky as often as the unskilled or unbriefed. Did the young and burgeoning aviation community increase integration of improved weather prediction? The answer is anticlimactic: Sort of.

⁴¹ The author consulted the Air Force Historical Research Agency, the United States Army Heritage and Education Center, and the Fairchild Research Information Center while researching this point. This paper does not claim the information does not exist, but rather that it has thus far escaped the author's notice.

Chapter 3

Off We Go, Into the Wild Blue Yonder

Considerable research and long hours of work by you and your associates resulted in the reconciliation of differences in forecasting methods and the development of a procedure which enabled me to receive the advice necessary for the selection of D-day with confidence.

-- Letter from Dwight Eisenhower to Sverre Petterssen, 19 September 1944

The Golden Age of Air Power

In World War II, aviation took another vast technological leap. All-metal aircraft, streamlined and stratospheric, replaced the canvas and wood relics of the previous generation. Designs reflected flashes of brilliance as well as the sweat of nose-to-the-grindstone, trial-and-error engineering. The vast variety of aviation concepts enabled by the malleability and durability of a metal skin and the improvement of the internal combustion engine combined to make the mid-twentieth century a golden age of air power. What air power promise had not been fulfilled? Rather than echoing Robert Oppenheimer's ominous "now I am become Death, the destroyer of worlds," the mushroom clouds which blossomed over Hiroshima and Nagasaki instead trumpeted the establishment of an era of unparalleled technological and social advancement.¹ The icon of the airplane pervaded society and spawned the Streamline Moderne adaptation of the Art Deco design school which recalls even today the confident attitudes of that period.²

The North American Aviation P-51 "Mustang" deserves recognition not just as an icon of World War II aviation but also as one of the reasons the Allies won the war in Europe.³ The Mustang story was first told with a British accent: in 1938, the Royal Air Force reached across the Atlantic for fighter planes. No existing model met the

¹ Bhagavad Gita 11:32, as translated by Robert Oppenheimer. For four more orthodox translations, see Srimad Bhagavad Gita, <http://www.bhagavad-gita.org/Gita/verse-11-30.html> (accessed 22 March 2010).

² Ghislaine Wood, *Essential Art Deco* (London: V&A Publications, 2003), 21; and Victoria and Albert Museum, "Art Deco Study Guide," Victoria and Albert Museum, http://www.vam.ac.uk/nal/guides/art_deco/index.html (accessed 22 March 2010).

³ Among many advocates of this position is Tami David Biddle, *Rhetoric and Reality in Air Warfare* (Princeton, NJ: Princeton University Press, 2002), 226-28 and 232. While not as decisive, long range escorts (mostly P-38s and P-47s) significantly enhanced bomber security in the Pacific theater as well. See Thomas E. Griffith, Jr., *MacArthur's Airman: General George C. Kenney and the War in the Southwest Pacific* (Lawrence, KS: University of Kansas Press, 1998), 184.

requirements of the European theater, so North American Aviation, already selling trainer aircraft to England, designed and flew in just six months a suitable multi-purpose aircraft.⁴ Several versions saw combat, but the P-51D serves as the best example of the type. Relatively inexpensive to build, especially when Packard's V-12 replaced the Rolls-Royce Merlin engine, the Mustang earned recognition as a fast, sturdy, and lethal aircraft.⁵ Robert S. Johnson, who had the second-highest number of air kills among American pilots in the European theater, noted the P-51 wrested air superiority from the German Focke-Wulf 190, which had parity with earlier Allied fighter planes.⁶

The Mustang proved long lived, serving as the United Nations' front line air superiority fighter in Korea until forced into a more limited ground attack role by enemy employment of jet fighters.⁷ Most histories note the P-51 completed its military service in foreign air forces in the middle 1980s.⁸ As one of the most capable and fastest propeller-driven small planes ever designed, the Mustang found a niche in air racing, setting several distance and speed records in the late 1940s and early 1950s.⁹ During World War II, the Mustang's 1,700 horsepower engine carried one crew member and a maximum takeoff weight of six tons over 1,600 miles at a maximum speed of over 430 miles per hour.¹⁰ This thoroughbred performance made a mule out of the Jenny.

The Boeing B-17 "Flying Fortress" was another aircraft with a stellar pedigree. While the prima donna B-24 had a higher top speed, longer range, and heavier payload, the Flying Fortress earned greater praise due to its legendary durability, survivability, and

⁴ Ken Delve, *The Mustang Story* (London: Cassell & Company, 1999), 12.

⁵ Marcelle Size Knaack, *Encyclopedia of U.S. Air Force Aircraft and Missile Systems: Volume 1, Post-World War II Fighters 1945-1973* (Washington, DC: Office of Air Force History, 1978).

⁶ Edward H. Sims, *Fighter Tactics and Strategy, 1914-1970* (New York, NY: Harper & Rowe, 1972), 197-202.

⁷ National Museum of the United States Air Force, "North American P-51 Fact Sheet," National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2214> (accessed 22 March 2010).

⁸ The Dominican Republic was the last to retire the P-51 from service in 1984. Inigo Guevara, "Dominican Republic since 1945," *Air Combat Information Group Journal*, 1 September 2003, http://www.acig.org/artman/publish/article_153.shtml (accessed 22 March 2010).

⁹ Don Dwiggins, *They Flew the Bendix Race: the History of the Competition for the Bendix Trophy* (Philadelphia, PA: J.B. Lippincott Company, 1965).

¹⁰ National Museum of the United States Air Force, "North American P-51 Fact Sheet," National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2214> (accessed 22 March 2010), with range figures using drop tanks from William Green and Gordon Swanborough, *The Great Book of Fighters: An Illustrated Encyclopedia of Every Fighter Aircraft Built and Flown* (Osceola, WI: MBI Publishing Company, 2001).

ease of flight in takeoff, formation operations, and landing.¹¹ The Flying Fortress catered to the airman's vision of air as a war-winning strategic medium. Designed to be able to defend itself on long-range missions deep into contested air space, able to wreak incredible destruction from extreme altitude, and able to take a surprising amount of punishment and remain controllable in flight, the Flying Fortress dropped more bombs than any other American aircraft in World War II.¹² The Flying Fortresses were not indestructible, however, suffering extensive losses during the massive and notorious raids on Schweinfurt's ball-bearing factories.¹³ Once Mustangs arrived in sufficient numbers to escort the Forts to their targets and back, raids like the ones during "Big Week" in February 1944 reduced loss rates from over 25 percent (on "Black Thursday") to below seven percent.¹⁴ The sturdy yet supercharged Flying Fortresses could lift 10 crewmen and 12 tons of bombs, fuel and ammunition nearly seven miles high at a climb rate of 900 feet per minute.¹⁵ Most impressive was its 1,400 mile combat radius, seven times greater than its NBS-1 ancestor, permitting potential combat missions from the UK to the Ukraine and back without refueling.¹⁶ The combination of range, maneuverability, firepower, and bomb load made the Mustang and Flying Fortress a lethal couple. The expanded ranges and ceilings of both types demanded from weathermen increased attention on synoptic meteorology at the expense of traditional climatology.

Equipment demands were not the only factor to have increased reliance on military meteorology. The cavalier attitudes of World War I were long gone: as early as 1919, flying squadron commanders received daily weather forecasts for flight

¹¹ Time and space limit this chapter to consideration of the European theater at the cost of the Pacific.

¹² Army Air Force Manual 50-13, *Boeing B-17 Pilot Training Manual*, 1 May 1945 and Bill Yenne, *The Story of the Boeing Company* (St. Paul, MN: Zenith Press, 2005), 46.

¹³ Edward Jablonski, *AIRWAR: An Illustrated History of Air Power in the Second World War*, vol. 2, *Tragic Victories* (Garden City, NY: Doubleday & Company, 1971), 189-92. Worth noting is that the 14 October 1943 Schweinfurt raid encountered "a particularly dense concentration of German fighters because German meteorologists accurately forecast it to be the only area over all of Germany in which daylight bombing was possible under prevailing weather conditions. See Arthur B. Ferguson, "POINTBLANK," in *The Army Air Forces in World War II, Vol. 2, Europe: TORCH to POINTBLANK, August 1942 to December 1943*, eds. W.F. Craven and J.L. Cate (Chicago, IL: University of Chicago Press, 1949), 702.

¹⁴ Donald Caldwell and Richard Muller, *The Luftwaffe over Germany: Defense of the Reich* (London: Greenhill Books Publications, 2007), 162.

¹⁵ David Donald, ed. *The Encyclopedia of World Aircraft* (London: Aerospace Publishing, 1997), 155.

¹⁶ National Museum of the United States Air Force, "Boeing B-17F Fact Sheet," National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2453> (accessed 22 March 2010).

operations.¹⁷ This was common practice by the 1930s, and grew to include mission weather briefings during World War II combat operations.¹⁸ Ad-hoc and unregulated weather briefings became standardized under the 1926 Air Commerce Act, echoed by Army Air Corps regulations directing individual flight weather briefings in the following decade.¹⁹

The Meteorological Golden Age

The first steps made by scientific meteorology haltingly followed its eighteenth century birth to Bernoulli. Those steps, outlined in Chapter One, included timely dissemination of weather observations taken more frequently than daily and plotted on large-scale maps for immediate analysis; composition of theories regarding storm structure, movement, and intensification; and creation of a national weather bureau under the War Department with responsibility both for meditative climate study and for dynamic storm warnings. War Department stewardship was sadly short-lived. The military weather service won by Myer in 1871 returned to the seasonal pace and climate-centric influence of the Department of Agriculture 20 years later. General John Pershing revived an urgent need for military meteorology as he deployed the Army Expeditionary Force to Europe. Due in large part to Pershing's impetus, the interwar and World War II period, a golden age for air power, was a similar stimulus to military meteorology.²⁰

Of the constraints impacting the era's military meteorologists, the most significant was the broad and precipitous demobilization of the American army after World War I. Even in interwar decline, the Air Service demanded most of the Signal Corps' weather support. The military air mail fiasco in 1934 highlighted inadequate meteorological attention to aviation operations, and resulted by 1937 in the transfer of military

¹⁷ Archives of the Naval Air Station Pensacola, the first weather office established to support naval aviation. Available online at http://cmapskm.ihmc.us/rid=1103741289924_1920848424_7533/METOC%20History.htm (accessed 24 March 2010). See also "Naval Aviation Chronology 1917-1919," Naval Historical Center, <http://www.history.navy.mil/branches/avchr2.htm> (accessed 6 April 2010)

¹⁸ Ogden, *Meteorological Services Leading to D-Day*, 2-3 and 7-13.

¹⁹ Nick A. Komons, *Bonfires to Beacons: Federal Civil Aviation Policy Under the Air Commerce Act 1926-1938* (Washington, D.C.: Smithsonian Institution Press, 1989), 151-52.

²⁰ Unless otherwise cited, the following three paragraphs cite Karl Larew, *Meteorology in the U.S. Signal Corps, 1870-1960*, Signal Corps Historical Division study (Washington, D.C.: Signal Corps Historical Division, 1960), 26.

meteorological responsibility from the Signal Corps to the Air Corps. With war looming in Europe, it made sense to all parties to align the weather tribe under its principle customer.

Notwithstanding the smart realignment of military meteorology under its principle customer, and the promise of increased funds as Europe marched toward war, another significant barricade impeded the growth of meteorology as a science. Until 1940, meteorological instruments were not products of assembly lines; rather, each instrument demanded skilled craftsmen to assemble. Attempts to prime the pump failed because other manufacturing plants, like those producing aircraft engines, artillery pieces, and uniforms, had higher funding priorities. Only after the Pearl Harbor attack did military demand usher standardization into the meteorological equipment industry.

In addition to equipment problems, interwar military meteorologists faced the problem of a dearth of data on wind currents in the upper atmosphere. Artillerists and naval gunners had long assumed air currents aloft mirrored surface winds, and grew dismayed as longer-range weapons did not follow predicted trajectories. At Pershing's behest, climatologists began to map upper air winds observed by occasional research balloons or rare pilot reports, meteorologists began to theorize about rivers of wind aloft, and administrators began to establish weather balloon observing and recording stations for investigation of the atmosphere over the United States, the Atlantic, and Western Europe. By 1930, French and Soviet scientists had developed radiosondes, instruments attached to balloons which measured temperature, humidity, atmospheric pressure, and wind speed and direction and which transmitted the information via radio to a ground receiver.²¹ Due to financial constraints, the Air Corps could not employ these semi-disposable devices routinely until 1938. By 1942, experimenters developed an aerograph, an aircraft-mounted weather sensor suite that provided aircrews with air pressure, temperature, humidity, altitude, and speed. Aviators increasingly logged these data and relayed them to weathermen to augment weather balloon observations, particularly on missions outside the United States.

²¹ John DuBois, Robert Multhauf and Charles Ziegler, *The Invention and Development of the Radiosonde, with a Catalog of Upper-Atmospheric Telemetering Probes in the National Museum of American History*, Smithsonian Institution (Washington, D.C., Smithsonian Institution Press, 2002), 26-27.

Interwar problems with organization, equipment standardization, funding, and scarce upper atmosphere data concealed spectacular academic growth. The science of meteorology advanced in large part due to the 1910s and 1920s work of the ‘Norway school,’ an informal group of meteorological theorists who gathered near Bergen, Norway’s second city, and centered on professor Vilhelm Bjerknes and his son Jacob.²² The Bjerkneses, along with Carl-Gustaf Rossby, Sverre Petterssen, and others, perfected two key concepts of scientific meteorology: air masses and fronts. The air mass is a large body of air with relatively uniform properties throughout, but with abrupt changes in those properties along its boundaries. Those boundaries are frontal zones, and it is along the frontal zones that the Norwegians applied the earlier work of the Americans Redfield, Loomis, and Espy regarding storm systems, or cyclones. The younger Bjerknes used weather observations gathered during his father’s World War I tours along Norway’s extensive coastline to posit the presence of dynamic interactions between relatively warmer and moister air moving parallel to and poleward of the frontal zone and the cooler and drier air moving parallel to and equatorward of the frontal zone. Figure 6 shows these interactions, which took place according to Bernoulli’s theories. Developing them into practical forecasting rules encouraged both practical study as the portents of war manifested in Europe, and deeper theorizing after World War II’s exhausting undertaking.

²² This paragraph references Kerry Emanuel, “Back to Norway: An Essay,” in *Synoptic-Dynamic Meteorology and Weather Analysis and Forecasting: A Tribute to Fred Sanders*, ed. Lance Bosart and Howard Bluestein (Boston, MA: American Meteorological Society, 2008), 87.

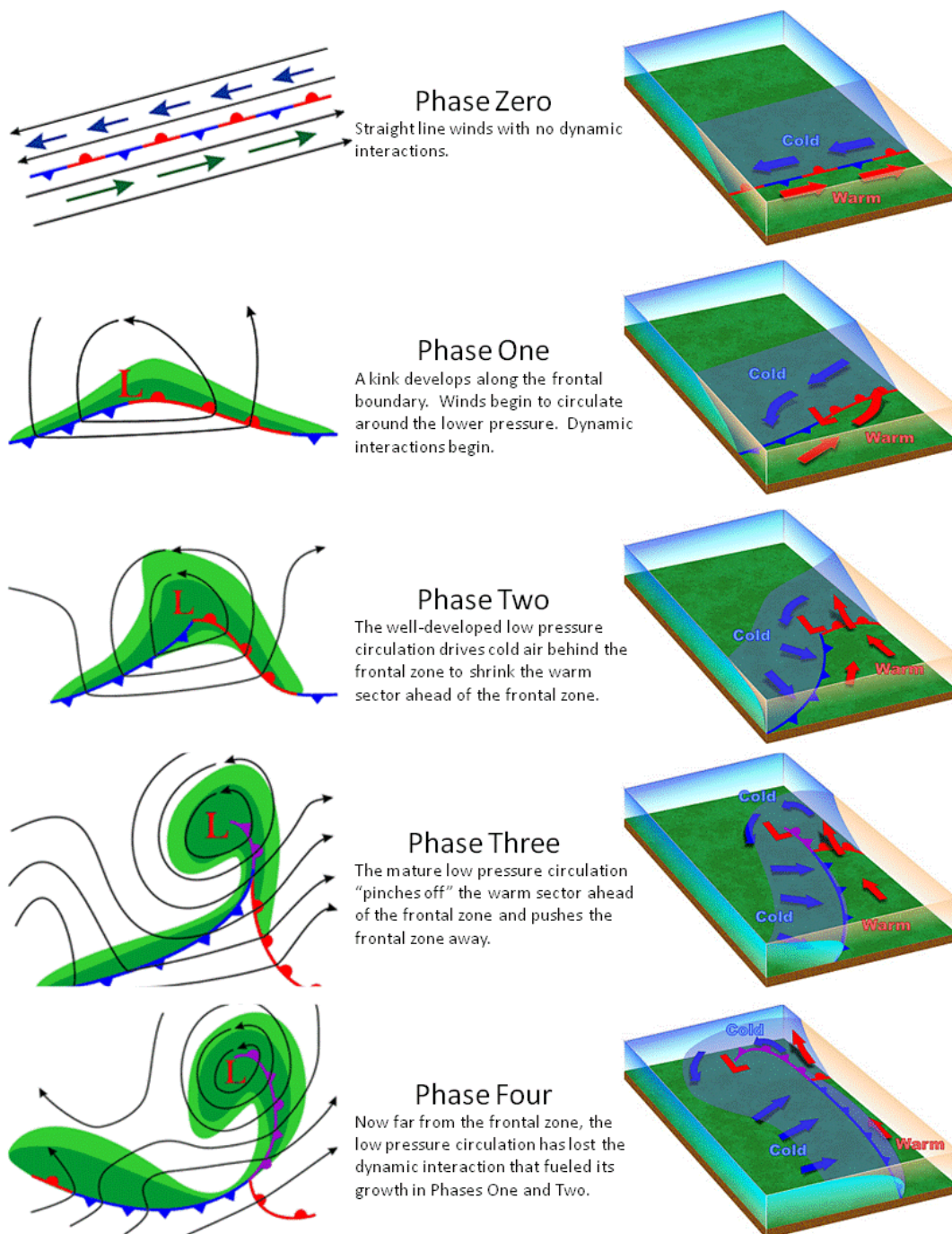


Figure 6. Norwegian Cyclone Model

Source: Adapted from National Weather Service JetStream – Online School for Weather, <http://www.srh.weather.gov/srh/jetstream/synoptic/cyclone.htm>²³

²³ "JetStream – Online School for Weather," National Weather Service, <http://www.srh.weather.gov/srh/jetstream/synoptic/cyclone.htm> (accessed 11 February 2010).

Robert Fleagle, one of many scientists drawn to meteorology by the compelling American commitment in World War II and now professor emeritus in atmospheric science at the University of Washington, found military meteorology in that conflict to be “in the process of transformation from a largely descriptive field to one based more solidly on scientific principles.”²⁴ Backward American atmospheric sciences took a leap forward when in 1928 the Massachusetts Institute of Technology lured Rossby away from Bergen to lead a doctoral program in meteorology. Two years later, MIT established a Meteorology Department and named Rossby its head. Fleagle, in 1942 an undergraduate at one of four Rossby-initiated parallel programs, found in departmental curricula a ready definition of the field of meteorology. Dynamic meteorology emphasized mathematics and equations, Rossby’s particular expertise. Physical meteorology emphasized the chemical composition of the atmosphere and matter’s attendant changes in phase and/or state (*e.g.*, ice to water to vapor). Synoptic meteorology dealt with the theories of Bernoulli as strengthened and challenged by the American pioneers, Leverrier, and the Norway school. Instruments and observations kept students on the forefront of atmospheric measurement technology and best practices for gathering, encoding, and transmitting those measurements for subsequent use. Analysis and forecasting examined the weather maps generated by the instruments and observations, largely to derive practical benefits. Last and not least, climatology taught statistical and empirical methods, as well as the composition and formation of the long-lived air masses the elder Bjerknes theorized. With a war on, Fleagle noted, “the focus on the courses was on 6-12 [hour] forecasting for aircraft and naval operations.” Fleagle continued, “forecasting for periods longer than a single aircraft flight led to interest in ‘index cycles’ and ‘blocking high pressure systems’ ... the civilian faculty was only a little ahead of us in absorbing some of these concepts.”

Sverre Pettersen, perhaps the most iconoclastic member of the Norway school, wrote a largely autobiographical history of the meteorological renaissance.²⁵ In a striking contrast to the meteorological backwater in the United States during the entire interwar

²⁴ This paragraph comes from Robert Fleagle, *Eyewitness: Evolution of the Atmospheric Sciences* (Boston, MA: American Meteorological Society, 2001).

²⁵ The following three paragraphs come from Sverre Pettersen, *Weathering the Storm: Sverre Pettersen, the D-Day Forecast, and the Rise of Modern Meteorology* (Boston, MA: American Meteorological Society, 2001).

period, Petterssen wrote of his early interwar experience in Norway, “these were exciting years – years of growth, and also years of speculative creations. The processes and phenomena of cyclones were treated in all three dimensions, but upper-air observations were sadly lacking. In the absence of such observations, there was room not only for hypothetical thinking but also for skepticism.” Twenty years before upper-air data and electronic computers enabled practical forecasting, Petterssen turned his back on the laws of physics to extract from observed information about weather systems a series of simple mathematical equations expressing the ‘what’ without answering the ‘why.’ The Bergen group found his work heretical, but his unorthodoxy attracted attention from Robert Millikan, a Nobel laureate in physics and president of the California Institute of Technology. Millikan had welcomed 1930 émigré Theodore von Kármán as the head of his Department of Aeronautics, and so also the meteorology division, and Petterssen recalled, “Millikan and von Kármán had become convinced that the expansion in aviation, typical of the thirties, would place increasing demands on meteorological services. They decided to try to establish a school for training practical forecasters.” Petterssen published his seminal 1933 paper on forecasting methods while working in the Caltech forecasting school. In 1939 he replaced Rossby at MIT, published two books in his brief tenure there, and then returned to Europe after the early 1940 invasion of Norway.

Petterssen’s perspective as an outsider familiar with American society gave him valuable insights into the state of meteorology during this period. Petterssen noted American isolationism in the Signal Service’s early focus, and experienced it first hand during his work in the 1930s with the International Meteorological Organization. He was particularly critical of Charles Marvin, Weather Bureau director from 1913 to 1934, “who spent much of his time in his basement instrument shop,” allowing technology and techniques to replace education and theory. Petterssen lauded the United States Navy for establishing in the interwar period a “small and efficient” weather service focused on the peculiar demands of naval aviation and gunnery, but criticized the Navy’s lack of a promotion path for professional meteorologists. For the United States Army Air Corps, the Norwegian had nothing positive to say, condemning first the slow recognition of the importance of practical weather forecasting, and then the subsequent filling of expanded

military meteorological organizations with ill-prepared, inexperienced, and hastily-promoted officers.

With the Nazi defeat of Norway looming, Petterssen did not return home but instead offered his services, with his king's blessing, to the Meteorological Research Council in Dunstable, England. Ever the iconoclast, Petterssen clashed with traditional weathermen to such a degree that he would likely have been shuffled aside but for his brilliance and his friendship with Sir Nelson King Johnson, the director of Britain's Meteorological Office. Rather than being sacked, Petterssen earned a small, like-minded staff of meteorologists who attempted to apply the upper-air wind current theories of the elder Bjerknes and thus to generate the painstaking upper-altitude wind forecasts increasingly demanded by Allied bombings following the Battle of Britain. Bomber Command eventually established a three-component air raid force, first Pathfinders with flares and incendiaries, then a wave of incendiary bombers, and finally a the main force with incendiaries and explosives. This scheme demanded strict time-over-target coordination, which required forecasts of high-altitude winds to be more accurate than any meteorology team had yet produced. Petterssen's group met the strident demands of mission planners and fighter and bomber commanders. In his memoirs, Petterssen noted a successful rendezvous and *en route* mission timing demanded "highly accurate wind forecasts," and outlined a process whereby minute-by-minute wind observations radioed from the air fleet resulted in frantic drift calculations radioed back to the fleet at 10-minute intervals "until the force crossed the coastline on its homeward journey."²⁶

Europe's early World War II experiences produced a change in attitude in the United States military about the importance of scientific meteorology. Besides the obvious demand for more, and more accurate, weather information for the Allies, members of the United States Weather Bureau who joined the war effort created a groundswell of positive press. Robert Martin, an Army Captain in the Coast Artillery, came to the military from his position as an assistant meteorologist in the Weather Bureau.²⁷ Writing in 1940 for the respected military publication *The Military Engineer*,

²⁶ Sverre Petterssen, *Weathering the Storm: Sverre Petterssen, the D-Day Forecast, and the Rise of Modern Meteorology* (Boston, MA: American Meteorological Society, 2001), 126.

²⁷ This paragraph cites Robert J. Martin, "Meteorology in Peace and War," *The Military Engineer* 32, no. 185 (September-October, 1940): 343-46.

Martin sketched the history of man and his interaction with weather, finding “his continued efforts to gratify these wants [to improve his lot beyond simple survival] are responsible for our modern economic system and the present state of our Sciences, one of the most important of which is meteorology.” Martin contrasted meteorology and climatology for his readers, emphasizing the abstract nature of meteorology and its importance as the mechanism which enables the climatological predictions of seasonal events to be narrowed to predictions of weather in the next hour, day, or weekend. Apt today is Martin’s assertion that “gains in technical and tactical lore did not free him from his dependence on weather and climate.” In his area of expertise, anti-aircraft gunnery, Martin discovered not only were projectiles subject to drift due to upper-atmosphere winds, but also “the rate of burning of a powder train fuze and hence the fuze range varies with temperature and air density,” demanding a greater knowledge and understanding of the meteorology of the upper air. Finally, Martin credited the Finnish Army’s exceptional performance in the winter of 1939 to 1940 on their “knowledge of appropriate winter tactics and to familiarity with the changes in terrain resulting from the extremely low temperature in winter,” that is, their tactics and equipment reflected their understanding that rivers become highways and marshes plains when frozen solid.

In the frigid waters between Norway, Greenland, and the North Pole, the military demand for weather information led to a conflict termed the “Weather War,” a squabble that ran from 1940 to 1942 and involved ships, planes, and land forces.²⁸ Understanding the synoptic flow of weather led meteorologists, then as now, to conclude information from Greenland, Iceland, and the Greenland Sea and its archipelagoes was critical to provide greater advance notice of storms than would be available if the first observations came from the Norwegian coast or the British Isles. Historian Mark Llewellyn Evans wrote, “the lack of detailed meteorological information was a tremendous disadvantage for Berlin, especially since so much of the world was under Allied control by virtue of the European colonial empires. When the war began, the international exchange of meteorological data was suspended, since accurate weather planning provided the possessor with a potent trump. In fact, looking at the efforts of both sides to outfox each

²⁸ Mark Llewellyn Evans, *Great World War II Battles in the Arctic* (Westport, CT: Greenwood Press, 1999), 49-70.

other in the quest for this information is like taking a page from James Bond.” By summer 1942, the Allies had reestablished control over the region’s land masses, leaving the Germans stuck with weather observations taken by submarines when they surfaced, or with the weather data they obtained through espionage. The work of the isolated and frozen weathermen in this region was crucial, opined naval historian Carl Schuster: “It was the weather data secured by this campaign which enabled the planning and execution of such critical operations as the Germans’ ‘Channel Dash’ [and] the Battle of the Bulge, the Allied landings at Dieppe and Normandy, and the entire strategic bombing campaign against the Third Reich.”²⁹

As the “Weather War” closed in 1942, evidence mounted that the Norway school had significant influence on American military meteorology. Elbert Pate, a naval weather officer, in 1942 addressed the same topic set as Robert Ward had for World War I.³⁰ Pate defined for the layman the polar front, a fundamental assertion of the elder Bjerknes and the Bergen group, and noted, “as an aid to forecasting, the position of this front is of primary importance. This importance was noted by the Germans, and several survey parties visited Greenland during the last few years for the purpose of obtaining meteorological information. The latest chapter in the history of these ventures was recently written by our Coast Guard when they captured a survey ship and interned the crew.” Anticipating the difficulty faced by the Allies during the lead-up to Operation Overlord, Pate found “it is highly improbable that any forecasting technique developed by the Germans could predict specific weather in advance for an operation of this magnitude [the invasion of Poland], but it is clearly indicated that their forecasts enabled the timing of the original break-through to coincide with a period of good *flying* weather.” (emphasis added) Pate also claimed the German drive to the sea achieved such rapid success because “the Stukas blasted all opposition, the parachutists captured an impregnable fort along with many points of control, and the mechanized forces rolled on at a truly furious pace,” and presented a counterfactual: “a moderate rain of short duration over a small area to impede the machine of destruction, mist or fog for a few hours to demobilize the air force by obscuring targets, a wind of even moderate velocity during

²⁹ Carl O. Schuster, “Weather War,” *Command* (Nov-Dec 1991), 70-73.

³⁰ This paragraph cites Elbert W. Pate, “Weather and the War in Europe,” *United States Naval Institute Proceedings* 68, no. 469 (March, 1942): 327-32.

the parachute attacks – any of these could have stopped the drive for a sufficient time to affect the outcome.” In the Mediterranean, the German assault on Crete “came by air in its entirety. Bombers prepared the way, fighters controlled the air, parachutists seized airfields and control points, air transports landed with troops, and other transports maintained supply. In order to succeed, the Germans had to maintain complete control of the air. Their other problem was to start the attack and carry it to completion during a period of fair weather ... the striking force had only to await a favorable forecast period to start the operation.” Pate concluded successful air operations constituted “a highly complex forecasting problem” which both sides committed to solve. Pate recommended the British consolidate their best forecasters, refine practical forecasting techniques, and admit “any invasion attempt and re-conquest of Europe must be timed with the weather in order to succeed.” Worthy of note is the emphasis on weather as a limitation to aviation and aviation-enabled capabilities, a key driver of meteorology during this golden age of weather science.

To capture as wide a range as possible of weather forecasting styles and aptitudes, the Operation Overlord weather forecasts briefed to General Dwight Eisenhower by Group Captain (Doctor) James Stagg were the product of three different weather prediction centers. The weather team from the Royal Navy had a voice in the conference calls, and Petterssen’s brilliance brought the British aviation weather team to the table.³¹ The Americans had established a forecast center in England which maintained close contact with their experts in Washington, D.C. The American group, alone among the three, remained married to pattern-recognition forecasting following climatological models. This out-of-date methodology, exacerbated by their leader, the “smug, supremely self-confident self-promoter” Doctor Irving Krick, made it difficult for the stronger British weather forecasting centers to influence Stagg.³² The British attempted in the first quarter of 1944 to counter the cock-sure and deterministic Americans, but the Yanks remained uncontested until May, when Petterssen supplanted the brilliant though hesitant British aviation lead meteorologist. Stagg found the subsequent conflicts

³¹ Petterssen, *Weathering the Storm*, 195. For a contrasting perspective, see R.J. Ogden, *Meteorological Services Leading to D-Day*, Occasional Papers on Meteorological History No. 3 (Reading, UK: Royal Meteorological Society, 2001), 14-15.

³² Kristine Harper, *Weather by the Numbers: The Genesis of Modern Meteorology* (Cambridge, MA: Massachusetts Institute of Technology Press, 2008), 57

between Krick and Petterssen to be so disturbing that he wrote in his memoir, “Should I ask the two weather services, U.S. and British, to arrange that for the remaining all-important series of discussions Krick and Petterssen never participate at the same sitting? This, I realized, was impracticable.”³³

Petterssen championed Britain’s weather forecasting methodology and won most arguments, though Krick never backed down. The D-day forecast Stagg delivered to Eisenhower bore a closer resemblance to its Norwegian uncle than to its British or US fathers. Petterssen found in retrospect “the two major storms that dominated the scene of June 5 did not even exist on May 31.” Krick, in his account, noted the most significant weather prediction disparity of the war was “that the chief German meteorologist and his staff had agreed that the weather following June 4 would be much too bad to permit an invasion attempt ... as a result, the German high command had relaxed and many officers were on leave.... Poor meteorology on the German side, therefore, contributed to the success of D-Day, as well as modern methods on the side of the Allies.”³⁴ Operation Overlord’s D-day forecasts proved meteorology was in its golden age.

Despite the customary precipitous demobilization following World War II, the Army’s Chief Signal Officer wrote, “lessons learned, and projects begun during the War would not be abandoned. The need for greater accuracy in forecasting, both long-range and short; the need for an understanding of meteorological effects on radar, radio, etc.; even the possible need for control of the weather—all needed further research.”³⁵ Even so, meteorology had come a long way, claimed two Army Command and General Staff college instructors writing near the end of World War II. Lieutenant Colonel Donald Ford found it possible to get a detailed forecast for almost any location and for any given period of time that would be correct 60-75 percent of the time. Major Albert Link claimed that for those areas most closely studied a forecast up to ten days in advance would be correct over 80 percent of the time.³⁶ This advance, Link posited, was due to

³³ James Martin Stagg, *Forecast for Overlord, June 6, 1944* (New York, NY: W.W. Norton, 1971), 64.

³⁴ Irving Krick and Roscoe Fleming, *Sun, Sea, and Sky; Weather In Our World and In Our Lives* (Philadelphia, PA: Lippincott, 1954).

³⁵ United States Army Signal Corps, *Report of the Chief Signal Officer, 1946* (Washington, D.C., Government Printing Office, 1947), 284.

³⁶ Donald H. Ford, “Base Your Plans on Future Weather,” *Military Review*, August 1944, 67-71.

the demand of aviation: “In fact it was the development of the airplane since World War I that forced the tremendous development of weather forecasting.”³⁷

Weather’s Toll on Combat Aviation

The modern era divorces the human cost paid by those who flew and fought in World War II. Much as no one wants to see the steps that result in the neat package of bologna hanging in the market’s refrigerator, there is little interest in rehearsing the thousands of everyday sacrifices made by stratospheric air war pioneers. Historian Donald L. Miller offered an unvarnished look at the rigors and horrors of the European theater war in the air in his book *Masters of the Air*.³⁸ Obvious dangers came from the enemy and from maintenance failures, but weather took many lives as well. Aircrews sometimes launched in unsafe weather due to mission requirements, and sudden fogs, cloud decks, rain or ice storms, or other weather phenomena sometimes turned landings into smoking craters. While aloft, hypoxia and frostbite were constant threats at higher altitudes; at lower altitudes, unexpected cloud decks concealed rugged terrain that claimed the lives of unlucky airmen.

Ira Eaker, an interwar air experimenter, made the first transcontinental flight on instruments alone – an experience which made him better able to command bombers flying through the unforgiving and unrelenting cloud masses of Europe. “Cloud cover sometimes extended to 23,000 feet, forcing most planes to fly blind,” wrote Miller, and some “lost their horizon, became hopelessly disoriented, and crashed into other bombers.”³⁹ Cold temperatures caused more bomber aircrew casualties than the enemy. In the first year of Eighth Air Force operations from England, Miller found over 1,600 men removed from flying duties due to frostbite, but only 1,200 removed due to combat wounds.⁴⁰ “Ball turret gunners who were forced to remain in their turrets for hours over enemy territory urinated in their clothing, freezing their backs, buttocks, and thighs ‘so badly muscles sloughed and bones were exposed,’” quoted Miller.⁴¹ Doctor Malcolm

³⁷ Albert E. Link, “War and the Weather--and the Staff,” *Military Review*, December 1943, 37-38.

³⁸ Donald L. Miller, *Masters of the Air: America’s Bomber Boys Who Fought the Air War Against Nazi Germany* (New York, NY: Simon & Schuster, 2006), 38.

³⁹ Miller, *Masters of the Air*, 84.

⁴⁰ Miller, *Masters of the Air*, 90.

⁴¹ Miller, *Masters of the Air*, 91.

Grow, Eighth Air Force chief surgeon, confessed he and his colleagues had overlooked the dangers of oxygen deprivation, never anticipating air planners and airplane capabilities would drive them to altitudes so high that thirty seconds with a leaky mask or an interrupted flow of oxygen would render a man unconscious, with death following in only two more minutes.⁴² Miller recorded a novel in-air truce enforced by weather conditions during a bomber-fighter confrontation: “When a Focke Wulf 190 came at them head-on, there was no answering fire. Every forward-facing gun in the entire Fortress formation was frozen.” Miller continued that the crew noticed “the oncoming German’s guns were mute as well. Passing them without firing a shot, the pilot turned to them and waved.”⁴³ Few weather-related malfunctions, regrettably, had such happy conclusions.

Summary

The triumphant Allies saw in their air forces both an instrument of victory and a totem of the future. Streamlined and stratospheric metal-skinned airplanes inspired and encouraged the can-do attitudes of the free world. These marvelous aircraft, unequaled in grace though later bested in power, demanded much from their intrepid pilots. In turn, these pilots, and those who employed them as instruments of war, demanded much from their supporting meteorologists.

Did aviation advances in the interwar and World War II era demand more from meteorologists than in earlier periods? Most assuredly, yes. Metal skins, arguably the most significant aviation advance in the interwar and World War II period, enabled the pressurized cabins required for high-altitude flight.⁴⁴ Metal replaced structural wood, enabling heavier fuel loads which extended flying ranges and enabling bigger engines which increased aircraft speeds. Higher altitudes presented forecasting challenges that could not be resolved by climatological means, as observations of weather conditions at those heights did not exist. Extended ranges meant extending the “now-casts” required

⁴² Miller, *Masters of the Air*, 93.

⁴³ Miller, *Masters of the Air*, 239.

⁴⁴ For arguments advancing horsepower per pound as the most significant aviation advance in this era, see John H. Morrow, Jr., *The Great War in the Air: Military Aviation from 1909-1921* (Tuscaloosa, AL: University of Alabama Press, 1993) and Robert Schlaifer and S. D. Heron, *Development of Aircraft Engines: Two Studies of Relations Between Government and Business* (Boston, MA: Division of Research, Graduate School of Business Administration, Harvard University, 1950).

for four hour flights to Fleagle's 6 to 12 hours, and even double that for B-29 missions late in the war. Finally, higher speeds presented largely theoretical questions about how the atmosphere would influence, and be influenced by, objects moving that fast through a manic fluid. In each case, aviation advances demanded more from the meteorologists.

Did the meteorologists meet the increased demand? Did they ever! The "abstract science" of meteorology provided the framework to answer the challenges of upper-atmosphere weather forecasting. Petterssen's influence in upper-air forecasting must not overshadow his earlier and more unorthodox work in using and later teaching synoptic meteorology as a basis for the practical weather forecasting so much in demand by mission planners and fighter and bomber commanders. As aircraft pushed the edges of propeller-driven speed limits, the old climatology held no answers to troublesome questions of physics, but meteorology again provided a framework which allowed research and exploration without simply shooting in the dark.

Finally, how had airmen integrated weather prediction into military aviation operations? The 1940 to 1942 Arctic "Weather War" showed clear recognition of the importance of weather observations to military operations. Finally, Operation Overlord stands as the best example among many wherein meteorologists provided specialized weather forecasts 72 hours or more in advance.⁴⁵ Military needs at last brought meteorology's state of the art to the front lines and the highest echelons of command. In summary, what had been cavalier was now businesslike; what had been ad-hoc was now governed by regulation; both sides contested weather observation stations ignored in the previous war; both sides demanded meteorological information at low, middle, and high echelons of command. The golden age of meteorology, ushered in by the golden age of aviation, set a standard for weather integration into aviation operations which had no equal in the past, and has not been equaled to date. Had integration improved? Absolutely.

⁴⁵ Unlike Operation Overlord, the weather stories for the Doolittle Raid, Big Week, and the atomic bomb employments appear only as spare sentences in aviation or military histories. Ogden, *Meteorological Services Leading to D-Day*, 2-6.

Chapter 4

Zipper-Suited Sky Gods

Having your ass handed to you in such a spectacular and repeated fashion causes some men to curse and mutter about 'one trick ponies' and so on. But for others, for those who are more invested in victory than in ego, it reveals a level of skill that instantly removes all swagger and competition and puts one in the place of a willing supplicant, eager for knowledge.

-- Bill Whittle, on John Boyd's \$40 bet that he could – and always did – win a dogfight from a lost position in under 40 seconds

Miracles of Modern Technology

Computers, inspired by World War II but arriving a little too late for broad application in that war, became essential in the mad, MAD, Cold War world. The Communist threat altered the precipitous military drawdown typical of American post-war planning. While Congressional funding provided the armed services sufficient amounts of men and equipment, Presidents Truman, Eisenhower, Kennedy, Johnson, Nixon, and Ford led the United States military into a modern era uniquely enabled by rapid technological advance. Especially sensitive to technology were the fields of aviation, space, and computers, each of which bloomed – or bloomed again, in the case of aviation – in the thirty years following World War II.

Military aviation, still a young field when compared to land or sea forces, entered the jet age at the end of the war and introduced the remarkable Lockheed Martin F-16 “Fighting Falcon,” or “Viper,” its unofficial but more commonly used nickname.^{1,2} The all-weather Viper was the brainchild of John Boyd, the enigmatic and brilliant progenitor of Energy-Maneuverability Theory and the Observe-Orient-Decide-Act (OODA) loop.³

¹ General Dynamics, which originally built the F-16, sold it to Lockheed Martin in March 1993. “Company News; Lockheed Finishes Purchase of General Dynamics Unit,” *New York Times*, 2 March 1993, <http://www.nytimes.com/1993/03/02/business/company-news-lockheed-finishes-purchase-of-general-dynamics-unit.html?pagewanted=1> (accessed 26 March 2010).

² For the origin and history of the Viper nickname, see http://www.f-16.net/articles_article10.html?module=pagesetter&func=viewpub&tid=2&pid=27 (accessed 26 March 2010)

³ Harry Hillaker, “Tribute to John R. Boyd,” *Code One*, July 1997, http://www.codeonemagazine.com/archives/1997/articles/jul_97/july2a_97.html (accessed 26 March 2010) and Eric Hehs, “Harry Hillaker – Father of the F-16,” *Code One*, April 1991 (part one) and July 1991 (part

Designed to turn circles around the ever-larger jets that carried the fighter designation but had little credibility in that role, the Viper, like the Jenny before her, quickly found other roles. Its versatility made it the choice of 25 nations, including the United States.⁴

GlobalSecurity.org, the website of a military watchdog group, in March 2010 noted the F-16 “continues as the world's most sought-after fighter,” with a backlog of firm orders through 2012.⁵ Manufacturers have built over 4,400 Vipers, and the production line remains open.⁶

Key Viper innovations included a seamless bubble canopy to improve pilot visibility and a side-mounted control stick and reclined seat to limit the negative influence of high-strain maneuvers on the pilot. Maneuverability was the key, claimed Boyd, and cockpit ergonomics reflected it.⁷ The Viper, already smaller and lighter than its immediate predecessors, benefitted from rapidly-advancing computer technology. To boost performance in a wide range of maneuvers, designers chose a variable-camber wing adjusted by computer based on flight characteristics.⁸ Though maneuverable, the Viper “was the world’s first aircraft intentionally designed to be slightly aerodynamically unstable ... at subsonic speeds, the fighter is constantly on the verge of going out of control.”⁹ The Viper’s flight control system accepts the pilot’s inputs and manipulates the control surfaces to produce the desired result without permitting the aircraft to go out of control. To do this, the computer takes thousands of measurements every second, and constantly makes corrections to counter unexpected deviations from what the computer

two), http://www.codeonemagazine.com/archives/1991/articles/jul_91/july2a_91.html (accessed 26 March 2010).

⁴ Andrew Jesmain, “U.S. Competitiveness in the Fighter Aircraft Export Market: Defense Industrial Initiatives Current Issues No. 12,” (Washington, D.C.: Center for Strategic and International Studies, 26 May 2009), http://csis.org/files/publication/090521_diiig_current_issues_12_fighter_sales.pdf (accessed 26 March 2010).

⁵ GlobalSecurity.org, “F-16 Fighting Falcon - International Users,” <http://www.globalsecurity.org/military/systems/aircraft/f-16-fms.htm> (accessed 26 March 2010).

⁶ <http://www.af.mil/information/factsheets/factsheet.asp?id=103>

⁷ Hillaker, “Tribute to John R. Boyd.”

⁸ “Lockheed Martin F-16 Fighting Falcon,” *Jane’s All The World’s Aircraft*, http://www4.janes.com/subscribe/jawa/doc_view.jsp?K2DocKey=/content1/janesdata/yb/jawa/jawa1348.htm@current&Prod_Name=JAWA&QueryText=%5Df-16 (accessed 26 March 2010); and Doug Richardson, *General Dynamics F-16 Fighting Falcon* (London: Salamander Books, 1990), 10ff.

⁹ David C. Aronstein and Albert C. Piccirillo, *The Lightweight Fighter Program: A Successful Approach to Fighter Technology Transition* (Reston, VA: American Institute of Aeronautics and Astronautics, 1996), 21 and Roger H. Hoh and David G. Mitchell, “Flying Qualities of Relaxed Static Stability Aircraft-Volume I,” Federal Aviation Administration (DOT/FAA/CT-82/130-I), September 1983.

believes to be the pilot's desired flight path.¹⁰ A jet age icon, the Viper has a combat radius of 340 miles and a ferry range of 2,600 miles, a top speed of 1,500 miles per hour, and a climb rate of 50,000 feet per minute.¹¹

A mountain to the Viper's molehill, the mammoth Lockheed C-5 Galaxy is another jet age marvel enabled by computers. Like the bumblebee, many considered it too big to fly. But computer-aided design, a new practice in the early 1960s, freed aeronautical engineers to test outside-the-box thinking without spending millions on scale models and wind tunnels.¹² Computers also are integral to Galaxy operation, though in a different way than the Viper. A computer-based Malfunction Detection Analysis and Recording system monitors and records data from 800 test points, allowing engineers to better predict when key components, *i.e.* the engines, might fail.¹³ The Galaxy's cavernous interior provides strategic heavy airlift of outsize and oversize cargo over intercontinental distances, with a refueled range limited only by aircrew endurance.¹⁴ The first operational Galaxy reported for duty in June 1970, and an ongoing modernization program upgraded an older model to the first C-5M "Super Galaxy" in 2009.¹⁵ Early models suffered wing cracks which limited payloads to as low as 50,000 pounds during peacetime operations, but new wings restored the capacity to 270,000

¹⁰ Richardson, *General Dynamics F-16 Fighting Falcon*, 10ff.

¹¹ National Museum of the United States Air Force, "F-16 Fighting Falcon Fact Sheet," National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=103> (accessed 26 March 2010) and AerospaceWeb.org, <http://www.aerospaceweb.org/aircraft/fighter/f16/> (accessed 26 March 2010).

¹² Carl Machover (computer graphics pioneer and president of Machover Associates Corporation), interviewed by Philip Frana, 20 June 2002, transcript, 14-15, Charles Babbage Institute Center for the History of Information Processing, University of Minnesota, Minneapolis, MN, also available online at <http://www.cbi.umn.edu/oh/pdf.phtml?id=323> (accessed 27 March 2010).

¹³ National Museum of the United States Air Force, "C-5 Galaxy Fact Sheet," National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=84> (accessed 27 March 2010); and Ed Thelen, "MADAR," working paper, <http://ed-thelen.org/comp-hist/JVG-MADAR.doc> (accessed 27 March 2010).

¹⁴ Outsized cargo is "a single item that exceeds 1,000 inches long by 117 inches wide by 105 inches high in any one dimension," and oversized cargo is smaller, but still exceeds "the usable dimension of a 463L pallet loaded to the design height of 96 inches, but equal to or less than 1,000 inches in length, 117 inches in width, and 105 inches in height." Joint Publication 1-02, *DOD Dictionary of Military and Associated Terms*, 12 April 2001, as amended through 31 October 2009, also available online at http://www.dtic.mil/doctrine/dod_dictionary/ (accessed 27 March 2010).

¹⁵ National Museum of the United States Air Force, "C-5 Galaxy Fact Sheet," National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=84> (accessed 27 March 2010).

pounds by 1987.¹⁶ The re-engined Super Galaxy adds 15,000 pounds to the payload while reducing takeoff roll and time-to-climb.¹⁷ To put in context the growth of aviation over 65 years, the first flight at Kitty Hawk was 23 feet shorter than the cargo hold of the Galaxy model which flew in 1968.¹⁸

The Viper and the Galaxy, computer-enabled miracles of modern technology, represent the amazing promise of the jet age, as well as its amazing risk. Why design an airplane to be purposely unstable, so much so that only a computer can make decisions at the speed required to keep it airborne? What is the benefit of having a computer-powered risk-of-failure system that ends up requiring the Galaxy to undergo an average of 16 hours of maintenance for every hour of flight?¹⁹ In each case, advantages at the edges of the aviation envelope made the risks calculated – and calculable – by computers able to perform operations thousands of times faster than the humans who designed and flew the aircraft. Could these computers perform similar miracles in meteorology?

Miracles of Meteorology

The more things changed in weather and in war, the more they stayed the same. In the Korean War, following right on the heels of World War II, both sides had to re-learn the lessons of Napoleon and Hitler about fighting in the cold. The battles which raged around Chosin Reservoir were as much against the frigid fingers of Mother Nature as between the United Nations and the Communists. Neither side was adequately prepared for the agony of combat when bare fingers froze to metal triggers; when medical officers thawed ampoules of morphine in their mouths; nor when mortar base plates

¹⁶ John W. Finney, "C-5A jet repairs to cost 1.5 billion; Pentagon outs outlay to fix Wing Defects at 1.3 Billion as 'Overruns' continue," *New York Times*, 15 December 1975, <http://select.nytimes.com/gst/abstract.html?res=F50616FA3955157493C7A81789D95F418785F9> (accessed 27 March 2010) and National Museum of the United States Air Force, "C-5 Galaxy Fact Sheet."

¹⁷ National Museum of the United States Air Force, "C-5 Galaxy Fact Sheet."

¹⁸ Carroll F. Gray, "The First Five Flights: The Slope and the Winds of Big Kill Devil Hill – The First Flight Reconsidered," *WW1 AERO – The Journal of the Early Aeroplane*, August 2002, 28, also available online at <http://www.thewrightbrothers.org/fivefirstflights.html> (accessed 22 March 2010); and National Museum of the United States Air Force, "C-5 Galaxy Fact Sheet."

¹⁹ This is a generous estimate; C-5A models required an average of 46 maintenance hours per flight hour. See "C-5 Service Life," GlobalSecurity.org, <http://www.globalsecurity.org/military/systems/aircraft/c-5-serv.htm> (accessed 27 March 2010).

shattered from recoil.²⁰ Gary Atkinson, in 1973 an airman at the Army War College, wrote of the Korea campaign: “Weather affected military operations on both sides; however, one gains the distinct impression that it hampered United Nation's forces more than the Communist forces. This is because on many occasions it negated the advantages which the United Nation's forces should have enjoyed due to their overwhelming air superiority.”²¹

Attempts to design all-weather aircraft to overcome weather obstacles continued from the earliest days of aviation. These efforts resulted in aircraft able to fly capably at night as well as during the day, and to navigate with confidence without visual reference; that is, while in the clouds. However, combat aviation required visual cueing, as the Viper’s bubble cockpit attested, and the smartest bombs of the pre-GPS era were unable to see through significant clouds, rain, fog, dust, or enemy smoke. Since neither aircraft nor munitions could be made impervious to weather, meteorology continued to move forward. Atkinson’s continued analysis of weather’s influence on war noted the most significant advances in meteorology in the Cold War era: atmospheric modeling, weather radar, and weather satellites.²²

The most fundamental change to meteorology was the advent of computerized atmospheric modeling. Vilhelm Bjerknes, one of the heroes of the golden age of meteorology, published a paper in 1904 claiming it possible to predict the weather by solving “a system of nonlinear partial differential equations.”²³ The possibility of practical application for complicated math drew some attention, and in 1922 Lewis Fry Richardson published a brilliant paper in which he proved Bjerknes right by applying the equations to European surface pressure forecasting.²⁴ Richardson saw in precise astronomical almanacs a goal for weather forecasting and committed to paper his belief

²⁰ Jack J. Gifford, “The Influence of Weather on Combined Arms Operations in Korea, 1950,” in *Combined Arms in Battle since 1939*, ed. Roger J. Spiller (Fort Leavenworth, KS: U.S. Army Command and General College Press, 1992), 291-99.

²¹ Lt Col Gary D. Atkinson, “Impact of Weather on Military Operations: Past, Present, and Future,” Research Report no. AD911125 (Carlisle Barracks, PA: US Army War College, 1973), 21.

²² Atkinson, “Impact of Weather,” 25.

²³ Vilhelm Bjerknes, 1904: “Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik,” *Meteorologie Zeitschrift* 21 (January 1904): 4. Also available online at <http://books.google.com/books?id=6AcAAAAAMAAJ> (accessed 30 March 2010).

²⁴ Lewis Fry Richardson, *Weather Prediction by Numerical Process* (Cambridge, England: Cambridge University Press, 1922). Also available online at <http://www.archive.org/details/weatherpredictio00richrich> (accessed 30 March 2010).

that predictions based on equations and computations, though complicated by the many variables in the atmosphere, could widen meteorological knowledge. He wrote, “some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream.”²⁵

The dream drew closer to reality in 1939 when Carl-Gustaf Rossby published the wave equation which today bears his name, and in the years to come as others developed complicated theories on which rested early atmospheric equations.²⁶ The ‘primitive equations’ – as the first formulae were termed – attempted to solve Bernoulli’s fluid dynamics problems for atmospheric velocity; that is, wind speed.²⁷ During World War II, graduate-level meteorologists obtained some exposure to numerical weather prediction, as the nascent art was termed.²⁸ At the end of the war, John von Neumann and Rossby established a project to design and test numerical models of the atmosphere “that could be developed to run on computers not yet available, but that could be reasonably anticipated within 2 or 3 years.”²⁹ The foci of the new field of electronic computer research were atmospheric modeling, numerical mathematics, and nuclear engineering.³⁰ Jule Charney’s work on atmospheric instability established his credibility in the project, and he became the head of the meteorology division in 1948.³¹ In 1950 at Princeton, the project produced its first modeled 24-hour forecast, of wind flow at 18,000 feet over North America, depicted in Figure 7.³²

²⁵ Richardson, *Weather Prediction by Numerical Process*, vii.

²⁶ Carl-Gustaf Rossby, “Relation between Variations in the Intensity of the Zonal Circulation of the Atmosphere and the Displacements of the Semi-Permanent Centers of Action,” *Journal of Marine Research* 2, no. 1 (January 1939): 38-55. To learn more about the complicated theories which underpinned early atmospheric equations, see Joseph Pedlosky’s *Geophysical Fluid Dynamics* (Springer, 1990) or Masaki Satoh’s *Atmospheric Circulation Dynamics and General Circulation Models* (Springer, 2004).

²⁷ *Glossary of Meteorology*, American Meteorological Society, <http://amsglossary.allenpress.com/glossary> (accessed 30 March 2010).

²⁸ Fleagle, *Eyewitness*, 3.

²⁹ Fleagle, *Eyewitness*, 8.

³⁰ Frederick Schuman, “History of Numerical Weather Prediction at the National Meteorological Center,” *Weather and Forecasting* 4, no. 3 (September 1989): 286. (for biblio, 286-296)

³¹ “The History of Numerical Weather Prediction: The Early Evolution,” National Oceanographic and Atmospheric Administration, http://celebrating200years.noaa.gov/foundations/numerical_wx_pred/ (accessed 30 March 2010).

³² “The Early History of Numerical Weather Prediction,” The European Centre for Medium-Range Weather Forecasts, http://www.ecmwf.int/products/forecasts/guide/The_early_history_of_Numerical_Weather_Prediction.html (accessed 30 March 2010).

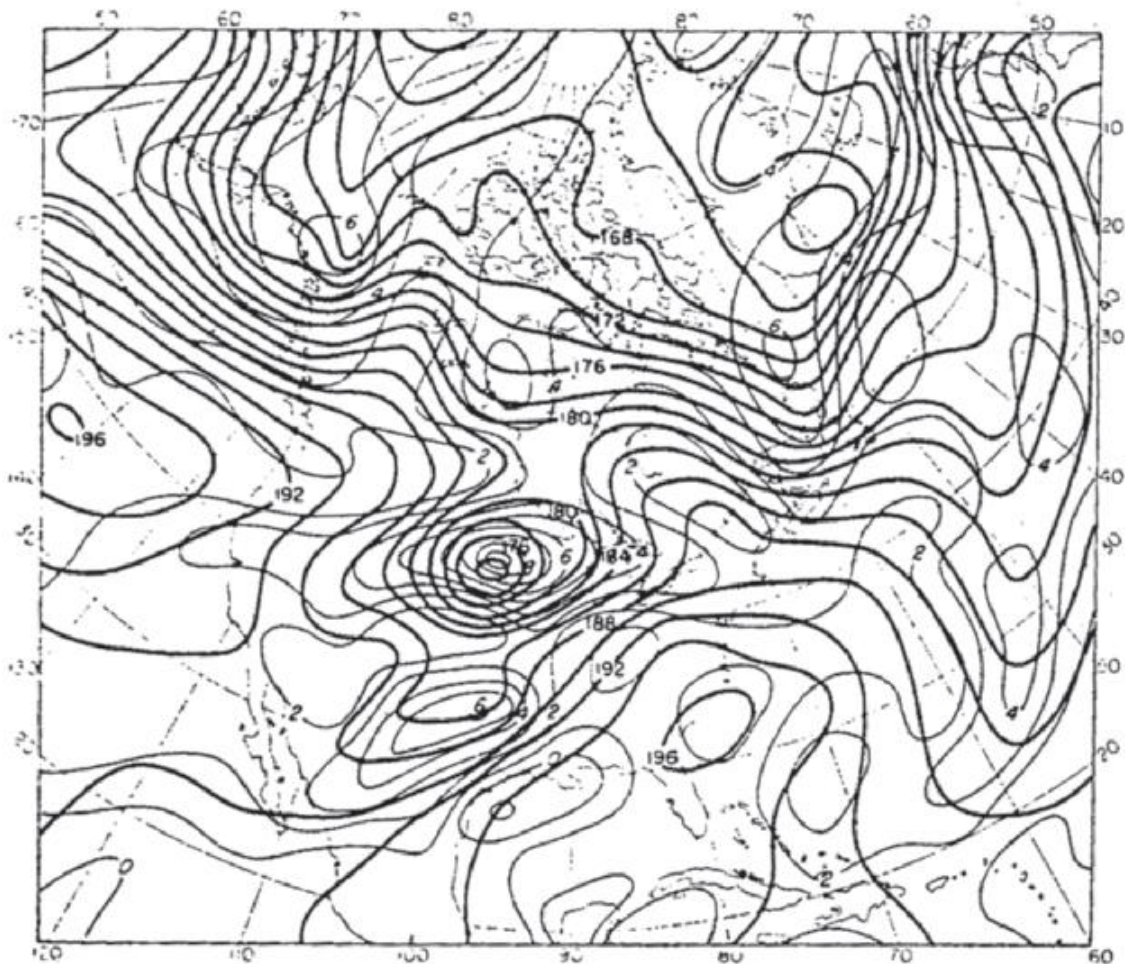


Figure 7. Depiction of the first computerized atmospheric model forecast. The darker lines show geopotential heights (highs and lows aloft; the bull's-eye in the central United States is about 18,000 feet above a surface storm). The fainter lines indicate counterclockwise atmospheric spin (more spin means stronger storms).
Source: Peter Lynch, "The ENIAC Forecasts: A Re-creation"³³

The United States Weather Bureau joined with the United States Air Force's Air Weather Service and the United States Navy's Naval Weather Service to form the Joint Numerical Weather Prediction Unit, which issued operational wind speed and direction forecasts at 3,000, 10,000, and 18,000 feet in the summer of 1955. These forecasts were woeful, as expected, and over the next three years, input from the field motivated the atmospheric modeler, the computer programmer, and the supervising meteorologist to

³³ Peter Lynch, "The ENIAC Forecasts: A Re-creation," *Bulletin of the American Meteorological Society* 89, no. 1 (January 1989): 48.

solve the problems of data assimilation, data analysis, and immature mathematics.³⁴ By the late 1950s, computer capability and increased upper-atmospheric data from balloons and aerial reconnaissance meant northern hemisphere models provided reliable winds and vertical movement – a critical factor for storm development – at 18,000 feet and wind direction and speed at 30,000 feet at 12, 24, 36, 48, and 72 hour increments.³⁵

Weather radar started out as a nuisance. World War II radar pioneers observed false echoes of nonexistent aviation targets which, when triangulated and cross-referenced, proved to be thunderstorms.³⁶ Shorter-wavelength radar sets seemed more susceptible to these false echoes, and engineers tuned radar sets to minimize the interference. In 1942, the Department of the Navy transferred 25 outdated aircraft radars to the civilian Weather Bureau for modification and employment as the seed of a national weather radar network.³⁷ Between 1953 and 1954, Raytheon installed the first purpose-built weather radars at military bases around the world.³⁸ Technology preceded operational know-how; the first weather radar operator's manual for the new equipment appeared in 1955, the same year the Air Force's Second Weather Group completed the concept of operations for weather radar-equipped bases.³⁹ Today's thunderstorm interrogation techniques, which can determine structure, severity, and the presence of hail or tornadoes, provide a rich field for scientific meteorology even as they form the foundation of the resource protection mission of government and civilian weather forecasters. Despite the dramatic advances in weather radar since its discovery as a nuisance, it remains, with few exceptions, a tool used in the tactical, rather than the operational, application of military meteorology.⁴⁰

³⁴ Schuman, "History of Numerical Weather Prediction at the National Meteorological Center," 287.

³⁵ History, 2d Weather Group, 1 January 1958 – 30 June 1958, 28.

³⁶ Roger C. Whiton, Paul L. Smith, Stuart G. Bigler, Kenneth E. Wilk, and Albert C. Harbuck, "History of Operational Use of Weather Radar by U.S. Weather Services, Part I: The Pre-NEXRAD Era," *Weather and Forecasting* 13, no. 2 (June 1998): 220.

³⁷ National Oceanic & Atmospheric Administration Central Library, "NOAA Legacy Time Line, 1900-1969," NOAA, http://www.history.noaa.gov/legacy/time1900_1.html (accessed 29 March 2010).

³⁸ Whiton *et al.*, "History of Operational Use of Weather Radar by U.S. Weather Services," 223.

³⁹ Whiton *et al.*, "History of Operational Use of Weather Radar by U.S. Weather Services," 223-24 and History, 2d Weather Group, 1 January 1955 – 30 June 1955, 4.

⁴⁰ In one notable use at the operational level, interdiction bombing along the Ho Chi Minh trail targeted areas where the absence of rainfall, as estimated by weather radars, made the supply route most suited for travel. See Atkinson, "Impact of Weather on Military Operations," 25.

A tool with much broader application burst on the scene in the aftermath of Sputnik. Signal Corps historian Karl Larew found “progress in meteorology had been in the past tied to man’s ability to observe the weather. Then man extended his knowledge by radiosondes, radar, photography, and other means. But as late as 1958, less than ten percent of the Earth’s surface was under meteorological observation.”⁴¹ Military space historian David Spires spoke of the inability of warriors to “gather needed information with conventional weather equipment over land and sea controlled by the enemy during conflicts and normally inaccessible during peacetime. Moreover, significant weather conditions frequently originated over water, where total coverage proved lacking, and spotty reports from ships or aircraft remained inadequate.”⁴² The first successful weather satellite, TIROS I, lifted off in 1960 and provided 78 days of cloud images, the best of which depicted nearly a quarter of a hemisphere.⁴³

Soon amazement turned to discontent, as military meteorologists and commanders demanded more and better.⁴⁴ Civilian weather satellites like TIROS proliferated during the space-crazed 1960s, and secret military weather satellites which could see in the dark joined them in the early 1970s.⁴⁵ The National Aeronautics and Space Administration budget was enormous in the 1960s, but the considerable funds spent for meteorological activity went to satellite design and construction over data analysis and atmospheric research by a factor of twenty to one.⁴⁶ Despite the imbalance, weather historian John F. Fuller noted in retrospect the “greatest technological advance brought to bear by military meteorologists during Vietnam was the weather satellite.”⁴⁷ Inspired by demands from Strategic Air Command, dual-use military weather satellites provided global strike

⁴¹ Karl Larew, *Meteorology in the U.S. Signal Corps, 1870-1960*, Signal Corps Historical Division study (Washington, D.C.: Signal Corps Historical Division, 1960), 74-75.

⁴² David N. Spires, *Beyond Horizons: A Half Century of Air Force Space Leadership* (Maxwell AFB, AL: Air University Press, 1998), 146.

⁴³ Vanguard 2 had photoreceptors for cloud detection, but due to poor satellite orientation the weather portion of the satellite mission was a failure (though the primary mission, atmospheric density measurement, is a rousing success as Vanguard 2 continues to fly). Constance McLaughlin Green and Milton Lomask, *Vanguard: A History*, The NASA Historical Series no. SP-4202 (Washington, D.C.: National Aeronautics and Space Administration, 1970), also available online at: <http://history.nasa.gov/SP-4202/chap12.html> (accessed 29 March 2010). Also see Fuller, *Thor’s Legions*, 290.

⁴⁴ History, 2d Weather Group, 1 January 1961 – 30 June 1961, 30-31.

⁴⁵ Fuller, *Thor’s Legions*, 290.

⁴⁶ Robert Fleagle, *Eyewitness: Evolution of the Atmospheric Sciences* (Boston, MA: American Meteorological Society, 2001), 47-48.

⁴⁷ John F. Fuller, *Thor’s Legions: Weather Support to the U.S. Air Force and Army, 1937-1987* (Boston, MA: American Meteorological Association, 1990), 290-91.

support to nuclear bombers; downloaded images four times daily to Vietnam mission planners; and relayed data on auroras to military and civilian researchers.⁴⁸

Worthy of particular note was precision bombing's demand for a nearly cloud-free environment, an infrequent commodity in Vietnam. Enemy aircraft, ground fire, and surface-to-air missiles required Air Force and Navy fighter-bombers to acquire their targets visually from their flight level of 15,000 feet. Refueling, an Air Force precision fighter-bomber requirement, also depended on a cloud-free deck. Television-guided and laser-guided bombs, as well as other sophisticated electronic gear, required good weather at the surface and in the bottom 5,000 feet of the atmosphere to be effective. Before the advent of weather satellites, nephelanalysis, the study and prediction of cloud cover, required observations from ground personnel and from aircraft flights at varying altitudes. American weather reconnaissance missions harkened back to the lighter-than-air period, when the young Signal Service used artillery observation balloons to gather weather information.⁴⁹ In World War II, the American military weather service had their own aircraft – WB-17s, WB-24s, and WB-25s – which functioned mostly as pathfinders along pending bombing routes, but which also conducted flights into data-sparse areas upstream to improve theater weather forecasts.⁵⁰ At its peak in 1963, the Air Weather Service flew 113 aircraft, including 43 WB-50 propeller-driven bomber types, 65 jet bomber types (WB-47s and WB-57s), and five WC-130s, the predecessors of today's Air Force Reserves WC-130J 'hurricane hunters.'⁵¹ During Vietnam, as in World War II and Korea, weather reconnaissance flights took place under fire; unlike World War II and Korea, the American public during the Vietnam era did not approve of the risk.⁵² As a result, "meteorological satellite imagery was the primary observational and short-term forecast tool to provide the environmental data needed to carry out a major part of the military effort, especially the Air War," wrote weather service veteran Henry Brandli, one of the foremost authorities on operational weather satellite meteorology.⁵³

⁴⁸ Fuller, *Thor's Legions*, 148, and Henry W. Brandli, "The Use of Meteorological Satellites in Southeast Asia Operations," *Aerospace Historian* 29, no. 3 (Fall/September 1982): 172-73.

⁴⁹ Fuller, *Thor's Legions*, 5.

⁵⁰ Fuller, *Thor's Legions*, 203-205 and 236.

⁵¹ Fuller, *Thor's Legions*, 236. Two of the WB-57s still fly with NASA, <http://jsc-aircraft-ops.jsc.nasa.gov/wb57/history.html> (accessed 30 March 2010).

⁵² Brandli, "The Use of Meteorological Satellites in Southeast Asia Operations," 172.

⁵³ Brandli, "The Use of Meteorological Satellites in Southeast Asia Operations," 172.

Weather satellite imagery proved key to such notable events as the 21 November 1970 raid on the Son Tay prisoner of war camp, the 27 April 1972 laser-guided-bomb strike which at last splashed the Thanh Noh bridge, and the 12 to 15 May 1975 *Mayaguez* incident.⁵⁴ Gushed Brandli, “the meteorological satellite was the most powerful weather observing tool ... supplying much needed weather information in an area that was nearly devoid of conventional weather stations.”⁵⁵ More credible, perhaps, was Seventh Air Force commander General William Momyer, who declared in a televised interview in 1967, “as far as I am concerned, this weather [satellite] picture is probably the greatest innovation of the war.”⁵⁶ Momyer’s comments may have empowered the subsequent formation of Air Force Space Command, where General Thomas S. Moorman, Jr., observed in the light of Desert Storm that satellites “played a crucial role in the outcome of the conflict.”⁵⁷

Like radar and satellite, computerized atmospheric modeling continued to improve through the decades. In 1955, man-made forecasts of altitude winds were accurate 40 to 45 percent of the time, better than the earliest operational computer products. By 1960, however, computerized forecasts were accurate 50 percent of the time and consistently out-performed man-made forecasts, which were discontinued. In 1970, an improved data input methodology combined with greater computing power boosted accuracy to 60 percent. By 1980, accuracy stood at just over 70 percent.⁵⁸ While these improvements meant little to the man on the street, who still could not trust the local weatherman’s advice about his need for an umbrella, they meant the world to military aviators who relied on accurate wind speed and direction forecasts at their flight levels to aid in navigation, fuel load, and bomb or cargo load. As an example, Air Weather Service’s WC-135B flying hours for pathfinder missions supporting Tactical Air Command fighter deployments across the Atlantic or Pacific dropped to a paltry 200

⁵⁴ Brandli, “The Use of Meteorological Satellites in Southeast Asia Operations,” 173-75.

⁵⁵ Brandli, “The Use of Meteorological Satellites in Southeast Asia Operations,” 175.

⁵⁶ Quoted in Maj Ernie R. Dash and Maj Walter D. Meyer, “The Meteorological Satellite: An Invaluable Tool for the Military Decision-Maker,” *Air University Review* 29, no. 3 (March – April 1978): 13.

⁵⁷ While General Moorman referred to all space systems in his address, weather satellites “made possible the planning and execution of the most sophisticated air campaign in history,” according to Spires, *Beyond Horizons*, 257-58 and 260.

⁵⁸ Adapted from Schuman, “History of Numerical Weather Prediction at the National Meteorological Center,” 288, Figure 1.

hours per year, and only on a non-interference basis with atmospheric sampling missions, starting in 1978 due to the increasing ability of computer models to accurately predict wind speed and direction at altitude.⁵⁹ Jet stream forecasting became possible, enabling high-flying aircraft to avoid the dangerous turbulence that invisible river produces. Doctor Robert D. Fletcher, Air Weather Service chief scientist and president of the American Meteorological Society, in 1972 opined, “the initiation of the operational use of the electronic computer in the weather business is really the most significant accomplishment in meteorology in the United States and in the world.”⁶⁰

No advance could have significant impact on the military bureaucracy without systematic implementation through regulation. In the mid-1950s, weather service regulations dictated consultation with planning staffs; presentation of seasonal weather outlooks for local flying, for exercises, and for operational planning; presentation of weather briefings for operational flights; and the ubiquitous plea for reports of weather experienced in flight.⁶¹ These requirements did not differ from what military weathermen had done in World War II; the only difference was that their duties now appeared in regulations. However, the failed rescue of American hostages held in Iran in 1980 presents a stark integration contrast with the Stagg briefs to Eisenhower. The weatherman hand-picked by the Joint Task Force commander was not allowed to brief the mission crews about the weather they would face; instead, Army intelligence officers interpreted his forecasts and provided aircrew feedback from training to mission execution. This over-compartmentalization ended up being a key reason the hostage rescue mission ended in catastrophe.⁶² Further magnifying the complexities of desert weather was the absence of dedicated military weather satellites. Through lack of funding in the 1970s, military weather satellites could not be replaced as they failed, leaving a gap inadequately filled by lower-quality civilian satellite images from 1976 to 1982.⁶³

⁵⁹ Fuller, *Thor's Legions*, 359.

⁶⁰ Robert D. Fletcher (Air Weather Service chief scientist and president of the American Meteorological Society), interview by John F. Fuller, 22 June 1972, quoted in Fuller, *Thor's Legions*, 223.

⁶¹ 2d Weather Group Regulation 55-92, *Tactical Staff Weather Officers*, 22 November 1955, 6 and 2d Weather Group Regulation 55-12, *Operations*, 16 May 1958, 2-3.

⁶² Fuller, *Thor's Legions*, 387-89.

⁶³ Fuller, *Thor's Legions*, 384.

Often forgotten in the technology-enamored Air Force are the men who advanced the organization. The weather officers who earned seats near powerful generals were of two stripes – the meteorologist-turned-officer, and the pilot-turned-meteorologist. Lieutenant General Oscar Senter was the typical Air Weather Service commander of the late war and postwar era. Senter, a first lieutenant Flying Fortress pilot in 1936, volunteered for a variety of schools to alleviate the boredom of a schedule with only four hours of flying per month.⁶⁴ After two years of silence, and just as flying hour budgets began to increase, Senter got orders to attend MIT for meteorology. By 1943, Senter had risen through the weather ranks to command the 7,500-man weather service as a colonel.⁶⁵ He found a way to return to the Flying Fortress, and finished the war as a flyer.⁶⁶ As bomb wings drew down after the war, Senter returned to weather. He commanded the weather service from 1950 to 1954 as a major general, then moved to Material Command and retired in 1966 as a lieutenant general.⁶⁷

Other pilot-meteorologists led the Air Weather Service until 1970, when the first meteorologist-officer, Brigadier General William Best, Jr., took command. His replacement was pilot-meteorologist Brigadier General (later Major General) John Collens, who subsequently relinquished command to meteorologist-officer Brigadier General Berry Rowe.⁶⁸ The promotion chances for meteorologists sank, as did Cold War weather briefings which devolved into tactical or mislabeled strategic flight briefs conducted face-to-face, by telephone, or by closed-circuit television.⁶⁹ Seeing no immediate need for senior meteorologists on strategic planning staffs, Air Weather Service commanders disappeared from the aeries of power, dropping from promotable

⁶⁴ Fuller, *Thor's Legions*, 28.

⁶⁵ Fuller, *Thor's Legions*, 44, and Air Force Weather Agency Historical Highlights,” Air Force Weather History Office, <https://afweather.afwa.af.mil/about/history/docs/AFWAHistoricalHighlightsBrochureMay2005.pdf> (accessed 7 April 2010).

⁶⁶ Fuller, *Thor's Legions*, 46, footnote 59.

⁶⁷ Air Force Weather Agency Historical Highlights,” Air Force Weather History Office, <https://afweather.afwa.af.mil/about/history/docs/AFWAHistoricalHighlightsBrochureMay2005.pdf> (accessed 7 April 2010), and “Lieutenant General William Oscar Senter,” Air Force biography, <http://www.af.mil/information/bios/bio.asp?bioID=7107> (accessed 25 April 2010).

⁶⁸ Air Force Weather Agency Historical Highlights,” Air Force Weather History Office, <https://afweather.afwa.af.mil/about/history/docs/AFWAHistoricalHighlightsBrochureMay2005.pdf> (accessed 7 April 2010).

⁶⁹ History, 2d Weather Group, 1 January 1956 – 30 June 1956, 3. So-called strategic weather briefings earned the term simply because the flights were conducted by Strategic Air Command, not because they took place at the strategic level of war.

two stars to promotable one stars to terminal one stars to terminal colonels between 1945 and 1991.⁷⁰

Summary

The Viper, the Galaxy, computerized atmospheric models, weather radar, and cloud pictures from space – like the protagonist in *Oklahoma*, one might think technology has “gone about as far as it can go.” Fifth-generation fighters represent a significant evolution, not a revolution, of the Viper’s sleek and lethal lines. Game-changing weather advances like Doppler radar and hyper-spectral satellite imagery are really just the next incremental advance. Yes, Doppler radar improves the observation of tornadoes, but has it significantly improved the weatherman’s ability to predict which storm will spawn the deadly funnel? Or even better, which frontal system will do so? Hyper-spectral satellite imagery enables scientists to tease out indications of thin cloud decks barely visible to the naked eye; however, this data is rarely of operational utility.⁷¹

Did aircraft and meteorological capabilities advance in tandem during the Cold War era? Aircraft speeds leapt through the sound barrier and kept going; endurance record flights circled the earth without stopping; aircraft climbed through the atmosphere into space. Weather surveillance radar vectored aircraft between thunderstorms; weather satellite images enabled air refueling and precision-guided munitions; and computerized atmospheric models helped Tactical Air Command safely deploy overseas. Yet despite aviation advances, aircraft still fell short of being truly all-weather capable; meteorology, enabled by technology, rose to the challenge.

The question of improved integration, however, requires deeper consideration. The state of aviation and meteorological integration at the close of World War II reflected the golden age of both disciplines, as the commander, pilot, or decision-maker had a

⁷⁰ “Air Force Weather Agency Historical Highlights,” Air Force Weather History Office, <https://afweather.afwa.af.mil/about/history/docs/AFWAHistoricalHighlightsBrochureMay2005.pdf> (accessed 7 April 2010).

⁷¹ The only aircraft influenced by a cloud deck nearly invisible to the naked eye are those which have no ability to fly in conditions of trace icing (the category of icing less intense than “light”). In today’s unclassified Air Force inventory, that means the remotely-piloted Predator and Reaper aircraft could have interest. However, because those aircraft are unmanned, operators are more likely to attempt flight into low-risk weather phenomena to accomplish their high-visibility missions. A reasonable evaluator could conclude that classified aircraft with high-visibility missions might be similarly driven.

meteorologist at his beck and call by practice and by regulation. Prop wash may have given way to jet thrust, but the integration of meteorology into tactical aviation operations seemed stuck in the 1950s, and integration at higher levels had retreated to a level similar to that which existed when Pershing had to demand more meteorologists accompany him to Europe for World War I.

Chapter 5

Man versus Machine

EDI is a Warplane. EDI must have targets.

*-- Extreme Deep Invader, an artificial-intelligence-piloted
Unmanned Combat Air Vehicle in the 2005 film Stealth,
voiced by Wentworth Miller*

Post-Modern Post-Honeymoon Problems

You can't see it; you can't catch it; you can't shoot it down – you might not even be able to sit in it. In the third millennium, military aviation faces fundamental questions even as it continues its incremental jet age advance. Stealth is an important element of every combat model and design, and stealth is a product of the synergistic application of a myriad of technologies from scattered scientific fields. Stealthier platforms are smaller platforms; humans and their ergonomic requirements take up significant space, one component of the manned versus unmanned argument. Efficiency remains essential to airborne logistics, but sustainability has entered the equation. Synthetic fuels are no pipe dream: in March 2010, the United States Air Force flew an A-10 on a blend of jet fuel and a biofuel created from animal fats and plant oils.¹ The emphasis on jet fuel is timely, as the Air Force struggles to obtain a much-needed replacement for the aging KC-135 Stratotanker. The melodrama surrounding the KC-X is less about the narrow concerns of military efficiency and effectiveness and more about the bigger picture, complicated in our wide-spectrum information age.

The Lockheed Martin/Boeing F-22A “Raptor” is a wide-spectrum aircraft. Ruggedized stealth, super-cruise, thrust vectoring, fly-by-wire flight control, do-it-all capabilities, and a non-traditional intelligence collection platform – what makes the Raptor cool? Everything. Primarily designed as an air superiority fighter to replace the aging F-15C “Eagle” fleet, the post-Cold War era offered no immediate challenger to an Eagle-Viper combination. Non-state actors, network-enabled terrorists, and multinational

¹ A1C Alina Richard, “Around the Air Force,” *Around the AF TV*, 26 March 2010, <http://www.af.mil/news/video/index.asp?cid=2&sid=12256> (accessed 31 March 2010).

groups provided an opportunity to save the Raptor by broadening its mission to include ground attack, electronic warfare, and signals intelligence collection.² Mission creep notwithstanding, the Raptor's ruggedized stealth is a dramatic improvement over earlier stealth aircraft which required special hangars to maintain their low-visibility coatings.³ Not only stealthy, the Raptor is also fast. General John P. Jumper, former United States Air Force Chief of Staff, flew faster than 1.7 Mach without afterburners in a 2005 sortie.⁴ With a wingspan only ten percent greater than the Wright Flyer, the Raptor can carry 26,000 pounds of fuel and munitions over a 410 mile combat radius or a 1,850 mile range, can exceed Mach 2 using afterburner, and can fly deep into the stratosphere.⁵

Despite its impressive capability as a war bird, the Raptor, like most thirsty fighters, requires frequent pit stops for fuel. Tankers are high-demand, low density aircraft, and there is no mission enabler of greater significance in the modern fight than the range-extending power of airborne refueling. KC-X is the name of the Air Force procurement program for the Stratotanker replacement. After normal legal gyrations, the Air Force in February 2008 selected the Northrop Grumman/EADS Airbus A330-based KC-45A.⁶ In June 2008 the Government Accountability Office upheld a Boeing protest, and the following month Defense Secretary Robert Gates took a mulligan.⁷ In a surprising step perhaps intended to strengthen a subsequent protest, the Northrop

² John Reed, "Official: Fighters Should Be Used for Spying," *Air Force Times*, 20 December 2009, http://www.airforcetimes.com/news/2009/12/airforce_deptula_121909/ (accessed 31 March 2010).

³ David A. Fulghum, "Away Game," *Aviation Week & Space Technology*, 8 January 2007, 6. Also available online at <http://www.thehowlandcompany.com/pdf/AW&ST8JAN07.pdf> (accessed 31 March 2010).

⁴ 2d Lt William Powell, "General Jumper qualifies in F/A-22 Raptor," *Air Education and Training Command News*, 13 January 2005, <http://www.af.mil/news/story.asp?storyID=123009594> (accessed 31 March 2010).

⁵ Air Combat Command Public Affairs Office, "F-22 Raptor Fact Sheet," http://www.af.mil/information/factsheets/factsheet_print.asp?fsID=199&page=1 (accessed 31 March 2010), Lockheed Martin Aeronautics Company, "Flight Test Data Performance Criteria," <http://www.f22-raptor.com/technology/data.html> (accessed 31 March 2010), and David A. Fulghum and Michael J. Fabey, "Raptor Scores in Alaskan Exercise," *Aviation Week & Space Technology*, 7 January 2007, http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=defense&id=news/aw010807p1.xml (accessed 31 March 2010).

⁶ Dominic Gates, "EADS/Northrop Trumps Boeing in Air Force Tanker Competition," *The Seattle Times*, 29 February 2008, http://seattletimes.nwsources.com/html/business/technology/2004251273_webtankerwin29.html (accessed 31 March 2010).

⁷ Michael R. Golden, "GAO Sustains Boeing Bid Protest," Government Accounting Office, http://www.gao.gov/press/press-boeing2008jun18_3.pdf (accessed 31 March 2010) and John J. Kruzell, "Pentagon Reopens Bidding on Tanker Contract," American Forces Press Service, <http://www.defense.gov/news/newsarticle.aspx?id=50453> (accessed 31 March 2010).

Grumman/EADS team in March 2010 “determined that it will not submit a bid to the Department of Defense for the KC-X program,” in the words of Northrop Grumman’s chief executive officer and president.⁸ Nearly a billion dollars in the fiscal 2011 Defense Department budget is set aside for tanker research and development money, to pave the way for an initial purchase of 179 aircraft.⁹ Whether the competition is single-source or competitive, a glance at the specifications of the next United States Air Force tanker put it in the same class as the Galaxy of the previous chapter, with upgrades consistent with the incremental changes in large aircraft aviation since the 1980s.¹⁰

Meteorological Stagnation?

There remains debate over whether the multidisciplinary advances in aviation technology, described above, is revolutionary or evolutionary. In the meteorological community, there is little debate. Meteorological advances since the Cold War have been multidisciplinary, impressive, and portentous, but few would claim they are revolutionary. Three interesting avenues of advance best characterize the last 30 years of meteorological application to aviation: forecast delivery via a networked “warfighter pull,” forecast presentation as probabilistic vice deterministic, and forecast preparation using an ensemble of computer models rather than just one.

Any effort to improve the ratio of tooth to tail is worth study. In the 1980s, the Army research laboratory at White Sands developed a tactical-scale atmospheric model called the Battlescale Forecast Model.¹¹ This tool comprised part of the Integrated Meteorological System, the weather component of the much larger Army Battle Command System, a network-centric command and control system designed to unify Army operations at every level, but only deployed thus far at the division level and

⁸ “Statement From Northrop Grumman on U.S. Air Force Aerial Refueling Tanker Program,” Northrop Grumman, 8 March 2010, http://www.irconnect.com/noc/press/pages/news_releases.html?d=186116 (accessed 31 March 2010).

⁹ Jim Garamone, “Budget Request Continues Reform Agenda,” American Forces Press Service, 1 February 2010, http://www.wivb.com/dpps/military/Defense-Department-budget-request-continues-reform-agenda_3216004 (accessed 31 March 2010).

¹⁰ Most significant is the 202,000 pound takeoff fuel load. “767 Airplane Characteristics for Airport Planning,” Boeing: United States Tanker, <http://www.unitedstatestanker.com> (accessed 7 April 2010).

¹¹ Robert Endlich, interviews by the author, March-April 1996. Bob led this effort before retiring from federal service after 30 years and ascending the ivory tower as a senior researcher at New Mexico State University.

below.¹² The Battlescale Forecast Model took as its initial conditions the best military forecast models and digitized terrain information, then projected conditions for 24 hours on a fine scale.¹³ Tactical weather forecasters could benefit from the finer scale, but more troublesome was the designed “warfighter pull” automation. The Army Battle Command System foresaw intelligence officers, artillerymen, and aviators drawing from their terminals an automated red-yellow-green weather assessment of their proposed missions.¹⁴ In the laboratory, the system was functional; during exercises, it was not. As a result of poor field testing, programmers blocked the automated “warfighter pull” capability, though meteorologists could still use the application. Few did. Similar to early computer-generated forecasts, until the weather assessments generated by computers outperform human forecasters, military meteorologists must remain close to the fight.

In the area of hurricane forecasting, computers do seem to outperform human meteorologists. Most have seen the National Hurricane Center forecasts which show current location and a swath predicting the hurricane’s path. The swath widens as it gets farther away from the origin: this widening reflects increased variance among different computer-generated forecasts over time, as shown in Figure 8. Variance is present in all aspects of weather forecasting, not just in hurricane movement. Figure 9 shows variance in temperature forecasting for a typical date in London.

¹² “PM Battle Command Common Software,” Program Executive Office Command Control Communications – Tactical, http://peoc3t.monmouth.army.mil/battlecommand/bc_common_software.html (accessed 1 April 2010).

¹³ Jeffrey E. Passner, “Post-Processing for the Battlescale Forecast Model and Mesoscale Model Version 5,” ARL-TR-2988 (White Sands Missile Range, NM: Army Research Laboratory, 2003), 3 and 10-22.

¹⁴ This automated system was called the Integrated Weather Effects Decision Aid, and relied on over 11,000 weather sensitivities collected by Army researcher Richard Szymber through the 1990s. For an example of Szymber’s work, see Army Research Laboratory Technical Report 3720, available online at <http://www.arl.army.mil/arlreports/2006/ARL-TR-3720.pdf> (accessed 1 April 2010).

Early-cycle track guidance valid 1200 UTC, 30 August 2009

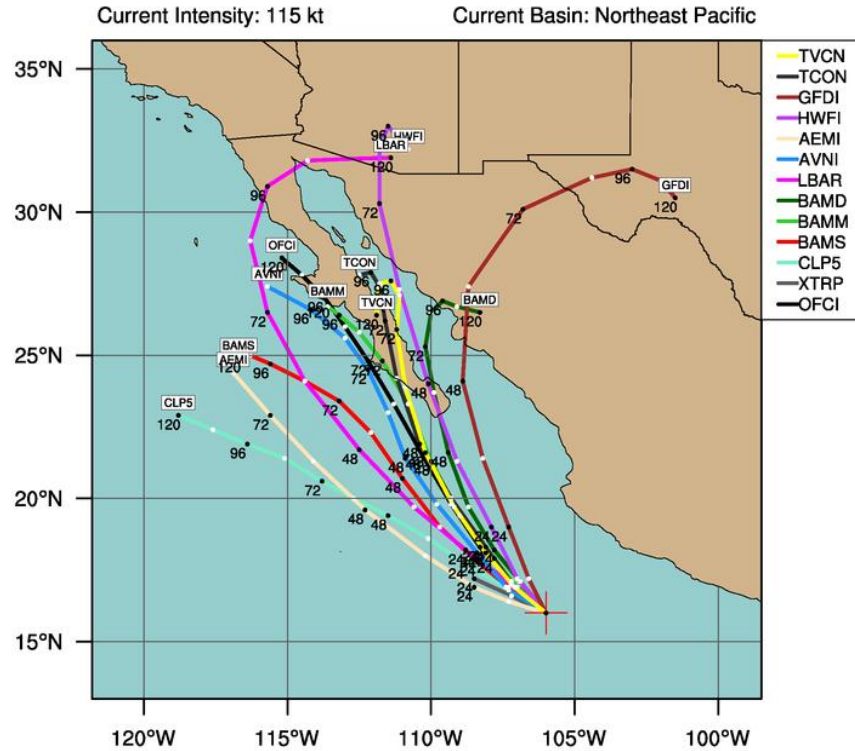


Figure 8. Comparison of hurricane movement forecasts.
Source: Personal Hurricane Center¹⁵

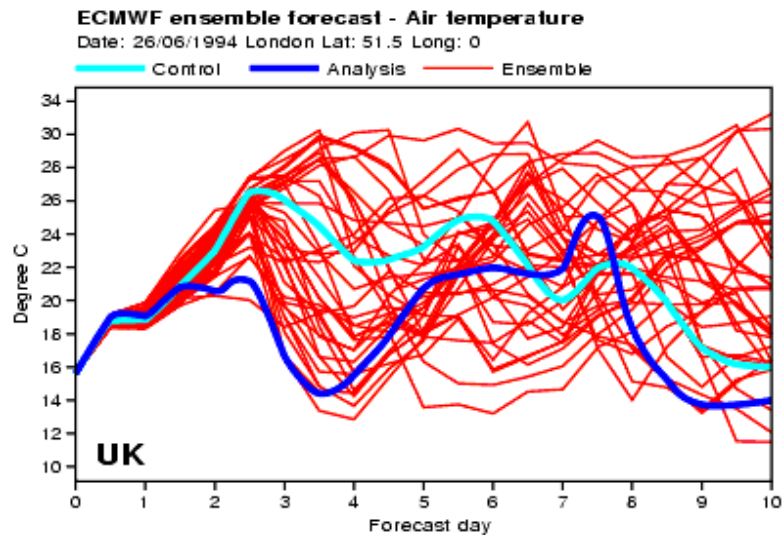


Figure 9. Example of computer atmospheric model error growth
Source: University Corporation for Atmospheric Research¹⁶

¹⁵ "Personal Hurricane Center: current and archived information on Atlantic and East Pacific tropical cyclones and hurricanes," <http://www.personalhurricanecenter.com/wp-content/uploads/2009/08/Hurricane-Jimena-Spaghetti-Models-30-Aug-2009-1200-UTC.png> (accessed 1 April 2010).

¹⁶ University Corporation for Atmospheric Research, Research Applications Laboratory, www.ral.ucar.edu/general/events/2007/part2_warner.ppt (accessed 30 March 2010).

However, commanders, pilots, and decision makers satisfied with the presentation of hurricane forecasts are not similarly satisfied with the presentation of other weather forecasts in such a probabilistic way. This was not always the case. Early military weather forecasts required the forecaster to give odds.¹⁷ In World War I, Pershing's preferred weather forecast format included odds as the last predictive element. A sample forecast for the Argonne in October 1918 called for fair skies during the day with dense overnight fog but not rain. The final line in the forecast read "odds in favor of forecast 10 to 1, except parag C [the fog forecast] 5 to 1."¹⁸

By the time of Operation Overlord, weather forecasters no longer provided such nuanced assessments. An extreme modern case is that of General David McKiernan, who commanded the land force when General Tommy Franks invaded Iraq in 2003 and later commanded the International Security Assistance Force in Afghanistan. While commanding the First Cavalry Division at Fort Hood, Texas, from 1999 to 2001, McKiernan liked his advisors to make their recommendations by voting with their thumbs; thumb up for go, and thumb down for no-go.¹⁹ Woe to the staff officer who presented a thumb any degree out of the vertical, or who interrupted the poll with a caveat. Probability and uncertainty is endemic in all human affairs, as it is in weather. Meteorology benefits from probabilistic forecasting applied to hurricanes, and similarly benefits from probabilistic forecasting applied to other elements as well.

A new and important element of probabilistic weather forecasting deserves more exploration. The spaghetti models used to examine the variance among multiple forecasts depicts very obviously that there are multiple computerized atmospheric models generating hurricane movement predictions. The same holds true for predictions of other weather phenomena. Cass Sunstein's *Infotopia* examined prediction markets, and cited forecasting expert J. Scott Armstrong: "Organizations often call on the best expert they can find to make important forecasts. They should avoid this practice, and instead

¹⁷ Karl Larew, *Meteorology in the U.S. Signal Corps, 1870-1960*, Signal Corps Historical Division study (Washington, D.C.: Signal Corps Historical Division, 1960), 34.

¹⁸ 1st Lt Kenneth S. Stice, "Weather Forecasting for the Army," *Chemical Warfare* 12, no. 3 (15 March 1926): 4.

¹⁹ Interviews with three First Cavalry Division staff officers by the author, late 1999 to early 2000, and personal experience serving under General McKiernan, early to middle 2000.

combine forecasts from a number of experts.”²⁰ These works, along with those of Condorcet *et al.*, were not written with meteorology in mind, but find immediate application therein. Edward Lorenz, the father of chaos theory and a meteorologist, founded his thesis on weather’s sensitive dependence on initial conditions.²¹ Writing from the National Center for Atmospheric Research in 1974, C. E. Leith proposed a methodology to improve numerical weather prediction by statistical manipulation of multiple runs of a single atmospheric model with minor changes to initial conditions.²² Computers proliferated, and by 1995 weather researchers attempted to apply statistical methods to multiple runs of multiple atmospheric models with multiple changes to initial conditions.²³ Today, numerical weather prediction centers in the United States, France, England, Canada, Japan, Australia, China, Korea, and others employ ensemble techniques to generate weather forecasts. The Air Force Weather Agency and the Navy’s Fleet Numerical Meteorology and Oceanography Center created a joint effort to provide ensemble-based probabilistic forecasts to Department of Defense customers by 2008.²⁴ These probabilistic forecasts will continue to take traditional deterministic forms, following the tradition since World War II, but the concepts that underpin them include mathematical uncertainty, complexity, and chaos.

²⁰ Cass R. Sunstein, *Infotopia: How Many Minds Produce Knowledge* (New York, NY: Oxford University Press, 2006), 39 and 103-145, and J. Scott Armstrong, “Combining Forecasts,” in *Principles of Forecasting*, ed. J. Scott Armstrong (Boston, MA: Kluwer Academic, 2001), 433.

²¹ Lorenz served as a military meteorologist in World War II, and obtained meteorology degrees from MIT upon his return. His early academic work culminated in his 1963 paper “Deterministic Nonperiodic Flow,” which stated in essence his chaos theory. Tim Palmer, “Edward Norton Lorenz,” *Physics Today* 61, no. 9 (September 2008): 81–82 and Edward N. Lorenz, “Deterministic Nonperiodic Flow,” *Journal of the Atmospheric Sciences* 20, no. 2 (March 1963): 130–141.

²² C.E. Leith, “Theoretical Skill of Monte Carlo Forecasts,” *Monthly Weather Review* 102, no. 6 (June 1974), 412-14.

²³ For an early example, see Zoltan Toth and Eugenia Kalnay, “Ensemble Forecasting at NCEP and the Breeding Method,” *Monthly Weather Review* 102, no. 12 (December 1997): 3297-319. The authors submitted the paper in April 1995, but the American Meteorological Society did not publish it until 20 months later.

²⁴ Timothy E. Nobis, Evan L. Kuchera, Scott A. Rentschler, Steven A. Rugg, Jeffrey G. Cunningham, Chris Synder, and Joshua P. Hacker, “Towards the Development of an Operational Mesoscale Ensemble System for the DoD Using the WRF-ARW Model,” Air Force Weather Agency Report (Offutt AFB, NE: Air Force Weather Agency, 2008).

Summary

The Raptor and the KC-X reflect their nature as advanced interdisciplinary hybrids. The Raptor is not just an air superiority fighter; it is a dozen other things. The KC-X is not just a replacement for the KC-135; it is an icon of trade protectionism and a weapon against globalization. Meteorology in the post-Cold War era benefitted from an interdisciplinary focus as well, thanks in large part to Edward Lorenz's chaos theory. Rapid computer development led to an effort to encourage "warfighter pull" instead of weatherman push; though it did not succeed, future initiatives may. Chaos, complexity, and uncertainty as math and physics concepts enabled hurricane movement depictions to reflect variance, providing a foot in the door for those who would expand probabilistic depictions of weather forecasts. Finally, the combination of computer advance and complexity math made real the dreams of those meteorology researchers who believed an average of many computerized forecasts would be better than just one, setting the climate for today's widespread ensemble modeling.

These rosy auguries will not silence the three questions central to this paper. Did aviation advances following the cold war demand more from meteorologists? Aviation opened few new frontiers, but mission requirements shifted the emphasis from Strategic Air Command to the strategic corporal. The dust storm at the inception of Operation Iraqi Freedom was just as debilitating as the cold at Chosin or the mud in Flanders, and aviation demanded the weatherman be right at the tactical, operational, and strategic levels. On the other hand, the proliferation of laser- and GPS-guided munitions eased the demand for highly technical electro-optic weather forecasting.²⁵ In this era, weather forecasts seem somewhat less in demand than in past eras, so the answer to the first question is a cautious no.

Despite the reduction in demand, meteorological advances improved weather forecasts during the period. Manpower reductions that eviscerated the Air Force and Navy weather forecaster ranks, particularly at the journeyman skill levels, barely influenced forecast accuracy scores as computerized atmospheric models and ensemble

²⁵ A significant advance between Operation Desert Storm and Operation Enduring Freedom was the advent of GPS-guided bombs. Bombs stored in huge numbers around the world could be retrofitted with a GPS receiver and "be launched at night or through bad weather" from a variety of aircraft. Michael W. Kometer, *Command in Air War: Centralized Versus Decentralized Control of Combat Airpower* (Maxwell AFB, AL: Air University Press, 2007), 227-28.

forecasting techniques improved. Promising though ultimately disappointing were attempts to take the forecaster out of the loop; and the jury is still out on whether or not probabilistic forecast depictions will spread to applications other than hurricane movement. While weather prediction advanced during this period, it is uncertain if aviation spurred the advances or if both aviation and meteorology advanced at the behest of the general advance in the sciences brought on by a renewed interdisciplinary approach.

The failed Army attempt to remove the human from the weather prediction loop in the 1990s was just one of several efforts to improve integration using a “warfighter pull.” None rescued aviation integration of weather information from apparent stagnation. At the strategic level, senior leaders generally remember to call for a climatology-based planning briefing almost as *pro forma* as he might request an invocation at a formal event. At the tactical level, weather briefings use the same forms and the same media to present information enriched by ensemble weather modeling but limited in scope by the same old forms and media. At the operational level, mission planning forecast briefings similarly benefit from ensemble weather modeling, but the methods of presentation remain unchanged from when Stagg briefed Eisenhower in 1944. Linear processes at the operational level of war occasionally enable the weatherman to interject mission-altering information, but even then entropy and impetus delay integration until many fleeting opportunities vanish.²⁶

²⁶ Source: interviews with Air Force Central Air Operations Center lead meteorologists Lt Col Lisa Shoemaker, Major Matthew Hauke, and personal experience in that role. Each of us spent a year in the job, and though our tours spanned seven years, our classified end-of-tour reports reflected the same frustrations with weather integration.

Conclusion

No Integration ‘Silver Bullets’

Airpower has not uncovered any “silver bullets.” Indeed, if we were to say there has been any development in this area, it has been the realization that airpower must become more effective at denying enemy ground forces sanctuary – the sanctuaries of night, weather, hiding places, and time.

-- Michael W. Kometer, Command in Air War

Summary of Aviation and Meteorology Advances and Integration

Has aviation technology reached its apex? Few would say so. The past three decades of evolutionary improvements suggest the potential for future revolutionary leaps. The science of aviation is still relatively young. One could argue the same holds true for the automobile, which has followed a more evolutionary path, but few wars are fought from the family sedan. By comparison, what is the nature of advances in weather prediction? Only a fool would say there is no room for improvement in that art, but only a fool would deny the meteorological advances of the twentieth century. Given that both realms continue to advance, poor weather prediction integration into military aviation would be increasingly irresponsible. The history of integration of weather prediction into military aviation operations appears to have been irregular and seems to have become stagnant.

As the aviation era dawned, the Wright brothers consulted climatological records before choosing their experimental launch sites along the Atlantic Coast and in Ohio, and took careful note of wind speed and direction at launch times.¹ The science of aviation was newly born, and the science of meteorology, though dating back to the days of Bernoulli, was likewise infantile. Because neither science had advanced very far, aviation’s integration of meteorology had little precedent. Initial integration of weather into movement over land or sea is lost in

¹ This is a necessary inference. There is no indication the Wrights observed weather conditions for meteorological study, but every recorded flight includes at a minimum a note of the wind state at launch.

the mists of time. The invention of the wheel predates recorded history, but logic dictates the first muddy road was both a literal and intellectual quagmire.² The earliest records of seafaring peoples do not suggest that weather's influence on ships was a novelty. Naval Academy professors William Oliver Stevens and Allan Westcot opined in 1920 that sensitivity to weather drove progress in ship design, until Nelson's "lumbering ships of the line made wretched speed and straggling formations but they were able to weather a hurricane and to keep the sea for an indefinite length of time."³ Despite improvements in construction, weather held significant influence on naval warfare in the age of sail. While no records exist of the first weather influence on land movement or sea movement, the Wrights provide evidence of the integration of meteorology – such as it was – into aviation operations – such as they were.

By the end of World War I, both sciences had advanced significantly. The unlikely Wright Flyer transformed into the recognizable Jenny, and aviation capabilities won limited use in the most dangerous game as the guns of war brought the sons of Europe, North America, and Asia to the battlefield. Aircraft speeds and payloads climbed as fast as their maximum altitudes to levels exponentially greater than those demonstrated by the earliest heavier-than-air models. Meteorology advanced as well, as the grandfathers of aviation weather forecasting supported General John J. Pershing in Europe and civil aviation novelties like Jenny-powered air mail back home. The integration of meteorology into the muddy, bloody, and olive-drab world of the doughboy followed Pershing's unmatched direction; however, integration of meteorology into the cocksure world of the lionized and scarf-clad aviator was still *ad hoc* and uneven. Though memoirs and scraps of service records indicate weathermen served at most civil and military airfields, obtaining a weather briefing – for mission planning or immediately before a flight – does not appear to have been anything more than optional.

² Maxwell G. Lay, *Ways of the World: A History of the World's Roads and of the Vehicles that Used Them* (New Brunswick, NJ: Rutgers University Press, 1992), 5-27.

³ William Oliver Stevens and Allan Westcot, *A History of Sea Power* (New York, NY: George H. Doran Company, 1920), 15-25. Also available online at <http://books.google.com/books?id=clx5FhtEAocC> (accessed 10 April 2010).

In the decade following World War II, both aviation and meteorology celebrated a golden age of advancement. The sleek and streamlined Mustang served as a front-line fighter for decades, a testimony to its endurance, maneuverability, speed, and firepower. From the mud to the stratosphere, Mustangs and Flying Fortresses were thoroughbreds to the Jenny's mule. Meteorology likewise found in its Norwegian fathers a golden age that turned the American and French grandfathers into fogeys. The advanced mathematics and theory of Bjerknes, Rossby, *et al.* and the iconoclasm and self-promotion of Krick and Petterssen synergized at the decisive point of World War II. The Allies validated Winston Churchill's prediction of their finest hour on D-day, and the integration of meteorology likewise had its finest hour when Stagg the weatherman presented the forecast which convinced Eisenhower to launch the Continental invasion. Integration of meteorology into aviation operations at that point was also at an apogee – no longer *ad hoc* but regulated, present at all levels of flight operations (civilian and military, domestic and international, and at all level of military air missions), and co-influential.

From the propeller age to the jet age, aviation again celebrated a revolution. The key advance in this era, the jet engine, increased force in such a way that horsepower was no longer a meaningful measure.⁴ Increased thrust resulted in speed unimaginable in earlier eras, as the sound barrier and its multiples quickly fell to fighters such as the Viper. Increased thrust also resulted in dramatic increases in payload, as evidenced by the cavernous Galaxy. Meteorology advanced in more evolutionary ways, but very nearly kept pace with aviation nonetheless. In the realm of weather observation, technology provided specially tuned radar sets first to locate and then autopsy atmospheric hazards; satellite imagery seized the ultimate high ground for observing weather features even over enemy territory. Computer advances enabled construction of atmospheric models almost as advanced as weather in the laboratory, and sufficiently accurate to boost numerical weather prediction accuracy higher than

⁴ For an easy-to-follow discussion of why horsepower and thrust are fundamental different, see <http://www.aerospaceweb.org/question/propulsion/q0195.shtml> (accessed 15 April 2010).

the most skilled human working without computer assistance. Aviation and meteorology both made significant strides during the Cold War era, but integration of the two loosely-coupled sciences suffered under the static missions of the Cold War and the advances in all-weather aircraft and munitions capabilities.⁵

Post-Cold War aviation's advances promised continued growth as the first decade of the twenty-first century closed. Top-secret stealth hit the front page in the opening hours of Operation Desert Storm, as the F-117 Nighthawk penetrated deep into one of the world's most defended airspaces. Engine technology matured and expanded in three areas: alternative fuels, hyper-efficiency, and supercruise. The aircraft itself, as exemplified by the Raptor, reflected a move away from specialization and toward becoming a novel multi-role platform. The interdisciplinary advances found congruence in the meteorological advance of ensemble weather modeling. Complex, adaptive systems like the atmosphere lend themselves to only partial understanding from any one perspective. Ensemble weather modeling allows multiple perspectives to have a vote on expected system behavior, and the truism holds that two heads (or more) are better than one. Integration of aviation and meteorology, however, appeared stagnant as efforts to develop a tool for easy "warfighter pull" fell short.

Colonel Kevin Lavin, Air Weather Association chairman and retired Air Force master meteorologist, started briefing pilots in 1962 "using DoD directives to write out DD Form 175-1s for all military and even civilian flights."⁶ Today's directives and forms differ little from those of 50 years ago.⁷ Figure 10 compares advances in military aviation and meteorology, and attempts to gauge integration

⁵ An interesting integration of atmospheric science and aviation in the Cold War was the WB-135 "sniffer" aircraft, modified to detect atmospheric evidence of atomic weapons tests.

⁶ James K. "Kevin" Lavin (Air Weather Association chairman), interview by the author, 1 April 2010.

⁷ The directives are now Air Force Instructions, and the forms include two small new blocks. In one the forecaster may indicate "no impact, marginal, or severe" expected solar influence on radio communications, GPS satellite interference, or direct radiation (for flights above 60kft). In the other, the forecaster may include solar and lunar data (morning twilight, sunrise, sunset, evening twilight, moonrise, moonset, and percent of lunar illumination) for a selected location. Because neither of these blocks appropriately pertains to meteorology, one would be correct in stating the forms have not adapted to changes in meteorology since their inception following World War II.

of the two elements in five different eras. Lavin's experience epitomizes the integration stagnation plateau.

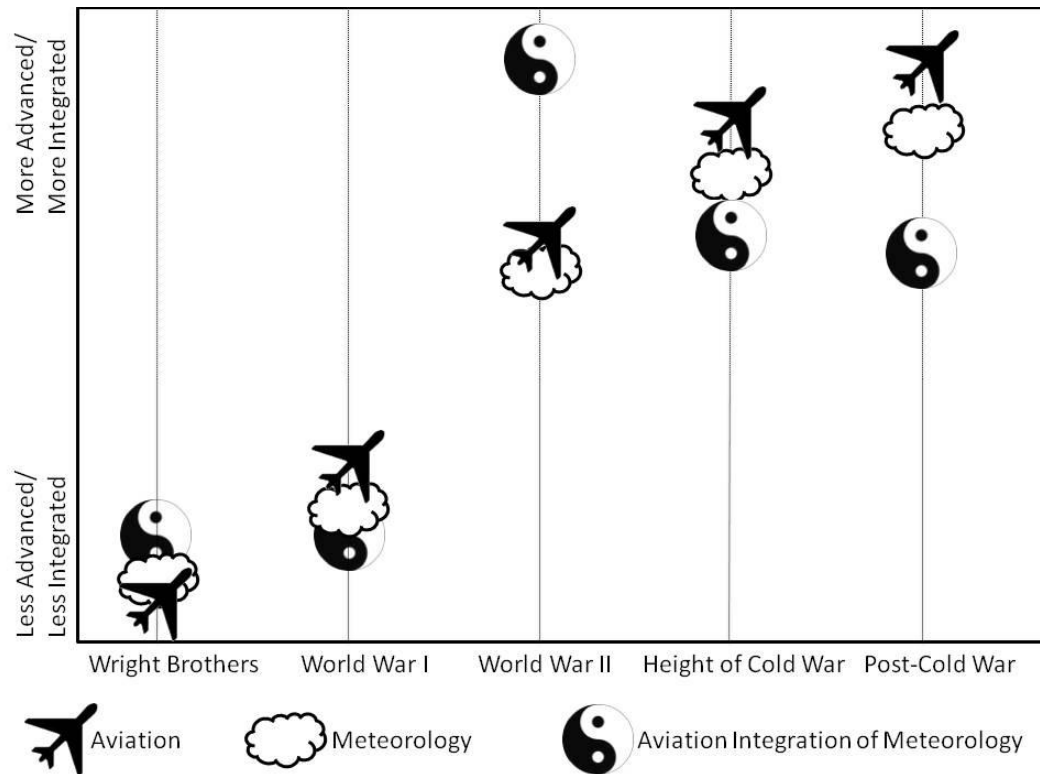


Figure 10. Depiction of aviation and meteorology advancement and integration.
 Source: Figure by author.

In the early years of the interaction between aviation and meteorology, integration was *ad hoc* of necessity. The first true test of their integration came in World War II, when both sciences coexisted and matured together. At every level of war in that conflict, aviation and meteorology worked as an integrated unit – not perfect, certainly not equal, but in harmony. The subsequent lapse in integration reflects aviation technology's efforts to minimize the impact of weather on aviation operations, largely successful in munitions with the development of the GPS-guided bomb but still short falling short of victory in airframe design. Another possible factor is the lack of revolutionary growth in weather prediction. Evolutionary improvement is boring "normal science." Rather than responding with glee to evolutionary changes in meteorology, commanders, pilots, and decision makers today essentially stifle yawns. James Fahey, a Command and Staff College instructor while a member of the Army Air

Corps, wrote of yet another factor crippling integration: “Despite lessons clearly pointed out in the past war, there is still a reluctance, especially on the part of some ground and service personnel, to bring weather into operational planning. This contention is borne out by the fact that in some of our service schools today, we find that weather as a subject on the curriculum has been only lightly treated.”⁸ The author’s experience at Air Command and Staff College in 2008-2009 was consistent with this assessment made over 60 years ago.⁹

Opportunities for Improvement

Despite dramatic leaps in both the aviation and weather fields, aviation integration of meteorology appears irregular and stagnant. Do commanders, pilots, and decision makers always place the right emphasis on the supporting elements of their pointy-end-of-the-spear weapon systems? For imperfect humans, the answer must always be no. But can humans improve? Can humans look past the pointy end of the spear to see the critical mass in the shaft, and the muscles in the body that propels it, and the senses that optimize its effective use? Yes. This paper is historical in scope, and does not pretend to offer a cure for what appears to be a problem of integration. Nevertheless, analysis of factors this paper identified as contributing to improved or worsened aviation integration of weather prediction is inevitable. Some of the factors provide a cure worse than the disease: a war for national survival improved aviation integration of weather prediction, but poorer integration is a small price to pay for the long absence of existential war fears in the United States. Similarly, the *ad hoc* nature of aviation integration of weather prediction, following revolutionary aviation technology advances, worsens integration, but that loss is a small price to pay for the benefits which accrue on the edge of chaos. This paper tentatively advances concepts which might benefit integration if attempted. Even if the attempt proves

⁸ Major James M. Fahey, “Get the Weather on Your Side,” *Military Review* 27, no. 1 (April 1947): 35.

⁹ The author highlighted every weather reference in every text and lecture and noted it in each subsequent seminar. Regardless, only one portion of one lesson, focused on “other” elements of operational planning, addressed weather specifically.

ineffective, like the Army's experimental automated weather decision tool described in Chapter 5, the effort both enlivens the discussion of the role of weather in modern warfare and serves as a data point to inform future integration improvements. The first concept is to shift weather briefings from a deterministic to a probabilistic format. The second concept is to provide a weather-sensor-to-shooter capability on the Global Information Grid. The third concept is to add weather officers to the already-growing pool of officers eligible to lead the Air Operations Center's Strategy Division. Each of the following three paragraphs is a brief précis of the concept.

Probabilistic Weather Forecasts: Everything Old is New Again. While the fundamental nature of warfare has not changed, the character of war changes from era to era. Early in the science of weather prediction, operational commanders demanded forecasters give odds on their forecast accuracy. Today, ensemble computer modeling leverages the power not only of computation but also the power of computational prediction markets. Operational commanders accustomed to go/no-go or red-yellow-green weather assessments may find a shift from deterministic briefings discomfiting at first, but the more nuanced probabilistic assessments actually give the decision maker more information. For example, an aerodrome weather forecast which states "the cloud ceiling tomorrow from 0800Z to 1100Z will be 900 feet" presents an unrealistic and dangerous illusion of precision. A pilot interested only in a 0815Z takeoff, and unable to take off if the ceiling is lower than 1,000 feet, understands the forecast to state, "at 0815Z, the cloud deck will be at 900 feet, not 1,000 feet." That level of precision is not generally attainable by any method other than hindsight. Nevertheless, the decision is made not to fly - but by whom? Did the pilot read the forecast and estimate the probability the weatherman could be wrong by 100 feet, or by 15 minutes? The pilot may have made a subjective assessment based on experience with general weather forecast accuracy and other relevant factors.¹⁰ More likely,

¹⁰ If the pilot has flown from the airfield for some time, he may also have experience with the local conditions, the weather forecasting team, and his specific weather briefer. None of these subjective experiences, however, compare favorably to the objective assessment of uncertainty extracted from ensemble weather modeling.

absent other information, the pilot took the weatherman at his presumed word. To mitigate this shift in decision-making from the pilot to the forecaster, the weather forecast instead could state, “the cloud ceiling tomorrow from 0600Z to 1100Z has an 85% probability of being between 1,000 feet and 1,400 feet, a 13% probability of being between 600 feet and 900 feet, and a 2% probability of being 500 feet or below.” Now the pilot can make a more informed decision. The World Meteorological Organization permits probabilistic forecasts for certain flight hazards, though the Department of Defense is more restrictive. Perhaps it is time to loosen those restrictions in order to better inform commanders, pilots, and decision makers.

Sensor-to-Shooter Meteorology: Weather in the Cockpit. Weather prediction is a demanding science and art, but generally the most important things pilots need to know fall well within the predictability envelope. Can I take off in an hour? Will weather hazards prevent my four-hour transit to and from the engagement area? Will target conditions permit engagement with the weapon and at the range and attack axis designated by mission planning? The bureaucratic processes which slow movement from attack planning to launch extend timelines to a surprising degree. Weather briefings may precede takeoff time by several hours, requiring updates by radio to allow a legal launch. Once the flight is in route, a cumbersome radio and telephone network connects pilots to meteorologists. Insufficient data sometimes makes the pilot, the only one to see below the clouds in the next valley over, the best source of weather information – yet he calls back to the weather station with a request for an update. Those radio calls can be frustrating for both parties. A sensor-to-shooter weather capability could mitigate the frustrations and save time. The Global Information Grid espoused by politicians and military advocates contains vast amounts of real-time and near-real-time weather data. Some of the weather data requires detailed analysis to be of value; others, such as satellite or surveillance or reconnaissance images, can inform any pilot.¹¹ While the Army’s effort at automation failed, that

¹¹ Weather familiarization training for pilots must comply with Federal Aviation Administration requirements. Of the 523 “Learning Statements” that compose the minimum training objectives

failure should not quash ongoing efforts to ensure relevant weather information rides on the command and control backbone of the military segment of the Global Information Grid.

A Weather Seat at the Table: AOC Strategy Division Chief. During times of survival warfare, leaders in the modern era saved a seat at or near the table for the weather forecaster. With the advent of increasingly all-weather systems as well as other factors, the meteorologist's seat has moved farther away from the center of decision. While this may be fitting based on function, it does not take full advantage of the often unique, unconventional characteristics which, in a heterogeneous environment best suited for out-of-the-box thinking, offer asymmetric advantage to the commander bold enough to employ them. Weathermen may be generally an idiosyncratic bunch, but they develop from military birth habits of strategic thinking as they attempt to predict the peculiarities of Mother Nature. Clausewitz would applaud the comparison of weather to an enemy general, and Jomini would recognize the *coup d'oeil* of a skilled meteorologist surveying the atmosphere, his battleground. The habits weathermen adopt in order to deal with a massively complex, self-organizing system that is phenomenally sensitive to initial conditions can yield great benefits when applied to other systems – like any system involving massively complex, self-organizing humans, who are phenomenally sensitive to their conditions. The author does not suggest weathermen should command the air fleet, but that a weatherman could run the Air Operations Center Strategy Division as well as a pilot, navigator, space and missile officer, or intelligence officer. How does this improve aviation integration of weather prediction? By keeping a weatherman close to the center of decision, lessons learned in existential conflicts might be more readily internalized rather than painfully remembered.

Considering these three modest proposals as potential mechanisms to improve aviation integration of weather prediction should not close the door to

for the most basic pilot's license, 76 pertain to meteorology. Federal Aviation Administration, "Learning Statement Reference Guide for Airman Knowledge Testing," 6 July 2009, 2-14. Also available online at http://www.faa.gov/training_testing/testing/airmen/media/LearningStatementReferenceGuide.pdf (accessed 19 April 2010).

other proposals. Improved aviation integration of weather prediction is a worthwhile goal, as long as improved integration improves the chance of better tactical, operational, strategic, and grand strategic outcomes. The purpose of the military meteorologist – to contribute to the fight – finds validation in those outcomes.

BIBLIOGRAPHY

Academic Papers

- Aristotle. *Meteorologica*. Translated by E.W. Webster. Adelaide, Australia: The University of Adelaide Library, 2007.
- Atkinson, Lt Col Gary D. "Impact of Weather on Military Operations: Past, Present, and Future." Research Report no. AD911125. Carlisle Barracks, PA: US Army War College, 1973.
- Bernoulli, Daniel, and Johann Bernoulli. *Hydrodynamics and Hydraulics*. Translated by Thomas Carmody. Mineola, NY: Dover Publications, 2004. Originally published in Latin in 1738.
- Frana, Philip. Transcript of interview with Carl Machover, 20 June 2002. Charles Babbage Institute, Center for the History of Information Processing, University of Minnesota, Minneapolis, MN. Available online at <http://www.cbi.umn.edu/oh/pdf.phtml?id=323> (accessed 27 March 2010).
- Green, Constance McLaughlin, and Milton Lomask. *Vanguard: A History*. The NASA Historical Series no. SP-4202. Washington, D.C.: National Aeronautics and Space Administration, 1970.
- Idrisi, Zohor. *The Muslim Agricultural Revolution and its Influence on Europe*. Foundation for Science Technology and Civilisation occasional paper. Manchester, England: FSTC, June 2005.
- Jesmain, Andrew. "U.S. Competitiveness in the Fighter Aircraft Export Market: Defense Industrial Initiatives Current Issues No. 12." Washington, D.C.: Center for Strategic and International Studies, 26 May 2009.
- Larew, Karl. *Meteorology in the U.S. Signal Corps, 1870-1960*. Signal Corps Historical Division study. Washington, D.C.: Signal Corps Historical Division, 1960.
- Millikan, Frank Rives. "Joseph Henry: Father of the Weather Service." Historical study. The Joseph Henry Papers Project. Washington, D.C.: Smithsonian Institution, 1997.
- Ogden, R.J. *Meteorological Services Leading to D-Day*. Occasional Papers on Meteorological History Number 3. Reading, United Kingdom: Royal Meteorological Society, 2001.
- Schultz, David M. "Perspectives on Fred Sanders's Research on Cold Fronts." Paper submitted to the Fred Sanders Symposium, September 2003. Norman, OK: Cooperative Institute for Mesoscale Meteorological Studies, 2 September 2003, revised 7 September 2006.
- Thelen, Ed. "MADAR." Working paper. <http://ed-thelen.org/comp-hist/JVG-MADAR.doc> (accessed 27 March 2010).

Articles

- Bentley, Richard. "Weather in War-Time." *Quarterly Journal of the Royal Meteorological Society* 33, no. 142 (April 1907): 81-138.
- Bjerknes, Vilhelm. "Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik." *Meteorologie Zeitschrift* 21 (January 1904): 4.
- Boeing: United States Tanker. "767 Airplane Characteristics for Airport Planning." <http://www.unitedstatetanker.com> (accessed 7 April 2010).

- Brandli, Henry W. "The Use of Meteorological Satellites in Southeast Asia Operations." *Aerospace Historian* 29, no. 3 (Fall/September 1982): 172-73.
- "Company News; Lockheed Finishes Purchase of General Dynamics Unit," *New York Times*, 2 March 1993.
- "A Chronological Outline of the History of Meteorology in the United States of North America." *Monthly Weather Review* 37, no. 3 (March 1909): 88-89.
- Dash, Maj Ernie R., and Maj Walter D. Meyer. "The Meteorological Satellite: An Invaluable Tool for the Military Decision-Maker." *Air University Review* 29, no. 3 (March – April 1978): 13.
- Downey, Fairfax. "When the Great, White Cold Walked at Eylau." *Army*, March 1974, 46-49.
- Edgecomb, Captain F.E. "Meteorology for Artillery." *Coastal Artillery Journal* 69, no. 3 (September 1928): 203-11.
- Fahey, Major James M. "Get the Weather on Your Side." *Military Review* 27, no. 1 (April 1947): 35-40.
- Finney, John W. "C-5A jet repairs to cost 1.5 billion; Pentagon outs outlay to fix Wing Defects at 1.3 Billion as 'Overruns' continue." *New York Times*, 15 December 1975.
- Ford, Donald H. "Base Your Plans on Future Weather." *Military Review*, August 1944, 67-71.
- Fulghum, David A. "Away Game." *Aviation Week & Space Technology*, 8 January 2007, 6-7.
- Fulghum, David A., and Michael J. Fabey. "Raptor Scores in Alaskan Exercise." *Aviation Week & Space Technology*, 7 January 2007, http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=defense&id=news/aw010807p1.xml (accessed 31 March 2010).
- Garamone, Jim. "Budget Request Continues Reform Agenda." American Forces Press Service, 1 February 2010, http://www.wivb.com/dpps/military/Defense-Department-budget-request-continues-reform-agenda_3216004 (accessed 31 March 2010).
- Garbett, Commander L.G., R.N. (ret). "Meteorology & the Fighting Services." *Journal of the Royal United Service Institution* 73, no. 492 (November 1928): 700-15.
- Gates, Dominic. "EADS/Northrop Trumps Boeing in Air Force Tanker Competition." *The Seattle Times*, 29 February 2008.
- "General Dynamics (now Lockheed Martin) F-16 Fighting Falcon Multi-Role Fighter." AerospaceWeb.org. <http://www.aerospaceweb.org/aircraft/fighter/f16/> (accessed 26 March 2010).
- Gibbs, Philip. "Mud the Chief Enemy as British Advanced." *New York Times*, 12 October 1917.
- GlobalSecurity.org. "C-5 Service Life," <http://www.globalsecurity.org/military/systems/aircraft/c-5-serv.htm> (accessed 27 March 2010).
- GlobalSecurity.org. "F-16 Fighting Falcon - International Users," <http://www.globalsecurity.org/military/systems/aircraft/f-16-fms.htm> (accessed 26 March 2010).

- Gray, Carroll F. "The First Five Flights: The Slope and the Winds of Big Kill Devil Hill – The First Flight Reconsidered." *WW1 AERO – The Journal of the Early Aeroplane*, August 2002, 26-39.
- Guevara, Inigo. "Dominican Republic since 1945." *Air Combat Information Group Journal*, 1 September 2003, http://www.acig.org/artman/publish/article_153.shtml (accessed 22 March 2010).
- Hadley, George. "Concerning the Cause of the General Trade Winds." *Philosophical Transactions* 39 (1735): 58-62.
- Hehs, Eric. "Harry Hillaker – Father of the F-16," *Code One*, April 1991 (part one) and July 1991 (part two), http://www.codeonemagazine.com/archives/1991/articles/jul_91/july2a_91.html (accessed 26 March 2010).
- Hillaker, Harry. "Tribute to John R. Boyd." *Code One*, July 1997, http://www.codeonemagazine.com/archives/1997/articles/jul_97/july2a_97.html (accessed 26 March 2010).
- Holcomb, Kevin. "Curtiss JN-4D - Specifications & Operating Instructions." Holcomb's Aerodrome, http://www.airminded.net/jenny/jn4_spec.html (accessed 2 December 2009).
- Kruzel, John J. "Pentagon Reopens Bidding on Tanker Contract." American Forces Press Service, <http://www.defense.gov/news/newsarticle.aspx?id=50453> (accessed 31 March 2010).
- Leith, C.E. "Theoretical Skill of Monte Carlo Forecasts." *Monthly Weather Review* 102, no. 6 (June 1974), 409-18.
- Link, Albert E. "War and the Weather--and the Staff." *Military Review*, December 1943, 37-38.
- Lockheed Martin Aeronautics Company. "Flight Test Data Performance Criteria." <http://www.f22-raptor.com/technology/data.html> (accessed 31 March 2010).
- "Lockheed Martin F-16 Fighting Falcon." *Jane's All The World's Aircraft*, http://www4.janes.com/subscribe/jawa/doc_view.jsp?K2DocKey=/content1/janesdata/yb/jawa/jawa1348.htm@current&Prod_Name=JAWA&QueryText=%5Df-16 (accessed 26 March 2010).
- Lorenz, Edward N. "Deterministic Nonperiodic Flow." *Journal of the Atmospheric Sciences* 20, no. 2 (March 1963): 130-141.
- Lynch, Peter. "The ENIAC Forecasts: A Re-creation." *Bulletin of the American Meteorological Society* 89, no. 1 (January 1989): 45-55.
- Martin, Robert J. "Meteorology in Peace and War." *The Military Engineer* 32, no. 185 (September-October, 1940): 343-46.
- Northrop Grumman. "Statement From Northrop Grumman on U.S. Air Force Aerial Refueling Tanker Program," 8 March 2010, http://www.irconnect.com/noc/press/pages/news_releases.html?d=186116 (accessed 31 March 2010).
- Palmer, Tim. "Edward Norton Lorenz." *Physics Today* 61, no. 9 (September 2008): 81-82.
- Pate, Elbert W. "Weather and the War in Europe." *United States Naval Institute Proceedings* 68, no. 469 (March, 1942): 327-32.

- Powell, 2d Lt William. "General Jumper qualifies in F/A-22 Raptor." *Air Education and Training Command News*, 13 January 2005,
<http://www.af.mil/news/story.asp?storyID=123009594> (accessed 31 March 2010).
- Prioreschi, Plinio. "Al-Kindi, A Precursor Of The Scientific Revolution." *Journal of the International Society for the History of Islamic Medicine* 1, no. 2 (October 2002): 17-19.
- Pfister, Christian *et al.* "Daily Weather Observations in Sixteenth-Century Europe." *Climatic Change* 43, no. 1 (September 1999): 111-50.
- Reed, John. "Official: Fighters Should Be Used for Spying." *Air Force Times*, 20 December 2009,
http://www.airforcetimes.com/news/2009/12/airforce_deptula_121909/ (accessed 31 March 2010).
- Reed, Thomas R. "Meteorology—An Aid to Aviation." *The Military Engineer* 18, no. 102 (November-December 1926): 476-79.
- Richard, A1C Alina. "Around the Air Force." *Around the AF TV*, 26 March 2010,
<http://www.af.mil/news/video/index.asp?cid=2&sid=12256> (accessed 31 March 2010).
- Rosby, Carl-Gustaf. "Relation between Variations in the Intensity of the Zonal Circulation of the Atmosphere and the Displacements of the Semi-Permanent Centers of Action." *Journal of Marine Research* 2, no. 1 (January 1939): 38-55.
- Schuman, Frederick. "History of Numerical Weather Prediction at the National Meteorological Center." *Weather and Forecasting* 4, no. 3 (September 1989): 286-296.
- Schuster, Carl O. "Weather War." *Command*, November - December 1991, 70-73.
- Stice, 1st Lt Kenneth S. "Weather Forecasting for the Army." *Chemical Warfare* 12, no. 3 (15 March 1926): 2-6.
- Toth, Zoltan, and Eugenia Kalnay. "Ensemble Forecasting at NCEP and the Breeding Method." *Monthly Weather Review* 102, no. 12 (December 1997): 3297-319.
- Victoria and Albert Museum. "Art Deco Study Guide." Victoria and Albert Museum,
http://www.vam.ac.uk/nal/guides/art_deco/index.html (accessed 22 March 2010).
- Ward, Robert DeCourcy. "The European Winter and the War." *The Journal of Geography* 13, no. 6 (February 1915): 169-71 and no. 7 (March 1915): 208-15 and Vol. 14, no. 3 (November 1915): 71-76 and no. 10 (June 1916): 373-84 and Vol. 15, no. 3 (November 1916): 79-86 and no. 8 (April 1917): 245-51 and Vol. 16, no. 2 (October 1917): 47-51 and no. 3 (November 1917): 86-90 and no. 8 (April 1918): 291-300.
- Ward, Robert DeCourcy. "The War and the Weather during the First Three Months of the Fighting." *Popular Science Monthly* 85, no. 36 (December 1914): 604-13.
- Ward, Robert DeCourcy. "Weather Controls Over the Fighting in the Italian War Zone." *The Scientific Monthly* 6, no. 7 (February 1918): 97-105 and no. 19 (April 1918): 289-304 and Vol. 7, no. 1 (July 1918): 24-33.
- Wells, Clarence F. "Weather and Warfare: The Military Uses of Meteorological Data." *Army Ordnance* 16, no. 92 (September-October 1935): 101-105.
- Wenstrom, First Lt. W.H. "Modern Meteorology." *The Signal Corps Bulletin* 22, no. 85 (July-August 1935): 8-27.

Whiton, Roger C., Paul L. Smith, Stuart G. Bigler, Kenneth E. Wilk, and Albert C. Harbuck. "History of Operational Use of Weather Radar by U.S. Weather Services, Part I: The Pre-NEXRAD Era." *Weather and Forecasting* 13, no. 2 (June 1998): 219-243.

Books

- Angelucci, Enzo. *Great Aeroplanes of the World*. London, England: Hamlyn, 1973.
- Armstrong, J. Scott. "Combining Forecasts." In *Principles of Forecasting*. Edited by J. Scott Armstrong (Boston, MA: Kluwer Academic, 2001).
- Aronstein, David C., and Albert C. Piccirillo. *The Lightweight Fighter Program: A Successful Approach to Fighter Technology Transition*. Reston, VA: American Institute of Aeronautics and Astronautics, 1996.
- Biddle, Tami Davis. *Rhetoric and Reality in Air Warfare*. Princeton, NJ: Princeton University Press, 2002.
- Bishop, Lt. Col. William A. *Winged Warfare*. Garden City, NY: Doubleday & Company, Inc., 1967.
- Bradley, Raymond S., and Philip D. Jones. *Climate Since A.D. 1500*. New York, NY: Routledge, 1992.
- Caldwell, Donald, and Richard Muller. *The Luftwaffe over Germany: Defense of the Reich*. London: Greenhill Books Publications, 2007.
- Delve, Ken. *The Mustang Story*. London: Cassell & Company, 1999.
- Donald, David, ed. *The Encyclopedia of World Aircraft*. London, England: Aerospace Publishing, 1997.
- DuBois, John, Robert Multhauf, and Charles Ziegler. *The Invention and Development of the Radiosonde, with a Catalog of Upper-Atmospheric Telemetering Probes in the National Museum of American History, Smithsonian Institution*. Washington, D.C.: Smithsonian Institution Press, 2002.
- Dunlop, Douglas M. *Arab Civilization to 1500 A.D.* New York, NY: Praeger, 1971.
- Dwiggins, Don. *They Flew the Bendix Race: the History of the Competition for the Bendix Trophy*. Philadelphia, PA: J.B. Lippincott Company, 1965.
- Emanuel, Kerry. "Back to Norway: An Essay." In *Synoptic-Dynamic Meteorology and Weather Analysis and Forecasting: A Tribute to Fred Sanders*. Edited by Lance Bosart and Howard Bluestein. Boston, MA: American Meteorological Society, 2008.
- Evans, Mark Llewellyn. *Great World War II Battles in the Arctic*. Westport, CT: Greenwood Press, 1999.
- Fahd, Toufic. "Botany and Agriculture." In *Encyclopedia of the History of Arabic Science, Vol. 3*. Edited by Rashed Roshdi and Régis Morelon. New York, NY: Routledge, 1996.
- Fahey, James C. *U.S. Army Aircraft (Heavier than Air) 1908-1946: The Ships and Aircraft of the United States Fleet*. New York, NY: Ships and Aircraft, 1946.
- Ferguson, Arthur B. "POINTBLANK." In *The Army Air Forces in World War II, Vol. 2, Europe: TORCH to POINTBLANK, August 1942 to December 1943*. Edited by W.F. Craven and J.L. Cate. Chicago, IL: University of Chicago Press, 1949.
- Fleagle, Robert. *Eyewitness: Evolution of the Atmospheric Sciences*. Boston, MA: American Meteorological Society, 2001.

- Fuller, John F. *Thor's Legions: Weather Support to the U.S. Air Force and Army, 1937-1987*. Boston, MA: American Meteorological Association, 1990.
- Gifford, Jack J. "The Influence of Weather on Combined Arms Operations in Korea, 1950." In *Combined Arms in Battle since 1939*. Edited by Roger J. Spiller. Fort Leavenworth, KS: U.S. Army Command and General College Press, 1992.
- Green, William, and Gordon Swanborough. *The Great Book of Fighters: An Illustrated Encyclopedia of Every Fighter Aircraft Built and Flown*. Osceola, WI: MBI Publishing Company, 2001.
- Griffith, Thomas E., Jr. *MacArthur's Airman: General George C. Kenney and the War in the Southwest Pacific*. Lawrence, KS: University of Kansas Press, 1998.
- Gulic, Fred E.C., and Spencer Dunmore. *On Great White Wings*. Shrewsbury, England: Airlife Publishing Ltd., 2001.
- Harper, Kristine. *Weather by the Numbers: The Genesis of Modern Meteorology*. Cambridge, MA: Massachusetts Institute of Technology Press, 2008.
- Holmes, Richard, ed. *The Oxford Companion to Military History*. New York, NY: Oxford University Press, 2001.
- Jablonski, Edward. *AIRWAR: An Illustrated History of Air Power in the Second World War*, vol. 2, *Tragic Victories*. Garden City, NY: Doubleday & Company, 1971.
- Knaack, Marcelle Size. *Encyclopedia of U.S. Air Force Aircraft and Missile Systems: Volume 1, Post-World War II Fighters 1945-1973*. Washington, DC: Office of Air Force History, 1978.
- Knowles Middleton, W.E. *Invention of the Meteorological Instruments*. Baltimore, MD: Johns Hopkins Press, 1969.
- Kometer, Michael W. *Command in Air War: Centralized Versus Decentralized Control of Combat Airpower*. Maxwell AFB, AL: Air University Press, 2007.
- Komons, Nick A. *Bonfires to Beacons: Federal Civil Aviation Policy Under the Air Commerce Act 1926-1938*. Washington, D.C.: Smithsonian Institution Press, 1989.
- Kosambi, D.D. *The Culture and Civilization of Ancient India in Historical Outline*. New Delhi: Vikas Publishing House, 1982.
- Krick, Irving, and Roscoe Fleming. *Sun, Sea, and Sky; Weather In Our World and In Our Lives*. Philadelphia, PA: Lippincott, 1954.
- Lays, Maxwell G. *Ways of the World: A History of the World's Roads and of the Vehicles that Used Them*. New Brunswick, NJ: Rutgers University Press, 1992.
- Lewis, Cecil. *Sagittarius Rising*. 2d ed. Harrisburg, PA: Stackpole Books, 1963.
- McCudden, Major James T.D. *Flying Fury: Five Years in the Royal Flying Corps*. Garden City, NY: Doubleday & Company, Inc., 1968.
- McFarland, Marvin W., ed. *The Papers of Wilbur and Orville Wright, including the Chanute-Wright Letters and other papers of Octave Chanute*. New York, NY: McGraw-Hill, 1953.
- Miller, Donald L. *Masters of the Air: America's Bomber Boys Who Fought the Air War Against Nazi Germany*. New York, NY: Simon & Schuster, 2006.
- Mitchell, William. *Winged Defense*. Tuscaloosa, AL: Fire Ant Press, 2009.
- Morrow, John H., Jr. *The Great War in the Air: Military Aviation from 1909-1921*. Tuscaloosa, AL: University of Alabama Press, 1993.
- Pedlosky, Joseph. *Geophysical Fluid Dynamics*. New York, NY: Springer, 1990.

- Petterssen, Sverre. *Weathering the Storm: Sverre Petterssen, the D-Day Forecast, and the Rise of Modern Meteorology*. Boston, MA: American Meteorological Society, 2001.
- Richardson, Doug. *General Dynamics F-16 Fighting Falcon*. London, England: Salamander Books, 1990.
- Richardson, Lewis Fry. *Weather Prediction by Numerical Process*. Cambridge, England: Cambridge University Press, 1922.
- Rickenbacker, Eddie V. *Fighting the Flying Circus*. Garden City, NY: Doubleday & Company, Inc., 1965.
- Satoh, Masaki. *Atmospheric Circulation Dynamics and General Circulation Models*. New York, NY: Springer, 2004.
- Schlaifer, Robert, and S. D. Heron. *Development of Aircraft Engines: Two Studies of Relations Between Government and Business*. Boston, MA: Division of Research, Graduate School of Business Administration, Harvard University, 1950.
- Sims, Edward H. *Fighter Tactics and Strategy, 1914-1970*. New York, NY: Harper & Rowe, 1972.
- Spires, David N. *Beyond Horizons: A Half Century of Air Force Space Leadership*. Maxwell AFB, AL: Air University Press, 1998.
- Stagg, James Martin. *Forecast for Overlord, June 6, 1944*. New York, NY: W.W. Norton, 1971.
- Stevens, William Oliver, and Allan Westcot. *A History of Sea Power*. New York, NY: George H. Doran Company, 1920.
- Sunstein, Cass R. *Infotopia: How Many Minds Produce Knowledge*. New York, NY: Oxford University Press, 2006.
- Tenant, John Edward. *In the Clouds Above Baghdad, Being the Records of an Air Commander*. London, England: Cecil Palmer, 1920.
- Tobin, James. *To Conquer the Air: The Wright Brothers and the Great Race for Flight*. New York, NY: Simon & Schuster, 2004.
- Udet, Ernst. *Ace of the Iron Cross*. Garden City, NY: Doubleday & Company, Inc., 1970.
- Wood, Ghislaine. *Essential Art Deco*. London, England: V&A Publications, 2003.
- Yenne, Bill. *The Story of the Boeing Company*. St. Paul, MN: Zenith Press, 2005.

Government Documents

- 2d Weather Group Regulation 55-12. *Operations*, 16 May 1958.
- 2d Weather Group Regulation 55-92. *Tactical Staff Weather Officers*, 22 November 1955.
- “Air Force Weather Agency Historical Highlights.” Air Force Weather History Office, <https://afweather.afwa.af.mil/about/history/docs/AFWAHistoricalHighlightsBrochureMay2005.pdf> (accessed 7 April 2010).
- Army Air Force Manual 50-13. *Boeing B-17 Pilot Training Manual*, 1 May 1945
- “The Early History of Numerical Weather Prediction.” The European Centre for Medium-Range Weather Forecasts, http://www.ecmwf.int/products/forecasts/guide/The_early_history_of_Numerical_Weather_Prediction.html (accessed 30 March 2010).

Espy, James P. *First Report on Meteorology, Made to the Surgeon General, U.S. Army*. Washington, D.C.: Public Printer, 1843.

“F-22 Raptor Fact Sheet.” Air Combat Command Public Affairs Office, http://www.af.mil/information/factsheets/factsheet_print.asp?fsID=199&page=1 (accessed 31 March 2010).

Golden, Michael R. “GAO Sustains Boeing Bid Protest.” Government Accounting Office, http://www.gao.gov/press/press-boeing2008jun18_3.pdf (accessed 31 March 2010).

History. 2d Weather Group, 1 January 1955 – 30 June 1955.

History. 2d Weather Group, 1 January 1956 – 30 June 1956.

History. 2d Weather Group, 1 January 1958 – 30 June 1958.

History. 2d Weather Group, 1 January 1961 – 30 June 1961.

“The History of Numerical Weather Prediction: The Early Evolution.” National Oceanographic and Atmospheric Administration, http://celebrating200years.noaa.gov/foundations/numerical_wx_pred/ (accessed 30 March 2010).

Hoh, Roger H., and David G. Mitchell. “Flying Qualities of Relaxed Static Stability Aircraft-Volume I.” Federal Aviation Administration (DOT/FAA/CT-82/130-I), September 1983.

Joint Publication 1-02. *DOD Dictionary of Military and Associated Terms*, 12 April 2001, as amended through 31 October 2009.

“Lieutenant General William Oscar Senter.” Air Force biography, <http://www.af.mil/information/bios/bio.asp?bioID=7107> (accessed 25 April 2010).

National Museum of the United States Air Force. “Boeing B-17F Fact Sheet.” National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2453> (accessed 22 March 2010).

National Museum of the United States Air Force. “C-5 Galaxy Fact Sheet.” National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=84> (accessed 27 March 2010).

National Museum of the United States Air Force. “F-16 Fighting Falcon Fact Sheet.” National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=103> (accessed 26 March 2010).

National Museum of the United States Air Force. “Martin MB-2 Fact Sheet.” National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2415>.

National Museum of the United States Air Force. “Martin NBS-1 Fact Sheet.” National Museum of the United States Air Force website, <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2416> (accessed 22 March 2010).

National Museum of the United States Air Force. “North American P-51 Fact Sheet.” National Museum of the United States Air Force website,

- <http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=2214> (accessed 22 March 2010).
- “Naval Aviation Chronology 1917-1919.” Naval Historical Center,
<http://www.history.navy.mil/branches/avchr2.htm> (accessed 6 April 2010).
- “NOAA Legacy Time Line, 1900-1969.” National Oceanic & Atmospheric
Administration Central Library,
http://www.history.noaa.gov/legacy/time1900_1.html (accessed 29 March 2010).
- “PM Battle Command Common Software.” Program Executive Office Command
Control Communications – Tactical,
http://peoc3t.monmouth.army.mil/battlecommand/bc_common_software.html
(accessed 1 April 2010).
- United States Army Signal Corps. *Report of the Chief Signal Officer, 1946*. Washington,
D.C., Government Printing Office, 1947.

Reports

- Nobis, Timothy E., Evan L. Kuchera, Scott A. Rentschler, Steven A. Rugg, Jeffrey G. Cunningham, Chris Synder, and Joshua P. Hacker. “Towards the Development of an Operational Mesoscale Ensemble System for the DoD Using the WRF-ARW Model.” Air Force Weather Agency Report. Offutt AFB, NE: Air Force Weather Agency, 2008.
- Passner, Jeffrey E. “Post-Processing for the Battlescale Forecast Model and Mesoscale Model Version 5.” ARL-TR-2988. White Sands Missile Range, NM: Army Research Laboratory, 2003.
- Szymler, Richard. “U.S. Army Tactical Weather Support Requirements for Weather and Environmental Data Elements and Meteorological Forecasts.” Army Research Laboratory Technical Report 3720. Available online at
<http://www.arl.army.mil/arlreports/2006/ARL-TR-3720.pdf> (accessed 1 April 2010).