IMPACTS OF WEATHER AND CLIMATE VARIABILITY

ON COMMERCIAL AVIATION OPERATIONS

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CHAPTER I. INTRODUCTION

Weather impacts aviation in numerous ways and is a major concern of the aviation community. Pilot's need to avoid weather that will negatively impact the safety of a flight and understand how it will impact the performance of the aircraft. Air traffic controllers need to understand where hazardous thunderstorms are located so that they can direct aircraft to safety. Dispatchers need to understand how the environmental temperatures will affect the takeoff and landing distances. Passengers need to know whether or not a coming hurricane will cancel future flights. From this small number of examples one can understand the impacts of the atmosphere on the aviation community. In fact, without the atmosphere aviation would be impossible! Over the decades, research has focused on developing products that can improve the safety and efficiency of flights. From radars to short term forecasts, every advancement in technology and understanding has driven the aviation community to new heights.

Besides impacts to the operations of airlines and other aviation community members, weather impacts the economic performance of the aviation community by creating delays and cancellations. In 2007, the total cost of airlines delays was $32.1 billion dollars (NEXTOR, 2008). When looking at weather's role in creating delays and cancellations, weather is a significant factor and is discussed in detail in Chapter IV and Chapter VI. While forecasts have allowed aviation operators to make some adjustments to operations, weather still impacts airlines since schedules are created and finalized weeks in advance. By better understanding the expected weather climatologies of an airport and how each specific weather type impacts each individual airport, planners and schedulers can create schedules that work to eliminate the impacts of expected weather predictions. For example, if an airport is prone to early morning fog and icing conditions in December and January, an airline scheduler can adjust the schedule to

take into account low visibility airport and aircraft deicing operations. One goal of this thesis is to develop a method to determine the weather climatologies of airports using aviation weather observations and determine the impacts of specific weather types on operations. With this knowledge, adjustments in the schedules can be made in areas where weather is creating delays or cancellations.

With the interest of improving the economic performance of companies and the impacts of global warming on aviation becoming a greater concern, more emphasis has been placed on seasonal forecasts and understanding how long time scale atmospheric phenomena impact businesses and societies. By understanding what the expected weather will be months in advance, this information can be used when the airline schedules are developed and finalized. For example, if an airline knows months in advance that airport hub A will experience more snow and freezing precipitation for the winter months than is normal and that airport hub B will have fewer occurrences of frozen precipitation than what is normally observed, an airline can adjust the operations so that airport B has more flights or higher revenue flights instead of airport A. The airline can also include the increased costs from delays and cancellations at airport A in its financial portfolio. The airline could also adjust its distribution of equipment, such as deicing equipment, so that airport A is better equipped to handle winter events and the weather impacts are minimized. Another major goal of this thesis is to determine how climate teleconnections impact the monthly weather at U.S. airports. By understanding how the Arctic Oscillation (AO) and the El Niño Southern Oscillation (ENSO) impacts past monthly weather observations, this information can be used to assess the future expected weather observations of an airport based on the forecasts of either the AO or ENSO. The AO and ENSO teleconnection patterns and airport impacts are discussed in Chapter III and Chapter VII.

A third goal and indirect goal of this thesis is to explore the use of messy, unconventional meteorological and aviation performance datasets in applied atmospheric research. The use METAR and Federal Aviation Administration datasets in an academic research framework may allow for new discoveries of relevant information or new uses for existing datasets. The weather climatologies, such as the diurnal patterns of fog or freezing precipitation, could also be used to help operational forecasters or other industries, such as the energy industry, in their day to day operations or research.

CHAPTER II. METEOROLOGICAL DATA

2.1 METARs

Hourly surface weather observations called METARs provide important information for aviation operations. METARs, also known as Meteorological Aviation Routine Weather Report, contain data for the temperature, dew point, wind speed and direction, precipitation, cloud cover and heights, visibility, and barometric pressure at a particular location. Another report similar to the METAR is the SPECI which is the name of the code for an aviation special weather report and has the same structure as the METAR. A detailed description of a METAR or a SPECI can be found in World Meteorological Organization publication number 782 *Aerodrome Reports and Forecasts: A Users' Handbook to the Codes*. METAR and SPECI reports are provided by human observers or by the Automated Surface Observing Systems (ASOS).

The primary function of the Automated Surface Observing System (ASOS) is to provide the METAR and SPECI aviation reports along with minute-by-minute weather observations for other purposes such as forecasting and scientific research and replaces the need for human observed observations. Refer to the *ASOS User's Guide* for more information regarding standard instrumentation and reporting capabilities. This information is used by the aviation community to plan safe and efficient operations, the public for planning day to day activities, and by hydormeteorologists, climatologists, and meteorologists for scientific research (ASOS User's Guide, 1998). The ASOS program is a joint effort of the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DOD).

2.1.1 Use of METARs for Aviation Weather Research

There are four main reasons in choosing raw METARs over post-processed surface observation datasets. First reason is that many surface observation datasets do not have a long enough history. For example, the National Climatic Data Center (NCDC) Quality Controlled Local Climatological Data (QCLCD) hourly data is only available up to January 1, 2005. Second, many datasets do not provide hourly resolution. For example, the NCDC Daily Station Summaries dataset only provides daily observations; aviation operations are affected by diurnal weather which will not be present here. Third, some surface observation datasets, such as the NCDC ASOS datasets, are not available at the current time and are available one or more days after the observation. This is not useful for the aviation community because they need real time weather observations for planning and maintaining safe observations. The fourth and final reason is that the aviation community uses METARs for surface weather observations and no other surface observations; this means that what is present in the METAR will impact present and future aviation operations and will be most useful for understanding the impacts of weather on aviation.

2.1.2 Iowa Environmental Mesonet (IEM)

METARs (including SPECI) are available on the Iowa Environmental Mesonet (IEM) server and are used in this study. Many of the METARs available on the IEM predate the 1950s and provide fairly complete hourly weather observations from when METARs where collected at various airports until now; also, METARs are available for most major and minor airports within the United States and foreign countries. One benefit of using the IEM is that both raw and variable delimited METARs can be retrieved.

2.2 Important Weather Variables for Aviation

2.2.1 Temperature, Dew Point, and Pressure

Temperature and dew point measurements are made either manually, using such devices as a sling psychrometer, or automatically by the ASOS hygrothermometer. The fully automated "HO-83" hygrothermometer uses a platinum wire Resistive Temperature Device (RTD) to measure ambient temperature and a chilled mirror to determine dew point temperature (ASOS User's Guide, 1998). Pressure measurements can be made either manually or via the ASOS station. The ASOS pressure sensor consists of redundant digital pressure transducers which uses capacitive sensors where one side of the sensor is permanently excavated to a vacuum to make it a barometric pressure sensor (ASOS User's Guide, 1998).

2.2.2 Density Altitude

Of particular importance for aviation is the calculation of density altitude which is the pressure altitude corrected for temperature deviations from the standard atmosphere. Density altitude is used to assess the performance of an aircraft under given atmospheric conditions. For this study, density altitude is calculated using METAR data acquired from the IEM.

In order to calculate density altitude, the station pressure first must be calculated. Eq. 2.1 shows the formula for the station pressure.

$$P_{sta} = P_a \times \left(\frac{(288 - 0.0065 \times h_m)}{288}\right)^{5.2561} \qquad \text{Eq. 2.1}$$

P_{sta} is the station pressure in units of inches of mercury, P_a is the altimeter setting in units of inches of mercury, and h_m is the airfield elevation in units of meters. Next the vapor pressure is derived (shown in Eq. 2.2).

$$e = 6.11 \times 10^{\left(\frac{7.5 \times T_d}{237.7 + T_d}\right)} \qquad \text{Eq. 2.2}$$

e is the vapor pressure in units of millibars and T_d is the dew point temperature in units of Kelvin. Next, the virtual temperature is derived (shown in Eq. 2.3).

$$T_v = \frac{T}{1-\left(\frac{e}{P_{mb}}\right)\times(1-0.622)} \qquad \text{Eq. 2.3}$$

T_v is the virtual temperature and T is the ambient temperature both in units of Kelvin. In order to calculate density altitude, the virtual temperature needs to be converted to units of Rankine (T_R). The formula for density altitude is shown in Eq. 2.4.

$$H_{density} = 145366 \times \left(1 - \left(\frac{17.326 \times P_{sta}}{T_R}\right)^{0.235}\right) \qquad \text{Eq. 2.4}$$

$H_{density}$ is density altitude in units of feet. Looking at the equations, we see the factors that increase density altitude: increasing airfield elevation, increasing ambient temperature, increasing the dew point temperature, and decreasing the altimeter.

2.2.2.1 Impacts of Density Altitude on Aircraft Performance

Density altitude can be thought of as a measure of the density of air. As air density decreases, the density altitude increases. Lower air densities (and therefore higher density altitudes) can negatively affect the performance of an aircraft. Higher density altitudes result in lower amounts of lift produced and decreases engine performance (FAA Safety, 2008). Higher density altitudes also result in increases to the true airspeed of an aircraft for the same indicated airspeed. These factors can combine to produce a potentially hazardous situation for an operating aircraft.

Decreased engine performance as a result of the higher density altitude, will cause the aircraft to accelerate more slowly to the required higher airspeed. This means that the takeoff

distance for the aircraft under these conditions has now increased. Also since the aircraft is now traveling at faster speeds, the stopping distance for the aircraft would also increase.

According to Federal Aviation Regulation (FAR) §121.189, a pilot or dispatcher must take field elevation, ambient temperature, wind component, and runway conditions (if applicable) into consideration for takeoff. Also according to FAR §121.189 and FAR §25.113, three takeoff field lengths must be taken into account: the All-Engine Go Distance, the Engine-Out Accelerate-Go Distance, and the Accelerate-Stop Distance. These are all shown in Figure 2.1. The All-Engine Go Distance is 115% of the actual distance required to accelerate, liftoff and reach a point 35 feet above the runway with all engines operating (FAR §25.113). The Engine-Out Accelerate-Go Distance is the distance required to accelerate with all engines operating, have one engine fail at V_{EF} [Engine Failure Speed] at least one second before V_1 [Takeoff Decision Speed], continue the takeoff, liftoff and reach a point 35 feet above the runway surface at V_2 [Takeoff Safety Speed] (FAR §25.113).

The Accelerate-Stop Distance is the distance requires to accelerate with all engines operating, have an engine failure or other event at least one second before V_1, recognize the event, reconfigure the aircraft for stopping and bring the aircraft to a stop using maximum wheel braking with the speed brakes extended (FAR §25.113). According to FAR §121.189, in order for a commercial aircraft to legally takeoff, the Accelerate-Stop Distance cannot exceed the length of the runway plus the length of any stopway nor can the All-Engine Go Distance or the Engine-Out Accelerate-Go Distance exceed the length of the runway plus the length of any clearway. Since runways at airports are a fixed length, the total weight (payload) must be reduced during certain atmospheric conditions (i.e. high density altitudes) in order for the aircraft to legally and safely takeoff. Reducing the number of passengers or cargo carried reduces the

overall efficiency of the flight and reducing the fuel carried reduces the range of the aircraft which may require a fuel stop in order to complete a mission to the given intended destination and therefore will reduce efficiency. One possible solution to the problem is to lengthen the runways but this has two weaknesses: 1) a runway cannot be lengthened suddenly and requires additional funds to lengthen and 2) an aircraft is limited by a predetermined speed in which the landing gear cannot structurally accelerate further; if the required takeoff speed is higher than the speed the landing gear can handle, the aircraft cannot safely takeoff. Another solution is to operate a special aircraft fleet for hot and high airports; however, operating a sub-fleet of special performance aircraft requires planning and additional operating expenditures.

High density altitudes result in poorer climb performance due to the reduced lift and reduced engine performance. This can negatively impact safety but can also increase the time in which an aircraft can climb to its cruising altitude. This can result in the flight being less efficient since the aircraft spends more time burning fuel while it is ascending and spends more time at lower altitudes where jet engines are less efficient.

Since higher density altitudes result in the need for higher approach speeds, a longer landing roll distance is required to safely land the aircraft. According to FAR §121.195, no turbine powered aircraft may takeoff unless the weight of the aircraft upon arrival would allow for a full stop landing at the intended destination airport such that the landing requires less or equal to sixty percent of the effective length of the most suitable runway described from below a point 50 feet above the intersection of the obstruction clearance plane and the runway during the anticipated atmospheric conditions at the time of landing. This means that an aircraft may need to carry fewer passengers or less cargo resulting in a lower flight efficiency or the aircraft may not be able to legally or safely land at all during times of high density altitude.

2.2.3 Wind Direction, Wind Speed, and Wind Gust

For automated wind observations from the an ASOS stations, the ASOS station uses a "F420" series of instruments that consists of a cup-driven Direct Current (DC) generator and a vane which uses electromagnetic signals generated by the two instruments to determine wind related quantities (ASOS User's Guide, 1998). Wind direction is determined by using the 2-minute average of the 5-second average wind directions and is reported in tens of degrees relative to true north (ASOS User's Guide, 1998). Wind speed is determined by using the 2-minute average of the 5-second average wind speed and is reported in knots (ASOS User's Guide, 1998). Wind gust is determined using the 5-second average wind speed if the above criteria for wind gust is met (ASOS User's Guide, 1998). Manual wind observations are made using a similar technique.

2.2.3.1 Wind Impacts on Safety and Performance

The direction and strength of the wind can either increase or decrease take-off or landing performance of an aircraft and decrease or increase the difficulty of a landing. In order to determine these affects, it is necessary to calculate the headwind, tailwind, and crosswind components of the wind. The headwind is the component of the wind that is blowing directly into the aircraft and is opposing forward motion. The tailwind is the component of the wind that is blowing directly in the direction of the aircraft's motion and is aiding in forward motion of the aircraft. The crosswind is the component of the wind that is blowing perpendicular to the aircraft.

Knowledge about the current or expected headwind, tailwind, and crosswind at an airport must be taken into account creating a flight plan and doing landing and takeoff calculations.

Headwinds can improve aircraft takeoff performance by decreasing the amount of runway length needed to achieve takeoff speed or safely stop the aircraft by decreasing the groundspeed for the required airspeed. Tailwinds do the opposite and increase the length of the runway used during a takeoff or landing roll. FAR §121.189 and FAR §121.195 require that wind conditions be considered when determining whether or not the aircraft will be able to meet takeoff and landing requirements. Also, many aircraft have wind component limitations that prohibit the operation of the aircraft under certain conditions.

Wind conditions can also impact commercial aviation operations in other ways. Airports will adjust their operations (i.e. change which runways are used for takeoffs and landings) so that aircraft will takeoff and land into the wind. This means that an airport may operate in a condition that is not the most efficient due to runway layout and reduces the number of takeoffs and landings that an airport can handle. Wind can also increase the likelihood that foreign object debris (FOD) can be blown onto vital airport surfaces and potentially damage aircraft creating safety hazards and economic losses. During especially windy periods, extra precautions and inspections may be required in order to reduce the likelihood of FOD appearing on runway, taxiway, or other aircraft movement area of the airport.

2.2.4 Visibility and Sky Condition

Visibility (or prevailing visibility) is defined as "the visibility that is considered representative of visibility conditions at the station" (FCM-H1-2005, 2005). When measuring visibility manually, the visibility is determined as the greatest distances that can be seen in all directions based on the available visibility reference points and reported in statute miles (FCM-H1-2005, 2005). The automated visibility observations recorded by the ASOS stations utilize a

forward scatter sensor in order to estimate the current prevailing visibility; the reportable visibility ranges from less than one quarter statute mile to greater than ten statute miles (ASOS User's Guide, 1998).

In order to determine the sky condition, the sky cover amount and the layer height needs to be determined. Sky cover is defined as "amount of the celestial dome hidden by clouds and/or obscurations" and layer height is defined as "the height of the bases of each reported layer of clouds/or obscurations or the vertical visibility into an indefinite ceiling" (FCM-H1-2005, 2005). A ceiling is a defined as "the lowest layer aloft reported as broken or overcast or the vertical visibility into an indefinite ceiling" (FCM-H1-2005, 2005). In order to manually observe sky cover, the amount of cloud coverage is determined over the whole sky and the procedure is repeated if multiple cloud layers are present (FCM-H1-2005, 2005). In order to manually determine the layer height, various methods can be used such as using pilot reported layer heights or using a helium filled balloon (FCM-H1-2005, 2005). The automated sky condition observations recorded by the ASOS station utilize a Cloud Height Indicator (CHI) that consists of a near infrared laser and uses Light Detection and Ranging (LIDAR) principles and computer algorithms to determine cloud height and cloud coverage information (ASOS User's Guide, 1998).

2.2.4.1 Visual and Instrument Meteorological Conditions and Impacts

Ceiling and visibility conditions have huge impacts on flight planning and operations of aircraft. Depending on the type of weather, the type of aircraft, and the type of operation, different FAR's will dictate different requirements for flight planning, fuel loads, equipment on board an aircraft, experience and ratings of the crew, and so on. FAR §91.155 describes the

weather criteria for Visual Flight Rules (VFR) from which the criteria for Instrument Meteorological Conditions (IMC) and Visual Meteorological Conditions (VMC) at airports can be deduced. Table 2.1 displays the various ceiling and visibility thresholds for the different meteorological conditions. Forecast low ceilings or visibilities may require the planning of an alternate airport. The addition of an alternate airport requires additional planning and fuel which reduces the efficiency of an overall flight; the regulations governing alternate airports are listed in FAR §121 Subpart 600.

In order to maintain safe flight operations and maximize efficiency, aircraft operators use special equipment and procedures during IFR conditions. Standard instrument departures (SID), Standard Terminal Arrival Routes (STARs), and instrument procedures are used by pilots and air traffic controllers to safely navigate aircraft to and from airports during periods of reduced visibility or low ceilings. When using these procedures, pilots must use instrument instead of visual references to navigate the NAS; this increases both pilot and air traffic controller workload and may reduce the overall efficiency of an airspace. During times of low ceilings or poor visibility, airports may not be able to operate in the optimal condition thereby reducing the number of aircraft an airport can handle. For example, San Francisco International Airport cannot use parallel approaches during IFR conditions therefore the capacity of the airport is reduced by fifty percent (Weather and Operations at SFO, 2010).

2.2.5 Present Weather

Contained in METAR and SPECI observations are weather types that are pertinent to aviation operations. Some of these present weather codes can be observed by ASOS stations whereas others can only be observed manually by a weather observer. In order to determine

certain weather types, the ASOS station uses a combination of sensors and algorithms in order to determine the present weather. A detailed account of the methods utilized is provided in the *Automated Surface Observing System (ASOS) User's Guide*.

2.2.5.1 Precipitation

Precipitation is any form of water particles, whether liquid or solid, that fall from the atmosphere and reach the ground. The types of precipitation included in aviation surface observations are drizzle (DZ), rain (RA), snow (SN), snow grains (SG), ice crystals (IC), ice pellets (PL), hail (GR), small hail and/or snow pellets (GS), and unknown precipitation (UP). Refer to Table 2.2 for precipitation type descriptions and intensity qualifiers.

Precipitation can impact aviation operations at an airport in multiple ways, such as by reducing visibility. Wet or contaminated runway and taxi surfaces can degrade braking performance and thereby increasing the landing roll or decreasing directional control (Stubbotin, 2013). Table 2.2 provides information on the impacts of braking depending on the type or degree of runway contamination. Poorer braking performance may increase the likelihood of a runway overrun or loss of control and may result in an accident or incident (Stubbotin, 2013). Slippery runway and taxiway conditions may require slower taxiing speeds and greater distance between aircraft on the ground; this may reduce the overall efficiency of the airport since fewer aircraft may be allowed on the movement areas and those aircraft may be taxiing at slower speeds (Oda, 2010). Slippery ramp areas may also increase the difficulty of other ground operations, such as pushing back an aircraft or loading cargo, and may result in gate delays or other performance decreases. In order to combat the negative impacts caused by frozen or freezing precipitation, airports employ various snow and ice removal techniques. Many of these

techniques, such as applications of chemicals, can close runways or taxiways and impede airport operations.

Precipitation that is frozen or freezes on contact to the surfaces, instruments, and engines of an aircraft can also pose a threat to aviation safety. Snow, freezing rain, etc. can all attach themselves to the wings of an aircraft; this prevents the smooth flow of air over the wings and can reduce lift. This may result in the wing of the aircraft stalling. Aircraft ice can also increase the weight and drag on aircraft resulting in poorer performance. Ice can also impact control of the aircraft, vital instruments and systems. Many aircraft have equipment to remove or prevent the buildup of ice on certain areas but these systems may not be effective on the ground. In order to ensure that necessary aircraft surfaces are not contaminated with ice, ground deicing must occur before takeoff. This increases the cost and complexity of operations resulting in decreased economic and operational performance.

2.2.5.2 Thunderstorms

A thunderstorm is defined as "a local storm produced by a cumulonimbus cloud that is accompanied by lightning and/or thunder" (FCM-H1-2005, 2005). Thunderstorms pose numerous safety threats to aircraft. Turbulence caused by thunderstorms can result in some uncomfortable bumps for passengers but also cause damage or result in a loss of control of the aircraft. Wind shear and microbursts can also be present in and around thunderstorms; wind shear and microbursts are particularly dangerous because they can result in sudden airspeed losses and losses of lift during critical phases of flight when the aircraft is at low altitudes and low airspeeds (AC-00-24C, 2013). Aircraft icing environments may also be present within thunderstorms posing additional threats to aircraft (AC-00-24C, 2013). Lightning strikes are

fairly common and can damage the skin of an aircraft and its systems but rarely result in major damage; this results in inspections and repairs that take aircraft out of service (AC-00-24C, 2013). High amounts of precipitation within or underneath a thunderstorm may result in engine damage or a flameout (AC-00-24C, 2013). For all these reasons, pilots avoid flying through thunderstorms.

Whenever thunderstorms are present at an airport, a ground stop may be issued until the thunderstorm passes or dissipates preventing planes from taking off. Landing aircraft may choose to enter a holding pattern until conditions improve or divert to an alternate airport. In order to prevent aircraft from flying into or near thunderstorms, ATC may give pilots vectors to bypass convective areas; this may decrease NAS efficiency and result in delays and cancellations (Kulesa, 2003). In order to protect employees from the dangerous effects of lightning, ground employees may be removed from the ramp areas until the threat has passed which may create delays (Matthias, 2014).

2.2.5.3 Obscuration and Other Present Weather Phenomena

Obscuration is defined as "any phenomenon in the atmosphere, other than precipitation, that reduces the horizontal visibility" (Surface Weather Observations and Reports). Mist (BR), fog (FG), smoke (FU), volcanic ash (VA), widespread dust (DU), sand (SA), haze (HZ), and spray (PY) are included in the obscuration category. Refer to Table 2.4 for obscuration type descriptions.

All obscuring phenomena impact commercial aviation operations by reducing visibility; the impacts of reduced visibility is discussed earlier in this chapter. Sand, dust, and volcanic ash can also present additional hazards to aviation due to their abrasive nature which can result in

increased wear of engines and other aircraft parts to simultaneous power loss in all engines (Flight Operations Briefing Notes: Volcanic Ash Awareness).

Other weather phenomena and descriptors of phenomena are located in Table 2.5 along with their description and identifier. Some of the descriptors can be attached to local weather phenomena to describe differences in quality or intensity.

CHAPTER III. CLIMATE TELECONNECTIONS

3.1 Introduction

Climate variability (also known as climatic variability) is defined as the temporal variations of the atmosphere-ocean system around a mean state and may be due to natural internal processes within the climate system or due to variations in natural or anthropogenic external factors (World Meteorological Organization). Seasonal or monthly changes in temperature, sea level pressure, or precipitation can all be considered as climate variability. These changes can have large impacts on society. For example, if less than normal precipitation falls for a given region during the growing season, crop failures from the resulting drought could mean large economic losses and impacts to human life (Intergovernmental Panel on Climate Change, 2007). Similar negative (or even positive) impacts to aviation could occur as a result of climate teleconnections. For example, increased winter storm activity from the usual average at an airlines key hub could unexpectedly result in increased delays and cancellations leading to lower operational and economic performance than what was normally expected.

Climate teleconnections can be used to identify, explain, and predict observations of climate variability in different regions of the world. A teleconnection is "a linkage between weather changes occurring in widely separated regions of the globe" (American Meteorological Society). These linkages may be identified by significant positive or negative correlations in the fluctuations of a field at widely separated points (American Meteorological Society). Teleconnections are made up of fixed spatial patterns with an associated index time series showing the evolution of their amplitude and phase; when teleconnections are applied to variability on monthly or longer timescales, the correlations suggest that information is propagating between distant points through the atmosphere (Intergovernmental Panel on Climate

Change). By understanding how teleconnections impact the local climate and weather of particular regions, the impacts of climate teleconnections on the efficiencies of commercial airlines can be better understood.

3.2 El Niño Southern Oscillation

3.2.1 Background

The El Niño Southern Oscillation is an important coupled ocean-atmosphere phenomenon causing global climate variability on interannual time scales (Intergovernmental Panel on Climate Change). Variations in sea surface temperatures of the equatorial Eastern Pacific Ocean have been a well observed phenomena. El Niño is characterized by anomalously warm sea surface temperatures (SST) in the equatorial Central and Eastern Pacific Oceans; La Niña is characterized by anomalously cool SSTs in the equatorial Central and Eastern Pacific Oceans (See Figure 3.1). In 1924, Gilbert Walker defined a low-latitude, planetary scale seesaw in sea level pressure between the eastern Pacific Oceans and the western Pacific-Indian Ocean region and defined this pressure oscillation as the Southern Oscillation (Bjerknes, 1969). The Southern Oscillation is associated with global patterns of atmospheric anomalies in circulation, temperature, and precipitation (Bjerknes, 1969). Later in 1969, Jacob Bjerknes recognized that the SST anomalies created by El Niño and La Niña were responsible for the many of the atmospheric anomalies observed associated with the Southern Oscillation; the coupled ocean – atmosphere interaction later become known as the El Niño Southern Oscillation [ENSO] (Bjerknes, 1969).

3.2.2 North American ENSO Teleconnections

ENSO affects the climate of the United States in many ways mainly by changing the patterns of the jet streams. During El Niño years, the Pacific Jet Stream is more persistent and stronger which results in the storm tracks being shifted to the southern part of the United States, and less storminess and milder-than-average conditions in the northern regions of the United States. Four main changes occur as a result of El Niño. First, there is an eastward extension and equatorward shift of the subtropical jet stream from the International Date Line to the southwestern United States (Diaz, 2000). Second, there is more west-east flow of the jet stream winds than in normal conditions (Diaz, 2000). Third, is a southward shift of the United States storm track (Diaz, 2000). The fourth change is a southeastward shift of the main region of cyclone formation to west of California (Diaz, 2000). These all combine to produce stormy winters and increased precipitation across California to the Southern United States and less stormy weather and warmer temperatures in the northern parts of the United States.

During La Niña years, the subtropical jet stream is more variable and features a wave-like pattern (Diaz, 2000). Three main changes occur as a result of La Niña. First, there is an amplification of the climatological mean wave pattern and increased meridional flow across the continent and the eastern North Pacific (Diaz, 2000). Second, there is an increased blocking activity over the high latitudes of the eastern North Pacific (Diaz, 2000). The third is a highly variable strength of the jet stream over the eastern North Pacific, with the mean jet position entering North America in the northwestern United States/ southwestern Canada (Diaz, 2000). The central United States experiences increased storminess and precipitation and an increase in cold outbreaks while the southern United States experience fewer storms and less precipitation (Diaz, 2000). For a visual depiction of ENSO impacts, Figure 3.2 shows the average El Niño

and La Niña winter impacts. Not only does ENSO impact winter weather, it impacts other seasons as well. For example, Allen et al. (2015) showed that ENSO impacted the frequency of tornado and hail storm occurrence in the U.S. with these types of severe weather being more frequent during La Niña and less frequent during El Niño. In relation to aviation, more severe weather from La Niña in the central U.S. may result in more delays and cancellations for airports within those regions, such as Dallas Love Field.

The majority of ENSO teleconnection and impacts to society research have focused on the temperature, surface pressure, and precipitation anomalies. By analyzing METAR data, the impacts of ENSO on the weather that affects aviation operations can be found and described allowing operators to better relate ENSO and their operations. Increased storminess in regions as a result of ENSO can now be defined by specific weather types instead of precipitation rate or temperature anomalies.

3.3 Arctic Oscillation

3.3.1 Background and North American Teleconnections

The Arctic Oscillations (AO) is an atmospheric circulation pattern over the middle to high latitudes of the Northern Hemisphere and creates the highest amount of variability in the winter months. The AO is characterized by the pattern of the 1000 millibar (mb) height anomalies over 20° N to 90° N (NCEI, 2016). The largest impact of the AO is on the north to south location of the mid-latitude jet stream which in turn steers storms and is most impactful during the winter months (Thompson, 2001).

The AO's positive phase is characterized by lower-than-average 1000 mb heights over the Arctic regions and higher-than-average pressure over the northern Pacific and Atlantic

Oceans (Figure 3.4a). During this phase, the jet stream is located farther north than average resulting in storms being shifted farther north (Thompson, 2001). During these conditions, mid-latitude locations experience fewer cold air outbreaks and decreased storminess than what is usually observed.

The AO's negative phase is characterized by higher-than-average 1000 mb heights over the Arctic regions and higher-than-average pressure over the northern Pacific and Atlantic Oceans (Figure 3.4b). The jet stream is located farther south during the negative phase of the AO (Thompson, 2001). As a result, cold air is allowed to penetrate further south and the jet stream flow becomes more meridional resulting in more cold air out breaks and increased storminess for the mid-latitudes including changes to precipitations an temperature (Figure 3.5) (Thompson, 2001). Figure 3.5 shows the precipitation and temperature anomalies associated with the negative and positive phases of the AO.

By analyzing METAR data, the impacts of the AO on aviation weather can be better determined. By understanding the impacts and using AO forecasts, aviation operators can better plan for the future weather and change schedules and equipment plans to mitigate delays and cancellations.

CHAPTER IV. AVIATION PERFORMANCE DATASETS

4.1 Introduction

The Federal Aviation Administration (FAA) maintains a database that contains information on the performance of the aviation industry as a whole and can be used to determine the impacts of specific weather types on the performance of the aviation community. These datasets contain information on the operational efficiency of airports, airlines, or airspaces and are available through the FAA Operations and Performance Data database. A majority of the datasets contained within the database are freely accessible; however, higher resolution or more specific information is only accessible with specific clearance. The datasets used within in this study were the Aviation System Performance Metrics (ASPM), Airline Service Quality Performance (ASQP), and the Operations Network (OPSNET).

4.2 Aviation System Performance Metrics

The ASPM dataset contains performance and efficiency information for 77 Unites States airports and designated ASPM carriers. The ASPM 77 airports are listed in Table 4.1. The ASPM carriers are listed in Table 4.2. The ASPM calculates various metrics using information from a variety of sources, including the ASQP, the Traffic Flow Management System (TFMS), and the National Weather Service (NWS) Quality Controlled Local Climatological Data (QCLCD) (ASPM: Data Sources and Currency / Update Cycle). ASPM records are updated gradually as the data becomes available from various sources. ASPM records based on preliminary data are available on a next day basis (ASPM: Data Sources and Currency / Update Cycle). These records are then updated over the next 6-8 weeks after the end of each calendar month (ASPM: Data Sources and Currency / Update Cycle). For this project, data from the

ASPM Data Download module and the ASPM Weather Factors Frequency Report Module from January 1, 2000 to July 31, 2015 are used.

The Data Download module provides hourly information on all flights, on-time flights, delayed flights, airport capacity, and airport efficiency for all domestic flights included within the ASPM (ASPM Data Download: Detail By Hour). The Data Download module provides 79 different metrics and does not include cancelled or diverted flights (ASPM Data Download: Definitions of Variables). For this work, seventeen different metrics are identified that present an overall view of aviation operations Each of the 17 metrics are described below.

Airport Departures provides the number of ASPM qualifying flights that departed the airport within the given hour (ASPM Data Download: Definitions of Variables). This number reflects the airport departure demand during each hour. Gate Departure Delays provide the number of aircraft that left the gate 15 minutes or more than what was recorded in the flight plan (ASPM Data Download: Definitions of Variables). The gate departure time is defined as the time in which the parking brake is released (ASPM Data Download: Definitions of Variables). Airport Departure Delays provide the number of aircraft that left that departed the airport 15 minutes or more than what was recorded in the flight plan (ASPM Data Download: Definitions of Variables). The departure time is defined as the time in which the air or ground sensor on landing gear is set to "airborne" state (ASPM Data Download: Definitions of Variables). A difference in the Airport Departure Delay and the Gate Departure Delay can be attributed to taxiing delays. The Average Airport Departure Delay is the average delay in minutes of total number of delayed airport departure flights in a given hour (ASPM Data Download: Definitions of Variables). The On Time Gate Departure provides the percent of flights that left the gate within 15 minutes of what was recorded in the flight plan for a given hour (ASPM Data

Download: Definitions of Variables). The On Time Airport Departure provides the percent of flights that departed the airport within 15 minutes of what was recorded in the flight plan for a given hour (ASPM Data Download: Definitions of Variables).

Airport Arrivals provides the number of ASPM qualifying flights that arrived at the airport within the given hour (ASPM Data Download: Definitions of Variables). This number reflects the airport arrival demand during each hour. Arrival Delays are the number of flights that arrived 15 minutes or more after the scheduled arrival and the arrival time is defined as the time in which the air or ground sensor on landing gear set to "ground" state (ASPM Data Download: Definitions of Variables). The Average Arrival Delay is the average time for all delayed arrivals in a given hour (ASPM Data Download: Definitions of Variables). The On Time Arrivals is the percent of flights that arrived at the airport within 15 minutes of the scheduled arrival (ASPM Data Download: Definitions of Variables).

The Average Taxi Out Delay is the difference between the actual taxi out time (which is the time from the gate departure to the airport departure) and unimpeded taxi out time [i.e. the taxi out time when there is no congestion or other delays causing impact] (ASPM Data Download: Definitions of Variables). Block time is the difference between the gate departure time and the gate arrival time. The Total Block Delay Minutes is the sum of the difference between the scheduled block time and the actual block time for all flights (ASPM Data Download: Definitions of Variables). The Expect Departure Clearance Times (EDCT) are the runway release times assigned to aircraft due to Traffic Management Initiatives (TMIs) that require holding aircraft on the ground at the departure airport (ASPM Data Download: Definitions of Variables). These are issued when traffic concerns exist at a specific airport or sector. The number of EDCT Holds at Other Airports indicates the total number of aircraft that

are to arrive at the designated airport are being held due to congestion at either the arrival or departure airport but most typically due to congestion at the arrival airport (ASPM Data Download: Definitions of Variables). The Airport Departure Rate is the number of departures an airport can handle per hour under the current conditions (ASPM Data Download: Definitions of Variables). The Airport Departure Rate can be affected by weather, runway closures, taxiway closures, etc. (ASPM Data Download: Definitions of Variables). The Airport Arrival Rate is the number of number of arrivals an airport can handle per hour under the current conditions (ASPM Data Download: Definitions of Variables). The Airport Arrival Rate can be affected by weather, runway closures, Instrument Approach equipment malfunctions, etc. (ASPM Data Download: Definitions of Variables). The Airport Efficiency Score is a scoring metric with 1 being the best score and 0 being the worst score that takes many metrics into account when determining the overall efficiency of the airport (ASPM Data Download: Definitions of Variables).

The Weather Frequency Report gives pertinent information on the occurrence of and impacts of certain weather types on individual ASPM 77 airports. The report categories available are: Severity of Local Weather Conditions, Visibility in Statute Miles, Ceiling in Hundreds of Feet, Wind Speed in Knots, Overall Impacting Conditions, Enroute Thunderstorms, Thunderstorms within 50 Miles, and Number of OPSNET Weather Delays (ASPM Weather Factors: Definitions of Variables). Only the first four report categories are used in this work since they are the only ones that either directly apply to the airport or can be calculated using the METAR datasets (ASPM Weather Factors: Definitions of Variables). Within each report, an impact severity is assigned to certain weather conditions based upon information given by the FAA. The visibility, ceiling, and wind speed thresholds vary from each airport in order that all the severity categories correctly match the expected impact on the airport. The severity of the

Local Weather conditions are supposed to be consistent for all airports; however, contrary to what is indicated in the description of the dataset, the impacts of the weather are based upon the operating efficiency of the airport during that time period. This means that a weather type can score in all three severity categories. The weather types and their severity categories are listed in Table 4.3. To determine the proper thresholds for ceiling, visibility, and wind speed the Weather Frequency Reports are used to compare with FAA calculated performance metrics.

4.3 Airline Service Quality Performance

The ASQP provides information about airline on-time performance, flight delays, and cancellations. It is based on data filed by airlines each month with the Department of Transportation's Bureau of Transportation Statistics as described in 14 Code of Federal Regulations (CFR) Part 234. Airlines with one percent or more of the total domestic passenger revenue are required to report certain flight data for all flights within the contiguous United States; in addition, smaller carriers can voluntarily report also (Airline Service Quality Performance). Since the start of the ASQP module, the number of carriers reporting has varied from 10 to 19 (Airline Service Quality Performance). A list of past and current ASQP carriers is provided in Table 4.4. The ASQP provides the time and cause of departure or arrival cancellations for a given airport. The reportable cancellation causes are: carrier, weather, National Air Space, and security (ASQP: Definitions of Variables). Contrary to the popular opinion of air traffic controllers, flights are cancelled as a result of problems within the National Air Space System. According to the Air Traffic Control System Command Center's Frequently Asked Questions webpage, they state "The FAA/Air Traffic Control [ATC] does not cancel flights. You will need to contact your airline to determine why they canceled your flight".

However, according to 14 CFR Part 234, cancellations as a result problems with the NAS is an admissible cause for cancellation. For example, if ATC is unable to meet the request for departure for an airline flight, the airline would have reason to cancel the flight as a result of the NAS. An example of such an incident occurred when a computer system that processes flight plans at the Washington Air Route Traffic Control Center crashed in August 2015; this caused numerous delays and cancellations along the East Coast (Hernandez-Author, 2015). The ASQP also provides the daily total minutes of carrier reported delays for the following causes: carrier, extreme weather, NAS, security, and late arrival (14 CFR 234).

4.4 Operations Network

The OPSNET provides information on the performance of the NAS for air sectors and select airports as mandated by the Federal Aviation Administration Order (FAAO) 7210.55F. The OPSNET provides the daily total minutes of NAS delays for the following causes: weather, volume, equipment, runway, and other (Operations Network). Since the ASQP and OPSNET are collected by different groups within the aviation community, differences can exist when comparing delay causes between the two modules.

4.5 Delay and Cancellation Causes

While modern advancements in technology has limited the impacts to air transportation, delays and cancellations are still a present problem. Carrier delays are delays that are considered to be within the control of the airline (Types of Delay). Some examples of causes for carrier delays are aircraft cleaning, bird strike, cargo loading, reservation computer outage, engineering inspection, late crew, removal of an unruly passenger, or slow boarding or seating of the aircraft

(Types of Delay). While some of these carrier delay causes are independent of the weather, such as delays caused by the removal of an unruly passenger, others, such as cargo loading or engineering inspection, may be negatively impacted by adverse weather conditions such as snow or thunderstorms. Late arrival delays are caused by an aircraft that was delayed at a previous point in the schedule where subsequent delays occur on flights utilizing the same aircraft; this is also referred to as delay propagation (Types of Delay). Enroute weather can be an attributing (contributing) factor in late arrival delays; however, since these delays occur at a point outside of the airport being examined, these are outside the scope of this project. Security delays can be caused by multiple issues pertaining to the safety of passengers or others. Some examples of security delays are evacuation of a terminal or concourse, re-boarding of aircraft because of security breach, inoperative screening equipment and/or long lines in excess of 29 minutes at screening areas (Types of Delay).

An extreme weather delay is caused by extreme or hazardous weather conditions that are forecasted or manifest themselves at the point of departure, enroute, or at the point of arrival (Types of Delay). Some examples of extreme weather include hurricane or blizzards (Understanding the Reporting of Causes of Flight Delays and Cancellations). A NAS delay is a delay caused by Traffic Management Initiatives (TMI) from ATC that causes an aircraft to be fifteen or more minutes late (OPSNET: Delays). In order to determine the causes of NAS delays, the OPSNET delay causes can used to infer the cause of the NAS delay. Weather delays are caused by weather conditions at the airport or enroute that reduce the capacity of the NAS (OPSNET: Delays). Equipment delays are caused by FAA or non-FAA equipment malfunctions (OPSNET: Delays). Volume delays are caused by a high volume of traffic at an airport that causes congestion (OPSNET: Delays). Runway delays are caused by a reduction to runway

capacity (OPSNET: Delays). Other delays are caused by any other delay causes (OPSNET: Delays). Cancellation causes are similar to those listed within the ASQP delay causes with the exception of late arrival delays (OPSNET: Delays).

4.6 Delays and Cancellations for the ASPM 77 Airports

Figure 4.1 shows the percent breakdown for the ASPM 77 Airports ASQP Delay Causes, OPSNET Delay Causes, and ASQP Cancellation Causes. When looking at the ASQP Delay Causes, only 7% of delays are caused by extreme weather. However, when considering that carrier, NAS, and late arrival delays can all be attributed to non-extreme weather, the impacts of weather on aviation performance can be considered to be much higher (Understanding the Reporting of Causes of Flight Delays and Cancellations). When looking at the causes of OPSNET Delays, weather is responsible for the largest percentage of delays at 82% of the total delay minutes. This shows the overall negative impact of weather on the ability of the NAS to function properly. Knowing that the great majority of NAS delays are attributed to weather, the overall total impact of weather in the ASQP delay spectrum is now considerably much greater. When looking at the ASQP Cancellation Causes, weather is again the greater contributor of airline cancellations at 42% of the total cancellations. This again highlights the overall negative impacts weather has on aviation and the need to better understand and predict the impacts weather will have on the aviation community as a whole.

Analyzing the operations at individual airports will provide a better picture of the impacts weather and climate have on airlines, airports, and the NAS. By also looking at multiple different variables that represent different phases of a commercial flight, the impacts of weather can be better diagnosed at specific parts. Maybe only certain types of weather phenomena

impact specific phases. With this information, operators can pinpoint the areas of possible improvements and develop remedies.

CHAPTER V. METHODS

5.1 Introduction

After reading in the METAR data, limited quality control methods were employed, such as removing values that are physically impossible (such as relative humidities of 300%) or outside of the NCDC climate extremes or obvious mistakes in transferring the data (such as the appearance of random (@#!2) code for a temperature value). Out of the approximately 600,000 observations per airport, less than 1% of the values required quality control. It is also interesting to note that nonsense values do appear in the ASPM Weather Frequency Report which leads me to question if quality control was completed for the ASPM weather values.

After quality controlling the METAR datasets, the severity binning scheme (i.e. applying a value of minor, moderate or severe weather impact) was applied to the local weather codes, visibility, ceiling and wind speed data. To determine the highest overall weather severity value for each observation, the highest score for the local weather codes was found and recorded. In order to eliminate over reporting (or representation) of the local weather codes and ASPM severity bins, numerous observations in a one hour period (which come from SPECI observations) were removed. During a given hour, the highest severity score of each category was recorded as the severity score for that hour. The same method was applied to find a precipitation occurrence array or obscuration occurrence array.

5.2 Monthly METAR and Weather Codes

Months with 90% or more missing hourly observations are excluded when determining monthly average values. The average monthly value for the hourly observations was found for all METAR values except the binary weather codes and discrete ASPM severity codes. This

method was also used to determine the monthly hourly patterns, e.g. diurnal cycles, from the daily data. For those values, the total monthly count was found because the original values are binary and not continuous. After doing this, the monthly time series values were detrended to remove any patterns or trends caused by natural occurrences or changes in observation techniques. The monthly normal (mean) was calculated for all values and is displayed in the subsequent graphs found in Chapter VI. Only values that occurred frequently and are important in analyzing aviation weather are shown. For example, the occurrence of funnel clouds is relatively rare so it will not be analyzed individually; however, funnel clouds are included in the overall weather severity score plots. Next, the monthly average value was subtracted from the detrended monthly time series to derive monthly anomalies time series.

Using the Southern Oscillation Index and the Arctic Oscillation climate indices, the monthly anomaly time series were correlated with the climate indices using the Spearman rank correlation in order to indicate whether or not climate teleconnections were present at the individual airport. The Spearman rank correlation was used due to the robustness of the correlation and that it is not impacted by the distribution of the data (Wilks, 2011). The Spearman rank correlation is similar to the Pearson correlation except that the Spearman correlation uses the rank of the magnitude of the values instead of the actual values' magnitudes (Wilks, 2011). A detailed description of the Spearman rank correlation can be found in Daniel Wilks' *Statistical Methods on the Atmospheric Sciences: Third Edition* pages 55 – 57. Next, the monthly differences were found for the METAR data when the specified climate index was in the opposite phase. In order to determine whether or not the difference in the monthly average weather values are significant between the positive or negative phases of the Arctic Oscillation or ENSO, the Wilcoxon-Mann-Whitney ranksum significance test was used. The Wilcoxon-

Mann-Whitney ranksum test is a robust, nonparametric test that is ideal for testing whether or not the differences are statistically significant (Wilks, 2011). Another benefit of the Wilcoxon-Mann-Whitney ranksum test is that the distribution of the data does not affect the accuracy of the test because each individual value is evaluated based on its rank and not its magnitude (Wilks, 2011). The Wilcoxon-Mann-Whitney ranksum tests works by first ranking the values of interest and then analyzing the magnitudes of the ranks of two populations (Wilks, 2011). For example, to test the whether or not ENSO affects temperatures at Chicago O'Hare (ORD), the temperature anomalies at ORD will first be ranked and then separated into two groups: temperature values recorded during El Niño and temperature values recorder during neutral or La Niña conditions. The sum of the ranks of the two groups will then be compared to determine if ENSO actually impacts temperature. A detailed description of the Wilcoxon-Mann-Whitney ranksum significance test can be found in Daniel Wilks' *Statistical Methods on the Atmospheric Sciences: Third Edition* pages 158 – 166.

5.3 Average Seasonal Diurnal Patterns

The average weather and delay seasonal diurnal patterns were identified in order to determine if certain weather phenomena changed with the seasons, if there was a change in the diurnal pattern between seasons, and how weather impacts aviation performance on a seasonal timescale. The seasons are defined as spring (March, April, and May, MAM), summer (June, July, and August, JJA), fall (September, October, and November, SON), and winter (December, January, and February, DJF).

5.4 Weather Delay Statistics

To determine the average impact a certain weather phenomena has, such as high winds or thunderstorms, the average of the delay statistics whenever that weather phenomena was present and total number of hourly observations in which that weather phenomena was present was determined. In order to more accurately define the impact of weather on commercial operations, weather and delay values were included only when the airport was active. This was done in order to eliminate skewing the values when little to no airport movements were occurring (e.g. in the middle of the night). As the overall number of aircraft that operate at an airport or utilize the airspace increases, the risk of airport congestion increases, overall efficiency decreases, and the amount of delays increase (Fact3: Airport Capacity Needs in the National Airspace System). Including time periods in which little to no aircraft movements occur will produce an unrepresentative view of the challenges airlines and other operators face as a result of weather. For example, if only one aircraft takes off during midnight and eighty aircraft take off during noon, the impacts of congestion on airport efficiency will be completely different and comparing the two time frames may result in improper conclusions about airport efficiency.

5.5 Cancellation Statistics

To determine airline cancellations due to weather, weather phenomena that were present whenever a flight cancellation occurred during the planned phase of flight in which the flight was at the airport in question were recorded. In order to better understand the impacts each weather phenomena had, the average number of flight cancellations per observation (i.e. hour) whenever the weather phenomena (e.g. snow or fog) was present was determined. This can give an operator or dispatcher an idea of the expected number of cancellations to expect during

different types of weather. However, some estimation errors may occur in this determination due to the fact that a flight may be cancelled due to weather enroute or a flight may be cancelled due to weather that was observed in the hour prior to or after the expected departure or arrival time.

Current federal statistics on commercial flight cancellations only provide the cancellation causes (carrier, weather, etc.) but do not supply the type of weather that was present during a cancellation. An operator or government official will not fully understand weather's role in creating cancellations and may assume that any weather type is likely to create a weather cancellation. By determining the role of each weather type in creating a cancellation, improvements can be to minimize the impacts of the highest cancellation causing weather. This research will promote a better understanding of the role of weather in creating cancellation.

CHAPTER VI. AIRPORT DELAY AND CANCELLATION CLIMATOLOGY

6.1 Introduction

It is important to look at airports individually when determining the impact of weather on operations. First, climates vary across the United States causing differences in weather delays and cancellations from one airport to another. For example, airports in the Gulf Coast portion of the United States may be more concerned about thunderstorms or rain instead of snow due to their southerly location. Another reason to look at airports individually is that airports have different layouts, different terrain features, different proportions of carriers, and different airline schedules that cause varying responses to specific weather types. For example, some airports may better handle fog or low visibility operations due to the layout of runways.

In order to study the impacts of weather and climate on airport operations, individual airports that had both a complete METAR and ASPM record were selected Also, airports that have not seen major changes in traffic due to airline mergers and subsequent dehubbing (such as in Memphis International Airport) were used so that the average delay and cancellation were relatively constant. Individual airports representative of different regions of the contiguous United States were also identified and used. The airports selected for in depth analysis were (also shown in Table 4.1): Chicago O'Hare International Airport, Dallas Love Field, Hartsfield - Jackson Atlanta International Airport, Miami International Airport, Minneapolis – St. Paul International Airport, New York John F. Kennedy International Airport, Phoenix Sky Harbor International Airport, Salt Lake City International Airport, San Francisco International Airport, and Seattle – Tacoma International Airport.

6.2 Hartsfield – Jackson Atlanta International Airport

6.2.1 Background

Hartsfield – Jackson Atlanta International Airport (ATL) has been the busiest passenger airport (number of passengers utilizing the airport) in the world since 1998 and the busiest operations (number of takeoffs and landings) airport in the world since 2003 (ATL Airport Statistics). Major airline operators at ATL include Delta Air Lines and Southwest Airlines with Delta Airlines operating roughly 1,000 flights daily. Currently, ATL has 5 parallel runways. In order to maximize capacity, ATL tends to operate in an arrival or departure priority mode, as opposed to a balanced operation (ATL - Capacity Profile). In order to increase efficiency, ATL configurations it's airspace to accept either more arrivals or departures instead of a balance between the two. An arrival or departure priority operation is only feasible when the airport's flight schedule is unbalanced for sustained periods of time (ATL - Capacity Profile).

6.2.2 ATL Weather Summary

ATL's weather is typical for an airport located in the southeast United States. Hot summers and mild winters are typical for ATL. Afternoon thunderstorms dominate during the summer period with few occurrences of winter precipitation. Detailed analysis the monthly average and seasonal, diurnal average of ATL's weather is provided in Appendix I 6.A.1.

6.2.3 Weather Impacts and Delays

Figure 6.1 displays 16 different metrics for ATL that are useful in analyzing the overall performance of the airport and the impacts weather has on delays. The number of hourly departures and arrivals per hour is similar for all seasons, with more departures and arrivals

occurring more in the summer and the lowest number occurring in winter due to lighter flight schedules due to weaker demand and increases in cancelled flights. Prior to 6:00, the number of departures and arrivals is minimal then increasing in volume; after 23:00 the traffic drops off sharply. The first noticeable trend is that JJA indicates an overall decrease in efficiency of the ATL for the afternoon to late evening hours. JJA shows an increase in gate departure delays, airport departure delays, average airport departure delay, average taxi out delay, total block delay minutes, arrival delays, average arrival delays, and number of EDCT holds at other airports and decreases in percent of on time gate departures, on time airport departures, and on time arrivals for the time span roughly ranging from 12:00 to 24:00. The overall decrease in summertime ATL efficiency coincides well with the large increase in the occurrence of afternoon thunderstorms seen in Figure 6.A.5. This suggests that the increase in thunderstorms is likely responsible for the decrease in overall efficiency.

The decreasing trend of on time gate departures, on time airport departures, and on time arrivals for all months between 7:00 to 21:00 is likely due to the cumulative effect of delays propagating through the flight schedules. In the times ranging from 6:00 to 12:00, DJF has the worst airport efficiency. From 7:00 to 12:00, DJF has an overall higher number of gate departure delays, airport departure delays, average total block delay minutes, number of arrival delays, number of EDCT holds at other airports and a lower percentage of on time gate departures, on time airport departure, and on time arrivals. The overall decrease in wintertime ATL efficiency coincides well with the increase in the occurrence of morning fog seen in Figure 6.A.5 and increased occurrence of severe ceiling and visibility seen in Figure 6.A.6. This suggests that the increase in severe visibility and ceilings and fog is likely responsible for the decrease in overall efficiency.

The ATC supplied airport departure and arrival rates also indicate that ATL is impacted by weather. The peak in the airport departure rate and trough in the airport arrival rate is likely due to ATC adjusting the airport configuration in order to maximize the number of departures. Airport departure rates are lowest for DJF indicating the impact that low visibilities and ceilings have on overall operations. Winter weather, such as snow and freezing precipitation, may also be contributing to the lower departure rate. The decrease in the airport arrival rate from 14:00 to 22:00 is likely due to the increase in afternoon thunderstorms.

Figure 6.2 displays the frequency of the four different local weather code categories, the average airport departure delay for each category, the average arrival delay for each category, and the airport score for each category of occurrence. Overall, as the severity of the local weather increases, the overall impacts to ATL increase. Also displayed with in Figure 6.2 are common local weather codes at ATL. Freezing precipitation then snow then thunderstorms have the overall greatest impacts to efficiency at ATL. However, the rather occurrences of snow and freezing precipitation mean that other weather phenomena, such as fog or thunderstorms, are likely to have higher annual impacts on the operating efficiency of ATL. Figure 6.3 displays the occurrence and overall impacts of the four wind speed severity categories, Figure 6.4 displays the occurrence and overall impacts of the four ceiling height severity categories, and Figure 6.5 displays the occurrence and overall impacts of the four categories severity categories. Overall, all figures show that the as the severity of the category increases, the occurrence frequency decreases. Also, as the severity increases, the overall delay impacts to ATL increases.

6.2.4 Weather Impacts and Cancellations

ATL has a majority of arrival and departure average weather cancellations in January, February, and December as seen in Figure 6.6. Figure 6.7 displays the number of cancellations per hour for various weather types and ASPM severity codes. Both freezing precipitation and snow vastly outnumber all other weather types in number of cancellations per hour. This indicates that the vast majority of winter weather cancellations is caused by snow and freezing precipitation.

6.3. Chicago O'Hare International Airport

6.3.1 Background

Chicago O'Hare International Airport (ORD) is an important international gateway and regional hub for the Midwest United States. In 2010, ORD was the world's third busiest airport in the world in terms of annual passengers (Chicago Department of Aviation). In 2014, ORD replaced ATL as the world's busiest operations airport (Chicago Department of Aviation). The two largest operators at ORD are American Airlines and United Airlines.

6.3.2 ORD Weather Summary

ORD weather is characterized by mild summers and cold winters with many occurrences of frozen precipitation and fog. A detailed description of ORD's weather is presented in Appendix I 6.A.2.

6.3.3. Weather Impacts and Delays

Figure 6.8 displays the hourly performance metrics for ORD. A majority of airport arrivals and departures occur between 6:00 to 23:00 with DJF having the lowest overall number of departures and arrivals. At first glance, DJF and JJA have the lowest overall performance and increases in delays. In the part of the day up to14:00, DJF has higher number of gate departure delays, higher number of airport departure delays, higher average airport departure delays, higher average taxi out delays, higher number of EDCT holds at other airports, and lower percent's of on time airport departures until being usurped by the JJA values. Throughout the day, DJF experiences higher total block delay minute, lowest percent of on time gate departures, higher number of arrival delays and lowest percent of on time arrivals. Snow, freezing precipitation, fog, low visibility and ceilings, and other impacting phenomena are likely responsible for the overall reduction of the overall efficiency of ORD and increase the number of delays. Snow and other frozen precipitation associated with winter increase the need for aircraft deicing further creating increasing delay times. Deicing procedures combined with the lower airport departure and arrival rates also contribute to the increased delays. In JJA, afternoon thunderstorms impact ORD and create delay and cancellation issues as evidenced by the higher number of delays and decreased efficiency. The airport departure and arrival rates are highest for JJA except for periods when thunderstorms are present as seen in Figure 6.A.11.

Figure 6.9 displays the frequency of the four different local weather code categories, the average airport departure delay for each category, the average arrival delay for each category, and the airport score for each category of occurrence. Overall, as the severity of the local weather increases, the overall impacts to ORD. Unlike ATL, ORD experiences greater delay impacts from thunderstorms. Also, the impact from snow is far lower; however, snow

observations are more common than in ATL meaning that the overall annual impact is higher. Figure 6.10 displays the impacts from wind, Figure 6.11 displays the occurrence and overall impacts of the four ceiling height severity categories, and Figure 6.12 displays the occurrence and overall impacts of the four visibility severity categories. Again, delays and decreases in efficiency increase as the severity increases.

6.3.4 Weather Impacts and Cancellations

Looking at Figure 6.13, a majority of ORD's weather cancellations occur in winter as a result of overall poorer weather conditions and higher occurrences of frozen precipitation and fog. Looking at Figure 6.14, freezing precipitation followed by fog are responsible for the highest number of cancellations per hour. Snow, thunderstorms, severe visibility, and severe wind also responsible for a relatively high number of cancellations per hour.

6.4. Dallas Love Field

6.4.1 Background

Dallas Love Field (DAL) is a unique airport for many reasons. First, DAL was largely restricted to short, domestic flights until October 13, 2014 when the Wright Amendment was repealed. Originally planned to deter use at DAL and other Metroplex airports and promote flights out neighboring Dallas – Fort Worth International Airport (DFW), the Wright Amendment restricted flights to Texas and four neighboring states (West). Over the years, the Wright Amendment was modified to reduce restrictions until finally being repealed. Due to the restrictions on flight distances, a majority of the flights captured by the ASPM are all shorter distance flights meaning flights that are primarily affected by the local climate of the southern

Midwest United States. DAL has relatively smaller amounts of traffic compared to other airports analyzed and only has three carriers: Southwest Airlines, Delta Air Lines, and Virgin America. DAL is also interesting in that Southwest Airlines operates a majority of flights out of DAL and controls 90% of gates (Dallas Love Field Airport - Terminal Tenant Handbook). This removes some variability in weather delay statistics since fewer airlines with different ways of handling weather operate from DAL.

6.4.2 DAL Weather Summary

DAL's weather is characterized by hot summers, thunderstorms primarily in the spring, and mild winters with few instances of frozen precipitation. A detailed analysis of the monthly average weather and monthly diurnal weather is discussed in Appendix I 6.A.3.

6.4.3. Weather Impacts and Delays

Figure 6.15 displays delay and performance for DAL. Looking at the average number of departures and arrivals, JJA has a lowest peak time departures and arrivals while SON has the highest. This is unique in that summer schedules are usually busier. It is interesting that for a majority of the metrics and times, SON has the least number of delays and highest on time performance despite being a busier season. Gate departure delays, airport departure delays, average airport departure delays, average taxi out delay, and total block delay minutes are all highest for DJF in the early morning hours (5:00 to 9:00) with on time gate departures, on time airport departures, and on time arrivals showing a decrease. This could be the result of reduced visibilities or ceiling heights or increases in deicing procedures. In the early afternoon to late evening hours (roughly 15:00 to 21:00), increases in gate departure delays, airport departure

delays, average airport departure delays, average taxi out delay, total block delay minutes, arrival delays, and average arrival delays and decreases in on time gate departure, on time airport departure, and on time arrivals are observed for JJA. This increase in delays and decrease in overall efficiency coincides with the afternoon peak in thunderstorms for JJA supporting the idea that thunderstorms at or near DAL are responsible for the negative efficiencies. The similarities between gate departure delays and airport departure delays and on time gate departures and on time airport departures combined with the low average taxi out delay all suggest that ground delays are not a significant problem for DAL. This seems plausible given the relatively low number of hourly departures and arrivals. The airport departure rate and the airport arrival rate is highest for SON and lowest for MAM. The relatively 'good' weather in SON would improve the overall rate at which DAL can handle traffic. Increased overall wind impacts, higher overall observations of thunderstorms, and increases in all minor impact categories may be responsible for the lower departure and arrival rates for DAL. But why doesn't MAM see more delays and worst performance in the other recorded metrics? MAM does experience lower performances metrics but it is more evenly distributed over the day; when closely analyzing the plots, MAM consistently sees higher delay and efficiency impacts throughout the whole day and not just at one time. This suggests that weather events that are most likely to occur at a given time are easier to diagnose and plan for. This also suggests that high impact weather events such as fog and thunderstorms are important in causing delays and disruptions than other categories such as rain or mist.

The impacts of weather phenomena (Figure 6.16), wind speed (Figure 6.17), ceiling height (Figure 6.18), and visibility (Figure 6.19) all corroborate that increasing weather severity increases delays and reduces airport efficiency. Looking at Figure 6.16, thunderstorms and fog

cause the greatest reduction in efficiency and result in more delays unlike snow or freezing precipitation. DAL's airport configuration or the smaller number of flights compared to ATL or ORD may mean that DAL is able to better handle snow and ice events. Also, ceiling impacts of some kind are observed 45% of the time meaning that lower ceilings are another contributor to delays at DAL.

6.4.4 Weather Impacts and Cancellations

Figure 6.20 displays the monthly averages for carrier, weather, NAS, and security cancellations. Overall DAL has a much lower number of monthly cancellations for all categories due to its lower traffic volume. Weather cancellations peak in December, January, and February (with February showing the highest peak) and in September. More observations of snow, freezing precipitation, fog and IFR weather result in more cancellations for DAL. It is difficult to pin point the cause of weather cancellations for DAL in September due to the relatively fair weather during that time period. There is a small peak in weather cancellations in May that coincides with the peak in thunderstorms. Figure 6.21 displays the number of cancellations per hour of observations. More severe impact categories result in a higher number of cancellations. For departure cancellations, snow then fog are responsible for the highest cancellation rate. However, when compared to the arrival cancellations, snow and fog have lower rates but freezing precipitation has higher rates.

6.5 Minneapolis – Saint Paul International Airport

6.5.1 Background

Minneapolis – Saint Paul International Airport (MSP) is a large airport serving the Northern Midwestern United States. In 2015, 36,582,854 passengers traveled through MSP with

404,762 airport operations (MSP Statistics). Peak operations occur during daylight hours with some freight and charter operations occurring at night (MSP Statistics).

6.5.2 MSP Weather Summary

MSP's northerly latitude and central location provides cold, snowy winters and temperate summers. A detailed analysis of the monthly average weather and monthly diurnal weather is discussed in Appendix I 6.A.4.

6.5.3 Weather Impacts and Delays

Figure 6.22 displays the 16 efficiency and delay metrics for MSP. JJA has the highest number of departures and arrivals while DJF has the least. An initial glance at the plots leads the viewer to believe that DJF followed by JJA has the most number of delays and worst overall efficiency. From the early morning hours to 14:00, gate departure and airport delays are highest for DJF and then replaced by JJA. Deicing processes of planes exposed over night that have accumulated snowfall, combined with regular deicing processes, along with low visibility operations as a result of fog, mist, and snow are likely responsible for DJF delays. The assumption that deicing is responsible for much of the DJF delays is validated by the increase in average taxi out delay minutes. In JJA, thunderstorm activity increases in the afternoon and evening hours when airport operations are still busy resulting in more delays. Average airport departure delays are relatively consistent for all seasons; however, JJA has the highest average departure delay and may be a result of thunderstorm activity throughout the day or some non-weather related issue. Percent of on time gate departures, on time airport departures, total block delay minutes, average number of arrival delays, average arrival delay, and percent of on time

arrivals all support the idea that low visibility and deicing operations are responsible for delays in winter and thunderstorms are responsible for delays in the summer. Average number of airborne delays is highest for JJA most likely as a result of thunderstorms. The patterns for average airport departure and arrival rates is harder to reason especially since no mention of the patterns are discussed in the FAA capacity profile for MSP. My best estimate is that both weather and non-weather factors are causing the airport rate profiles to look as they do.

Figure 6.23 displays the impacts of various weather phenomena have on MSP. As weather severity increases, the impacts to MSP also increase. Freezing precipitation, thunderstorms, and fog have the greatest impacts on MSP. However, these are less common than other phenomena meaning that snow or rain observations have a greater overall impact. This also suggests that MSP is equipped to handle snow better than other airports, such as ATL, where snow is less common. Figure 6.24 displays the wind severity impacts. Delay increases and efficiency decreases increase as wind severity increases. However, moderate and severe wind impacts are relatively rare. Figure 6.25 and Figure 6.26 display the impacts ceiling and visibility have on MSP. As expected, as either severity score increases, delays increase and efficiency decreases.

6.5.4 Weather Impacts and Cancellations

Figure 6.27 displays the average monthly departure and arrival cancellations for MSP. December, January, February, and March have the highest monthly weather cancellations. This is due to poorer weather conditions as a result of frozen precipitation, fog, and reduced visibility. Figure 6.28 displays the number of cancellations per hour of specific weather observations. Freezing precipitation, fog, and severe visibility all have the highest cancellation rates. These

weather phenomena occur most often in winter and results in increased weather cancellations during the winter months.

6.6 John F. Kennedy International Airport

6.6.1 Background

John F. Kennedy International Airport (JKF) is an airport serving the New York City area and an international gateway into the United States. JFK has a large number of international and domestic flights with JetBlue Airlines, American Airlines, and Delta Air Lines being the primary operators. In 2014, the airport have 422,415 plane movements carried 53,254,533 passengers (JFK Airport Statistics). In order to optimize the airport, JFK operates in an arrival or departure priority mode (JFK - Capacity Profile).

6.6.2 JFK Weather Summary

JFK's northerly latitude and coastal location provides cold, snowy winters and warm summers. A detailed analysis of the monthly average weather and monthly diurnal weather is discussed in Appendix I 6.A.5.

6.6.3 Weather Impacts and Delays

Figure 6.29 displays the seasonal, diurnal patterns for 16 delay and performance metrics for JFK. Both the departure and arrival profiles show an unbalanced profile. Also, JJA has the highest number of operations and DJF has the lowest number of operations. In the later part of the day, gate departure delays, airport departure delays, average airport departure delay, average taxi out delay, total block delay minutes, arrival delays, average arrival delays, and EDCT holds

at other airports all increase while on time gate departures, on time airport departures, and on time arrivals all decrease for JJA. This decrease in performance and increase in delays is caused by thunderstorm activity. It is also interesting to note that DJF has a higher overall increase in delays and decrease in performance for all hours. This is most likely caused by increasing in obscuring phenomena and frozen precipitation. Overall, the influence of weather on the performance of JFK is easily seen.

Figure 6.30 displays the delay impact different present weather categories have on JFK. As expected, as the severity of the weather increases so does the overall impact on JFK. Freezing precipitation and thunderstorms have the highest overall impact. However, thunderstorms occur more frequently and therefore have a higher impact on JFK. Figure 6.31 displays the impacts different wind severities have on JFK with severe wind impacts having the highest delay impact. Figure 6.32 and Figure 6.33 show the delay impacts for different categories of ceiling and visibility impacts. Again, as the severity increases, the impacts to JFK increases. This supports what was previously concluded.

6.6.4 Weather Impacts and Cancellations

Figure 6.34 displays the average monthly cancellations for JFK. Overall, most weather cancellations occur in December, January, and February most likely as a result of winter storms. Figure 6.35 displays the cancellation rate per hour for specific weather types. Freezing precipitation followed by severe wind speed have the two highest cancellation rates; however, both events are relatively rare occurrence in the year. Snow has the third highest cancellation rate and is relatively common in the winter months suggesting that it is responsible for a large share of the weather cancellations.

6.7 Salt Lake City International Airport

6.7.1 Background

Salt Lake City International Airport (SLC) is a major airport serving the western United States. SLC is a major hub for Delta Air Lines which is responsible for 75% of the scheduled flights. In 2014, the airport served 21,141,610 passengers and averaged 315 daily scheduled departures. Because of SLC's high elevation, high density altitudes are a major concern for airport operations.

6.7.2 SLC Weather Summary

SLC's western and central location provides cold, snowy winters and warm, dry summers. A detailed analysis of the monthly average weather and monthly diurnal weather is discussed in Appendix I 6.A.6.

6.7.3 Weather Impacts and Delays

Figure 6.36 displays the 16 delay and performance metrics for SLC. JJA has the highest number of hourly departures and arrivals while SON has the least. Overall, DJF has markedly worse performance and more delays than other season for almost all hours of the day. This is likely due to poor weather conditions caused by frozen precipitation, obscuring phenomena, low visibilities, and low ceiling heights. However, JJA shows an increase in delays and lower performance in the afternoon hours. This is coincides with the increased occurrence of thunderstorms and is the likely culprit for the decreasing the airport's efficiency.

Figure 6.37 displays the delay impacts that weather has on SLC. Freezing precipitation and fog have the highest impacts on SLC and are commonly observed during the winter months.

This supports the idea that weather has its biggest impacts on SLC during the winter. Figure 6.38 displays the wind speed impacts which are relatively rare occurrence. However, as the speeds increase, so do the impacts on SLC. Figure 6.39 and Figure 6.40 display the ceiling and visibility impacts on SLC. Again, the impacts of conditions on SLC increase with severity. Figure 6.37 through Figure 6.40 all lead to the conclusion that weather impacts are responsible for the seasonal changes in delay and performance profiles and that DJF is overall the biggest impacting season.

6.7.4 Weather Impacts and Cancellations

Figure 6.41 displays the average monthly number of departure and arrival cancellations for SLC. December and January have the highest number of weather cancellations most likely as the result of poor visibility, low ceilings, frozen precipitation, and obscuring phenomena. Figure 6.42 displays the cancellation rates for various weather types. Fog and freezing precipitation have the highest cancellation rate along with the more severe weather conditions. Issues cause by freezing precipitation have already been discussed; however, conditions with reduced visibility are especially hazardous in mountainous areas due to the losses of visual situational awareness in relation to terrain. This may be the reason for the high number of cancellations during periods of fog, severe ceiling heights, and severe visibility.

6.8 Seattle – Tacoma International Airport

6.8.1 Background

Seattle – Tacoma International Airport (SEA) is a large airport serving the Northwestern United States. In 2015, 42,340,537 airports passed through SEA with a total of 381,408 airport

operations averaging 1,045 daily operations. SEA is a major hub for Alaska Airlines and Delta Air Lines.

6.8.2 SEA Weather Summary

SEA's northwestern location provides a temperate climate. A detailed analysis of the monthly average weather and monthly diurnal weather is discussed in Appendix I 6.A.7.

6.8.3 Weather Impacts and Delays

Figure 6.43 displays the seasonal, hourly patterns for 16 different metrics for SEA. Probably the most important item to recognize is that JJA departures and arrivals are considerably higher than other seasons. This fact alone is likely responsible for some of the increases in delays and decreases in performance observed and not from impacts from weather which is almost nonexistent during these months when compared to other seasons. Delays at other airports or enroute may also be a contributing factor. DJF sees an increase in delays and decrease in performance. This is likely caused by weather impacts from obscuring phenomena, frozen and non-frozen precipitation, reduced visibility and low ceilings. This observation is supported by what is observed in Figure 6.44 (weather delay impacts), Figure 6.45 (wind delay impacts), Figure 6.46 (ceiling delay impacts), and Figure 6.47 (visibility delay impacts).

6.8.4 Weather Impacts and Cancellations

Figure 6.48 displays the average number of monthly departure and arrival cancellations for SEA. Weather cancellations are highest in December and January as a result of the aforementioned poorer winter weather. Figure 6.49 shows the cancellation rate for various

weather types. Overall freezing precipitation and snow are responsible for the highest number of hourly cancellations.

6.9. San Francisco International Airport

6.9.1 Background

San Francisco International Airport (SFO) is a major transpacific gateway located in California. A major hub for United Airlines and Virgin America Airlines, the airport averages 3,702 weekly flights and carried 50,067,094 passengers in 2015. SFO is unique in that its runways are placed closely together creating unique separation challenges during periods of low visibility.

6.9.2 SFO Weather Summary

SFO's coastal and central location provides a temperate climate. A detailed analysis of the monthly average weather and monthly diurnal weather is discussed in Appendix I 6.A.8.

6.9.3 Weather Impacts and Delays

Figure 6.50 displays the seasonal delay and performance profiles for SFO. The higher number of delays and lower performance for JJA is likely caused by two factors: higher volume of traffic and delays at other airports or enroute to or from the airport. However, weather is a likely contributing factor in the DJF delays and lower airport performance. Also, the high number of late day departures is likely from red-eye flights to the east coast. Figure 6.51 shows the impacts different weather phenomena have on SFO. Due to such low observations of snow, freezing precipitation, and thunderstorms, the values displayed can't be viewed as the overall

impact. Other more common weather types do definitely have an impact on SFO weather. Wind speed delays in Figure 6.52 clearly show that impacts increase as wind speed increases and high winds are a serious threat for SFO. Figure 6.53 and Figure 6.54 show the impacts caused by different ceiling height and visibility severities. It is clear that more higher ceiling and visibility scores result in greater impacts to SFO.

6.9.4 Weather Impacts and Cancellations

Figure 6.55 displays the average number of monthly departure and arrival cancellations. Most weather cancellations occur during December, January, and February most likely as a result of low visibility and ceiling heights. Looking at the cancellation rates in Figure 6.56, severe weather and severe wind speeds have the highest number of cancellations. Severe wind speed impacts are rare events at SFO but due to the arrangement of the airport, wind is likely to cause major cancellations.

6.10. Phoenix Sky Harbor International Airport

6.10.1 Background

Phoenix Sky Harbor International Airport (PHX) is a major airport serving the dessert southwest. American Airlines and Southwest Airlines have major operations at PHX. In 2015, PHX had 44,006,205 passengers carried and 440,411 total operations.

6.10.2 PHX Weather Summary

PHX's desert location provides a temperate hot and dry climate with few observations of precipitation. A detailed analysis of the monthly average weather and monthly diurnal weather is discussed in Appendix I 6.A.9.

6.10.3 Weather Impacts and Delays

Figure 6.57 displays seasonal, hourly delay and performance data for PHX. The offset in the peaks for many of the plots is the result of Arizona not following daylight savings time. JJA shows an increase in delays and decreases in performance in the later hours most likely as a result of thunderstorms. DJF also shows higher incidences of delays and decreases in performance as a combined result of weather at PHX and weather outside of PHX. Remember, PHX has very minimal weather impacts when compared to other airports. Figure 6.58, Figure 6.59, Figure 6.60, and Figure 6.61 show the impacts of weather, wind speed, ceiling heights, and visibility on PHX. Overall increases in severity of the different categories result in greater impacts for PHX; however, impacts of moderate or severe types are almost nonexistent.

6.10.4 Weather Impacts and Cancellations

According to Figure 6.62, almost no weather cancellations occur outside of December, January, February, and March. PHX's overall good weather favors a lack of monthly cancellations. According to Figure 6.63, the highest rate of weather cancellations is caused by severe wind speeds. The low numbers also suggest that weather cancellations at PHX are likely as a result of weather enroute or at other airports.

6.11 Miami International Airport

6.11.1 Background

Miami International Airport (MIA) is a major international gateway to the Caribbean and Central and South America. It currently ranks second in the USA in number of international travelers. In 2015, it carried 44.3 million passengers and had 409,324 flight operations.

6.11.2 MIA Weather Summary

MIA's southern and coastal location provides a warm climate that experiences afternoon thunderstorms and impacts of tropical cyclones. A detailed analysis of the monthly average weather and monthly diurnal weather is discussed in Appendix I 6.A.10.

6.11.3 Weather Impacts and Delays and Cancellations

Figure 6.64 displays the hourly, seasonal delay and performance metrics for MIA. The higher number of DJF and MAM departures and arrivals is likely due to travelers escaping the harsh northern winters and traveling to the warmer climate of Miami. The increase in delays and lower performance for JJA in the later hours is likely caused by thunderstorms. Other patterns are likely caused by non-weather related issues or weather at other airports or enroute. Figure 6.65, Figure 6.66, Figure 6.67, and Figure 6.68 all show the delay impacts individual phenomena have on MIA and validate what was said earlier.

6.11.4 Weather Impacts and Delays

Figure 6.69 displays the average number of monthly cancellations for MIA. The usual peak in winter time weather cancellations is associated with weather at other airports. However,

the August to October weather cancellation peak is most likely associated with hurricanes and tropical storms. This idea is validated by Figure 6.70which shows that moderate and severe wind impacts has the highest cancellation rate.

6.12 Conclusion

Probably the most important takeaway from this chapter is that every airport delay and cancellation climatology is different and it is important to look at each airport individually. Airports all have their own unique climates, layouts, and operation procedures meaning that all airports will be affected differently by weather. As is seen, some airports handle certain weather phenomena, such as freezing precipitation or low visibility, differently. Also, some weather phenomena may not be as frequent at one airport as it is at another airport. Airports all have different layouts and surrounding terrain that may make operations in certain weather types more challenging than what would be at another airport. Airports also have different majority airline operators who have different procedures and this impacts the overall delay and cancellation patterns. In all, generalizing weather impacts for all airports may prove an ineffective way to understand how weather impacts commercial operations.

Another important takeaway from this chapter is while weather and impacts at other airports do impact the overall delay and cancellation statistics and there is no current way to truly remove outside impacts; these methods do provide much meaningful information on the impacts specific weather types have on individual airports and provides a more meaningful view that was in described in many of the OPSNET, ASPM, and ASQP premade reports. Delays and cancellations overall are not solely caused by one party, but by multiple parties who impact each other. These are currently not accurately depicted in the FAA datasets.

This analysis provides a stepping stone for developing new delay products and better understanding the issues and problems caused by weather. By looking at more than the departure and arrival rates and the overall efficiency scores, specific problem areas can be identified and corrected. Also, it depicts that weather and other delay causes do not just affect the hour of operations in which they occur but they affect the subsequent operating hours as well.

CHAPTER VII. IMPACTS OF CLIMATE TELECONNECTIONS ON AIRPORT WEATHER

7.1 Introduction

In order to assess the impacts of climate teleconnections on aviation seven impacting weather phenomena were selected. Density altitude, IFR conditions either from low visibility or low ceilings, rain, snow, freezing precipitation, thunderstorms, and fog were selected due to their adverse impacts on aircraft performance or impacts on delays or cancellations. Environmental temperature was also selected so comparisons could be made to existing climate teleconnection research. Most climate teleconnection research focuses on changes of temperature, surface pressure, and precipitation rates; the analysis of these specific weather types is novel in that insights into changes of specific weather phenomena, such as thunderstorms, can be observed.

7.2 ENSO Climate Teleconnections

Table 7.1 displays the annual, average monthly difference between El Niño month observations and Non-El Niño month observations. Using the Wilcoxon-Mann-Whitney statistical significance test, statistically significant differences at the one percent (underlined and bolded), the five percent (italicized), and the ten percent (asterisk) levels were also found. When El Niño resulted in a lower value than normal or La Niña conditions, the value is shown in red. Looking at the monthly temperature differences, cooler temperatures occurred during El Niño months at airports located in the western and southern regions of the U.S. while warmer temperatures occurred at airports located in the Midwest, Northwest, and Northeast U.S. with many temperature changes being statistically significant.

Density altitude changes follow a similar trend as the environmental temperature changes. Airports that are plagued by high density altitudes, such as Hartsfield – Jackson

Atlanta International (ATL), Phoenix Sky Harbor International (PHX), and Salt Lake City International (SLC), observe lower density altitudes during El Niño conditions resulting in better aircraft performance and operating economics. More IFR observations occur at airports during El Niño conditions except for Chicago O'Hare International (ORD), Dallas Love Field (DAL), and Miami International (MIA); San Francisco International (SFO) and Seattle – Tacoma International (SEA) both exhibit statistically significant increases of IFR observations at the one percent level during El Niño conditions. Increases in the observations of IFR conditions can mean more delays and cancellations for airlines and travelers. Also, air traffic controllers at SFO and SEA can use this information to begin making preparations for more IFR approaches whenever the possibility of El Niño event becomes likely. Fog shows statistically significant increases in observations for SEA and statistically significant decreases in observations for SFO during El Niño conditions. Again, changes in fog observations will likely result in delay and cancellation changes for the affected airports. Airlines typically begin planning future schedules months in advance but the final airline schedule is finalized one to two months prior to the schedule being flown. Since ENSO is relatively long phenomena lasting for several months and can be forecast months in advance, schedulers and other operators affected by weather can begin making preparations to respond to the impacts stated above.

Rain observations significantly increase for ATL, DAL, MIA, and PHX during El Niño months as is expected from Figure 3.2. While rain is not a significant cause of delays and cancellations for the airports observed, knowing this can help in predicting future aviation performance forecasts. It also presents a different view of the impacts of El Niño on rain since most studies focus on rainfall amounts and not actual rain events. The METAR data could be useful for determining the impacts of ENSO on high precipitation events. Snow observations

decrease for most of the airports with ORD, MSP, SLC, and SEA all showing statistically significant decreases during El Niño events. Freezing precipitation observations also decrease for most of the airports with ATL, MSP, and JFK all showing statistically significant decreases during El Niño events. Knowing how ENSO impacts individual airports will not only allow airlines to better forecast seasonal delays and cancellations but also allow operators to better prepare for winter events. Airlines and airport operators can adjust the amount of deicing equipment needed for a given winter season based on ENSO predictions.

Most airports show an increase in thunderstorm observations during El Niño months. JFK, PHX, and SFO all show statistically significant increases in thunderstorms during El Niño periods. Increased thunderstorm activity will likely result in airport delays. Including more airports in the analysis of ENSO on thunderstorm activity may provide a better understanding of the impacts of ENSO on society and aviation.

Knowledge of how ENSO can change the weather that impacts aviation can allow for airport operators, airlines, and air traffic controllers to make estimates of future delays and cancellations and implement changes to planned schedules and operations in order to mitigate future negative weather impacts. Future analysis of individual months will improve the understanding of when and how ENSO affects weather and will be a topic of future research.

7.3 Arctic Oscillation Climate Teleconnections

Table 7.2 displays the difference between monthly averages for the Arctic Oscillation (AO) with the same conventions as Table 7.1. As expected from Chapter Three, a negative AO phase allows for cooler temperatures. ATL, ORD, DAL, MSP, JFK, PHX, SFO, and SEA all show statistically significant decreases in temperature during negative AO events while MIA

shows an increase in environmental temperature. Density altitude significantly decreases for ATL, ORD, MSP, SFO, and SEA for the negative AO phases and increase for DAL and MIA. Lower density altitudes will again result in better aircraft performance and economics.

IFR observations show statistically significant increases for DAL, JFK, and PHX and decreases for ATL, ORD, MSP, and SFO during negative AO phases. Fog observations increase for ATL, MSP, and JFK and decrease for PHX during negative AO phases. Increases in obscuring phenomena, lower visibilities, and lower ceilings as a result of the AO can result in aviation system performance decreases; however, knowing how the AO impacts these weather phenomena can be used in future planning and delay and cancellation mitigation.

Statistically significant increases in rain observations occur at ORD and PHX while decreases occur at SFO during negative AO phases. Again, this information can be used to understand rainfall occurrence instead of rainfall amounts and presents a different way of looking at the impacts of the AO on precipitation. Statistically significant increases in snow observations occur at ATL and PHX while decreases occur at MSP, JFK, and SFO during negative AO phases. Statistically significant decreases in freezing precipitation observations occur at SFO. Understanding how the AO impacts wintery precipitation will allow for better planning and forecasting of weather related delays and cancellations. Only JFK shows a statistically significant decrease in thunderstorm activities during the negative phase. AO may not impact thunderstorm occurrences at a majority of the selected airports but may impact other airports in the aviation system and impact flights enroute to and from the selected airports. The inclusion of more airports is likely to be necessary to assess the total impact of the AO on U.S. thunderstorms. In closing, knowing how the AO modifies the aviation related weather will be useful in mitigating future weather delays, cancellations, and other weather associated risks.

CHAPTER VIII: CONCLUSIONS

This thesis has proven the feasibility and usefulness of using METAR and FAA performance data in determining the local weather climatologies for specific airports, assessing the impacts of weather on different segments of airline operations, and identifying the impacts of the AO and ENSO on weather phenomena. Also, looking at all available variables related to aviation system performance provides more insights into the impacts of weather on aviation than just looking at departure and arrival on time performance. Other important findings include:

1. That differences in airport weather and airline operations impact the efficiencies of airport operations and it is important to assess airports individually.
2. That understanding the differences in airport weather climatologies can allow for improvements in the aviation operations.
3. That weather impacts all aspects of aviation operations not only ATC operations.
4. Climate teleconnections impact specific weather phenomena, such as the occurrence of fog or thunderstorms.

This information and these methods can be used to improve not only aviation operations but other fields of applied atmospheric research. For example, wind energy companies can use this research to understand the impacts of climate teleconnections on wind climatologies at specific sites. Future work will continue to investigate aviation operations and the impacts of weather and climate on societies and businesses. I would also like to expand the research to regions outside of the continental United States.

TABLES

Category	**Ceiling**		**Visibility**
LIFR	Below 500 feet AGL	And/or	Less than 1 SM
IFR (IMC)	500 to below 1,000 feet AGL	And/or	1 to less than 3 SM
MVFR	1,000 to 3,000 feet AGL	And/or	3 to 5 SM
VFR (VMC)	Greater than 3,000 feet AGL	And/or	Greater than 5 SM

Table 2.1. Weather categories for airport conditions based on visibility and ceiling height. Categories are low IFR (LIFR), IFR, marginal VFR (MVFR), and VFR. Technically, LIFR is really IFR and MVFR is VFR.

Precip. Type	Abbr.	Description/Definition	Intensity Qualifier (Rate)	Intensity Qualifier (Visual)
Drizzle	DZ	Fairly uniform precipitation composed exclusively of fine drops with diameters of less than 0.02 inch (0.5 mm) very close together and appears to float while following air currents, although unlike fog droplets, it falls to the ground.	NA	**Light:** Vis. ≥ 1/2 mile **Moderate:** 1/2 > Vis. ≥ 1/4 mile **Heavy:** Vis < 1/4 mile
Rain	RA	Precipitation, either in the form of drops larger than 0.02 inch (0.5 mm), or smaller drops which, in contrast to drizzle, are widely separated.	**Light:** Max of 0.01 inch in 6 min. **Moderate:** More than 0.01 inch to 0.03 inch in 6 min. **Heavy:** more than 0.03 inch in 6 min.	**Light:** Drops do not completely wet an exposed surface. **Moderate:** Individual drops are not clearly identifiable. Spray is observable just above pavements and other hard surfaces. **Heavy:** Individual drops are not identifiable. Heavy spray to a height of several inches is observed over hard surfaces.
Snow	SN	Precipitation of snow crystals, mostly branched in the form of six-pointed stars.	NA	**Light:** Vis. ≥ 1/2 mile **Moderate:** 1/2 > Vis. ≥ 1/4 mile **Heavy:** Vis < 1/4 mile
Snow Grain	SG	Precipitation of very small, white, and opaque grains of ice.	NA	NA
Ice Crystal	IC	A fall of unbranched (snow crystals are branched) ice crystals in the form of needles, columns, or plates.	NA	NA
Ice Pellet	PL	Precipitation of transparent or translucent pellets of ice, which are round or irregular, rarely conical, and which have a diameter of 0.2 inch (0.5 mm), or less.	NA	**Light:** Scattered pellets that do not completely cover an exposed surface regardless of duration. Visibility is not affected. **Moderate:** Slow accumulation on ground. Visibility reduced by ice pellets to less than 7 statute miles. **Heavy:** Rapid accumulation on ground. Visibility reduced by ice pellets to less than 3 statute miles.
Hail	GR	Precipitation in the form of small balls or other pieces of ice falling separately or frozen together in irregular lumps	NA	NA
Small Hail / Snow Pellet	GS	Precipitation of white, opaque grains of ice	NA	NA
Unknown Precipitation	UP	Precipitation type that is reported if the automated station detects the occurrence of precipitation but the precipitation discriminator cannot recognize the type.	NA	NA

Table 2.2. METAR precipitation phenomena including abbreviation code, definition and description, intensity based on rate, and intensity based on appearance and visual cues. Light intensities are indicated by (-) minus sign, nothing indicates moderate intensity, and heavy intensities are indicated by a (+) plus sign. Definitions and values are taken from FCM-H1-2005.

Runway Condition Description	**Deceleration or Directional Control Observation**	**Pilot Reported Braking Action**
• Dry	NA	NA
• Frost • Wet (Includes damp and less than 1/8 inch depth of water) *Less than 1/8 inch depth of:* • Slush • Dry Snow • Wet Snow	Braking deceleration is normal for the wheel braking effort applied AND directional control is normal.	Good
-15ºC and Colder outside air temperature: • Compacted Snow	Braking deceleration OR directional control is between Good and Medium.	Good to Medium
• Slippery When Wet (wet runway) • Dry Snow or Wet Snow (any depth) over Compacted Snow *1/8 inch depth or greater of:* • Dry Snow • Wet Snow *Warmer than -15ºC outside air temperature:* • Compacted Snow	Braking deceleration is noticeably reduced for the wheel braking effort applied OR directional control is noticeably reduced.	Medium
1/8 inch depth or greater of: • Water • Slush	Braking deceleration OR directional control is between Medium and Poor	Medium to Poor
• Ice	Braking deceleration is significantly reduced for the wheel braking effort applied OR directional control is significantly reduced.	Poor
• Wet Ice • Water on top of Compacted Snow • Dry Snow or Wet Snow over Ice	Braking deceleration is minimal to non-existent for the wheel braking effort applied OR directional control is uncertain.	Nil

Table 2.3. Braking and directional control performance for aircraft under specified runway conditions. Information adapted from the FAA AC 91-79A "Mitigating the Risks of Runway Overrun Upon Landing."

Obscuration Type	Abbreviation	Description/Definition
Mist	BR	A visible aggregate of minute water particles suspended in the atmosphere that reduce visibility to less than 7 statute miles but greater than or equal to 5/8 miles.
Fog	FG	A visible aggregate of minute water particles (droplets) which are based at the Earth's surface and reduces horizontal visibility to less than 5/8 statute mile and unlike drizzle, it does not fall to the ground.
Smoke	FU	A suspension in the air of small particles produced by combustion.
Volcanic Ash	VA	Fine particles of rock powder that originate from a volcano and that may remain suspended in the atmosphere for long periods.
Widespread Dust	DU	Fine particles of earth or other matter raised or suspended in the air by the wind.
Sand	SS	Sand particles raised by the wind to a height sufficient to reduce horizontal visibility.
Haze	HZ	A suspension in the air of extremely small, dry particles invisible to the naked eye and sufficiently numerous to give the air an opalescent appearance.
Spray	PY	An ensemble of water droplets torn by the wind from the surface of an extensive body of water, generally from the crests of waves, and carried up a short distance into the air.

Table 2.4. METAR obscuration phenomena including abbreviation code and definition and description. Definitions are taken from FCM-H1-2005.

Type	Abbr.	Description/Definition	Commonly Attached To:
Shower	SH	Precipitation characterized by the suddenness with which they start and stop, by the rapid changes of intensity, and usually by rapid changes in the appearance of the sky.	RA, SN
Freezing	FZ	When fog is occurring and the temperature is below 0°C, "freezing" shall be used to further describe the phenomena. When drizzle and/or rain freezes upon impact and forms a glaze on the ground or other exposed objects, "freezing" shall be used to further describe the precipitation	RA, DZ, FG
Thunderstorm	TS	A local storm produced by a cumulonimbus cloud that is accompanied by lightning and/or thunder.	NA
Vicinity	VC	Weather phenomena occurring beyond the point of observation (between 5 and 10 statute miles) shall be reported as (in the) vicinity.	RA, SN, TS, FG, FU, VA, DU, SA, SS, DS, BR
Squall	SQ	A strong wind characterized by a sudden onset in which the wind speed increases at least 16 knots and is sustained at 22 knots or more for at least one minute.	NA
Funnel Cloud	FC	A violent, rotating column of air touching the ground OR a violent, rotating column of air which does not touch the surface OR a violent, rotating column of air that forms over a body of water, and touches the water surface.	NA
Sandstorm	SS	Particles of sand carried aloft by a strong wind. The sand particles are mostly confined to the lowest ten feet, and rarely rise more than fifty feet above the ground.	NA
Dust Storm	DS	A severe weather condition characterized by strong winds and dust-filled air over an extensive area.	NA
Shallow	MI	The descriptor shallow shall only be used to further describe fog that has little vertical extent (less than 6 feet).	FG
Partial / Patches	PR / BC	The descriptors partial and patches shall only be used to further describe fog that has little vertical extent (normally greater than or equal to 6 feet but less than 20 feet), and reduces horizontal visibility, but to a lesser extent vertically.	FG
Blowing	BL	When dust, sand, snow, and/or spray is raised by the wind to a height of 6 feet or more, "blowing" shall be used to further describe the weather phenomenon.	DU, SN, PY
Drifting	DR	When dust, sand, or snow is raised by the wind to less than 6 feet, "low drifting" shall be used to further describe the weather phenomenon.	DU, SA, SN

Table 2.5. Other METAR phenomena and descriptors including abbreviation code, definition and description, and common attachments to other phenomena. Definitions are taken from FCM-H1-2005.

ASPM 77 Airports

1. Albuquerque Intl. Sunport (ABQ)
2. Austin-Bergstrom Intl. (AUS)
3. Baltimore/Washington Intl. (BWI)
4. Birmingham Intl. (BHM)
5. Bob Hope (BUR)
6. Boston Logan Intl. (BOS)
7. Bradley Intl. (BDL)
8. Buffalo Niagara Intl. (BUF)
9. Charlotte Douglas Intl. (CLT)
10. Chicago Midway (MDW)
11. **Chicago O'Hare Intl. (ORD)***
12. Cincinnati/Northern Kentucky Intl. (CVG)
13. Cleveland Hopkins Intl. (CLE)
14. **Dallas Love Field (DAL)***
15. Dallas/Fort Worth Intl. (DFW)
16. Dayton Intl. (DAY)
17. Denver Intl. (DEN)
18. Detroit Metropolitan Wayne County (DTW)
19. Fort Lauderdale/Hollywood Intl. (FLL)
20. Gary Chicago Intl. (GYY)
21. George Bush Houston Intercontinental (IAH)
22. Greater Rockford (RFD)
23. **Hartsfield-Jackson Atlanta Intl. (ATL)***
24. Honolulu Intl. (HNL)
25. Houston Hobby (HOU)
26. Indianapolis Intl. (IND)
27. Jacksonville Intl. (JAX)
28. John Wayne-Orange County (SNA)
29. Kahului (OGG)
30. Kansas City Intl. (MCI)
31. Lambert Saint Louis Intl. (STL)
32. Las Vegas McCarran Intl. (LAS)
33. Long Beach (LGB)
34. Long Island Mac Arthur (ISP)
35. Los Angeles Intl. (LAX)
36. Louis Armstrong New Orleans Intl. (MSY)
37. Louisville Intl. (SDF)
38. Manchester (MHT)
39. Memphis International (MEM)
40. Miami Intl. (MIA)*
41. Milwaukee General Micthell Intl. (MKE)
42. **Minneapolis/St. Paul Intl. (MSP)***
43. Nashville Intl. (BNA)
44. **New York John F. Kennedy Intl. (JFK)***
45. New York LaGuardia (LGA)
46. Newark Liberty Intl. (EWR)
47. Norman Mineta San Jose Intl. (SJC)
48. Oakland Intl. (OAK)
49. Omaha Eppley Airfield (OMA)
50. Ontario Intl. (ONT)
51. Orlando Intl. (MCO)
52. Oxnard (ONX)
53. Palm Beach Intl. (PBI)
54. Palm Springs Intl. (PSP)
55. Philadelphia Intl. (PHL)
56. **Phoenix Sky Harbor Intl. (PHX)***
57. Pittsburgh Intl. (PIT)
58. Portland International (PDX)
59. Providence Francis Green State (PVD)
60. Raleigh/Durham Intl (RDU)
61. Ronald Reagan Washington National (DCA)
62. RSW - Southwest Florida Intl. (RSW)
63. Sacramento Intl. (SMF)
64. **Salt Lake City Intl. (SLC)***
65. San Antonio Intl. (SAT)
66. San Diego Intl. (SAN)
67. **San Francisco Intl. (SFO)***
68. San Juan Luis Munoz Intl. (SJU)
69. **Seattle/Tacoma Intl. (SEA)***
70. Stewart Intl. (SFW)
71. Tampa Intl. (TPA)
72. Ted Stevens Anchorage Intl. (ANC)
73. Teterboro (TEB)
74. Tucson Intl. (TUS)
75. Van Nuys (VNY)
76. Washington Dulles Intl (IAD)
77. Westchester County (HPY)

Table 4.1. List of the ASPM 77 Airports along with IACO identifier. Airport that are bolded and have an asterisk indicate airports analyzed in this thesis.

ASPM Carriers

1. Air Canada (ACA)
2. Airtran Airways (TRS)
3. Alaska Airlines (ASA)
4. Aloha Airlines (AAH)
5. American Airlines (AAL)
6. American Eagle (EGF)
7. America West (AWE)
8. ATA Airlines (AMT)
9. Atlantic Coast (BLR)
10. Atlantic Southeast Airlines (ASQ)
11. Atlantic Southeast Airlines (CAA)
12. Comair (COM)
13. Continental Airlines (COA)
14. Delta Air Lines (DAL)
15. ExpressJet Airlines (BTA)
16. FedEx (FDX)
17. Frontier Airlines (FFT)
18. Hawaiian Airlines (HAL)
19. Independence Air (IDE)
20. Jetblue Airways (JBU)
21. Mesa Airlines (ASH)
22. Northwest Airlines (NWA)
23. Pinnacle Airlines (FLG)
24. Skywest Airlines (SKW)
25. Southwest Airlines (SWA)
26. TWA (TWA)
27. United Airlines (UAL)
28. United Parcel Service (UPS)
29. US Airways (USA/AWE)
30. Virgin America (VRD)

Table 4.2. List of ASPM Carriers including ICAO carrier codes. Note some of these are defunct but past records are still included in ASPM metrics. This is not an exhaustive list.

Local Weather Codes and Severity Values

Code	Description	Severity Value
DZ	Drizzle	1
UP	Unknown Precipitation	1
HZ	Haze	1
PY	Spray	1
RA	Rain	2
BR	Mist	2
FU	Smoke	2
DU	Dust	2
SA	Sand	2
SH	Showers	2
SN	Snow	3
SG	Snow Grains	3
IC	Ice Crystals	3
PL	Ice Pellets	3
GR	Hail	3
GS	Small Hail or Snow Pellets	3
FG	Fog	3
VA	Volcanic Ash	3
PO	Dust/Sand Whirls	3
SQ	Squalls	3
FC	Funnel Cloud	3
+FC	Tornado or Waterspout	3
SS	Sandstorm	3
DS	Duststorm	3
TS	Thunderstorm	3
FZ	Freezing	3
MI	Shallow	-1
PR	Partial	-1
BC	Patches	-2
VC	In the Vicinity	-2
DR	Low Drifting	1
BL	Blowing	1
+	Heavy	1
-	Light	No change

Table 4.3. Local weather codes and abbreviations along with severity value. MI, PR, BC, VC, DR, BL, and + are attached to certain weather codes to change their severity impact based on past observations. One indicates a weather phenomenon that has “minor” impacts on operations, two indicates a weather phenomenon that has “moderate” impacts on operations, and three indicate a weather phenomenon that has “severe” impacts on operations.

ASQP Carriers

1. American Airlines (AAL)
2. Alaska Airlines (ASA)
3. JetBlue Airways (JBU)
4. Delta Air Lines (DAL)
5. Atlantic Southwest Airlines (CAA)
6. Frontier Airlines (FFT)
7. Hawaiian Airlines (HAL)
8. American Eagle (EGF)
9. Spirit Airlines (NKS)
10. SkyWest Airlines (SKW)
11. United Airlines (UAL)
12. US Airways (USA)
13. Southwest Airlines (SWA)
14. Mesa Airlines (ASH)

Table 4.4. Near current list of ASQP reporting carriers and ICAO carrier code. This is not an exhaustive list.

El Nino - Non El Nino Months								
Airport	**Temperature**	**Density Altitude**	**IFR**	**Rain**	**Snow**	**Freezing**	**Thunderstorm**	**Fog**
Hartsfield - Jackson Atlanta International	**-0.3707**	*-108.389*	21.4756	*12.167*	-2.1927	-1.8746*	0.6668	-0.37073
Chicago O'Hare International	*0.2261*	*58.6099*	-0.3253	7.6894	*-5.861*	-1.4488	0.4472	0.8401
Dallas Love Field	**-1.8930**	*-73.9836*	-1.4348	**13.6884**	0.80032	0.0869*	2.8792	-0.3019
Miami International	-1.0659	23.5487	-0.1636	*8.0725*	NA	NA	2.6011	-0.7353
Minneapolis - St. Paul International	**0.5086**	**65.5283**	1.5019	14.9920	**-10.2651**	-1.8779*	3.4786	-1.0267
New York John F. Kennedy Internationa	1.6547	117.3516	10.1227	10.1762	1.9169	**-0.40916**	0.3804*	1.4356
Phoenix Sky Harbor International	**-2.1376**	*-85.9691*	0.4707	*4.1110*	-0.2085	-0.2088	**1.8905**	0.0380
Salt Lake City International	-0.5665	-92.1663	2.5801	5.6747	*-3.4441*	1.6297	2.0668	2.0871
San Francisco International	*-1.9185*	**78.6513**	**4.3252**	-1.0904	*-0.2855*	-0.2855	0.0598*	-2.4978*
Seattle-Tacoma International	**1.7496**	**166.3204**	**11.0338**	7.4815	**-4.4670**	-1.9444	-1.0177	*5.0894*

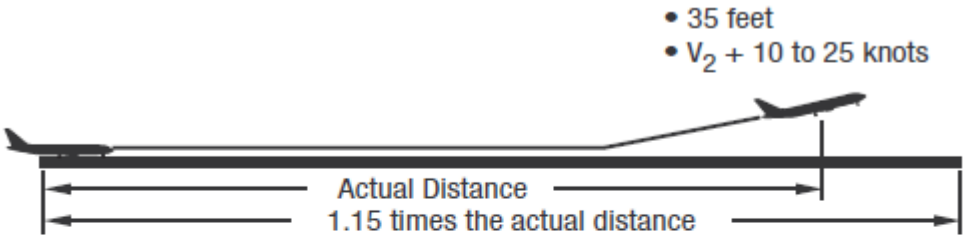
Table 7.1 Changes in monthly temperature (°F), density altitude (feet), and observations of Instrument Flight Rules (IFR) conditions, rain, snow, freezing precipitation, thunderstorms, and fog as a result of ENSO. The values in Table 7.1 show the difference of average monthly values during El Niño minus Non El Niño conditions. Values in red show an overall decrease. Underlined and bolded values indicate statistical significance at the 1% values, italicized values indicate statistical significance at the 5% value, and asterisks indicate statistical significance at the 10% value.

Arctic Oscillation (Negative - Positive)								
Airport	**Temperature**	**Density Altitude**	**IFR**	**Rain**	**Snow**	**Freezing**	**Thunderstorm**	**Fog**
Hartsfield - Jackson Atlanta International	**-0.2749**	**-65.7326**	**-13.8663**	9.7385	*0.69623*	0.3522	0.25265	**1.8226**
Chicago O'Hare International	**-0.9213**	**-95.8807**	-1.2679*	7.3409*	-2.7922	-0.5543	-0.7387	0.92132
Dallas Love Field	**-1.184**	*109.224*	*0.9326*	-0.1332	0.0836	0.9534	-0.2299	-0.01758
Miami International	**0.3448**	**5.9047**	-1.5376	1.0365	NA	NA	-1.6178	-0.17904
Minneapolis - St. Paul International	**-1.1057**	**-96.2785**	**-3.4259**	1.8671	**-3.2543**	0.1062	-0.9466	0.7208*
New York John F. Kennedy Internationa	**-0.9989**	-139.7410	*5.4567*	2.2533	**-1.7262**	-0.8412	*-0.8802*	*1.5648*
Phoenix Sky Harbor International	*-1.1134*	-90.3586	*0.2883*	1.1182*	.0023	.2187	-0.3586	-0.0446*
Salt Lake City International	-1.6546	-132.1511	-11.1054	0.7724	-0.8433	-1.8937	-2.0728	-1.3839
San Francisco International	*-0.6980*	**-84.6503**	*-6.9149*	**-2.0898**	**-0.0219**	**-0.0219**	-0.1256	-0.3968
Seattle-Tacoma International	**-1.6755**	**-156.934**	9.2786	9.2317	*1.6992*	-0.1052	-0.2883	0.7935

Table 7.2 Changes in monthly temperature (°F), density altitude (feet), and observations of Instrument Flight Rules (IFR) conditions, rain, snow, freezing precipitation, thunderstorms, and fog as a result of Arctic Oscillation. The values in Table 7.2 show the difference of average monthly values during negative AO phases minus positive AO phases. Values in red show an overall decrease. Underlined and bolded values indicate statistical significance at the 1% values, italicized values indicate statistical significance at the 5% value, and asterisks indicate statistical significance at the 10% value.

FIGURES

a)



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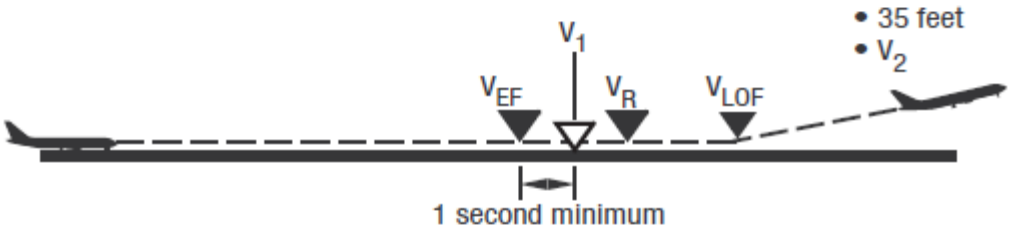

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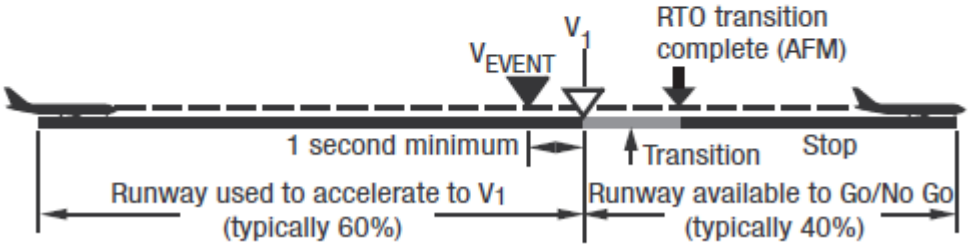
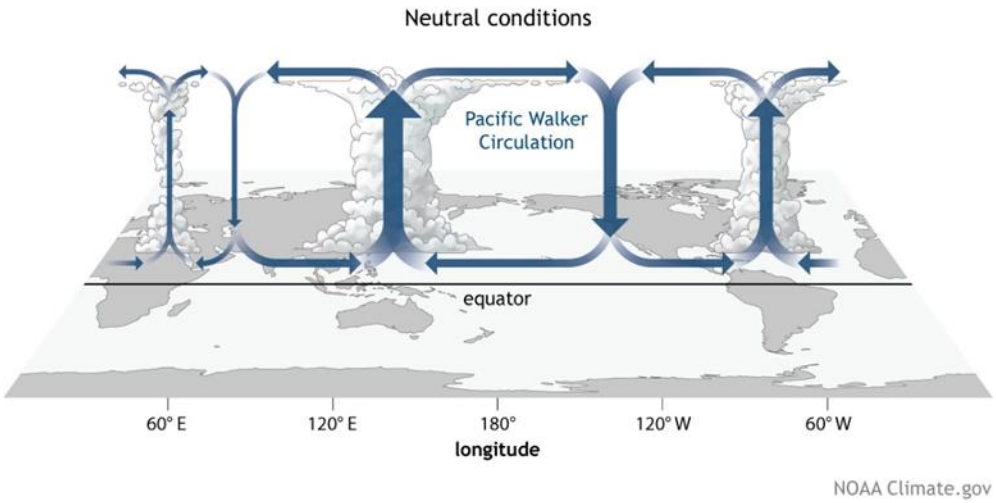


Figure 2.1. Diagram of all-engine go distance (a), engine-out accelerate-go distance (b), and accelerate - stop distance (c). Taken from the FAA's "Pilot Guide to Takeoff Safety".

a)



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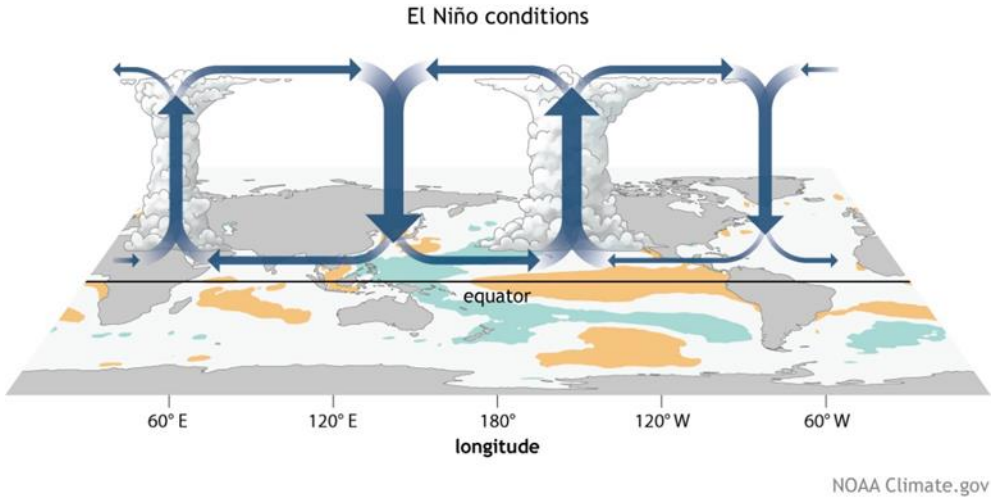

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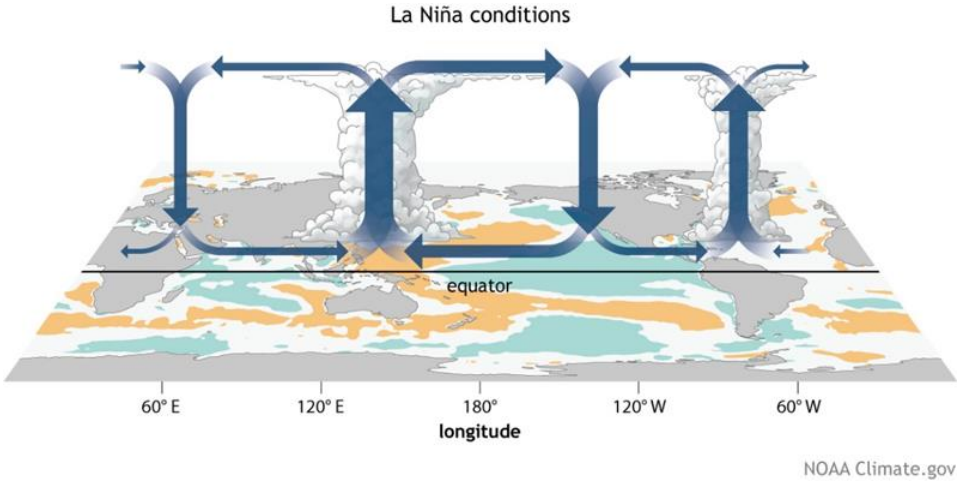
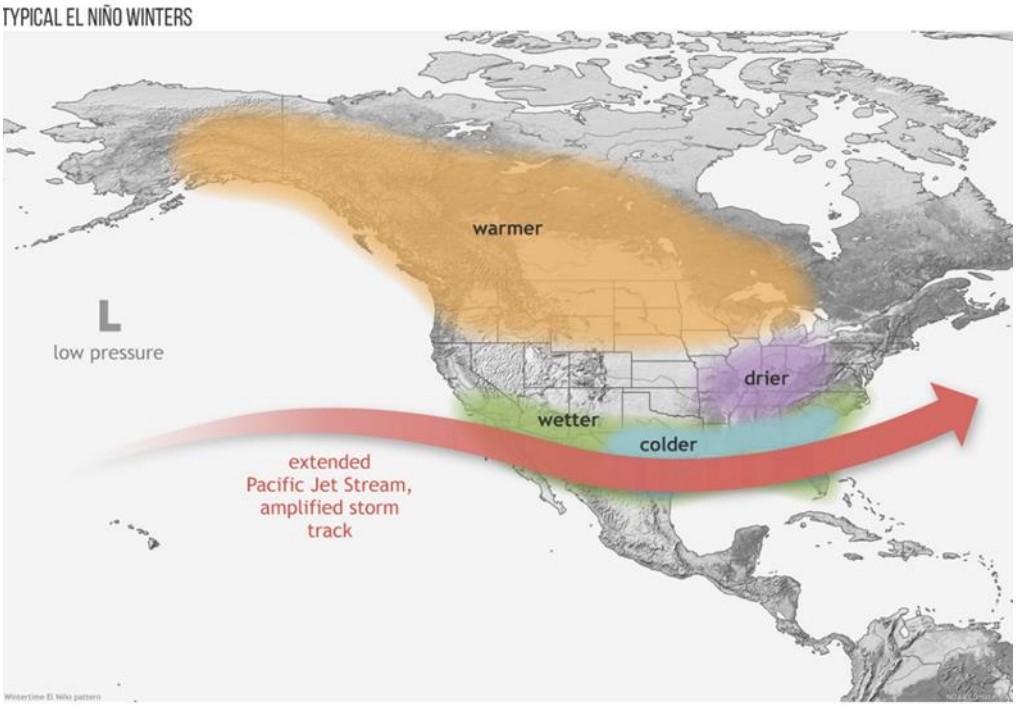


Figure 3.1 Sea surface temperature anomalies and resulting changes in planetary circulation for a) normal, b) El Niño, and c) La Niña conditions. Adapted from Liberto, 2014.

a)



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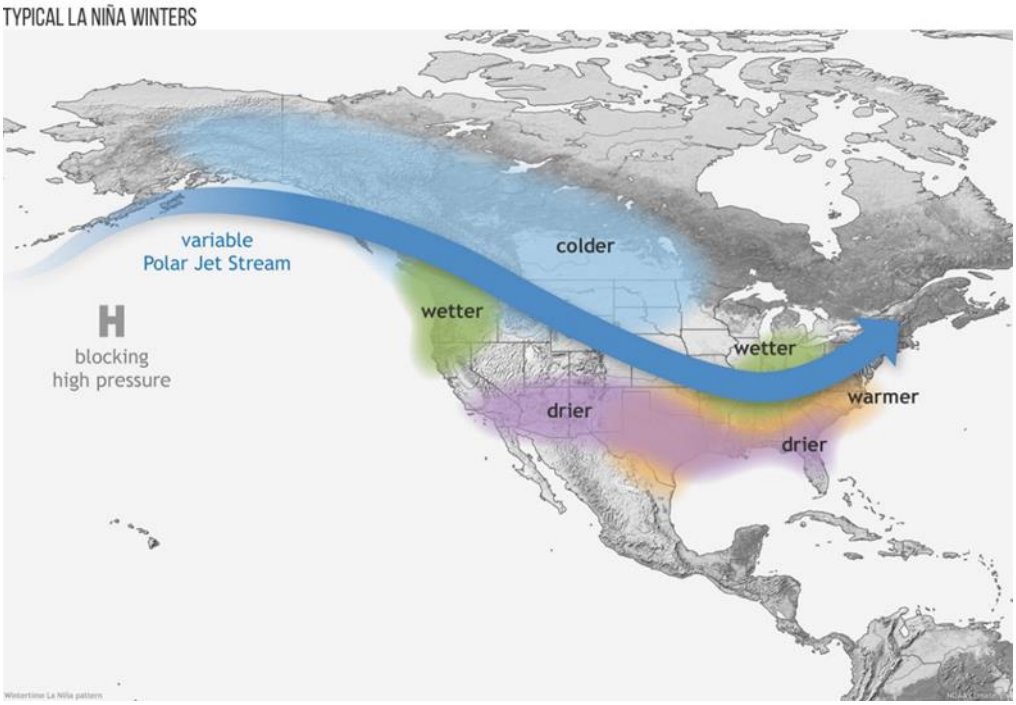


Figure 3.2 Typical a) El Niño and b) La Niña winter weather impacts. Adapted from Lindsey, 2016.

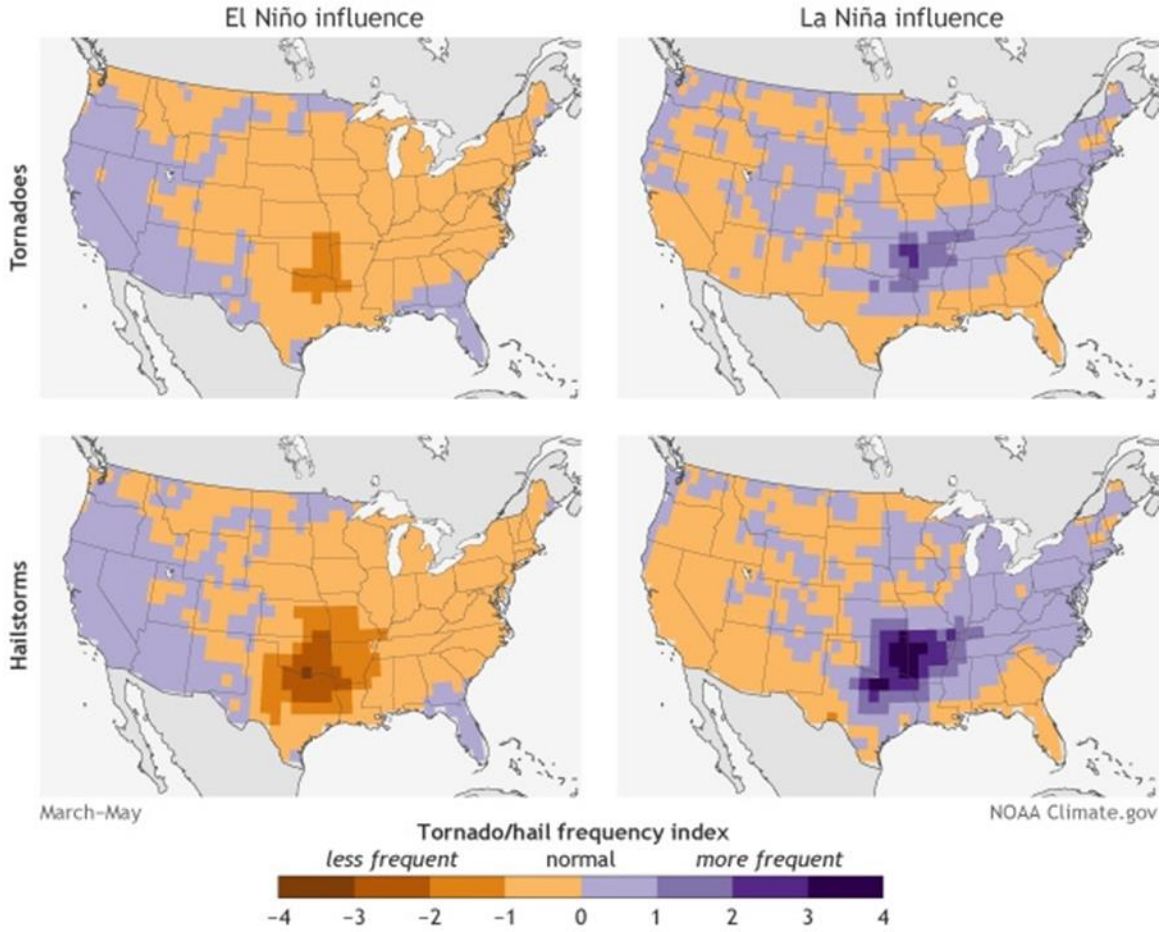
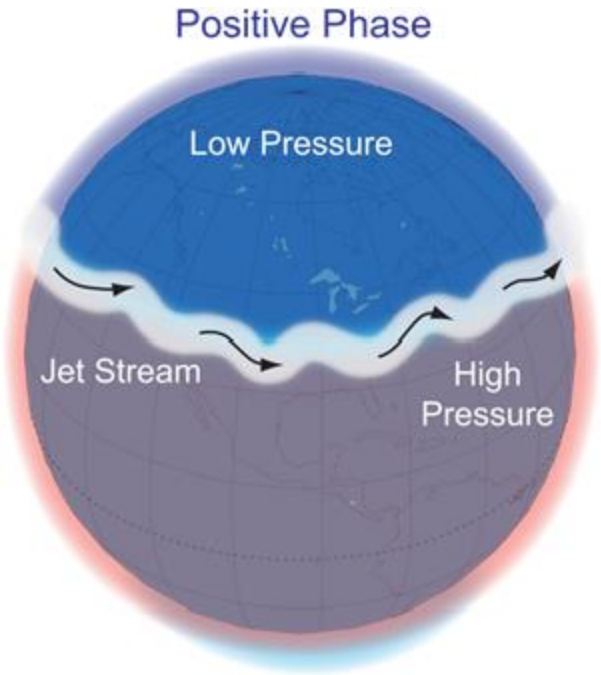


Figure 3.3 Impacts of El Niño and La Niña on tornado and hailstorm frequency. Taken from Scott, 2015.

a)



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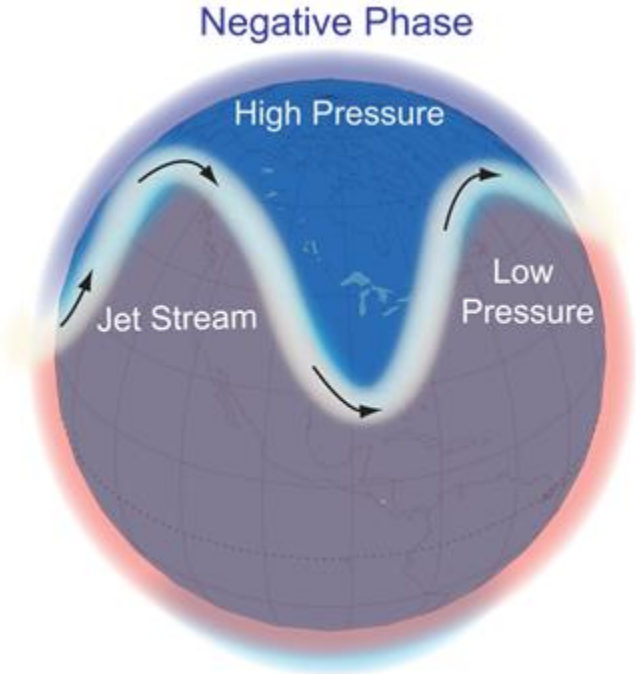
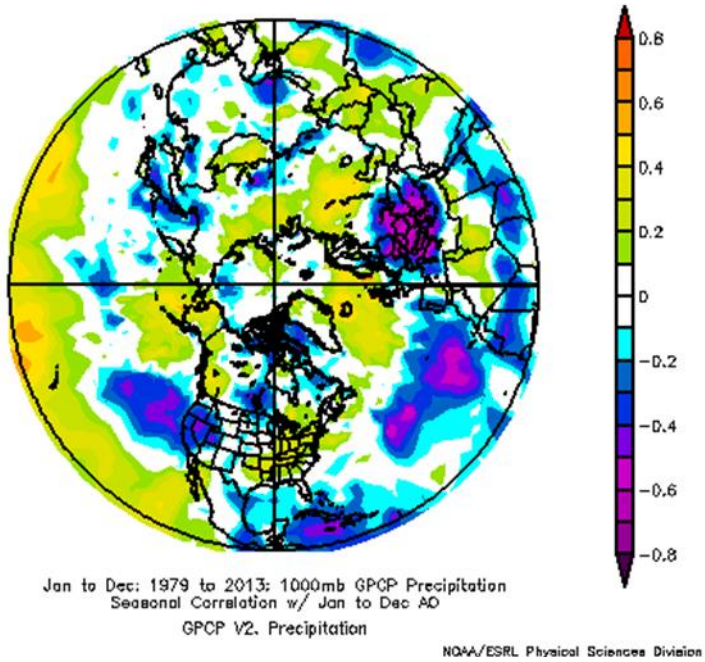


Figure 3.4. Typical patterns for the a) positive and b) negative phases for the Arctic Oscillation. Note that increased meridional flow in 3.4a) is assoacieated with increased storminess. Taken from the AMS "State of the Climate in 2010".

a)



b)

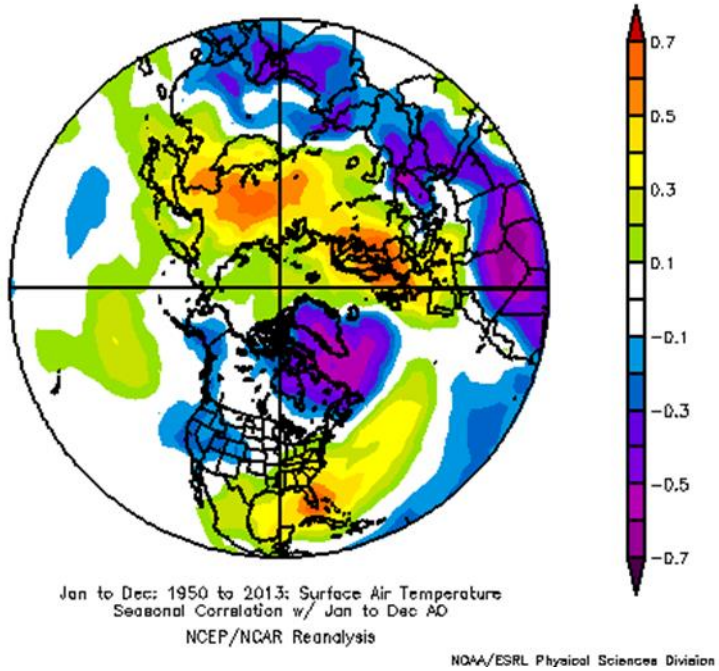


Figure 3.5. AO correlation patterns with a) surface air temperature and b) precipitation. Made using the Earth System Research Laboratory interactive webpage http://www.esrl.noaa.gov/psd/data/correlation/.

ASPM 77 Delay and Cancellation Statistics

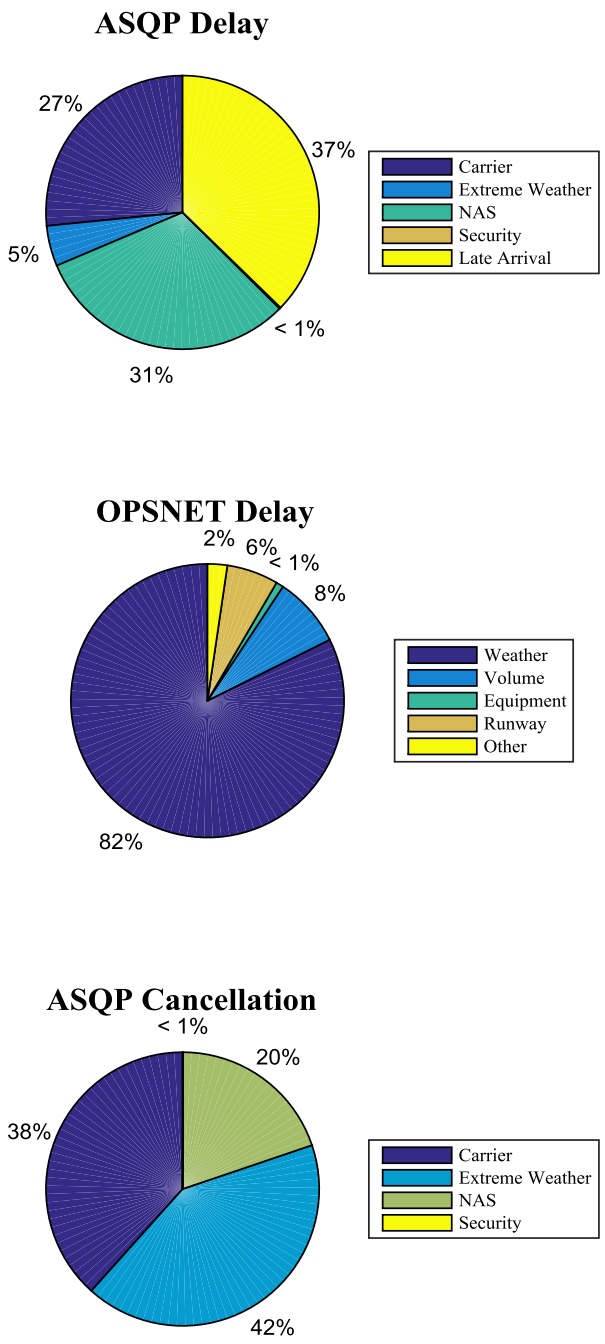


Figure 4.1. ASQP Delay, OPSNET Delay, and ASQP Cancellation causes for ASPM 77 Airports. Data range used was from October 2003 to July 2015.

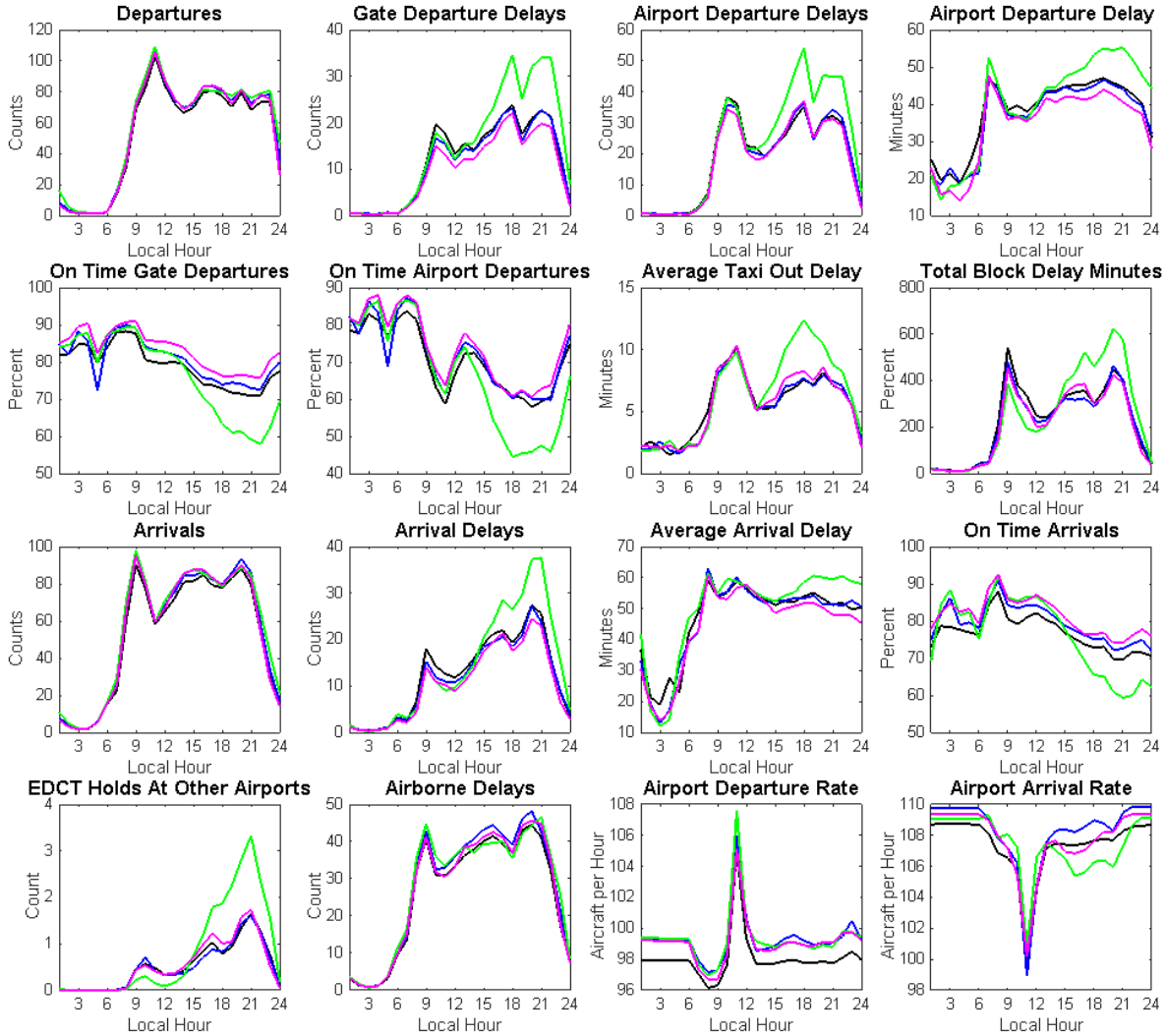


Figure 6.1. ATL hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

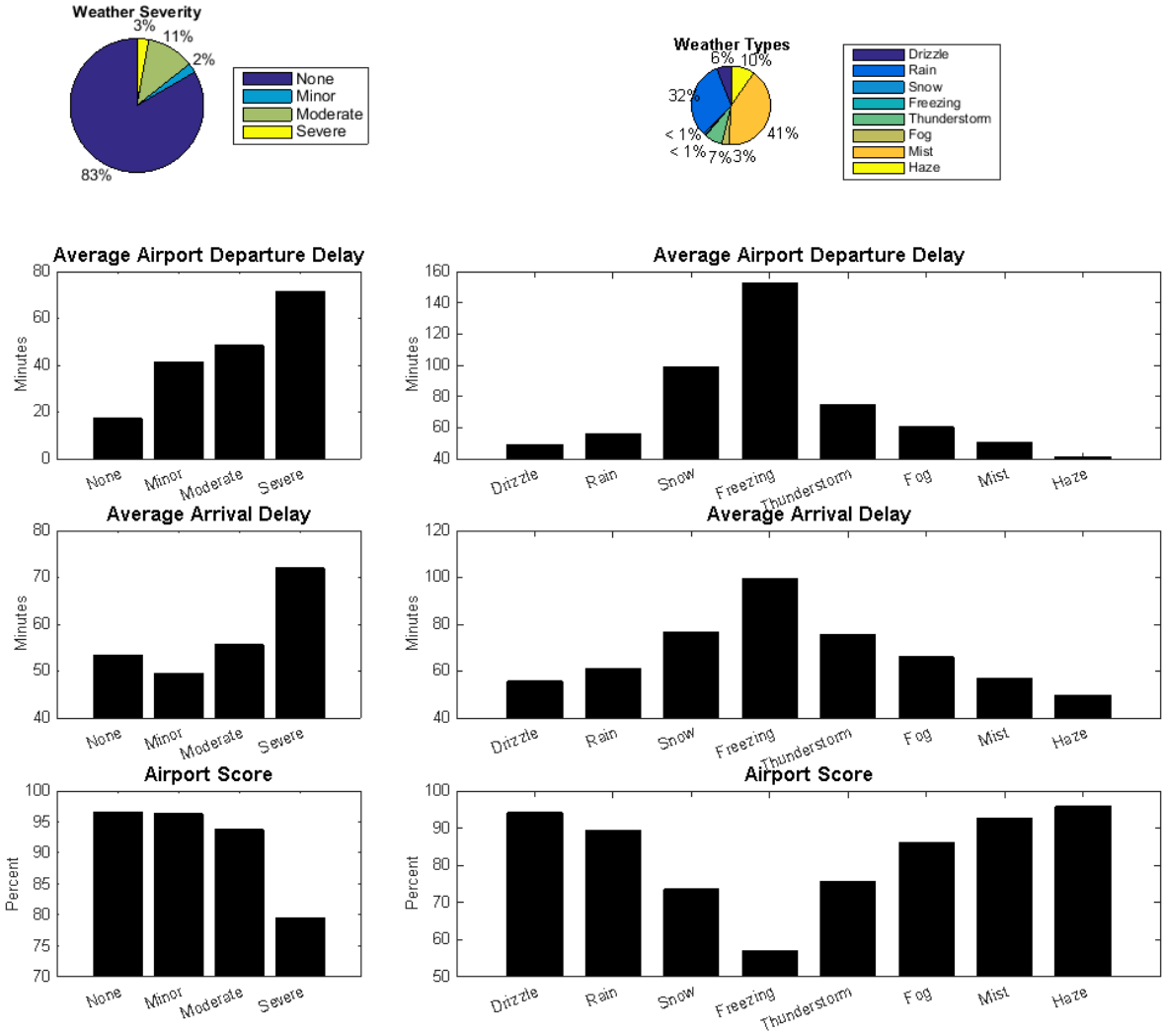


Figure 6.2. ATL average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

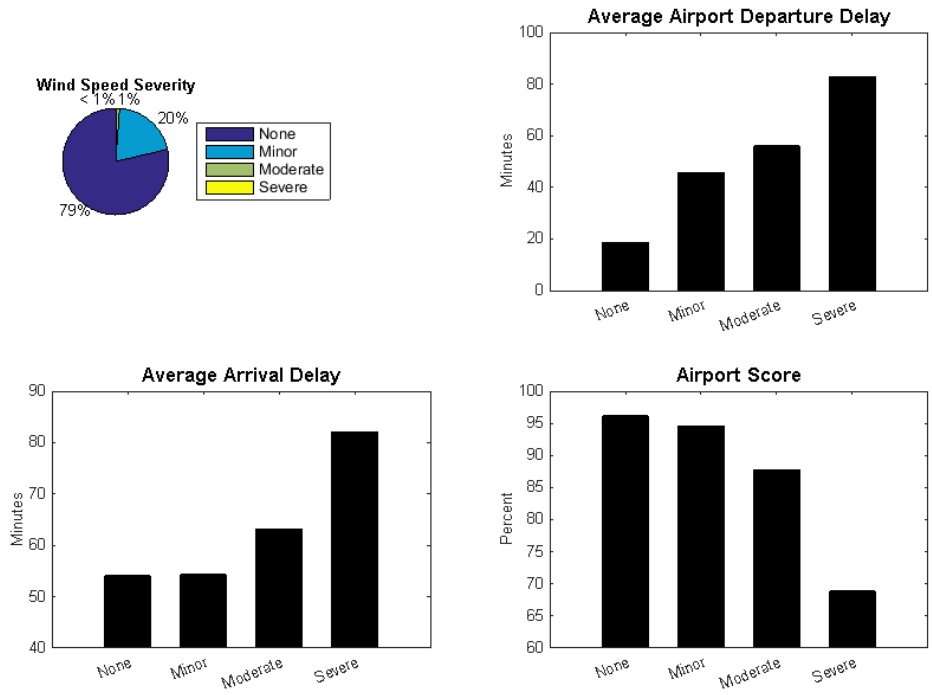


Figure 6.3. ATL average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

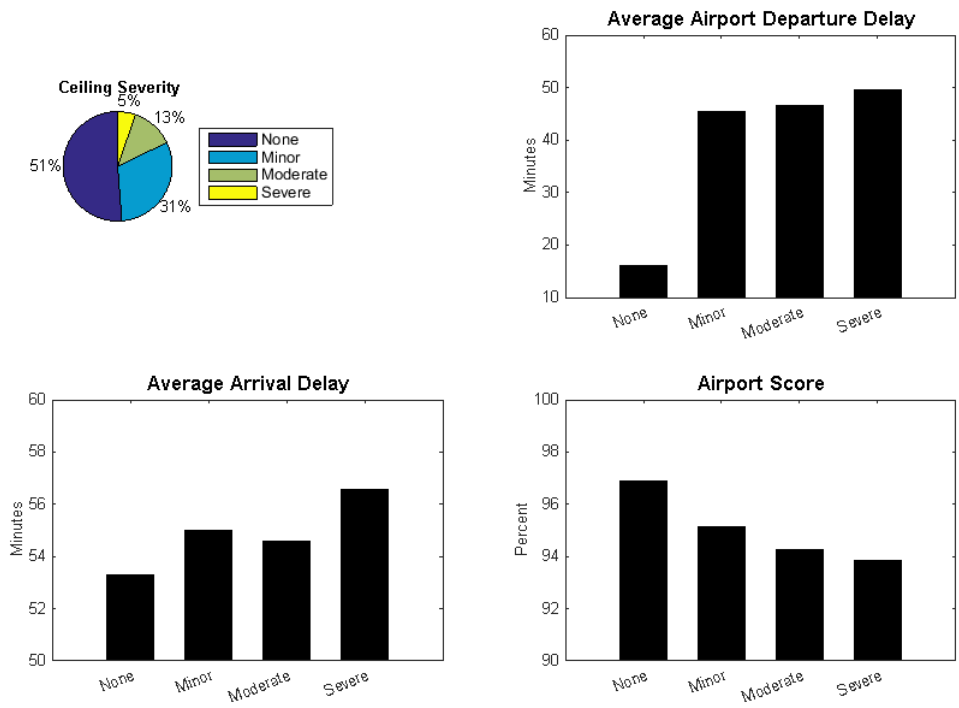


Figure 6.4. ATL average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

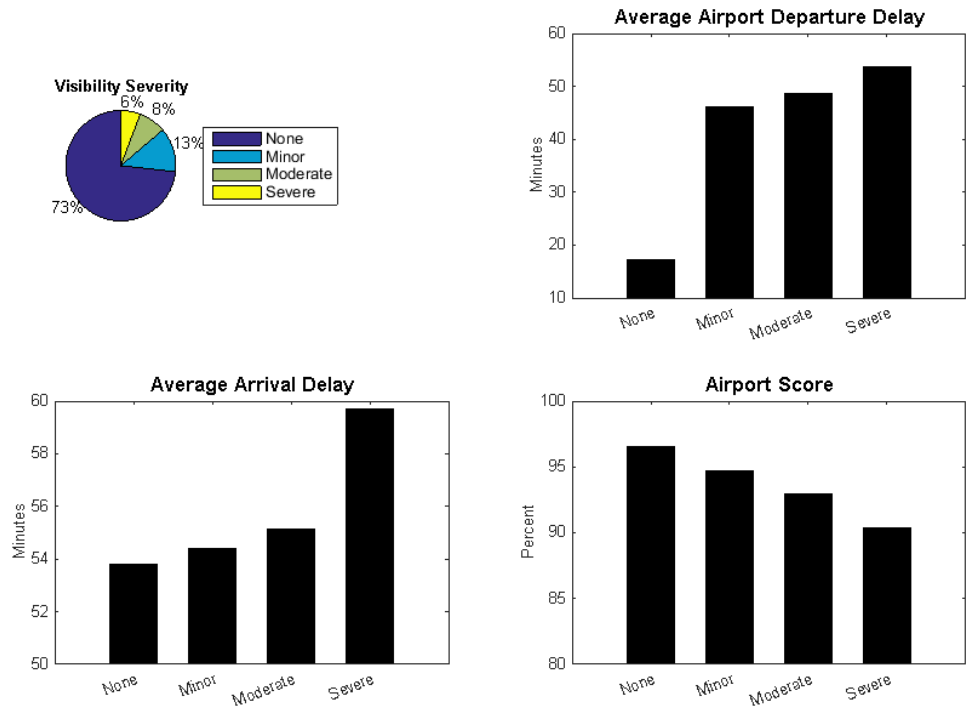


Figure 6.5. ATL average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

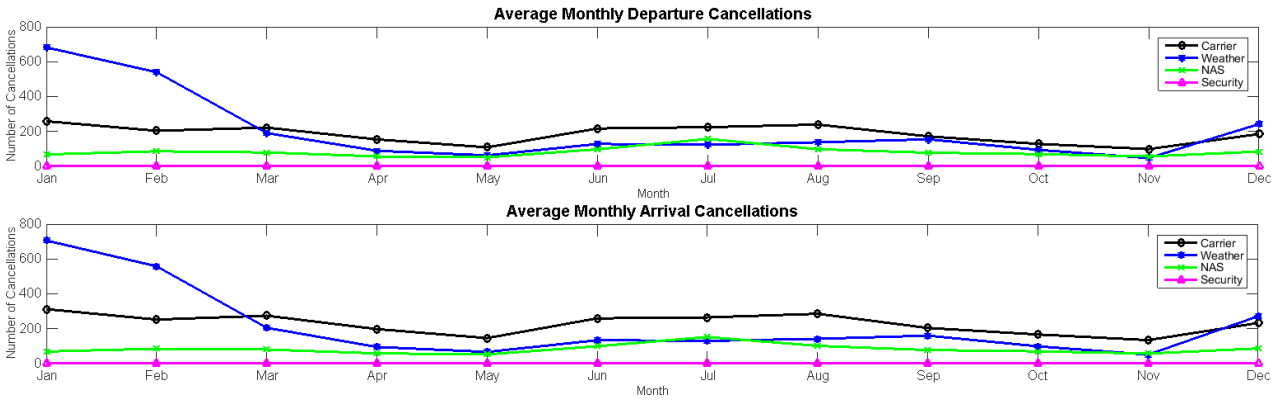


Figure 6.6. ATL average monthly departure and arrival cancellations.

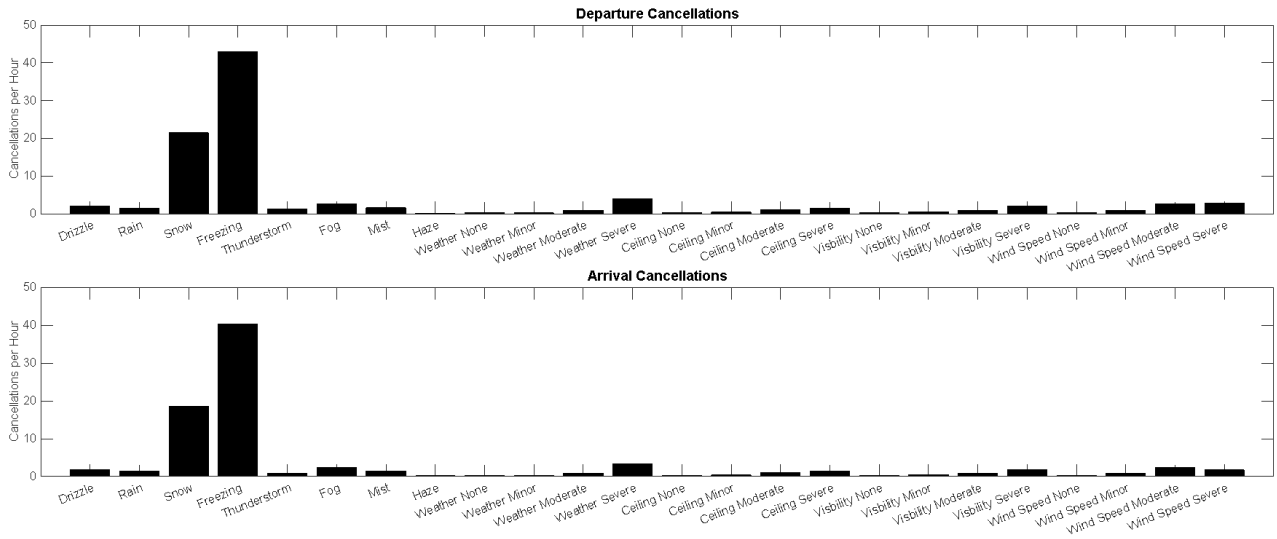


Figure 6.7. ATL average number of departure and arrival cancellations per hour of observed phenomena.

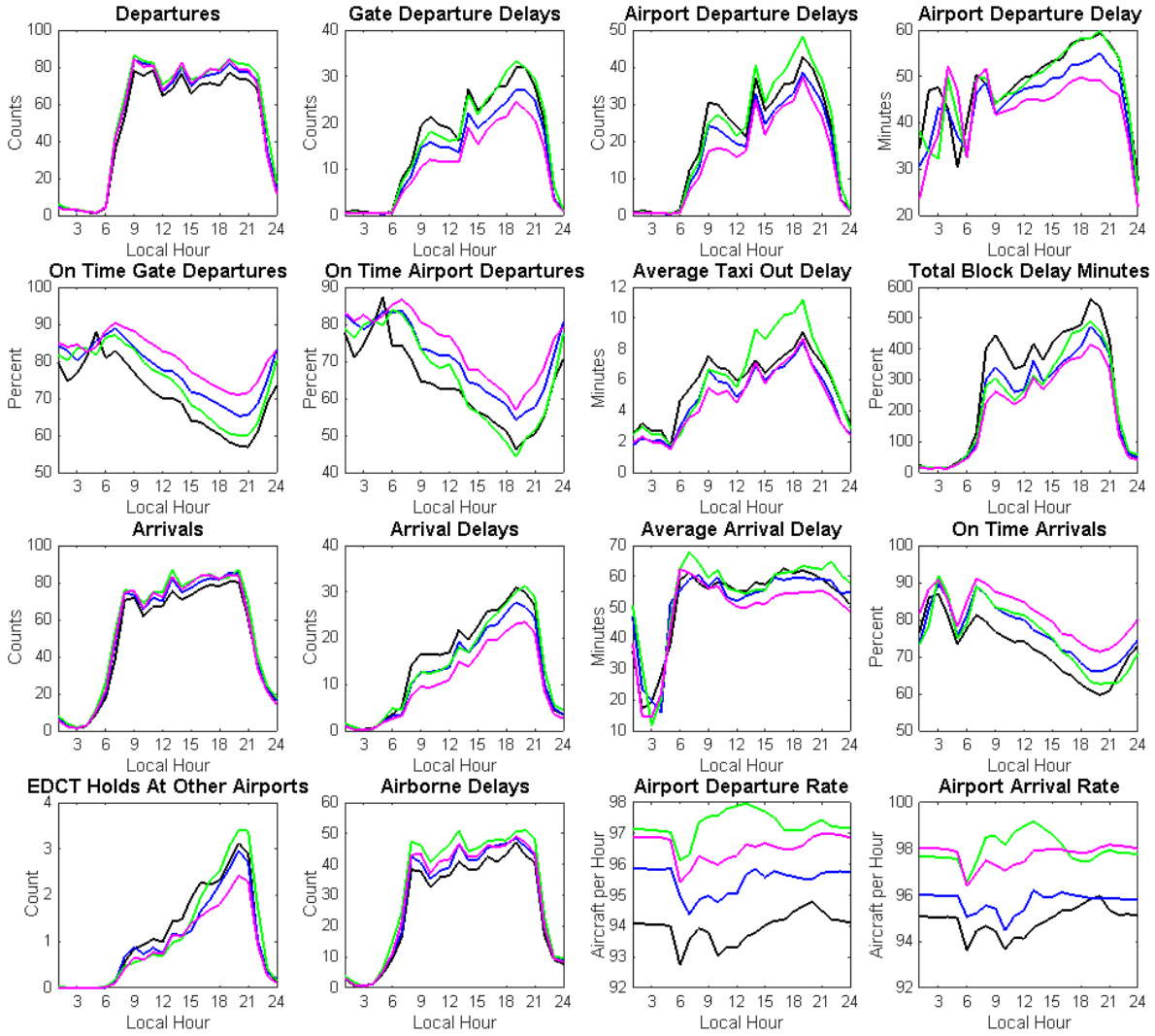


Figure 6.8. ORD hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

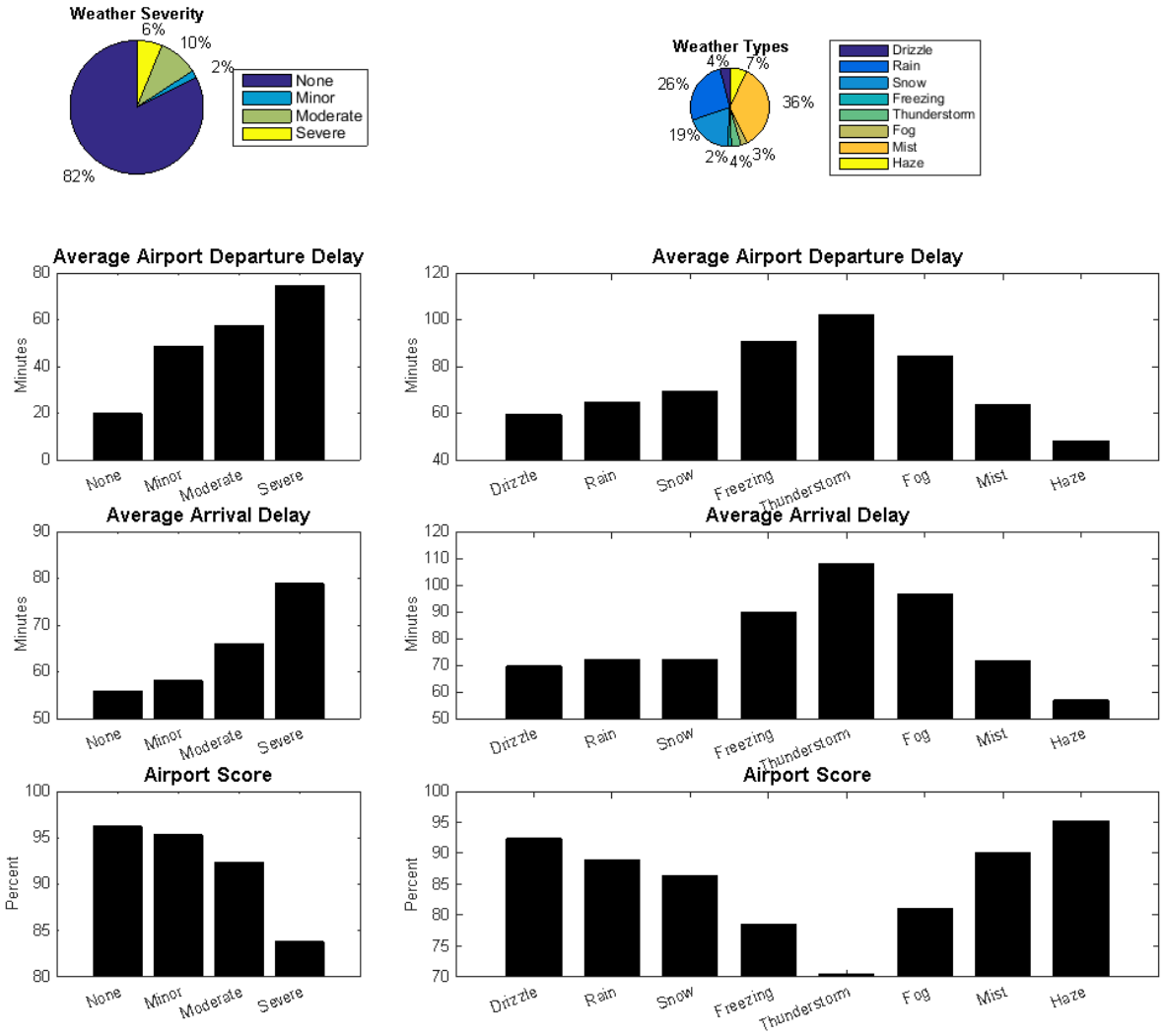


Figure 6.9. ORD average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

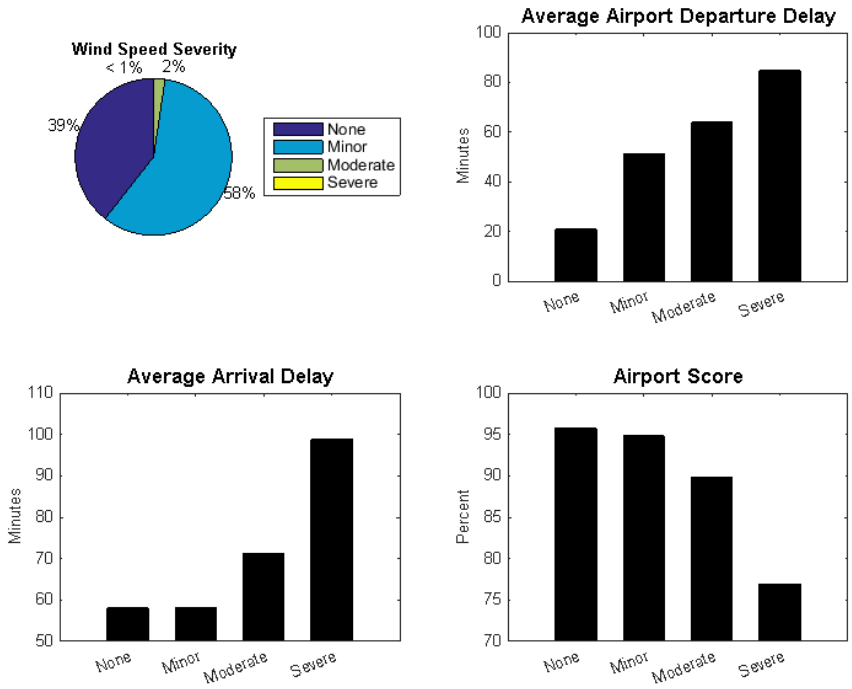


Figure 6.10. ORD average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

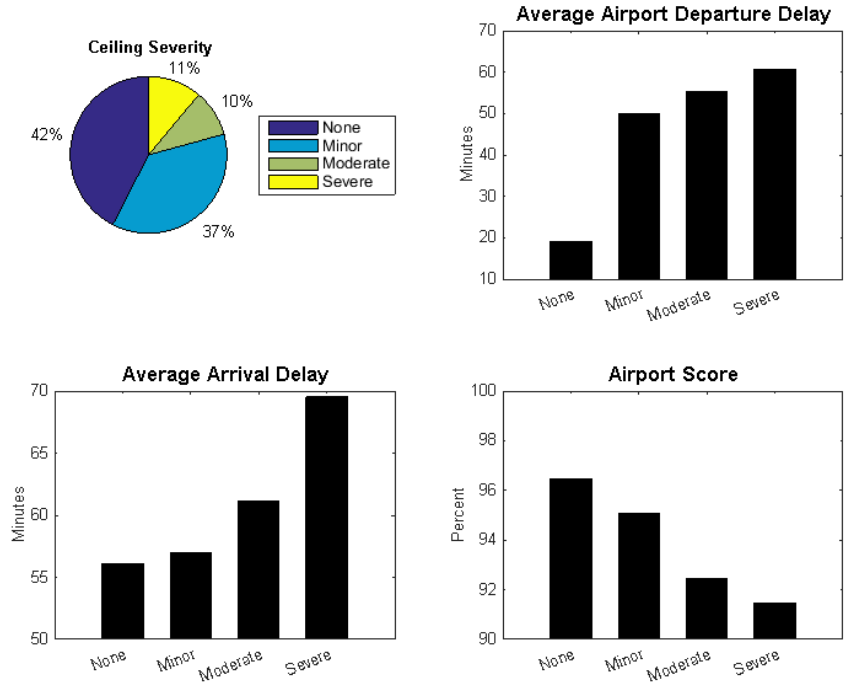


Figure 6.11. ORD average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

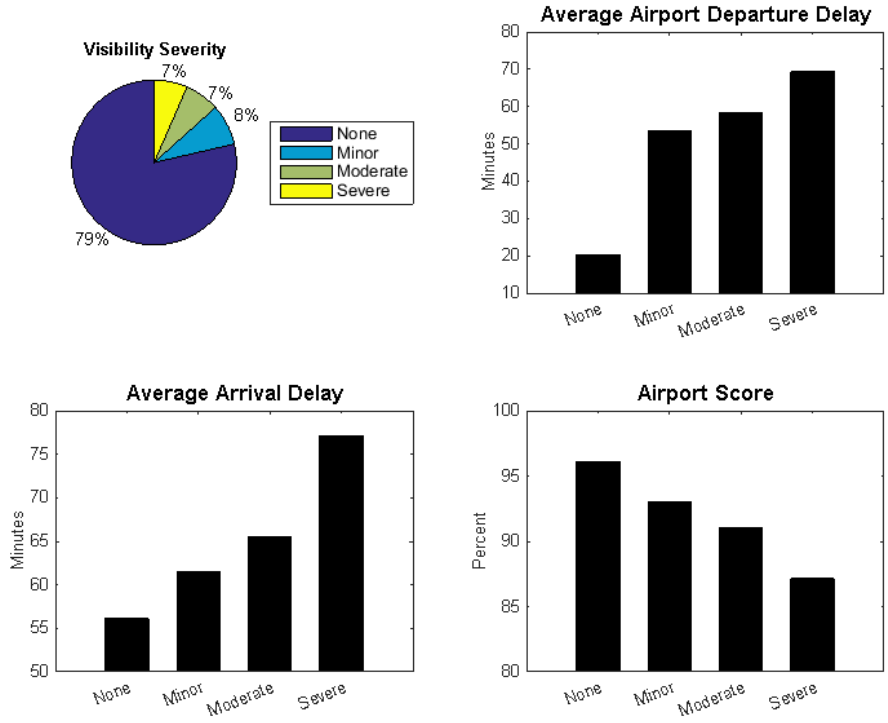


Figure 6.12. ORD average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

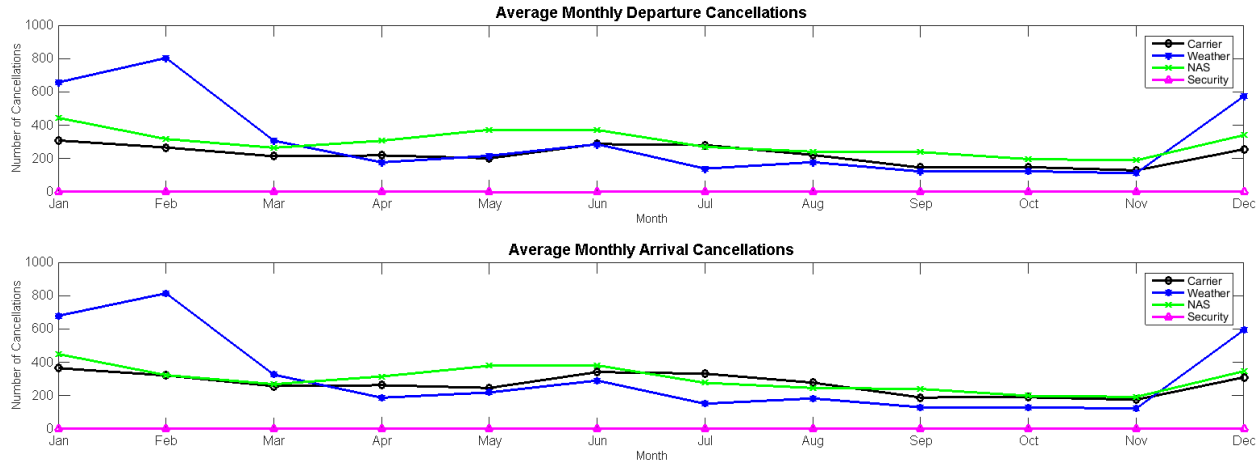


Figure 6.13. ORD average monthly departure and arrival cancellations.

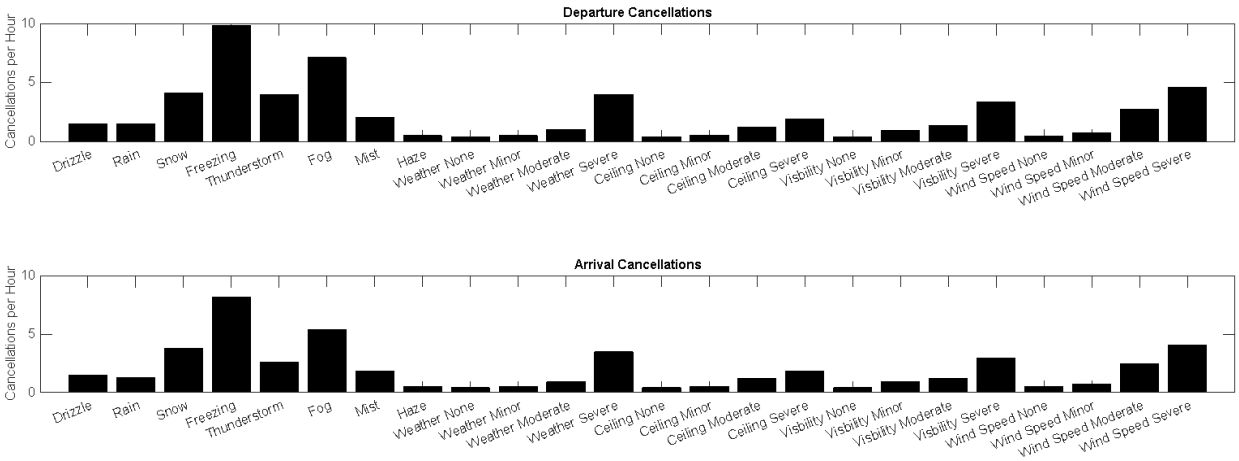


Figure 6.14. ORD average number of departure and arrival cancellations per hour of observed phenomena.

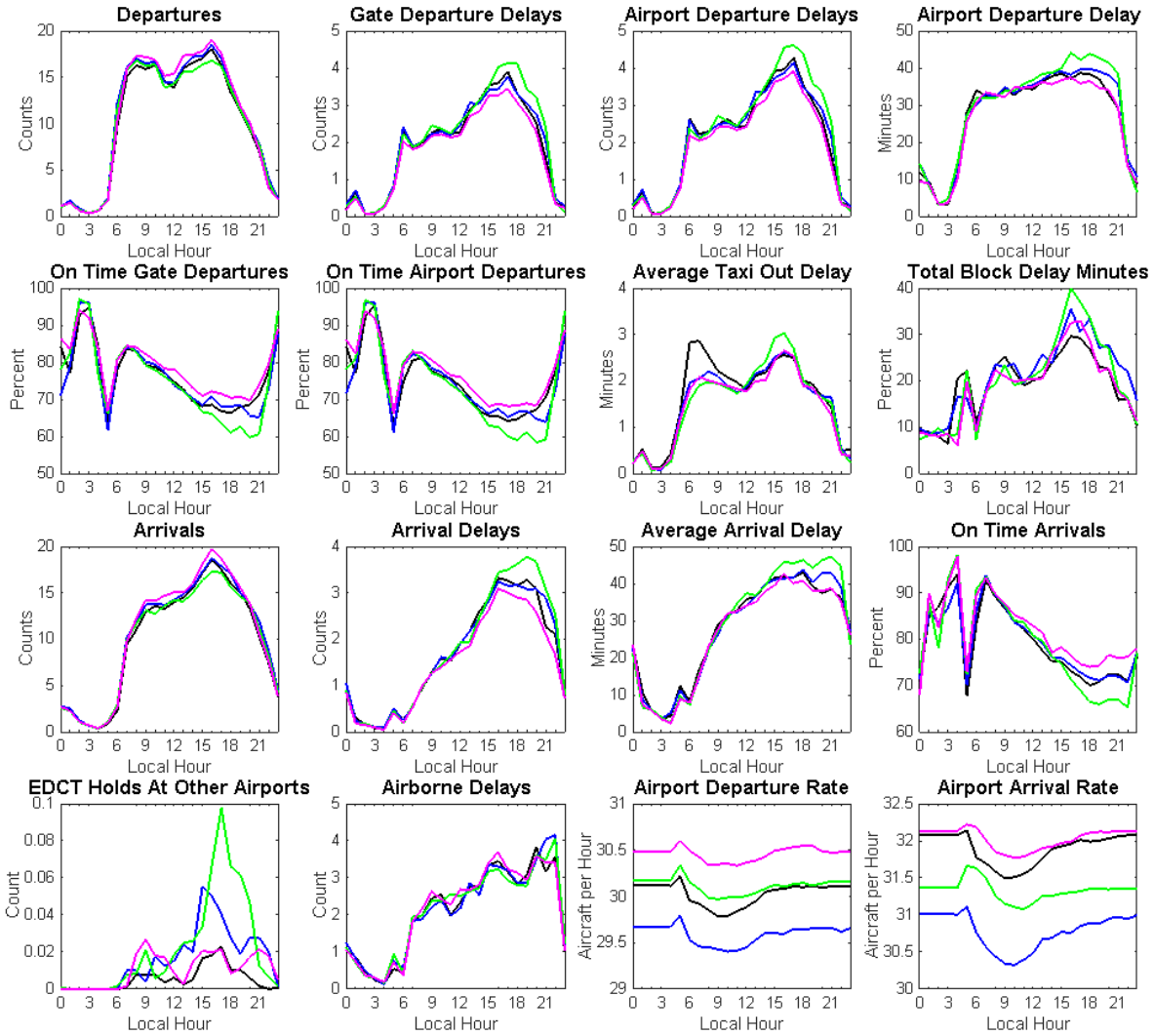


Figure 6.15. DAL hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

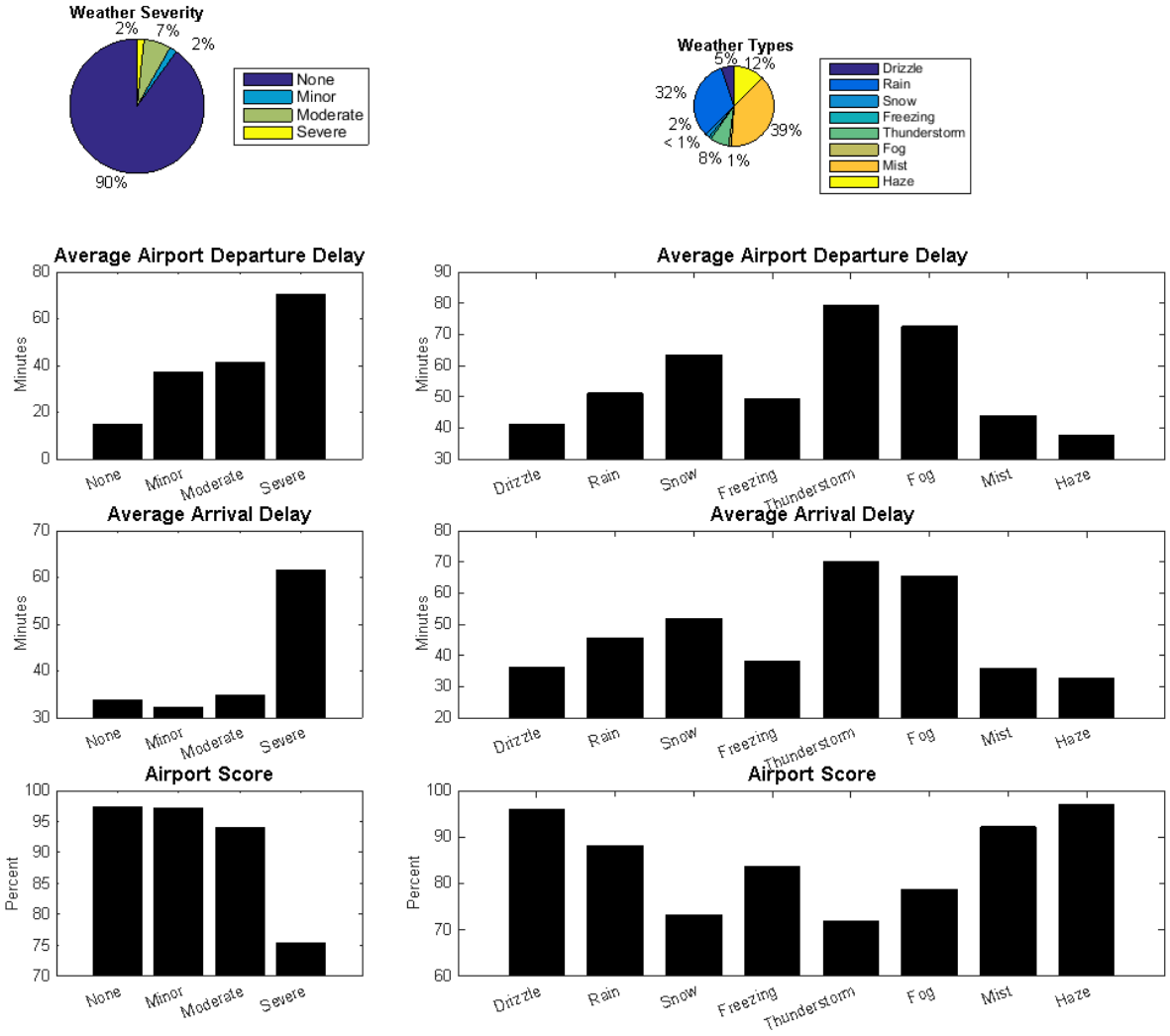


Figure 6.16. DAL average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

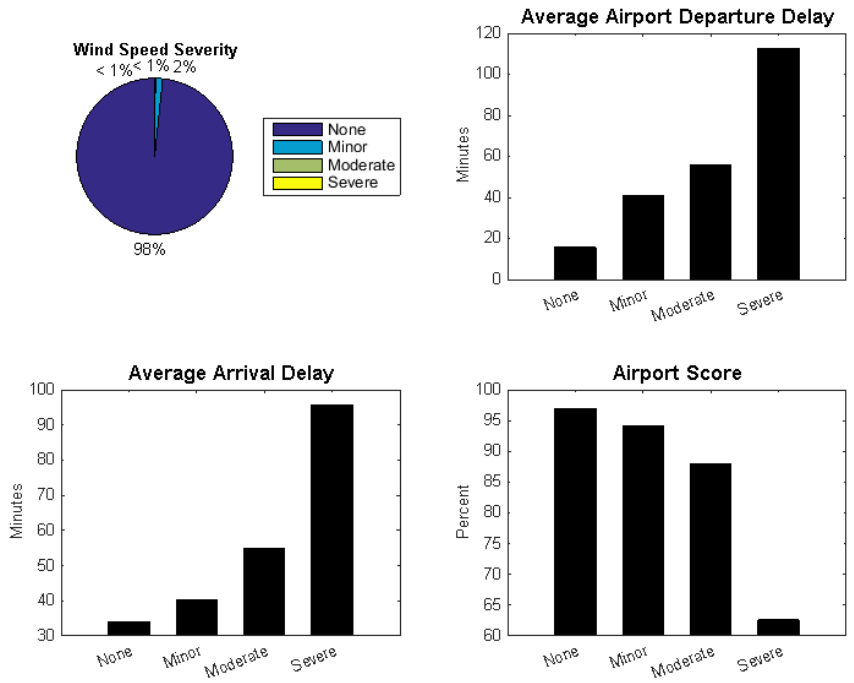


Figure 6.17. DAL average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

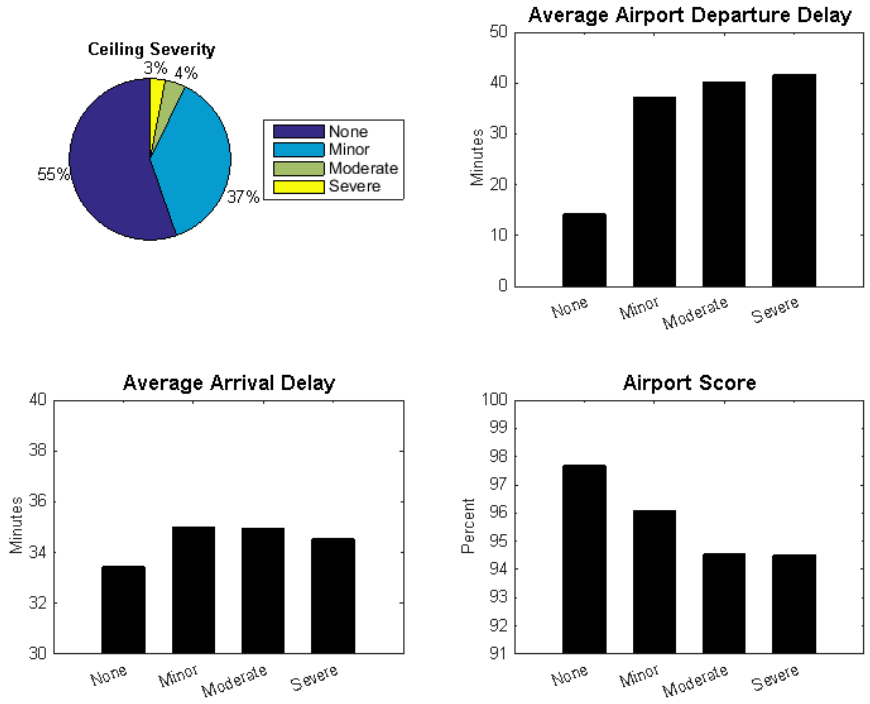


Figure 6.18. DAL average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

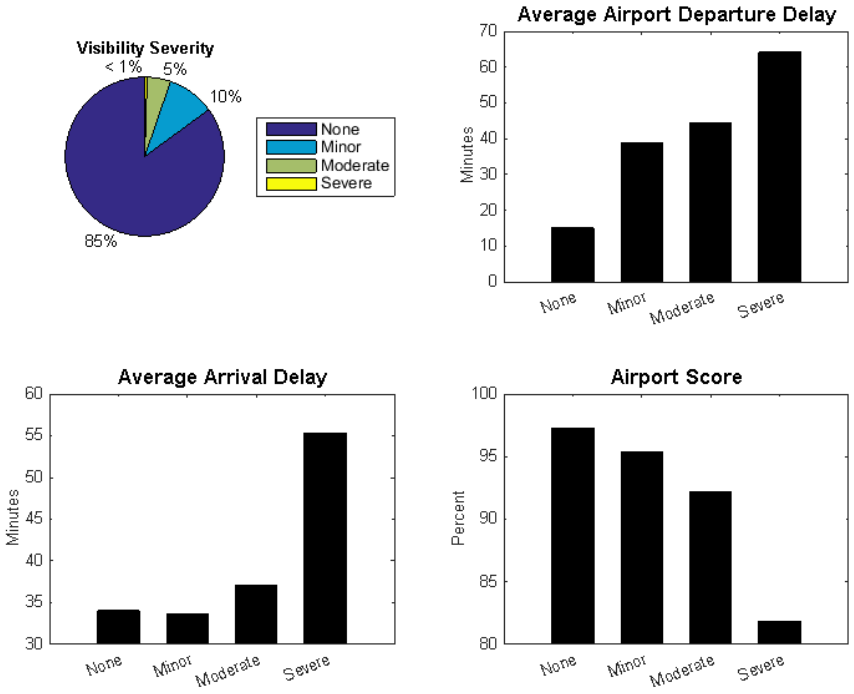


Figure 6.19. DAL average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

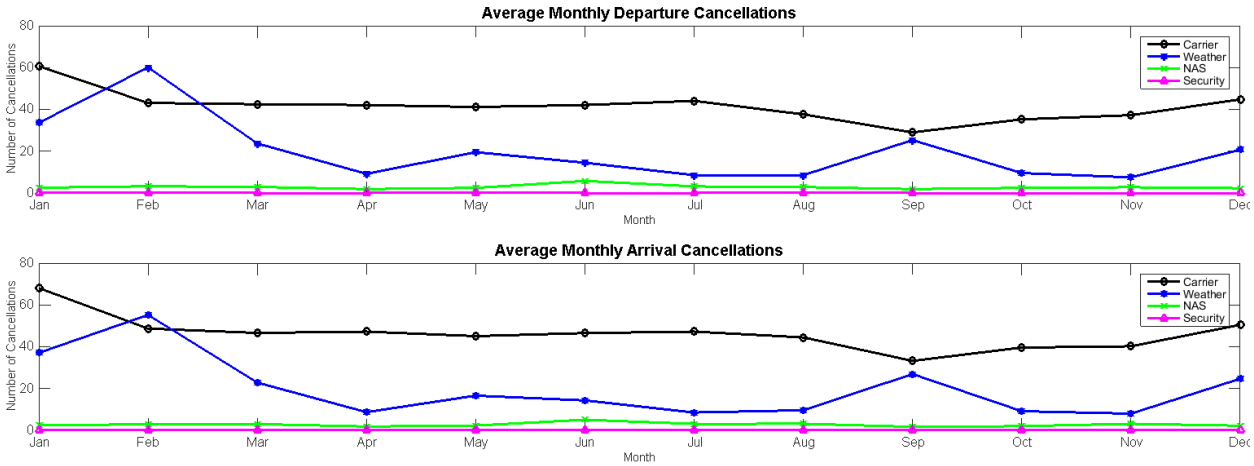


Figure 6.20. DAL average monthly departure and arrival cancellations.

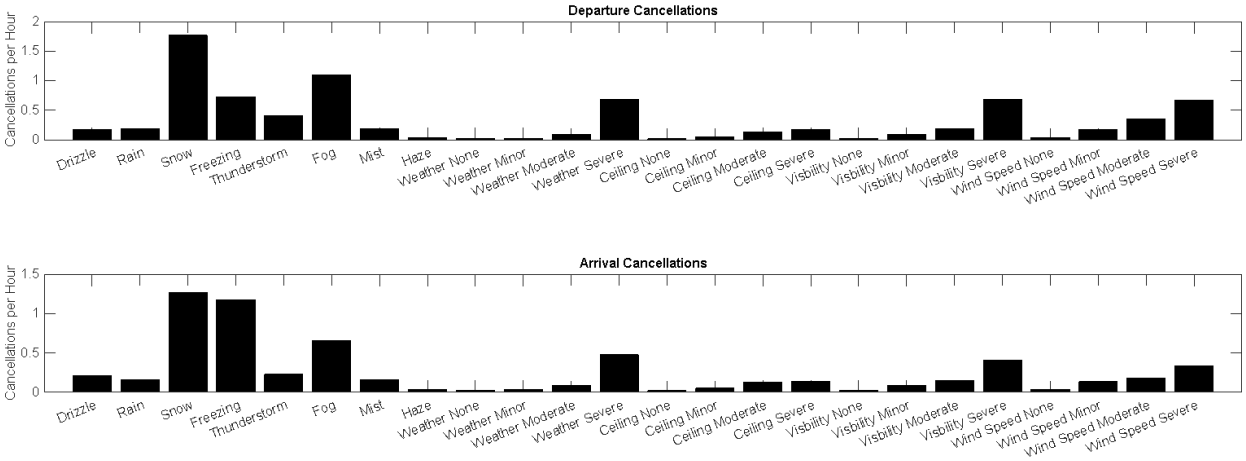


Figure 6.21. DAL average number of departure and arrival cancellations per hour of observed phenomena.

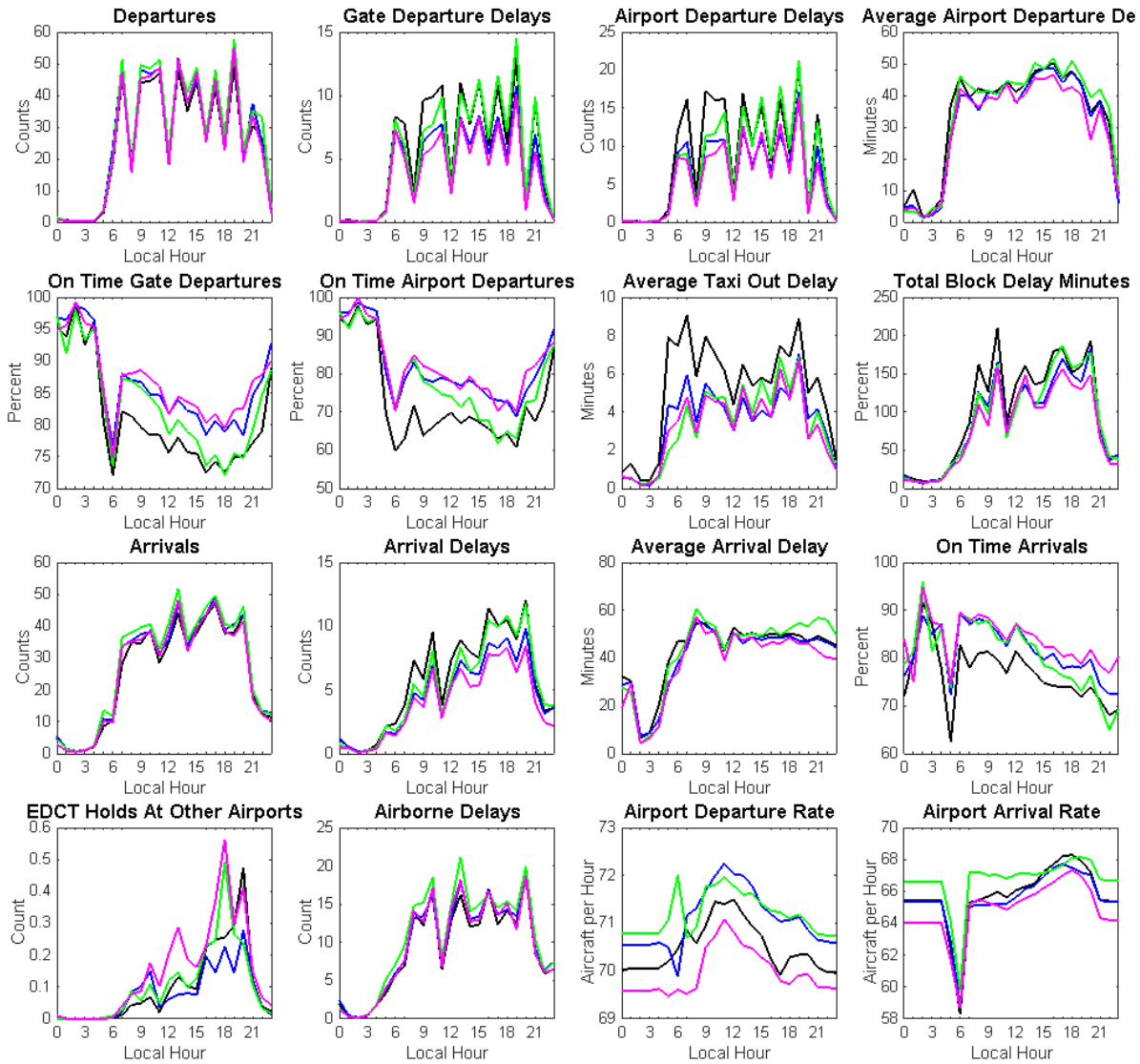


Figure 6.22. MSP hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

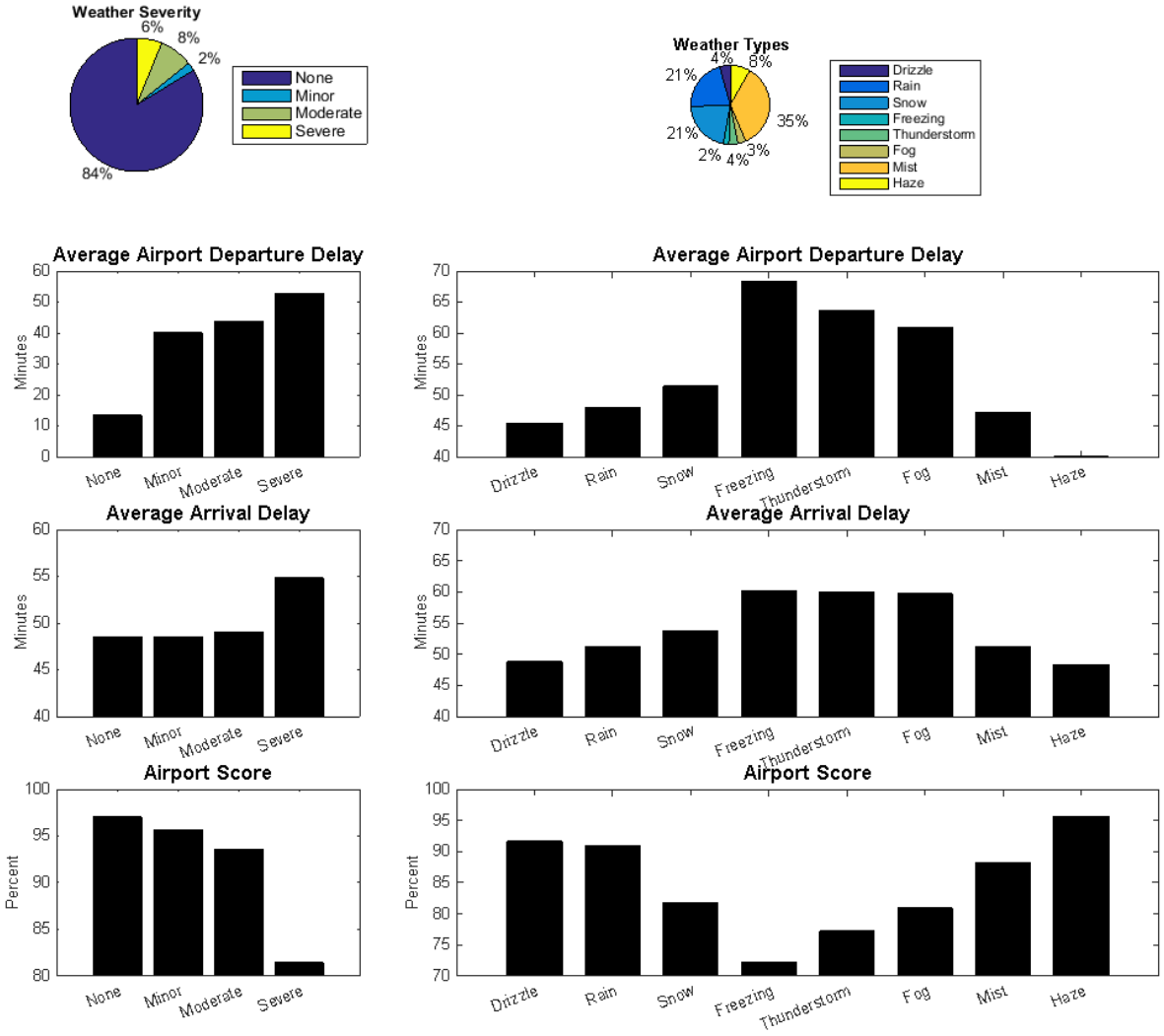


Figure 6.23. MSP average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

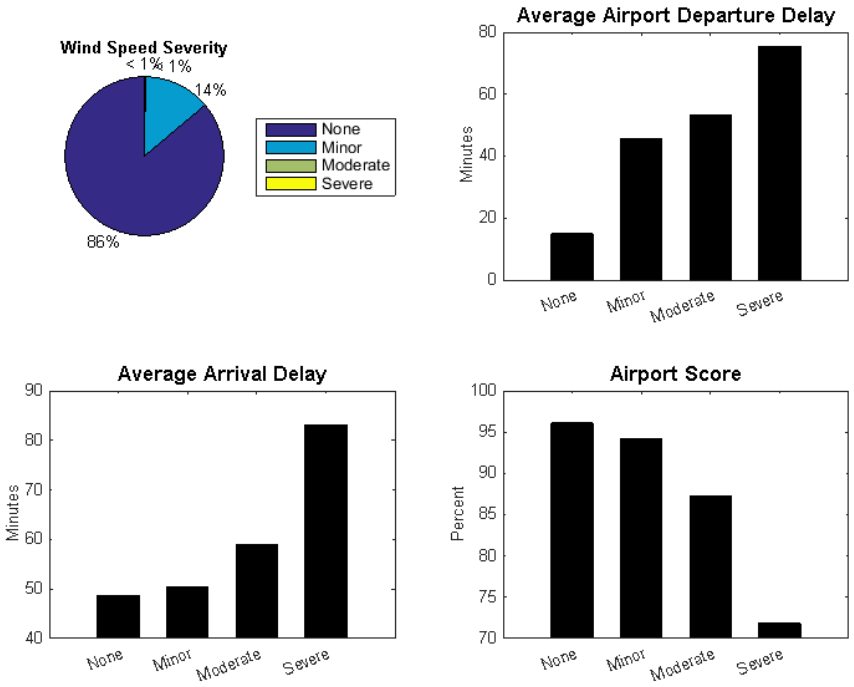


Figure 6.24. MSP average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

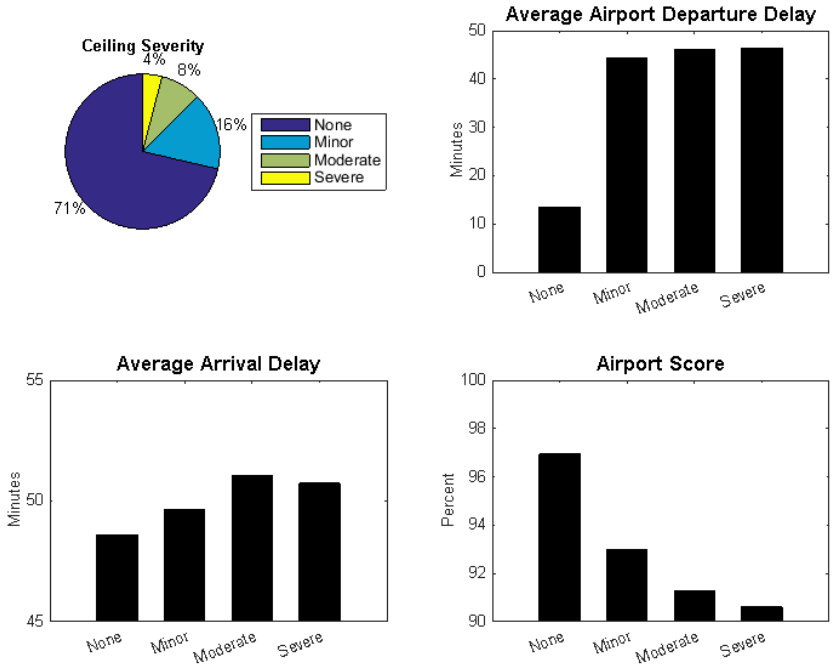


Figure 6.25. MSP average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

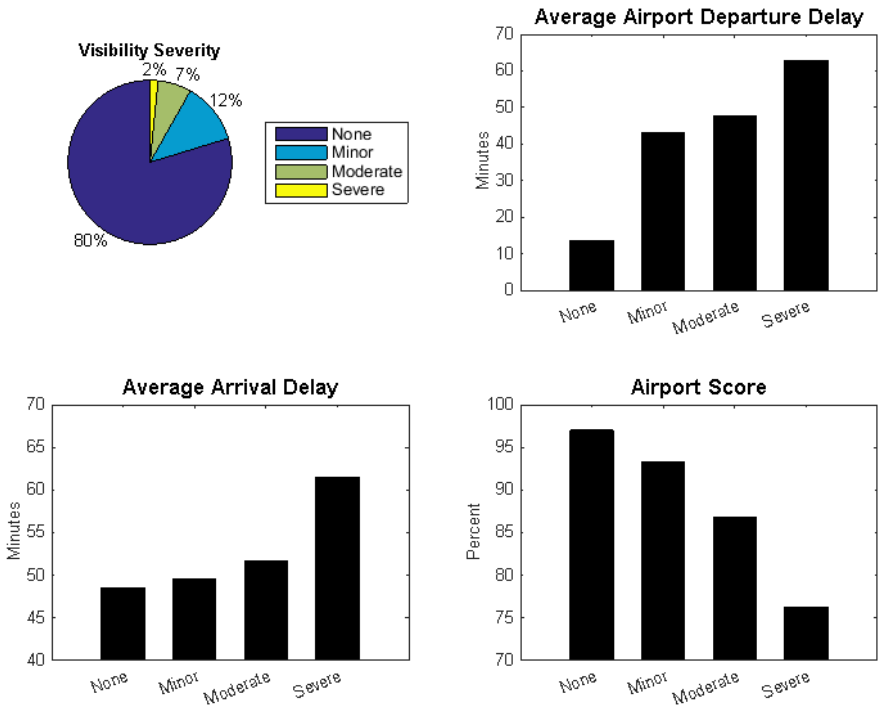


Figure 6.26. MSP average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

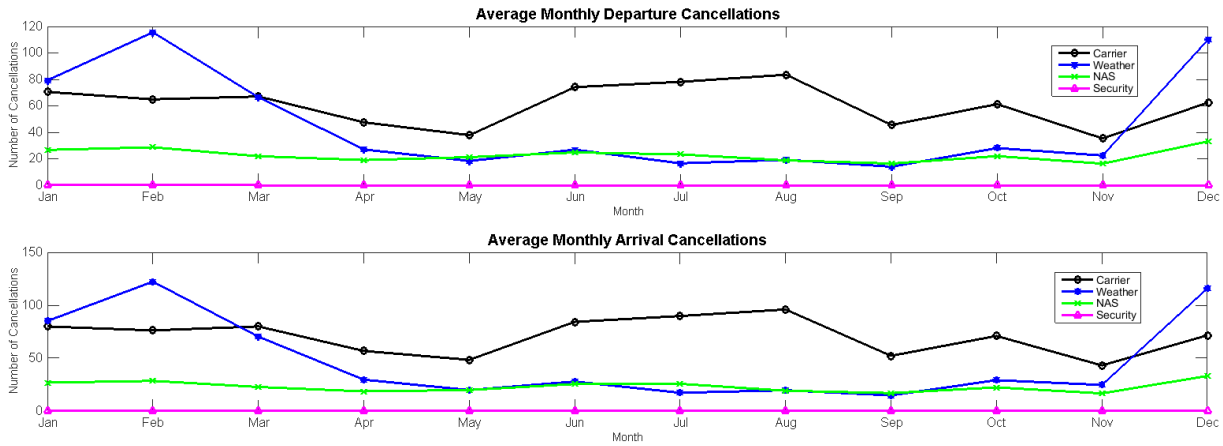


Figure 6.27. MSP average monthly departure and arrival cancellations.

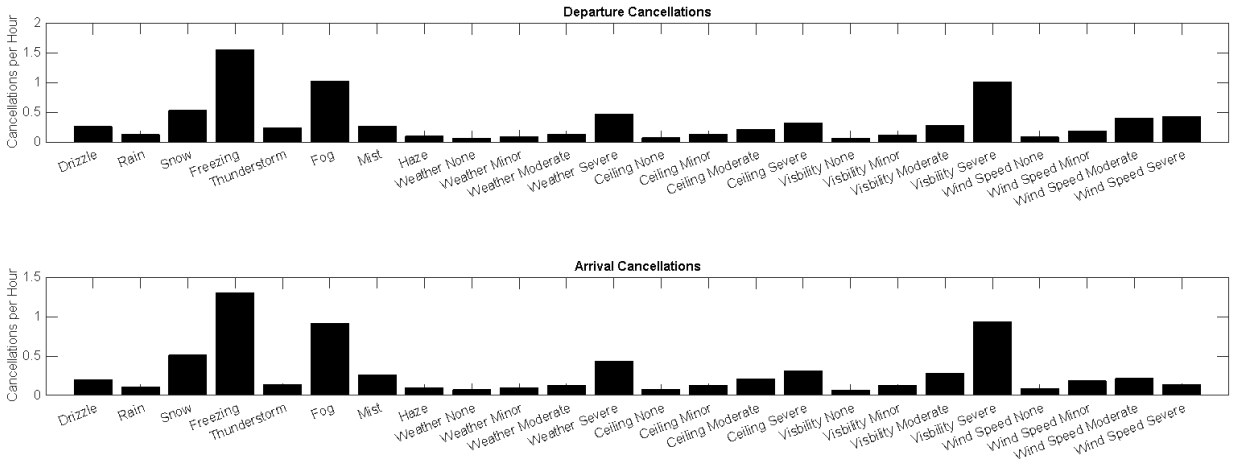


Figure 6.28. MSP average number of departure and arrival cancellations per hour of observed phenomena.

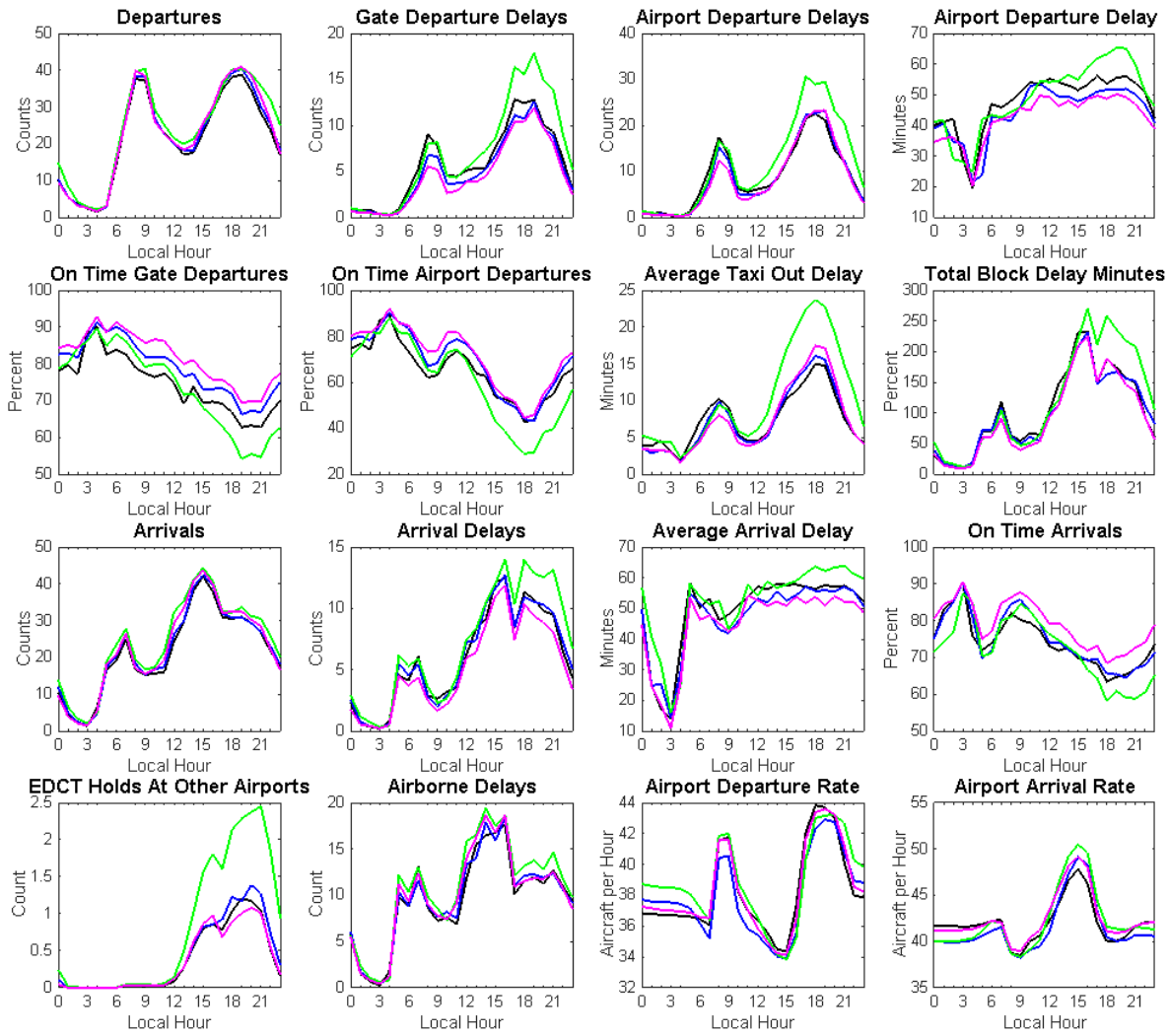


Figure 6.29. JFK hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

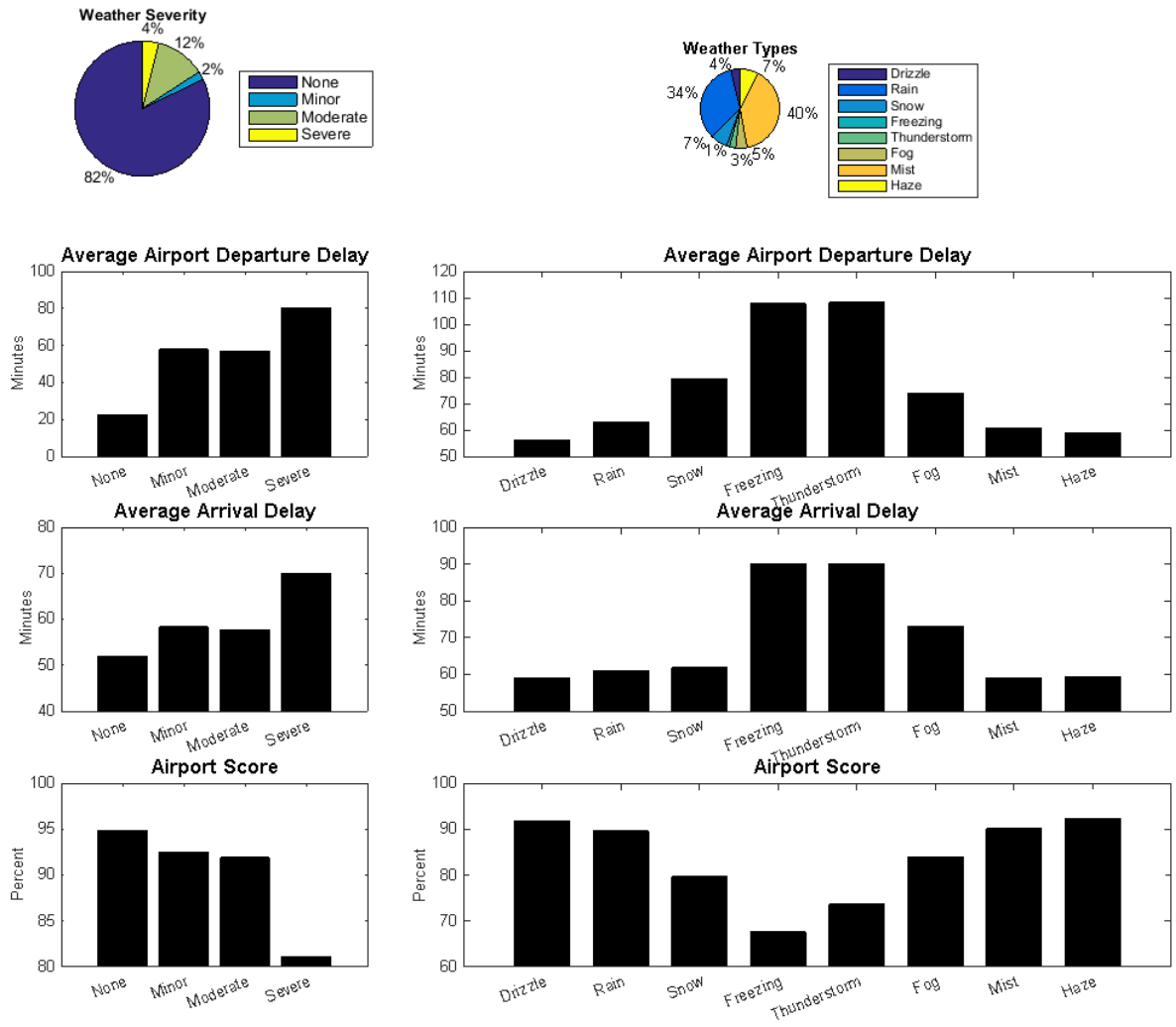


Figure 6.30. JFK average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

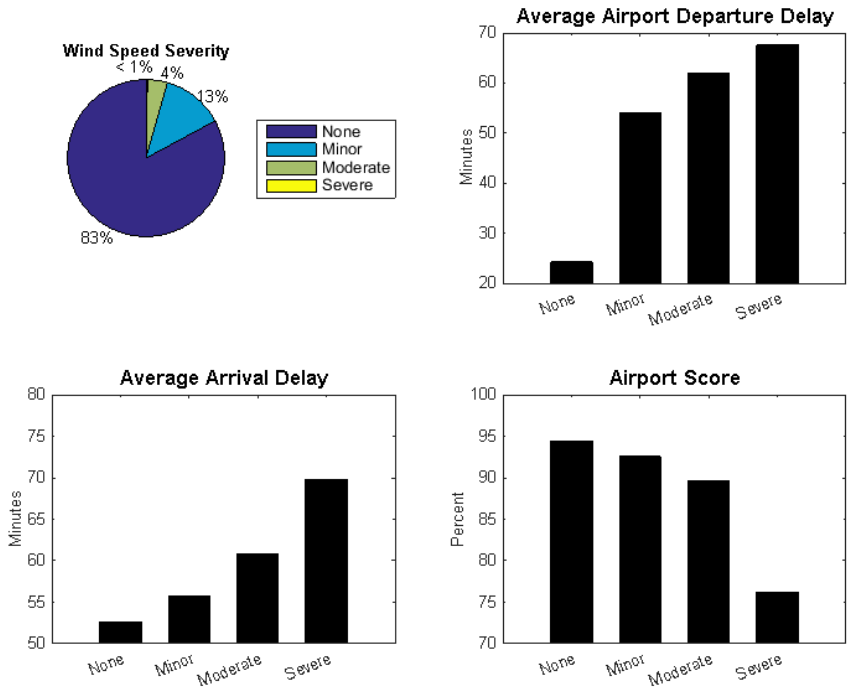


Figure 6.31. JFK average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

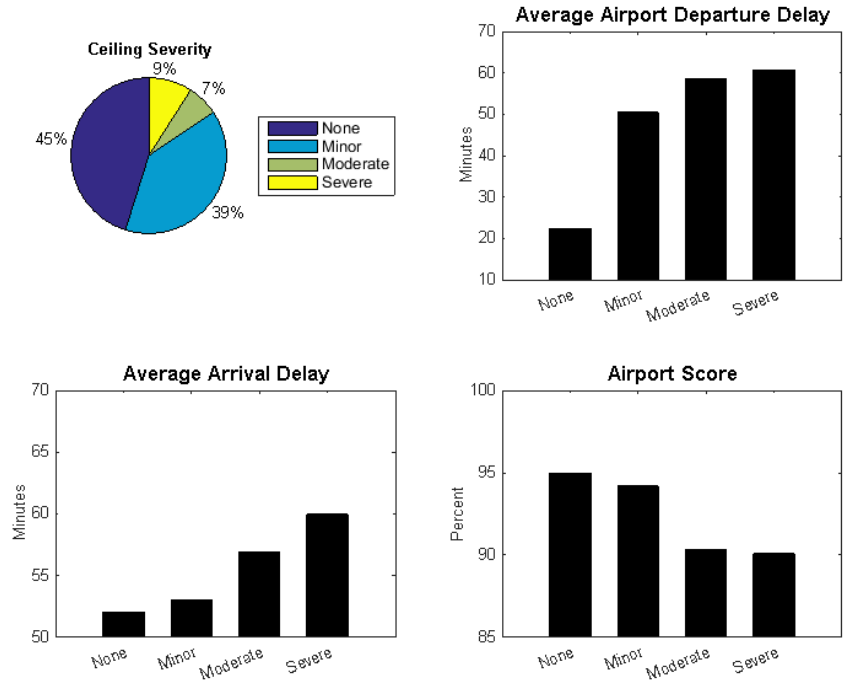


Figure 6.32. JFK average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

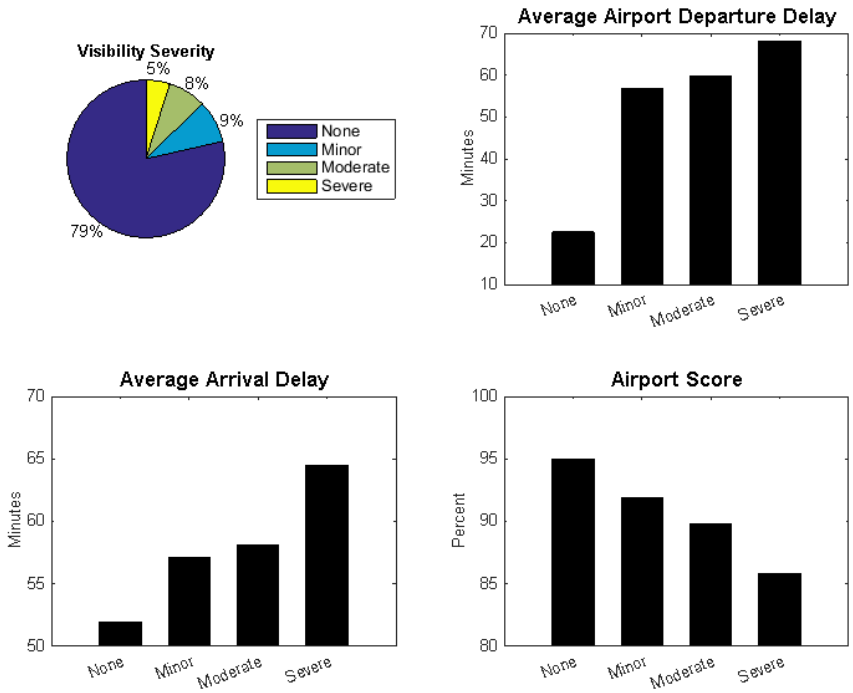


Figure 6.33. JFK average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

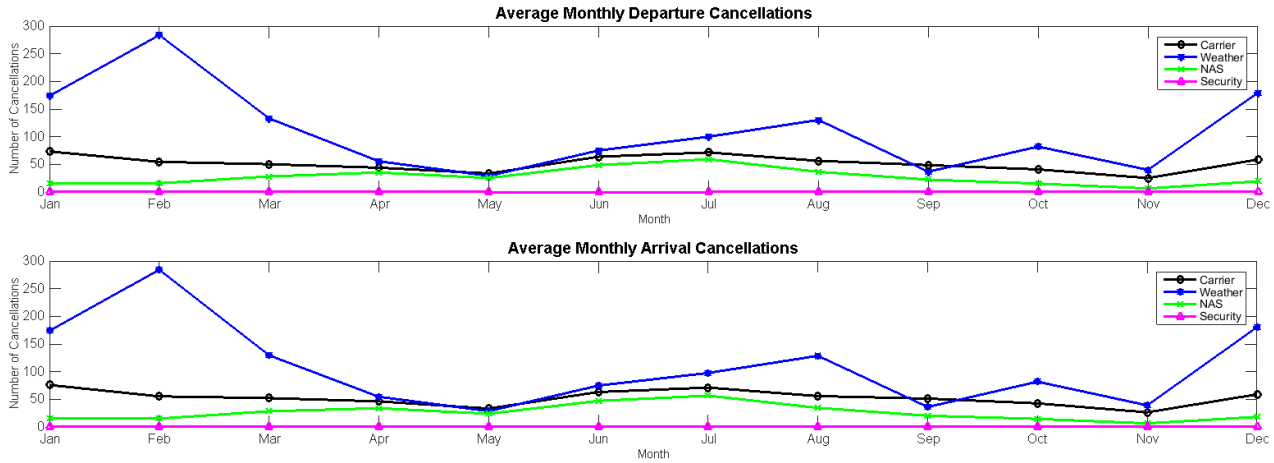


Figure 6.34. JFK average monthly departure and arrival cancellations.

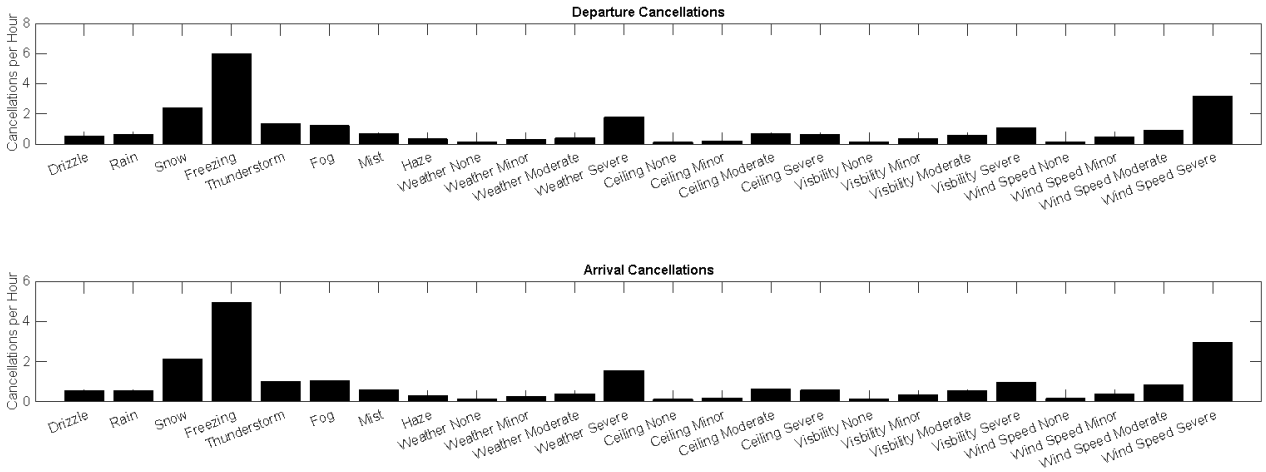


Figure 6.35. JFK average number of departure and arrival cancellations per hour of observed phenomena.

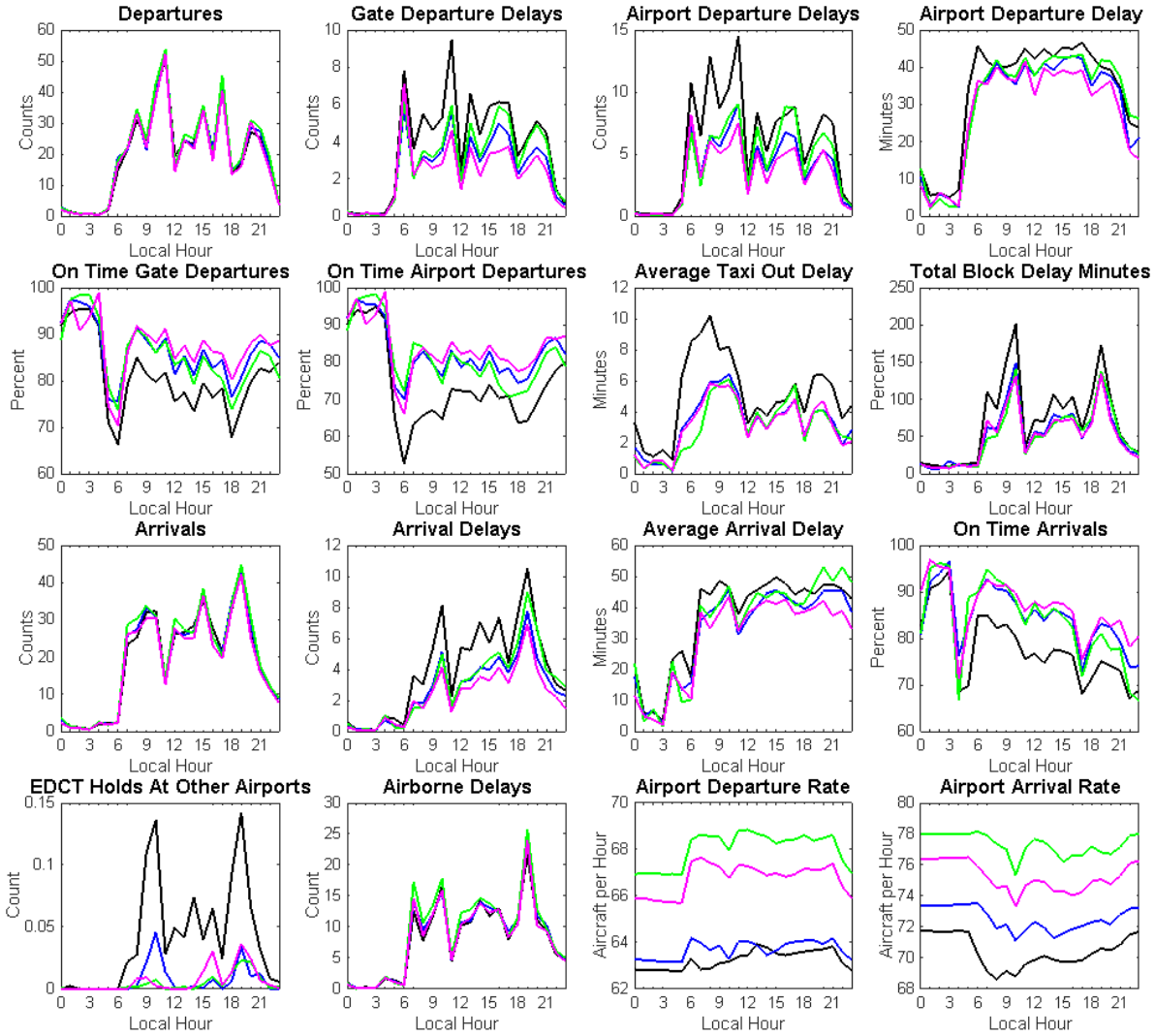


Figure 6.36. SLC hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

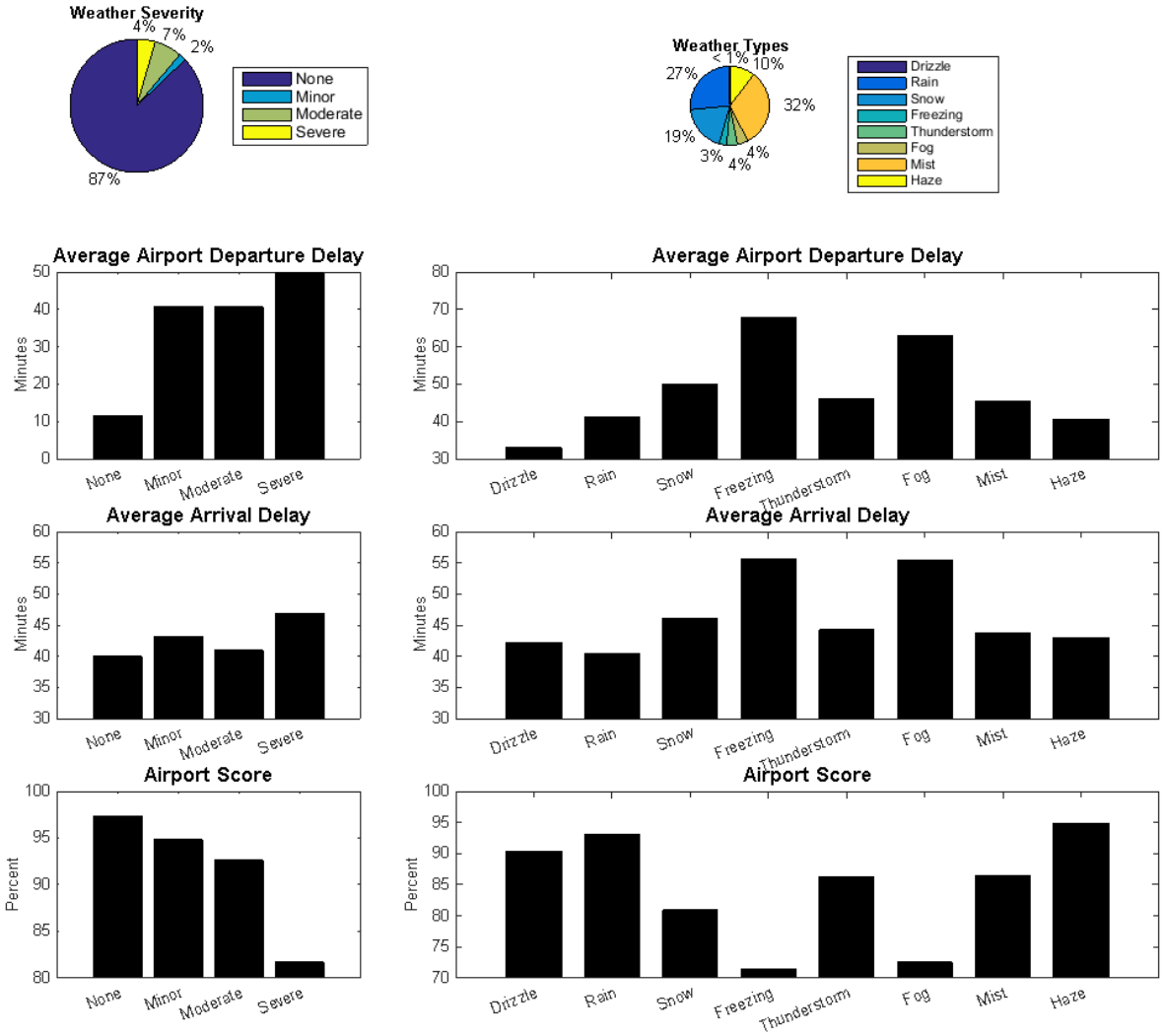


Figure 6.37. SLC average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

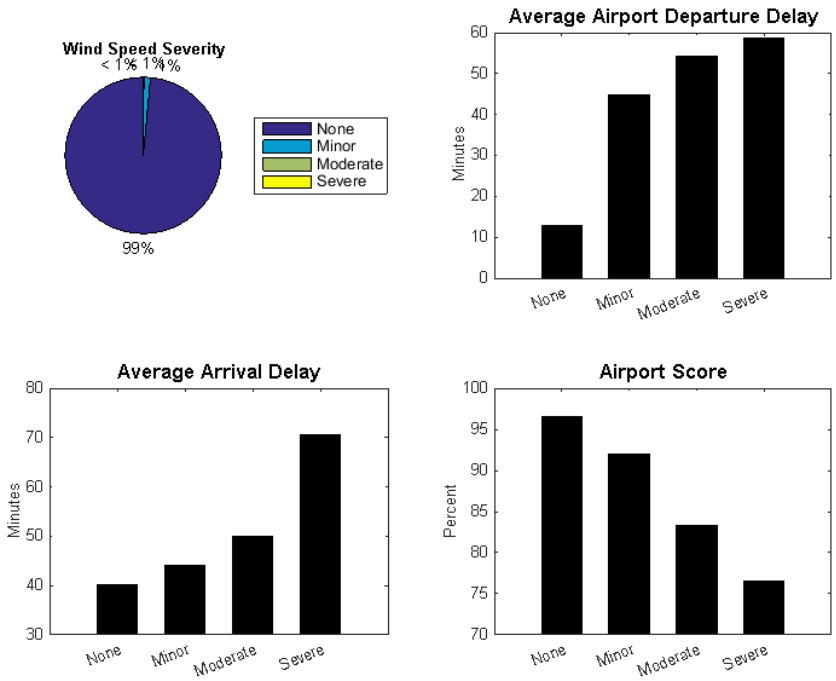


Figure 6.38. SLC average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

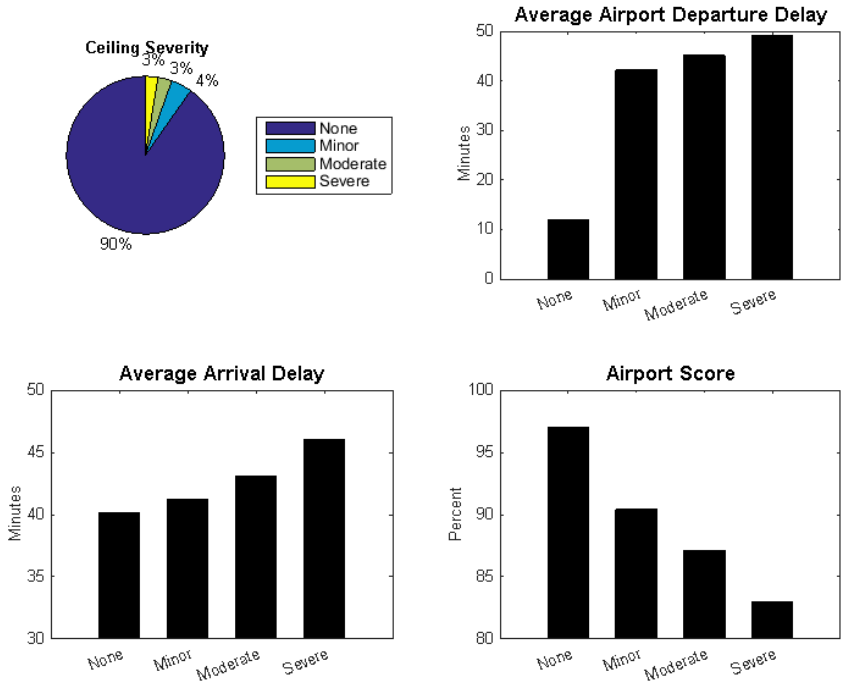


Figure 6.39. SLC average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

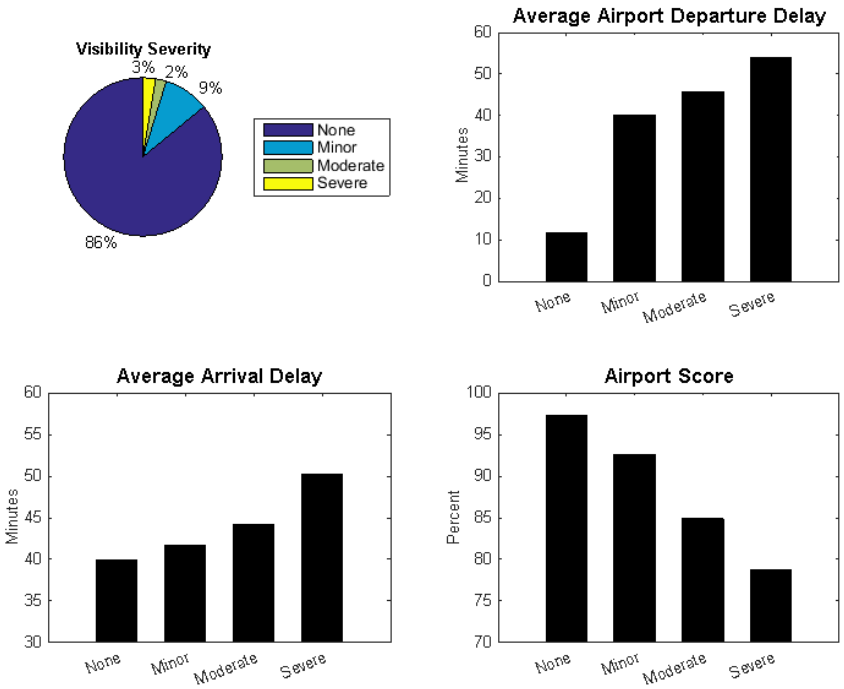


Figure 6.40. SLC average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

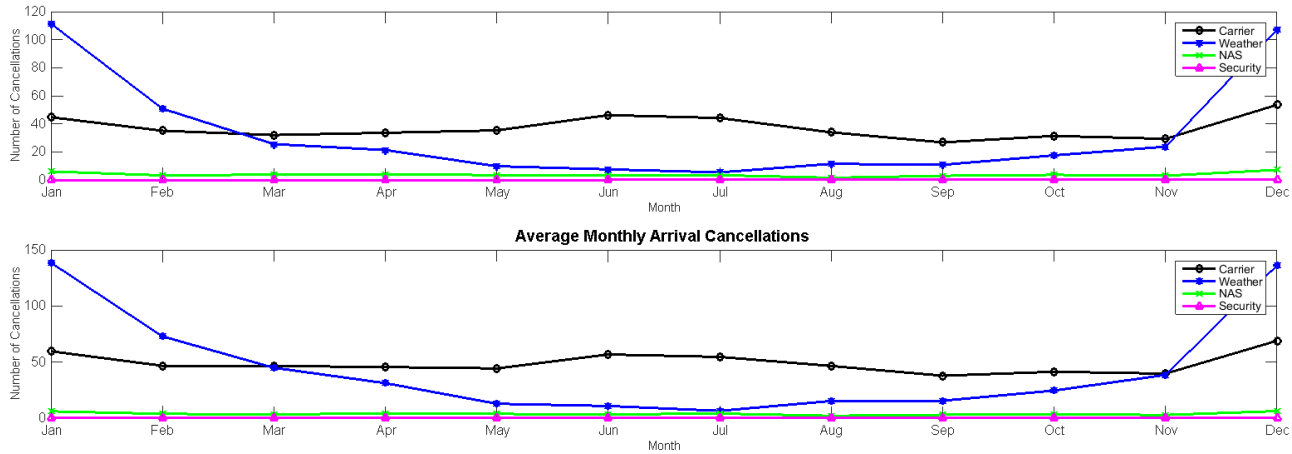


Figure 6.41. SLC average monthly departure and arrival cancellations.

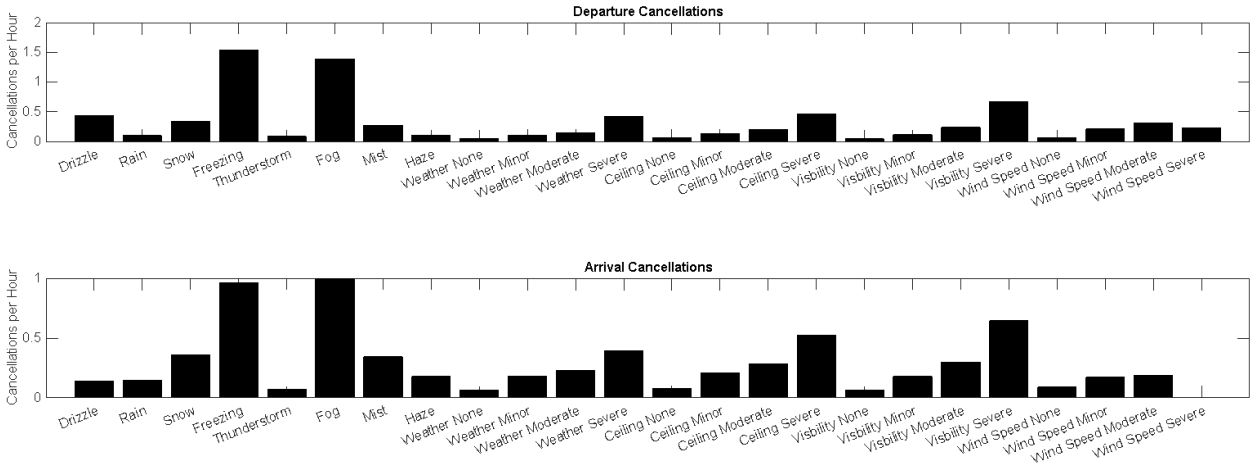


Figure 6.42. SLC average number of departure and arrival cancellations per hour of observed phenomena.

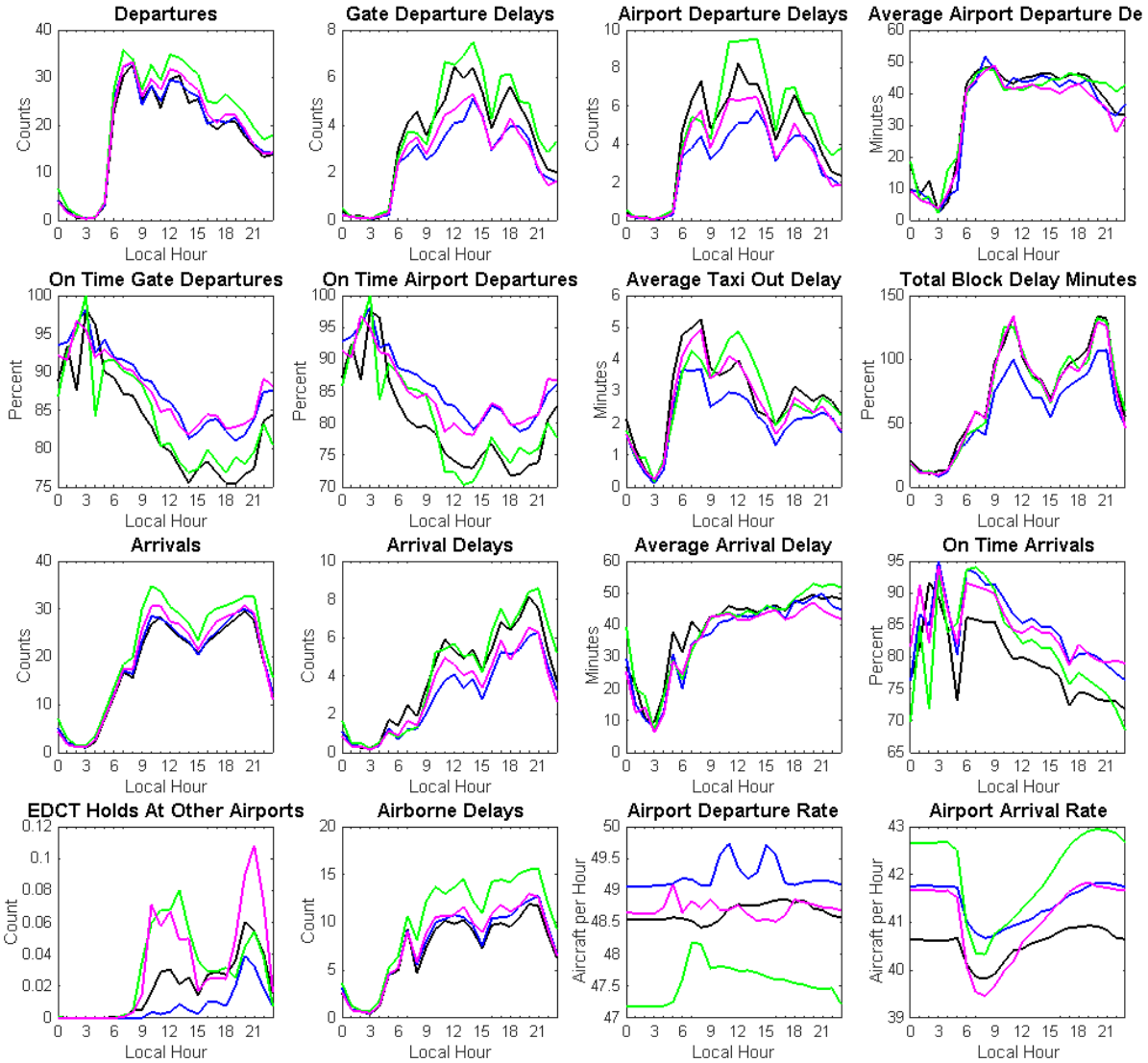


Figure 6.43. SEA hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

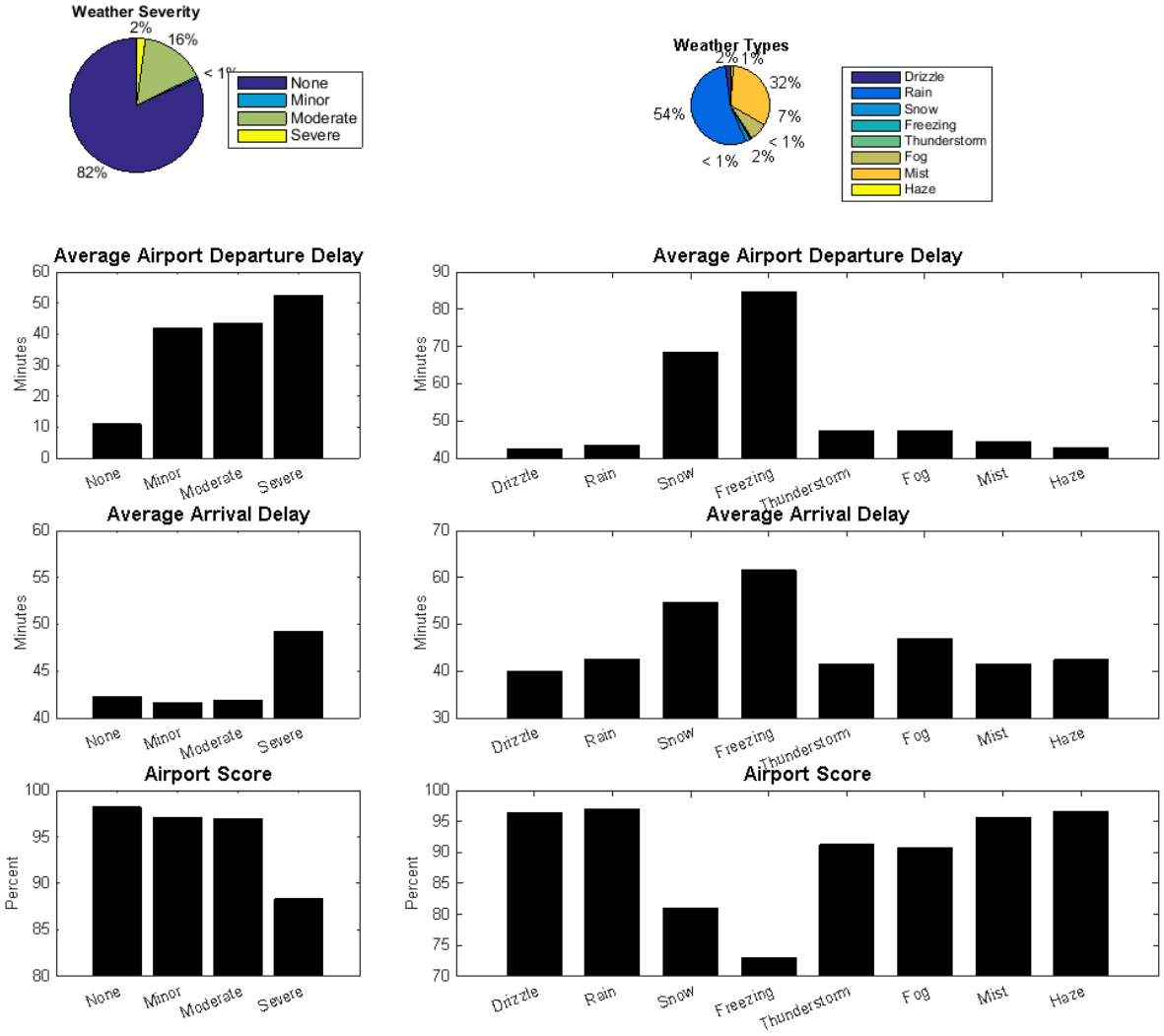


Figure 6.44. SEA average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

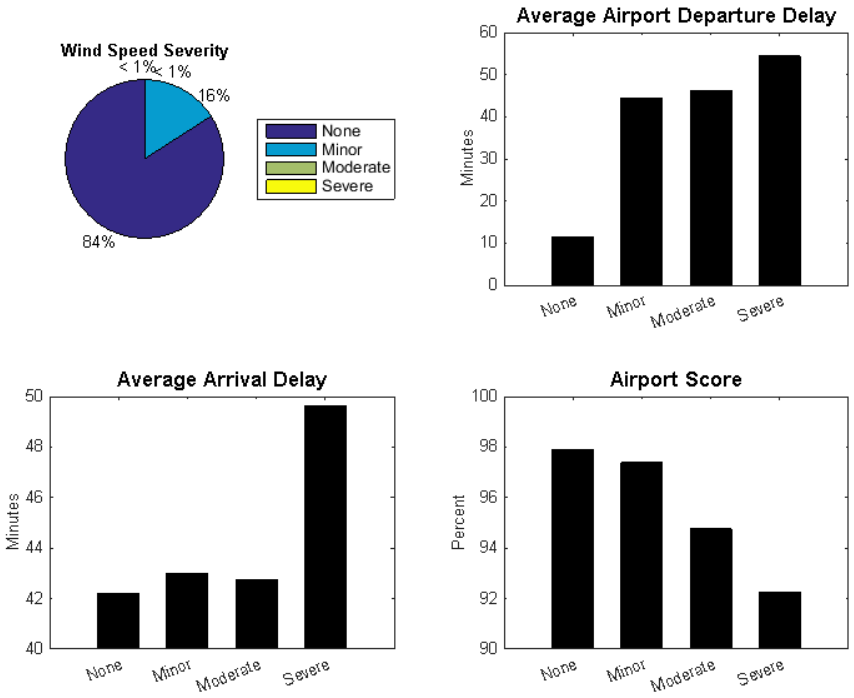


Figure 6.45. SEA average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

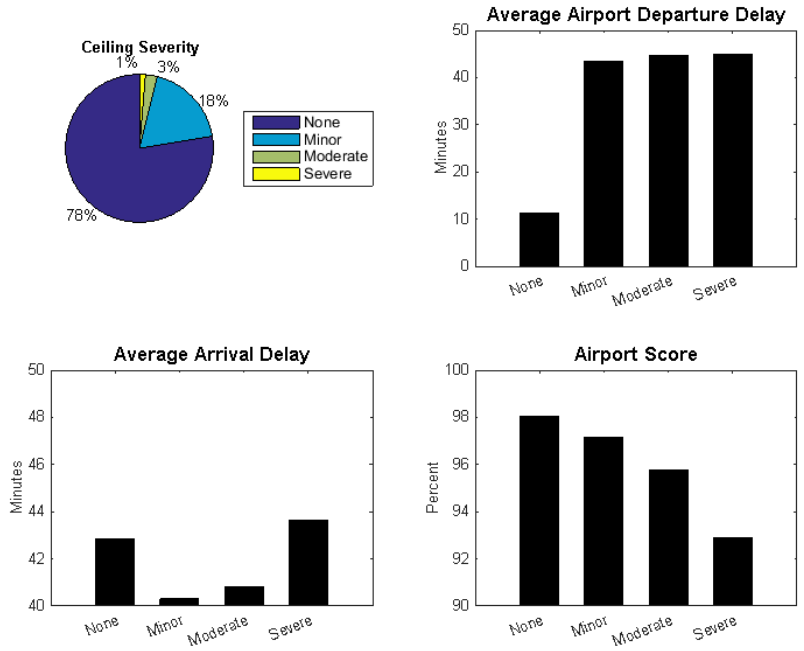


Figure 6.46. SEA average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

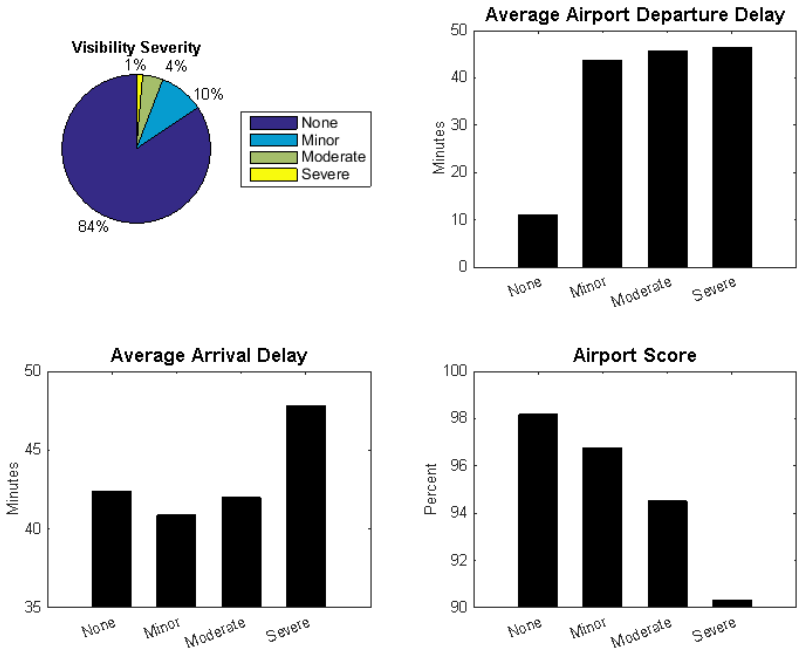


Figure 6.47. SEA average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

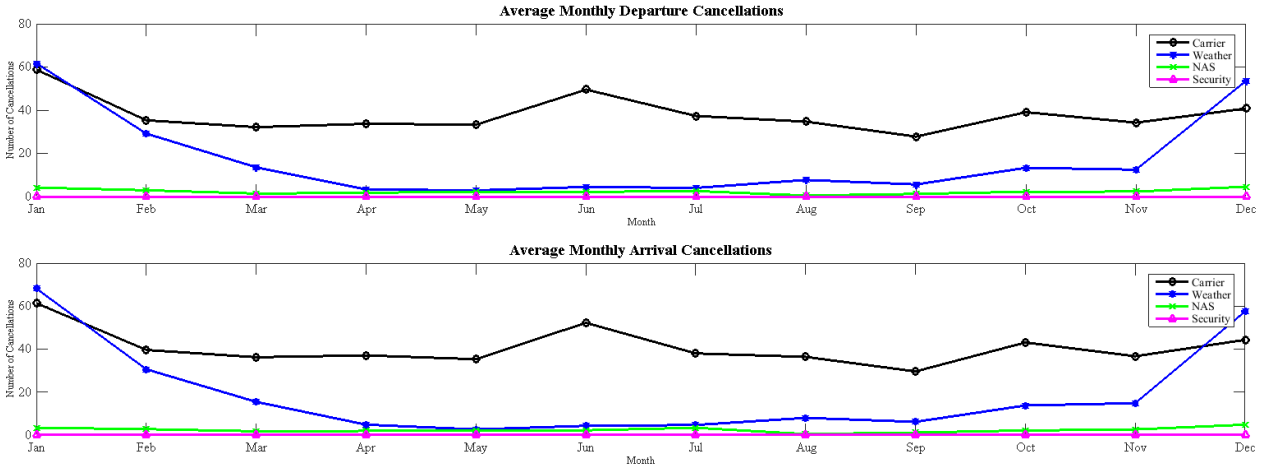


Figure 6.48. SEA average monthly departure and arrival cancellations.

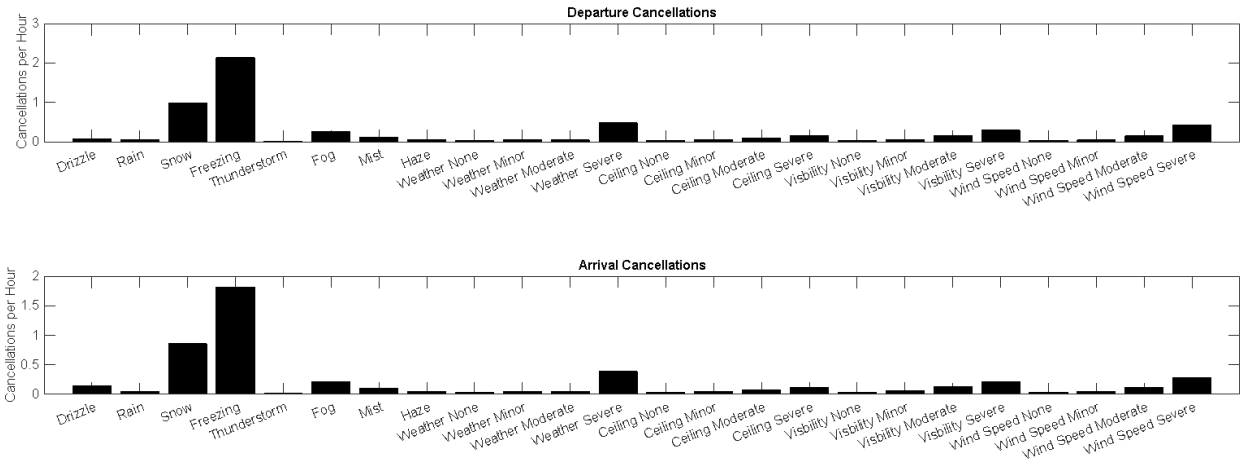


Figure 6.49. SEA average number of departure and arrival cancellations per hour of observed phenomena.

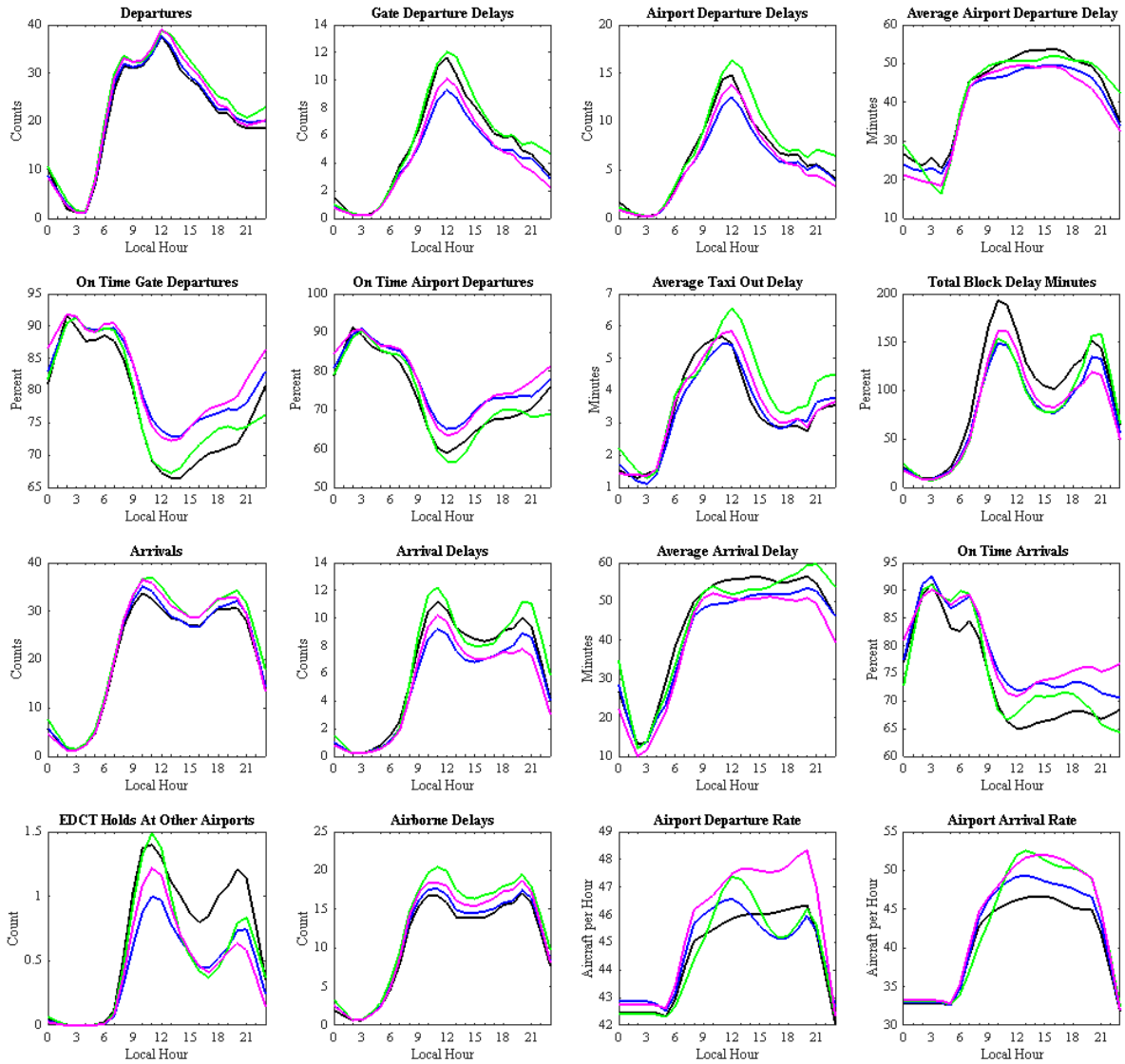


Figure 6.50. SFO hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

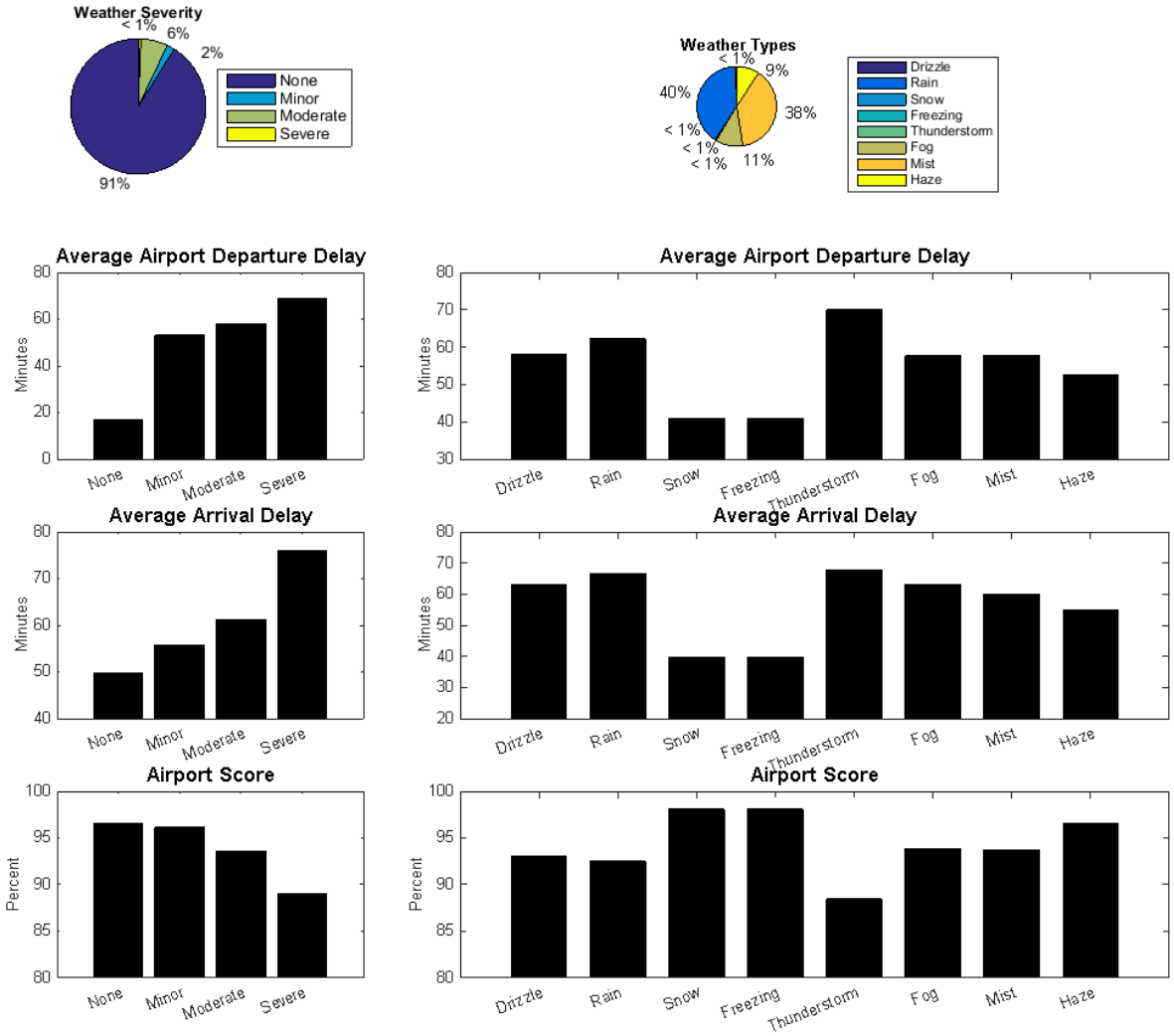


Figure 6.51. SFO average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

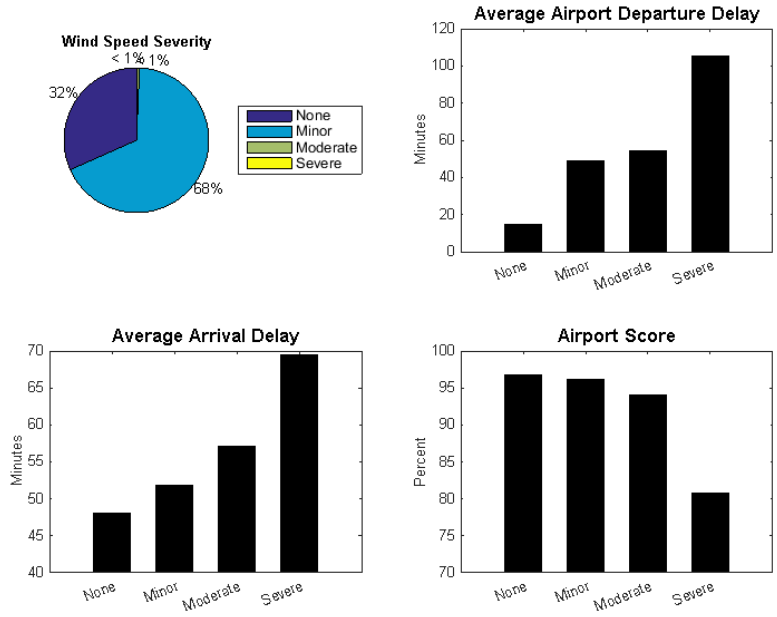


Figure 6.52. SFO average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

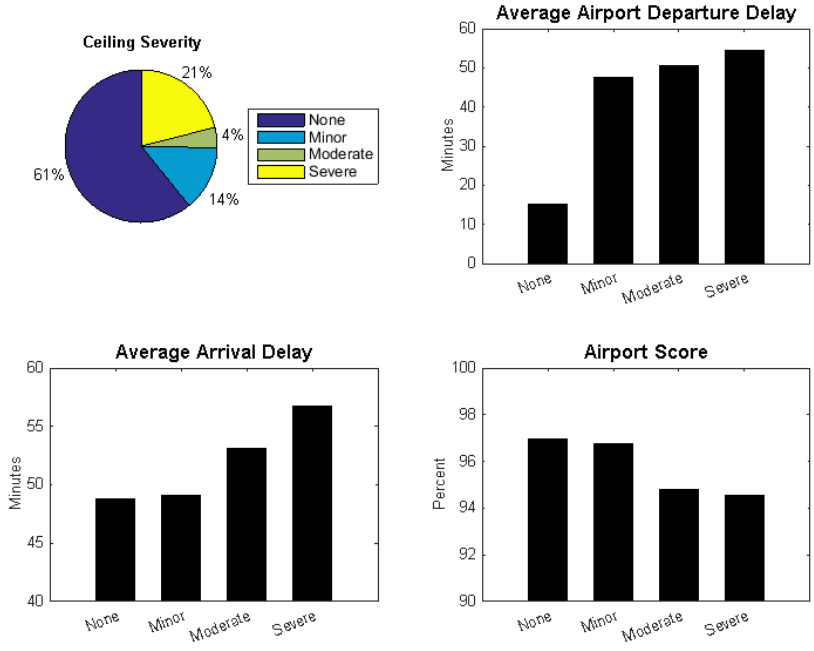


Figure 6.53. SFO average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

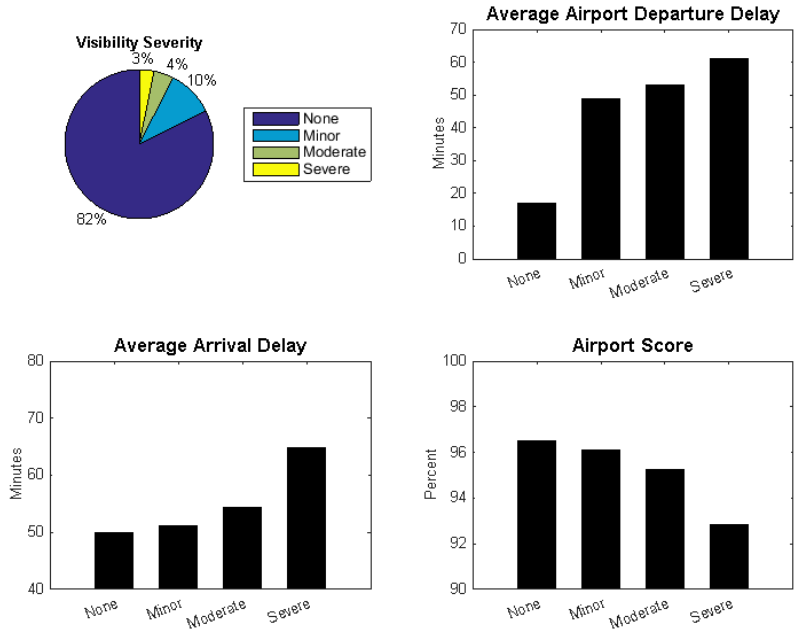


Figure 6.54. SFO average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

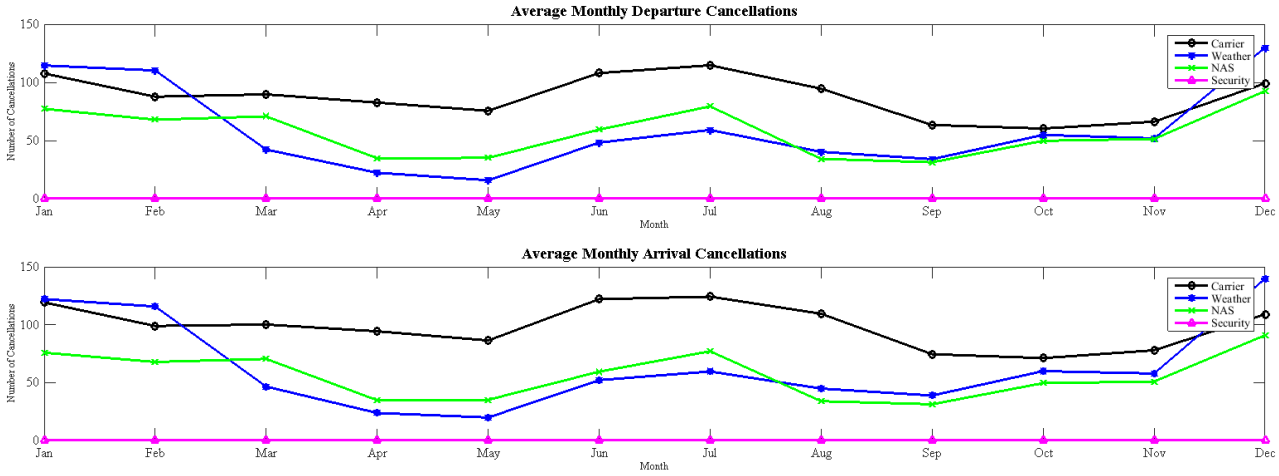


Figure 6.55. SFO average monthly departure and arrival cancellations.

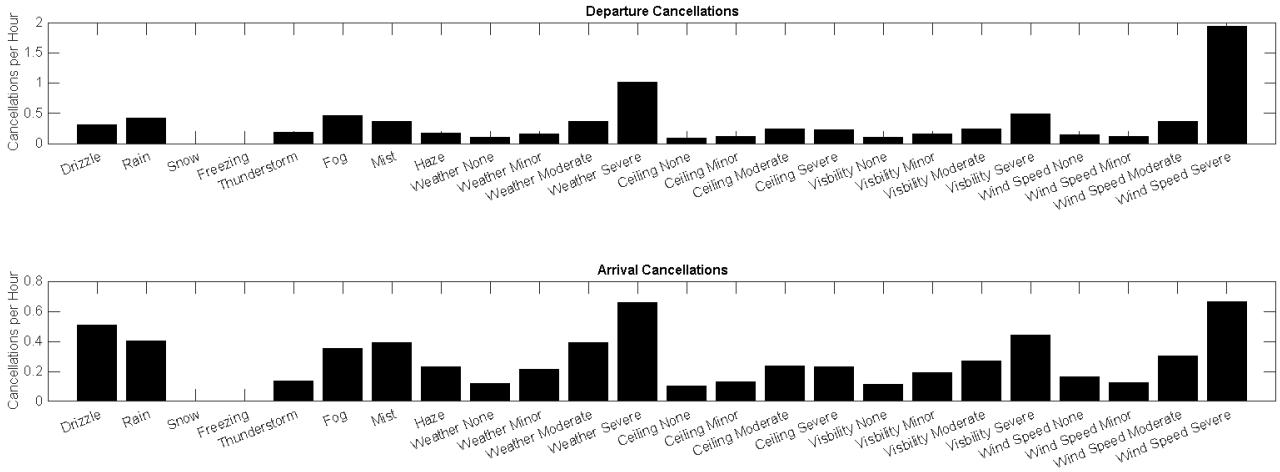


Figure 6.56. SFO average number of departure and arrival cancellations per hour of observed phenomena.

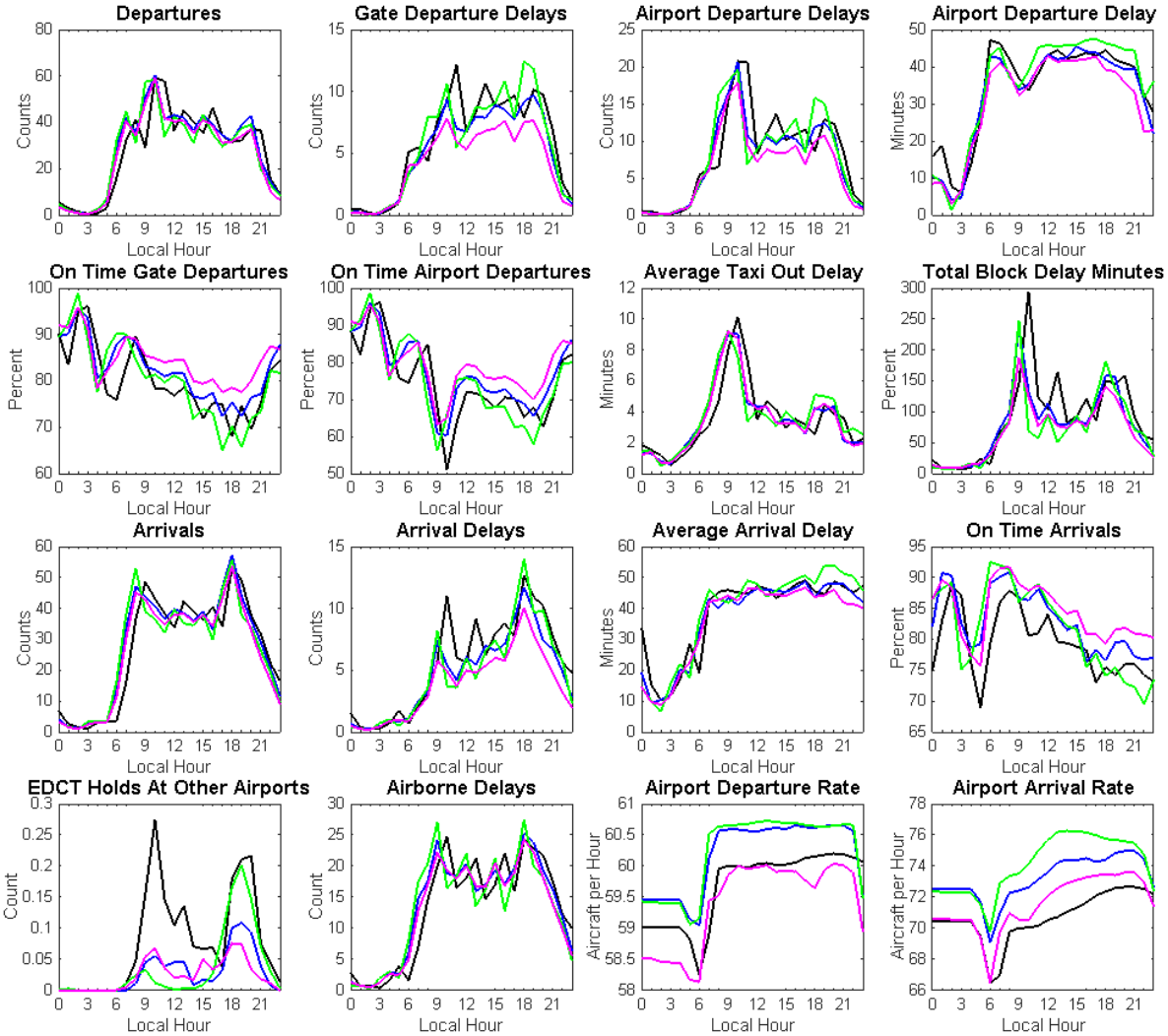


Figure 6.57. PHX hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

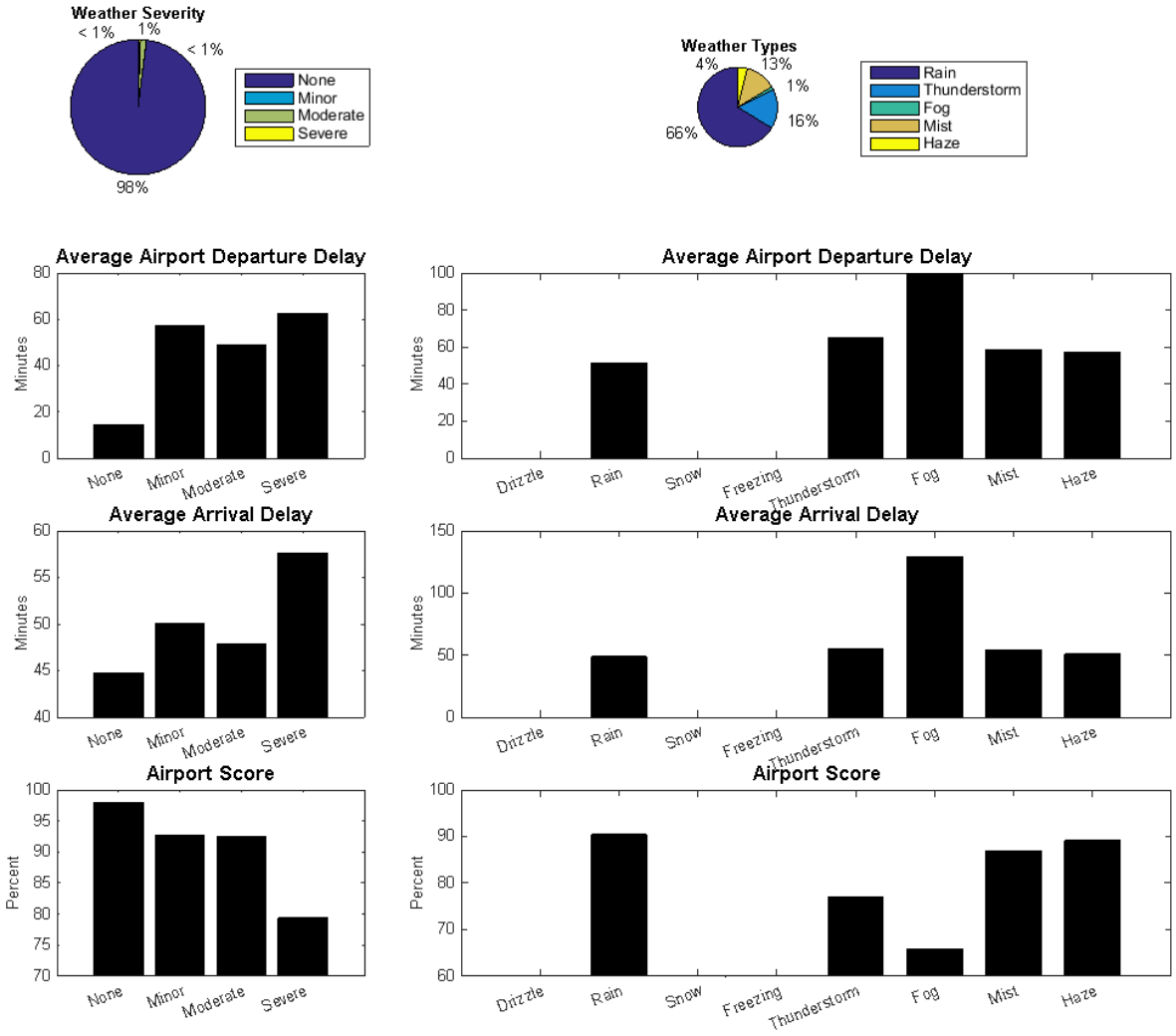


Figure 6.58. PHX average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

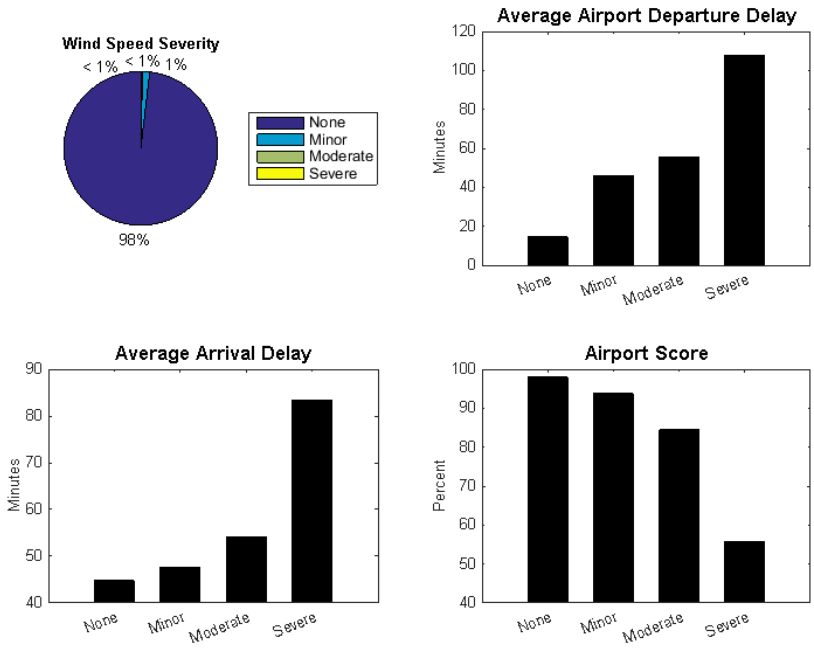


Figure 6.59. PHX average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

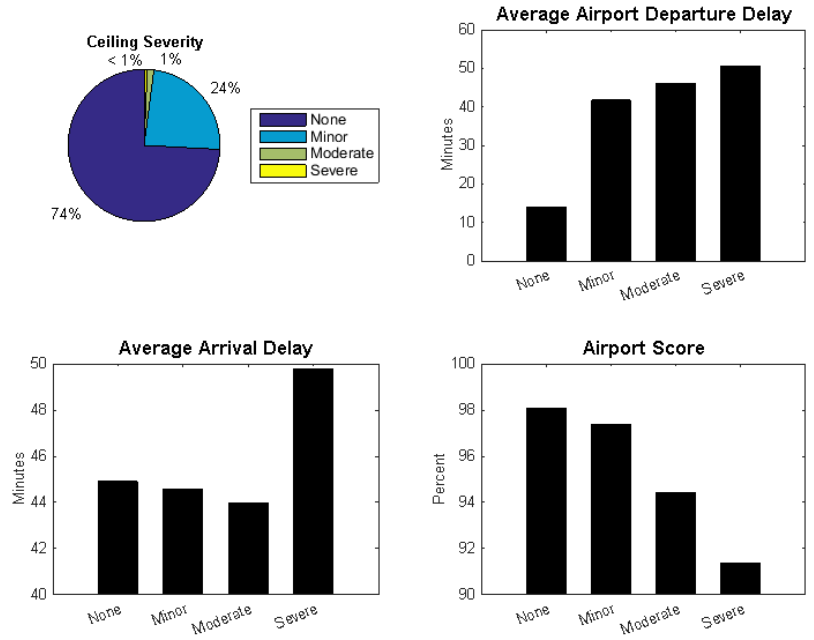


Figure 6.60. PHX average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

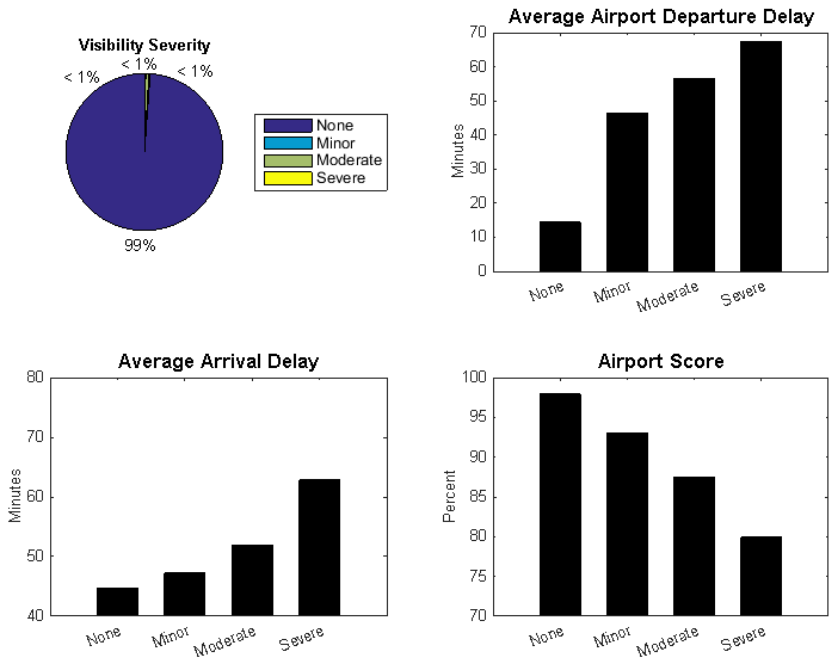


Figure 6.61. PHX average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

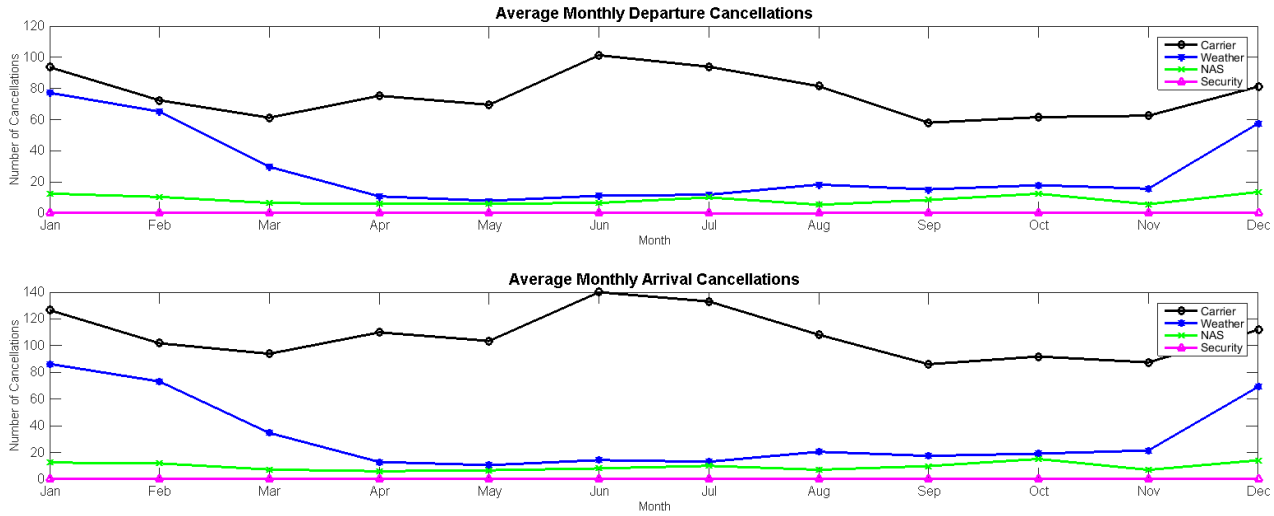


Figure 6.62. PHX average monthly departure and arrival cancellations.

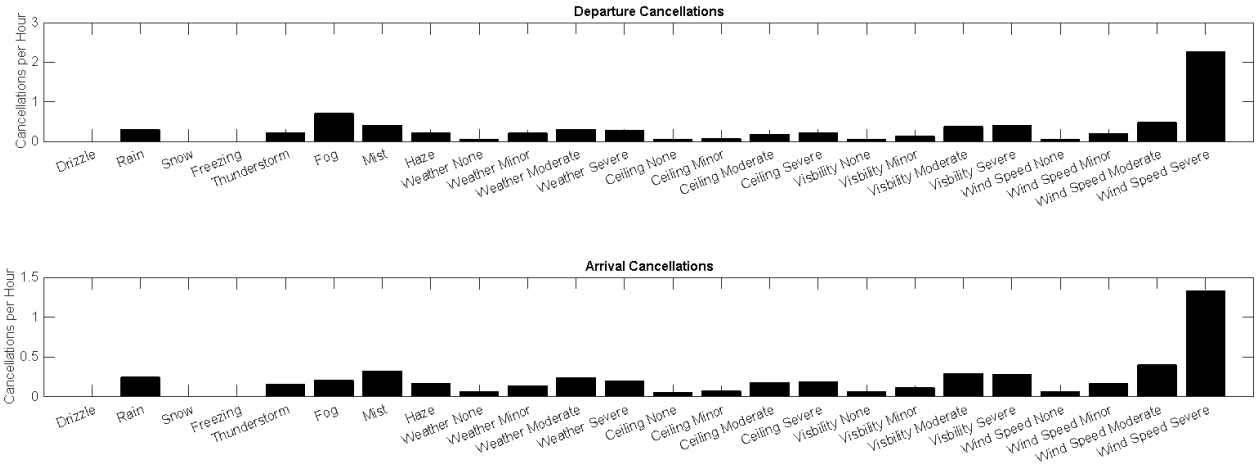


Figure 6.63. PHX average number of departure and arrival cancellations per hour of observed phenomena.

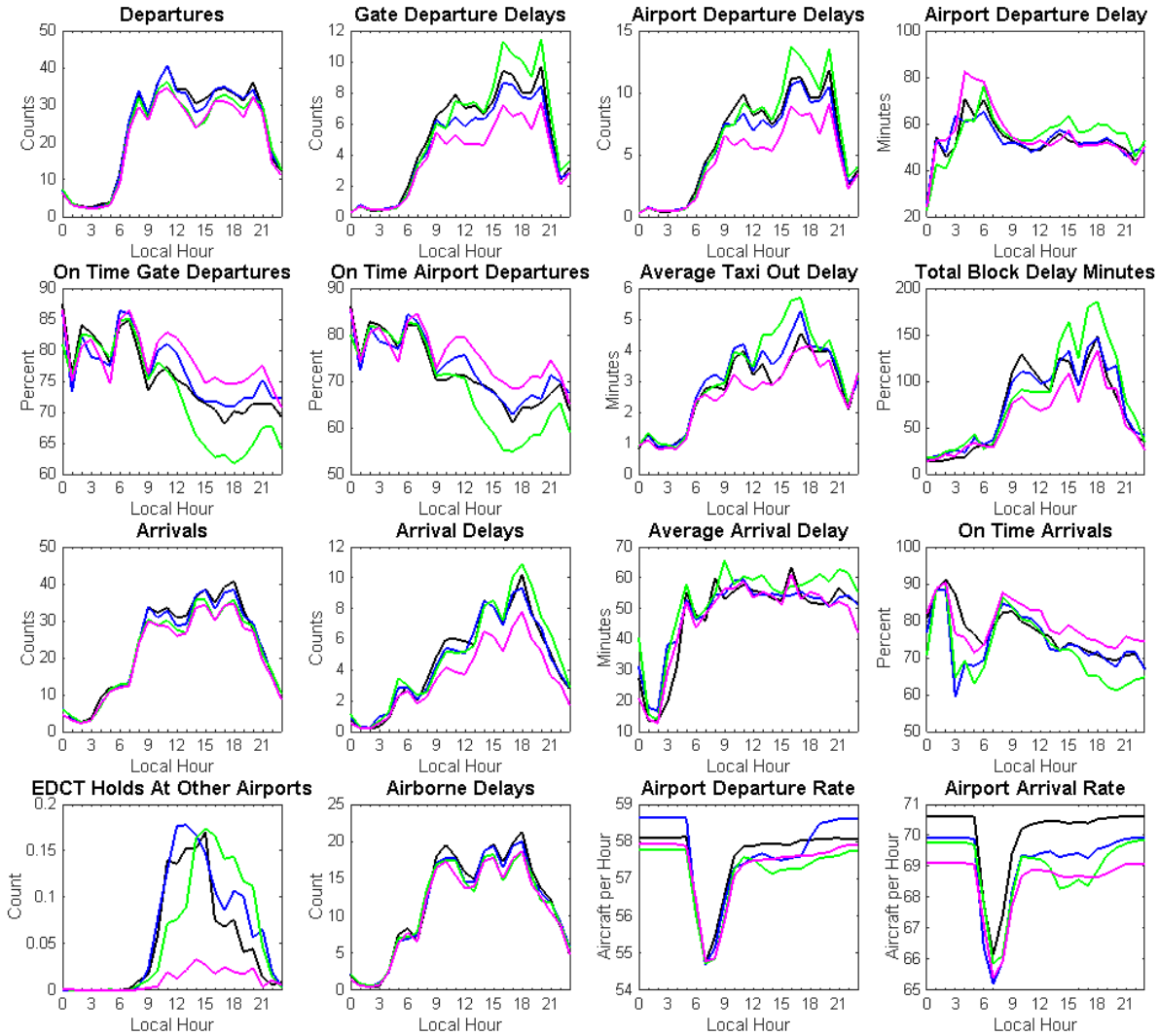


Figure 6.64. MIA hourly, seasonal average ASPM values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

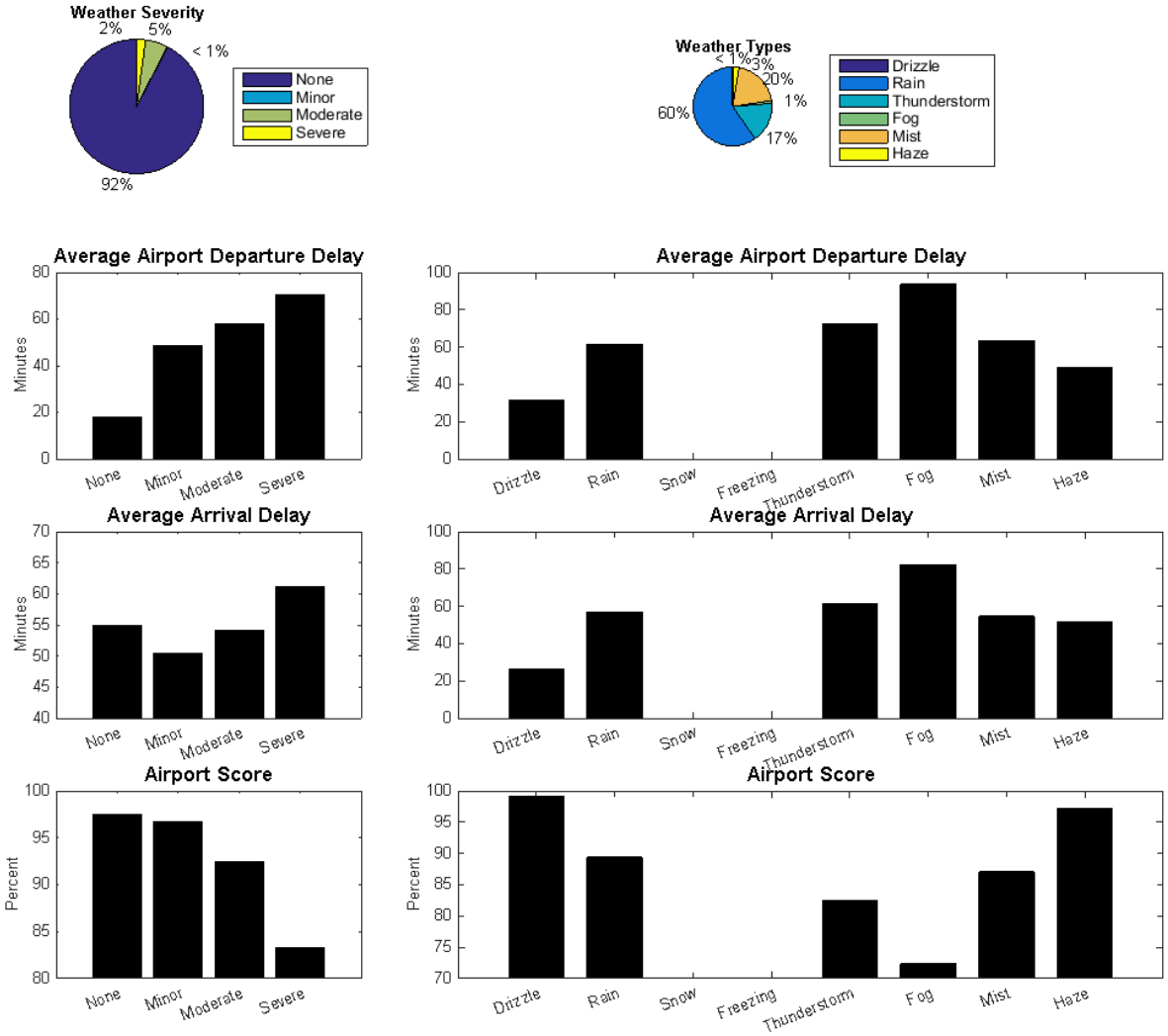


Figure 6.65. MIA average airport departure delays, average airport arrival delays, and airport scores for weather impacts and specific weather types.

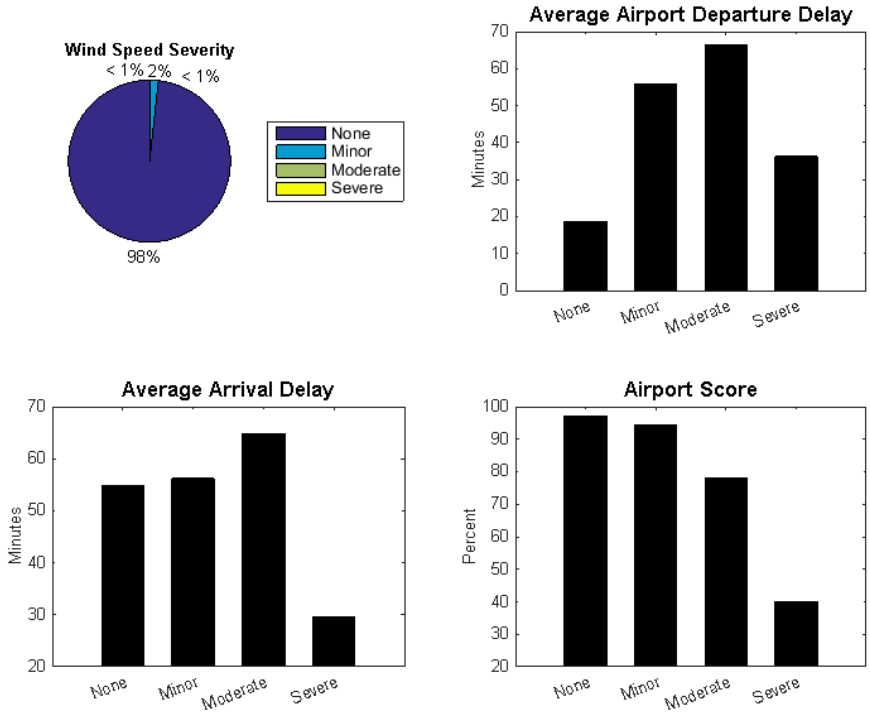


Figure 6.66. MIA average airport departure delays, average airport arrival delays, and airport scores for wind speed impacts.

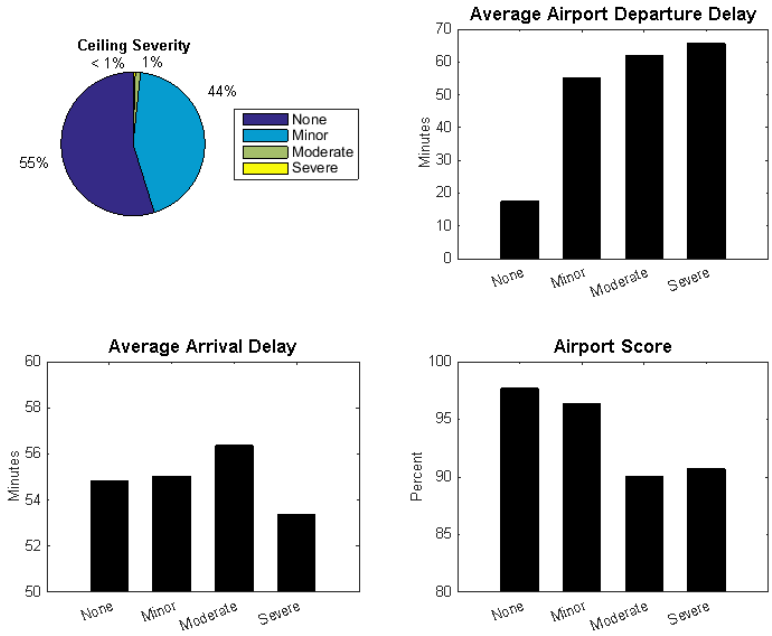


Figure 6.67. MIA average airport departure delays, average airport arrival delays, and airport scores for ceiling height impacts.

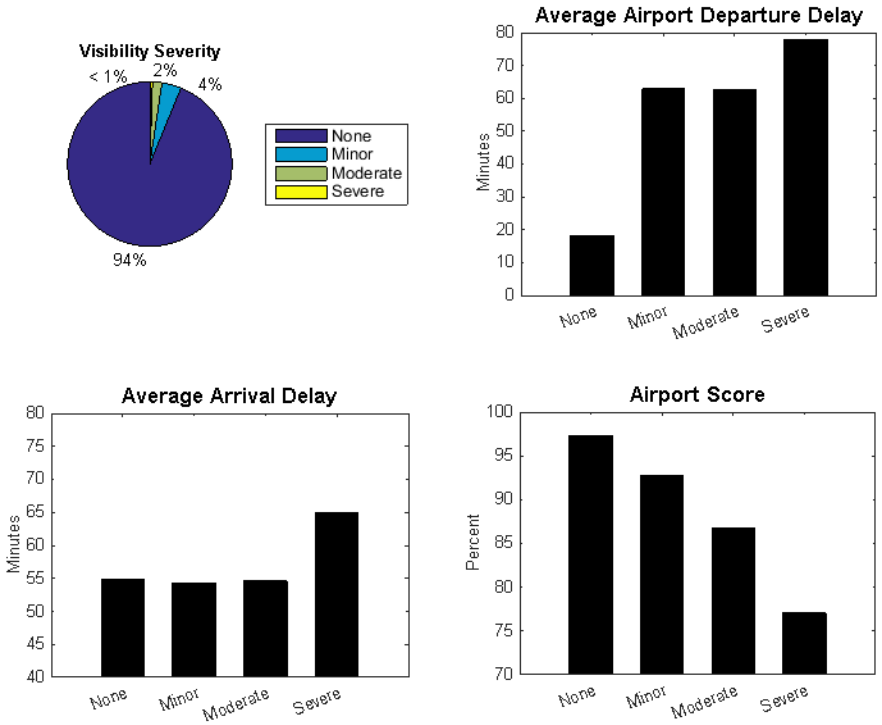


Figure 6.68. MIA average airport departure delays, average airport arrival delays, and airport scores for visibility impacts.

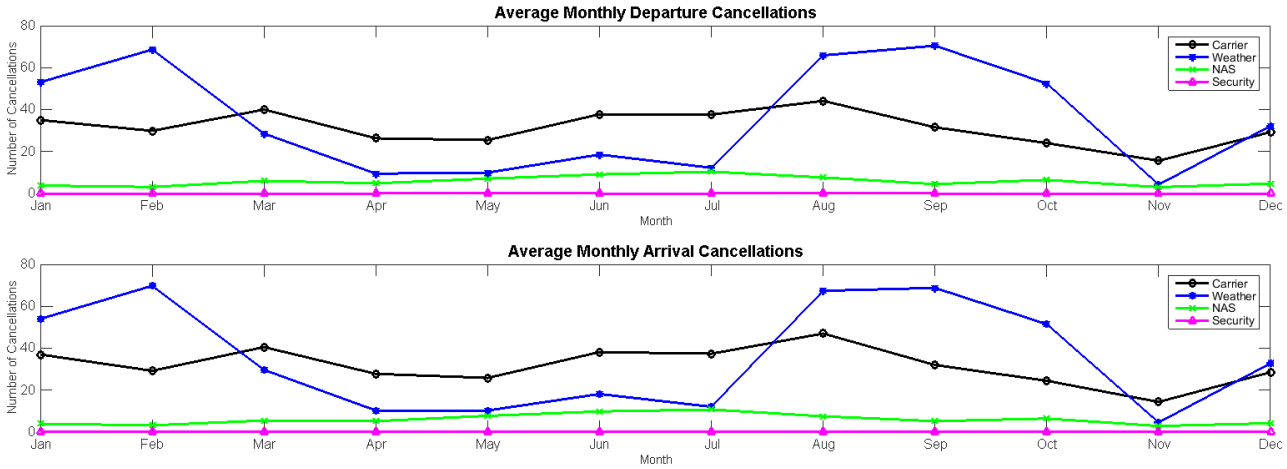


Figure 6.69. MIA average monthly departure and arrival cancellations.

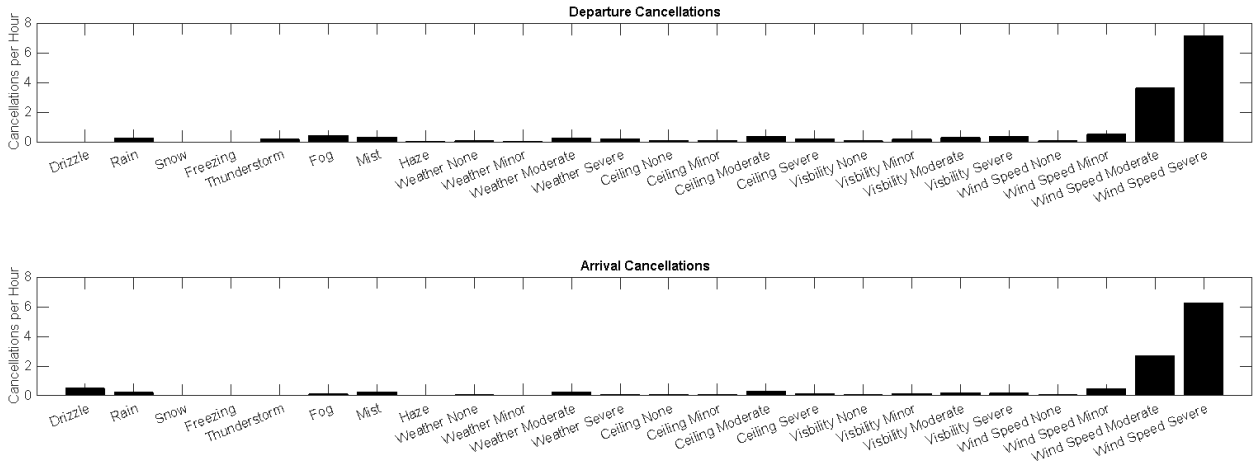


Figure 6.70. MIA average number of departure and arrival cancellations per hour of observed phenomena.

APPENDIX I. AIRPORT WEATHER

6.A.1 Atlanta Hartsfield-Jackson International Airport (ATL) Weather Climatology

6.A.1.1 ATL Monthly Weather

ATL's location in North-Central Georgia places the airport within the humid subtropical climate Köppen classification with four distinct seasons. When looking at the monthly weather averages for the ATL METAR observations, the general trends align well with what is expected for a humid subtropical climate classification. Looking at Figure 6.A.1, both the hourly averages of the ambient temperature and dew point temperature shows maximums in July and August with minimum values in January; this is expected due to seasonal changes in insolation. Relative humidity shows its highest maxima in July, August, and September, a second maxima in December, and a minima in February, March, and April. Geffen and Ross observed similar trends in relative humidity for the southeastern United States (Geffen et al., 1998). The altimeter setting shows higher values during the cool season and lower values in during the warm period. Higher temperatures, higher relative humidities, and lower altimeter values in the summer months combine to increase the density altitude in the summer months and lower the density altitude in the winter months. The increase in both average density altitude and number of hours with a density altitude above 3,000 feet indicate that aircraft performance reductions occur during the summer (warm season) months. ATL wind patterns also show monthly changes. Both monthly average wind direction and gust speed show changes, however the pattern is not clearly distinguishable; average wind speed shows highest values from December to March with wind speed decreasing after March until August and then increasing again. As a result of stronger temperature differences between the North Pole and equator and the subsequent increase in the pressure gradient, wind speeds are greatest in mid-winter to early spring (Klink, 1999).

Decreased ceiling heights in the cool season are associated with decreased surface heating (Warren et al., 2006). Decreases in visibility during the winter months and August can are associated with increases in visibility obscuring phenomena. Together, decreased visibility and ceiling heights during cool season months result in a higher occurrence of IFR conditions at ATL and the potential for increased delays or cancellations.

Figure 6.A.2 displays the average number of hourly observations of frequent weather types at ATL. Rain and drizzle have the highest occurrence in December through March. During the cool season, moisture advected from the Gulf of Mexico combines with winter storms to produce more precipitation over the Southeast United States. Due to ATL's southerly location, few occurrences of snow, ice pellets, and freezing precipitation occur in the winter months. Thunderstorm occurrences reach their peak for ATL in June, July, and August as a result of increased diabatic heating. Fog is more likely to occur in December or January while mist is more likely to occur from December to March due to cooler temperatures. Haze peaks in August due to warm temperatures and high humidities. As expected, overall precipitation peaks from December to March. Obscuration shows two peaks: one in December and January which is due to the occurrence of fog and mist and again in summer which is due to the occurrence of haze.

Figure 6.A.3 provides the monthly averages of the ASPM defined impacting weather. Minor impacting weather peaks in August as a result of the maximum occurrence of haze. Moderate impacting weather peaks from December to March as a likely result of the occurrence of drizzle and rain. Severe impacting weather has two peaks: one in the winter months as a result of fog and frozen precipitation and in the summer months as a result of thunderstorms. Overall, the largest wind speed and ceiling impacts occur in the winter months. Minor and

moderate visibility impacts peak in the summer months while severe visibility impacts peak in the winter months.

6.A.1.2 Seasonal, Diurnal Weather

Looking at the seasonal and diurnal cycles, new features are resolved and a better understanding of how solar radiation impacts the local weather at ATL can be gained. Looking at Figure 6.A.4, the influence of solar heating can be seen in the temperature and relative humidity profiles. The altimeter setting shows two peaks spaced roughly 12 hours apart; this is caused by gravitational pull of the moon and the thermal heating by the sun. Together, these two forces combine to produce a large-scale oscillation of the atmosphere called the atmospheric tide (Lindzen et al., 1969). The density altitude pattern is dominated by the ambient temperature and peaks during the hottest part of the day and the highest values in the JJA. Wind speed shows a peak from 9:00 AM to 3:00 PM with the DJF and MAM months have the highest overall value. Gust speed shows two peaks at around 4:00 AM and 8:00 PM with JJA having the highest peak in the evening hours (this could be associated with thunderstorms). Visibility and ceiling heights have their lowest values right before sunrise when surface temperatures are at their lowest. As a result, IFR observations peak prior to sunrise.

Evaluation of the present weather codes in Figure 6.A.5 leads to some unique observations. There is a pronounced peak of thunderstorms in the late afternoon during JJA when surface heating is at its maximum resulting in the formation of instability. The minor peaks in MAM and SON are likely due to the same cause. As a result of afternoon thunderstorms, JJA rain observations have a peak that aligns with the occurrence of thunderstorms. The diurnal pattern for snow, ice pellets, and freezing precipitation is more

difficult to diagnose due to their relatively low occurrence frequency. Fog, mist, and haze all have peaks (except for SON haze) prior to or at sunrise. Drizzle also has peaks after sunrise.

Looking at Figure 6.A.6, moderate weather observations peak near sunset and are most likely influenced by the observations of mist. DJF, MAM, and SON see severe weather observations peak around sunrise; DJF has the highest sunrise peak and all three seasons' sunrise peaks are most likely caused by fog observations. JJA shows an afternoon peak as a result of thunderstorms. Minor and moderate wind impact observations peak between noon and early afternoon for all seasons. JJA shows a pronounced severe wind impact observation peak in the evening that coincides with the peak in thunderstorm observations. Moderate and severe ceiling height and visibility impacts observations show prominent peaks for all months near sunrise.

6.A.2. Chicago O'Hare International Airport (ORD) Weather Climatology

6.A.2.1 Monthly Weather

ORD's location in northeastern Illinois and proximity to Lake Michigan creates cold winters and warm summers. Lake Michigan acts to moderate the local temperature extremes and increase yearly snowfall amounts through lake-effect snow. Lake Michigan also acts to increase summertime cloudiness and decrease summertime precipitation. ORD's northerly location means that it is located near the polar jet stream (especially in fall, winter, and spring) and near the epicenter for the creation or movement of mid-latitude cycles that can create a variety of hazardous weather.

Figure 6.A.7 displays the monthly temperature, dew point, and relative humidity changes for ORD. April, May, and June have the lowest altimeter setting; density altitude again is dominated by changes in temperature and shows the highest values and observations of density

altitude above 3000 feet in June, July, and August. Wind speed and gust speed show the greatest values in the cool season months. Visibility and ceiling heights show the lowest values in December, January, and February with highest values in the summer months; this combines to produce the highest number of IFR observations in the winter months.

Figure 6.A.8 displays the monthly averages for local weather types for ORD. Precipitation observations peak in December and are at a minimum in July. Rain observations show two peaks: one in April and the other in October. ORD frozen precipitation peaks in winter months and has higher counts than ATL. During the winter months, frozen precipitation dominates and replaces rain observations and is responsible for the bimodal nature of the rain observations. Observations of thunderstorms peak in the warm season months due to increased surface heating. Fog, mist, and haze all have peaks in the cool season months; haze has a secondary peak in June and August. When fog, mist and snow observations are combined, the obscuration counts increase in the cool season.

Figure 6.A.9 displays the monthly average observations for the different severity impacts. No local weather impacts have the highest occurrence in the warm season months. Moderate weather impacts have a peak in occurrence in December and a smaller peak in April most likely caused by the combination of rain and mist observations. Severe weather impacts peak in DJF as a result of snow, freezing precipitation, and fog. Overall wind impacts are lowest in June, July, August, and September. Minor, moderate, and severe wind impacts occur most frequently from October to April. Minor, moderate and severe visibility and ceiling height impacts are most pronounced from November to March with DJF having the highest percent of visibility and ceiling height impacts. Overall cool season months see the highest impacts from different weather phenomena.

6.A.2.2 Seasonal, Diurnal Weather

ORD shows some differences in the diurnal patterns of weather than what was observed at ATL. Looking at Figure 6.A.10, the typical patterns of ambient temperature and relative humidity is observed. Average density altitude and observations of density altitude above 3000 feet peak around 14:00 when the ambient temperature is highest. The two peaks in the altimeter setting are the result of atmospheric tides. Wind speed peaks at 14:00 when surface heating is at its maximum and the boundary layer is the most turbulent. Visibility and ceiling height are lowest near sunrise and gradually improve moving away from sunrise; this results in IFR conditions occurring more frequently in early morning hours. The smaller changes in visibility in DJF may be a result in the smaller changes of relative humidity, winter storms, or snow occurrences.

Figure 6.A.11 shows the seasonal, diurnal patterns for ORD local weather codes. In DJF, rain, drizzle, snow, and ice pellets all have a peak in the late evening to early night periods. MAM does not have as noticeable of a precipitation pattern except that rain occurs least often around noon. JJA has a rain and drizzle peak around 4:00 and are associated with thunderstorm activity. SON has rain occurrence peak in the evening and drizzle peak around 5:00. Thunderstorm activity is highest during JJA followed by MAM. Two thunderstorm peaks occur for JJA: a gradual peak centered near 20:00 and a sharper peak centered near 2:00. The second peak of thunderstorms may be a result of a nocturnal low-level jet (Pitchford et. al, 1962). MAM has a thunderstorm peak around 20:00. Mist most commonly occurs near sunrise whereas haze peaks after sunrise. For MAM, JJA, and SON, fog occurs most often near sunrise and then diminishes rapidly; MAM then shows a gradual increase in the occurrence of fog after noon. In DJF, fog peaks between 5:00 to 15:00. Overall, obscuring phenomena are most likely to occur

near sunrise. For all seasons, weather impacts are most likely to occur in late night to early morning hours.

Looking at Figure 6.A.12, minor and moderate weather impacts occur most often around sunrise through the early morning. Severe weather impacts are more difficult to diagnose. JJA has two peaks: one centered around 16:00 and the other around 4:00. Thunderstorms are the most likely cause for the two peaks. DJF has a peak near 19:00 as a result of snow or frozen precipitation. MAM and SON do not have a well-defined pattern. Moderate weather impacts peak between 4:00 to 5:00 and JJA has a lower magnitude as a result of fewer observations of mist. Overall, all wind impact categories have their highest values from mid-day to early afternoon. Minor and severe ceiling impacts peak near sunrise while moderate ceiling impacts peak after sunrise. DJF has the highest overall occurrence of moderate and severe ceiling impacts. Visibility impacts occur most often near sunrise; DJF has the highest overall occurrence of visibility impacts most likely as a result of higher occurrence fog and snow.

6.A.3 Dallas Love Field (DAL) Weather Climatology

6.A.3.1 Monthly Weather

DAL's location in North Central Texas causes large annual variations in temperature and precipitation. Winters are relatively mild but extreme cold temperatures can occur; snowfall is relatively rare but can occur. Spring and fall are usually characterized by fair weather but thunderstorms (some being severe) occur mainly in the spring. Summers are hot with temperatures exceeding 100° F frequently, and hot spells are usually broken up by thunderstorms. Overall most precipitation occurs at night and is commonly associated with thunderstorms or cold fronts.

Figure 6.A.13 displays the monthly averages for temperature, dew point, and relative humidity. Altimeter setting is lowest in the warm season months. Combined with higher temperatures, the average summer density altitude is well above 2,000 feet with the highest number of observations of density altitude above 3,000 feet occurring in August. Wind speed shows a primary peak in April and secondary peak in November and gust speed is lowest in July and August and highest in April. Ceiling and visibility values are highest in the summer months and decrease in the cool season; this results in an overall increase in IFR observations in the cool season.

Figure 6.A.14 displays the average number of monthly weather observations for DAL. Rain observations are least common in the July and August and increase in other months. Drizzle observations are most common in the cool season months as well as is fog and mist. Haze observations overall are highest from December to May (with May having a very strong peak) and decrease from June to November. Obscuration observations are highest in the cool season and are low in June, July, and August. Counts of frozen or freezing precipitation are commonly observed from November to March with February having the largest peak. Overall precipitation observations are highest during the cool season months.

Figure 6.A.15 displays the average severity observations for weather, wind, ceiling height, and visibility. For weather severity impacts, the overall weather impact on DAL is lower than ATL and ORD and fewer weather impacts are likely to occur in the warm season. Minor and moderate impacts occur most often in the cool season months as a result of more observations of precipitation, mist, and haze. Severe weather peaks in February as a result of snow and freezing precipitation and in May as a result of more thunderstorms. Wind impacts are greatest in the first half of the year from January to Jul. Low ceiling impact are lowest in JJA

and highest during the cool seasons. Like ceilings, visibility impacts are lowest in JJA and increase in the cooler months. Overall, weather impacts to DAL are highest during the cooler months and a minimum in JJA.

6.A.3.2 Seasonal, Diurnal Weather

Figure 6.A.16 shows the typical patterns for temperature, dew point, relative humidity and the two peaked altimeter setting. Density altitude and observations of density altitude above 3,000 feet is again maximum during the warmest part of the day at around 15:00. Wind speed peaks from the afternoon to early evening with MAM displaying the highest overall wind speeds. Gust speed peaks around 21:00 for MAM, JJA, and SON and remains relatively constant for DJF. Visibility and ceiling heights are lowest prior to or at sunrise; this contributes to the highest occurrence of IFR observations prior to or at sunrise. It is interesting to note that DJF has a lower overall visibility and MAM has the lowest ceilings and that DJF has the highest occurrence of IFR observations; this suggests that a majority of IFR observations are caused by low visibility.

Figure 6.A.15 shows the seasonal weather patterns for DAL. In general, precipitation occurrences are greatest in the late night to early morning periods. DJF, MAM, and SON have relatively constant occurrences of rain with s peak around 5:00; JJA has a minimum occurrence of rain at 21:00, peaks at 7:00 and gradually decreases until 17:00 at which it time the rain occurrence rapidly decreases. Thunderstorm activity peaks around midnight for DJF, MAM, and SON with MAM having the highest overall occurrence of thunderstorm activity; thunderstorm activity has a primary peak at 15:00 and secondary peak at 3:00 for JJA. Fog and mist all peak around at or before sunrise; haze however peaks after sunrise with JJA having a smaller

secondary peak at 17:00. Overall, obscuration phenomena occur most frequently near sunrise. DJF experiences the greatest impact from weather phenomena while JJA experiences the lowest.

Figure 6.A.16, Figure 6.A.17, and Figure 6.A.18 display the seasonal, diurnal patterns for DAL. Overall, most weather impacts occur in the early morning with DJF having the most weather impacts. Moderate weather impacts (most likely caused by mist or rain) are highest for DJF and lowest for JJA. Looking at severe weather impacts, DJF and MAM have the highest occurrences. Severe weather for DJF is highest from 3:00 to 6:00 most likely caused by the occurrence of fog, snow, freezing precipitation or heavy rain. MAM has a minimum occurrence of severe weather at 10:00 and maximum at 0:00 and is most likely caused by thunderstorms. JJA has two severe weather peaks: a major peak at 15:00 and a secondary peak at 3:00. The most likely cause is again thunderstorms. Wind impacts for DAL are strongest for MAM and have the most notable from 11:00 to 14:00. In the moderate wind impacts graph for MAM, there is an unusual peak at 0:00. The overall rare occurrence of severe wind impacts at DAL make analyzing severe wind impacts difficult and uncertain. MAM sees the highest occurrence of minor ceiling and visibility impacts, whereas DJF has the highest occurrence of moderate and severe ceiling and visibility impacts. Both moderate and severe ceiling and visibility impacts occur near sunrise for all months.

6.A.4 Minneapolis - St. Paul (MSP) International Airport Weather Climatology

6.A.4.1 Monthly Weather

MSP's northern location provides cold winters and pleasant warm summers. Figure 6.A.19 displays the averages monthly temperature, dew point, and relative humidity values for MAP. Winters are cold with average temperature below zero while summer temperature are

relatively mild and less humid. The altimeter setting is lowest during April, May, and June; this combined with the temperature patterns show high density altitudes in the summer with observations of density altitudes above 3000 feet peaking in June. Wind and gust speeds peak in April and in October-November and are a minimum in July and August. Visibility and ceiling heights are highest in the warm season months and decrease in winter with December showing the lowest values. This results in an increase in IFR observations in the cool season months especially in December.

Figure 6.A.20 displays the average monthly occurrence for certain weather phenomena. Rain observations peak in May and October for MSP and diminish in December, January, and February. Snow, ice pellet, and freezing precipitation observations occur most frequently in cool season months; occurrence of frozen precipitation is responsible for the winter decrease in in rain observations. Snow also has a much higher observation magnitude than rain or any other precipitation type. Looking at the average precipitation counts, precipitation is most likely to occur in the cool season months particularly in December. Thunderstorm activity increases from March to June then gradually decreases. Observations of fog are more sporadic, however there is a minimum in fog observations in May, June and July. Mist shows a pronounced pattern with occurrences peaking in December and minimizing in July. Haze observations are most common in the cool season months. Combined, obscuration observations are most common in December and least common in July.

Figure 6.A.21 displays the average monthly weather, wind, ceiling, and visibility impacts for MSP. Overall, cool season month are more impacted by weather. Minor weather impacts peak from November to March most likely as a result of haze or drizzle. Moderate weather impacts show a more interesting pattern with peaks in May and then between October and

December. The combined occurrence of rain, drizzle, and mist is likely responsible. Severe weather impacts occur most often in December, January, and February as a result of snow. Overall, wind impacts occur most often in the spring followed by fall. Minor and moderate wind impacts occur most often in April followed by October-November. The peak in June for moderate and severe wind impacts is likely as a result of thunderstorms. Ceiling height and visibility impacts occur most often in the cool season months particularly December.

6.A.4.2 Seasonal, Diurnal Weather

Figure 6.A.22 displays the seasonal, diurnal patterns for temperature dew point, relative humidity, and altimeter. The patterns all show what is expected in the daily changes a result of changing insolation throughout the day. This again results in density altitude and observations of density altitude above 3,000 feet are highest for JJA and peak during the warmest part of the day. Wind speed peaks during the afternoon hours for all seasons. Gust speed is more variable (again due to the fewer observations of wind gusts) than wind speed; however DJF, MAM, and SON all have higher overall values and peak around 18:00 and again at 2:00 whereas gust speed peaks at 22:00 and 1:00 for JJA. Due to MSP's higher latitude, the sunrise and sunset times vary greatly between the seasons causing changes in the visibility and ceiling patterns. DJF has the worst overall visibility and ceiling heights and therefore the highest observations of IFR weather whereas summer has the best visibility and ceiling heights. Changes in sunrise and sunset times mean that the valleys in visibility occur later in the morning hours as the days get shorter. This could potentially cause disastrous delays in the winter time when lower visibilities occur more frequently and later when the airline schedules are busier. Most variability with ceiling heights between the seasons is seen around midnight when ceiling heights are highest. Ceiling heights

are lowest around the time when sunrise occurs. IFR observations are most common near sunrise, again this poses a problem in DJF when airport operations are already underway.

Figure 6.A.23 displays the seasonal, diurnal patterns for various weather types. Overall, MAM has the highest observations of rain that peak at 16:00 while JJA rain peaks at 4:00. SON and DJF rain observations do not have as clear of a pattern but appear to peak during the midday. Drizzle observations have a less defined pattern but JJA shows a clear increase in observations around 4:00. Thunderstorm activity is greatest for JJA and is at a minimum at 10:00 and peaks at 1:00. MAM and SON shows peaks at midnight. Snow and freezing observations show a maximum in the early morning hours for DJF. Fog observations show a unique pattern. MAM, JJA, and SON all show steep rises in fog until around sunrise and then quickly diminish after peaking. DJF fog observations show a more gradual increase in fog until sunrise and then slowly diminishes after that. This means that fog is an impacting factor for a majority of the average day instead of during an expected window. Mist observations peak in the early morning hours near sunrise and DJF has the highest over values. Haze observations peak after sunrise and DJF has the highest overall values. Combining all the weather observations indicates that overall weather impacts occur earlier in the day near sunrise with DJF having the largest overall impacts.

Figure 6.A.24 displays the weather severity impacts for MSP. Minor weather impacts are most common for DJF and for all seasons, the impacts are most likely to early morning to midday. Moderate weather impacts all occur at roughly the same time between 5:00 to 6:00 and MAM, SON, and DJF all roughly have the same values. DJF has a much higher observation of severe weather impacts as a result of frozen precipitation and peaks at 8:00. MAM and SON do not have diurnal noticeable pattern of impacts of severe weather. JJA has a peak in severe weather impacts from 1:00 to 4:00 as result of thunderstorms. Overall wind impacts are most like

to occur from 12:00 to 14:00 for all seasons with MAM having the highest number of observations. JJA has the least number of ceiling impacts and DJF has the highest observations of ceiling impacts. Severe ceiling impacts are most likely to occur near sunrise for all months. Moderate ceiling impacts peak after severe ceiling impacts at around 8:00 to 10:00. Minor ceiling impacts peak even later near noon. It is interesting to observe that as ceiling severity decreases, the time period in which peak for observation occurs is even later. Visibility impacts are greatest for DJF with the peak for all observations occurring near sunrise for all seasons.

6.A.5 John F. Kennedy (JFK) International Airport Weather Climatology

6.A.5.1 Monthly Weather

JFK's location in the northeastern United States ensures that the airport experiences weather impacts from all four seasons. Figure 6.A.25 displays the temperature, dew point, and relative humidity profiles of JFK. JFK experiences warm, humid summers and cold, drier winters. Due to JFK's northern latitude and low elevation, high density altitudes are not a concern. Wind and gust speeds are highest during the cool season months with peaks in February. Visibility is highest from August to November and lowest in May. Ceiling height patterns are sporadic with the lowest average ceilings observed in May, June, and September. Overall, the highest occurrences of IFR hours occur in May.

Figure 6.A.26 displays the monthly average number of weather observations for JFK. Rain observations have two peaks in April and in December. Drizzle has a large peak in May and is almost nonexistent in July, August, and September. As expected, frozen precipitation is most common during the cool season months. Snow observations are highest for January, freezing precipitation is highest in February, and ice pellet observations are highest in March.

Overall, precipitation is most common in the cool season months. Thunderstorm observations are most common in the July and the overall plot looks almost perfectly Gaussian. Fog occurrences are most common in December with another smaller peak in May. Mist occurrences are relatively high throughout the year with the largest observance in May. Haze is primarily seen in the summer months with July having the highest amounts of observations. Overall, obscuring phenomena are most commonly seen in May.

Figure 6.A.27 displays the monthly average percent's of observation for weather, wind, ceiling, and visibility impacts. Minor weather impacts are most common in June, July, and August. Moderate weather impacts are most likely to occur in May and severe weather impacts occur most often in December, January, and February. Wind impacts are likely to occur on the cool season months. Ceiling impacts are least likely to occur in July, August, and September and severe ceiling impacts are most likely to occur in May. Minor and moderate visibility impacts are likely to occur in the summer months but severe visibility impacts are most likely to occur in May.

6.A.5.2 Seasonal, Diurnal Weather

Figure 6.A.28 displays the profiles for temperature, dew point, relative humidity, altimeter, and density altitude for JFK. All show the expected seasonal patterns for JFK. Wind speed is highest during the noon to evening time periods for all seasons. Gust speed is relatively consistent for all seasons except summer where the gust speed is lowest at 11:00. Visibility and ceiling height are lowest for all seasons near sunrise with higher occurrences of IFR conditions occurring near sunrise.

Figure 6.A.29 displays the seasonal, diurnal weather observations for JFK. When looking at different precipitation observations, some patterns are distinguished. Rain and drizzle observations increase in the first part of the day for MAM, whereas rain observations are lowest in the predawn hours for DJF and highest at 18:00 for JJA. DJF snow observations show a decrease in snow observations during the midday hours. Coinciding with the increase in rain is an increase in thunderstorms in the late afternoon to early evening periods particularly for JJA and also MAM and SON. Fog and mist show higher observations in the early morning hours near sunrise and haze shows an increase in observations after sunrise.

Figure 6.A.30 displays the seasonal, diurnal percent observations for weather, wind, ceiling, and visibility impacts. Overall, weather impacts are most likely to occur near sunrise for all seasons. Severe weather impacts are highest for DJF with a peak near sunrise. JJA severe weather observations occur most frequently near 18:00 as a result of thunderstorms. Wind impacts occur most frequently near 15:00. Minor ceiling impacts occur most often in the afternoon to evening hours. Moderate and severe ceiling impacts occur most often near sunrise. Visibility impacts are least likely to occur during the midday hours and most likely to occur in the morning hours.

6.A.6 Salt Lake City (SLC) International Airport Weather Climatology

6.A.6.1 Monthly Weather

SLC has a semi-arid climate characterized by dry, hot summers and cold, snowy winters. Figure 6.A.31 displays the average monthly temperature, dew point, and relative humidity profiles for SLC. Large changes in temperature and moisture can be seen in SLC as a result of its arid climate. As a result of high temperatures and high elevations, high density altitudes

occur often throughout the summer month; in fact from March to October, almost all observations of density altitude are above 3,000 feet. Wind speed values are highest in the warm season months whereas gust speeds are highest during the cool season months. Average visibility values are highest from May to October and lowest in December and January. Ceiling heights are lowest in December and January. These patterns may be the result of a strong temperature inversion that develops over Salt Lake City in the winter months (Climate of Utah). IFR conditions do occur in the winter months and are almost nonexistent in the summer months.

Figure 6.A.32 displays the average number of monthly observations for certain weather types. Rain occurs most frequently in April and May with a smaller peak in October. Drizzle and ice pellet observations are relatively rare but occur most frequently in the cooler months. Snow occurs most often in December. Freezing precipitation occurs more often than at other airports examined with January having the highest number of observations. Thunderstorm observations gradually build until peaking in August and then rapidly decrease. Fog, mist, and haze all peak in January and are almost nonexistent in the summer months.

Figure 6.A.33 displays the average monthly values for weather, wind, ceiling, and visibility impacts. Minor, moderate, and severe weather impacts all peak in either December or January. Minor, moderate, and severe wind impacts all peak in April. Visibility and ceiling impacts all peak in the winter months. It is safe to assume that the winter months should see the worst weather impacts on delays and cancellations.

6.A.6.1 Seasonal, Diurnal Weather

Based on what was seen in previous airports and from the SLC average monthly values; the seasonal, diurnal profiles for temperature, dew point, relative humidity, altimeter, density

altitude, and observations of density altitude above 3000 as seen in Figure 6.A.34 all show was is expected. Wind speed peaks in the afternoon and is highest for MAM and JJA. Gust speed a noticeable increase in JJA at 18:00 and is most likely associated with thunderstorms. For DJF, MAM, and SON ceiling and visibility averages, the lowest values occur near sunrise. In JJA, the lowest values are seen around 17:00. DJF has the highest observations of IFR hours which are most likely to occur near 9:00.

Figure 6.A.35 displays the average seasonal, diurnal patterns for weather types at SLC. Rain observations are highest in MAM; JJA shows a peak in rain during the afternoon to evening hours as a result of thunderstorms. Snow and freezing precipitation show an increase in observations for DJF from 7:00 to 8:00. Thunderstorms occur most frequently in JJA and occur from noon to after midnight. Fog occurs most often in DJF and peaks at 6:00. Mist occurs most often during DJF and relatively constant from midnight to 6:00. Haze also occurs most frequently for DJF and peaks at 13:00.

Figure 6.A.36 displays the patterns of weather, wind, ceiling, and visibility impacts for SLC. Overall, DJF has the worst impacts from weather, ceiling, and visibility impacts. DJF minor weather impacts peak at 13:00, DJF moderate weather impacts peak at 14:00, and DJF severe weather impacts peak at 7:00. JJA severe weather impacts display a noticeable increase in the afternoon hours as a result of thunderstorms and heavy rain. Minor, moderate, and severe wind impacts peak from noon to 18:00 for almost all seasons. Ceiling and visibility impacts are greatest for DJF and peak most often prior to noon.

6.A.7 Seattle - Tacoma (SEA) International Airport Weather Climatology

6.A.7.1 Monthly Weather

SEA northerly location on the Pacific Coast gives it a relatively moderate and wet climate. In order to eliminate the need to repeat already explained or obvious trends in the METAR data, only important trends will be discussed. Figure 6.A.37 displays the average density altitude for SEA. Due to the moderate climate and low elevation, density altitude is not an important weather related factor to SEA. Visibility and ceiling heights are lowest in the cool season months meaning that IFR conditions are most likely to be expected during the cool season months.

Figure 6.A.38 displays the monthly average number of weather occurrences for SEA. Rain and drizzle are least likely to occur in the warm season months leading to dry summers. Overall thunderstorm is very low for SEA; however most thunderstorms occur from June to September. It is easy to deduce that thunderstorms are not important annual delay cause based on their relatively small appearance. Snow, ice pellet, and freezing precipitation observations are also lower than some other northern airports. Fog and mist are most likely to occur from October to January. Haze has a relatively low occurrence but is least likely to occur in December and February through June. Overall, SEA is most likely to be impacted by weather observations in the winter months. Figure 6.A.39 displays the occurrences for weather, wind, ceiling, and visibility impacts. Overall, impacts from all categories are most likely to occur in the cool season months. However, the magnitudes of these averages are lower than what was observed at other airport previously analyzed.

6.A.7.2 Seasonal, Diurnal Weather

Figure 6.A.40 displays the seasonal, diurnal patterns for select observations for SEA. All of the patterns display what is to be expected based on what was observed at other airports. It is

worthwhile to note thought that the patterns for IFR observations are relatively consistent between all seasons suggesting that IFR conditions are commonly observed throughout the year. Figure 6.A.41 displays the seasonal, diurnal weather patterns for SEA. Drizzle is least likely to occur during the midday hours for all seasons. Thunderstorm activity peaks between noon to midnight for all seasons. One distinct pattern is seen for DJF freezing precipitation. Freezing precipitation peaks in the nighttime hours and clearly decreases during the daytime hours. Fog and mist observations are highest for DJF and SON and are most likely to occur near sunrise. Haze occurs most often for SON and peaks during daytime hours. Figure 6.A.42 displays the seasonal, diurnal patterns for weather, wind, ceiling, and visibility impacts. Not much is to be explained that can't be easily seen from the previous plots and explanations. It is important to note that DJF suffers from the highest impacts of all weather categories and types.

6.A.8 San Francisco (SFO) International Airport Weather Climatology

6.A.8.1 Monthly Weather

San Francisco's local climate is modulated by the varying topography and the cool waters of the Pacific Ocean and San Francisco Bay. Summertime in San Francisco is characterized by cool marine air and persistent coastal stratus clouds and fog (Null, 1995). Spring and fall are usually characterized by clearer weather and fewer cloudy days (Null, 1995). Wintertime sees cool temperatures with occasional radiation fog that is thicker but less frequent than what is seen in the summertime (Null, 1995). Most rainfall occurs between November and March and both snow and thunderstorms are rare occurrences (Null, 1995).

Looking at Figure 6.A.43, it can be clearly seen that density altitude is not an issue for SFO as a result of cool temperatures and low elevation. Wind speed is highest for May.

Visibility is lowest in the winter months while ceiling height is lowest in the summer months. IFR observations are most common in July and August and in December and January. This observation is plausible and validated by the NWS San Francisco climate narrative. Figure 6.A.44 paints a very boring narrative of the monthly weather at SFO. Rain observations are most commonly observed in the cool season months. Drizzle, thunderstorms, snow, ice pellets, and freezing precipitation are uncommon events that most likely have little impact on the delay and cancellation climatology of SFO. Fog observations are most common in the summer months of July and August. Both mist and haze are most common in January and February. Obscuration counts are most frequent in January and December. Figure 6.A.45 displays the average observations for weather, wind, ceiling height, and visibility severity impacts. Overall, cool winter months (especially January and December) see the highest impacts. Based on the three figures, winter months are most likely to be impacted by weather.

6.A.8.2 Seasonal, Diurnal Weather

Figure 6.A.46 shows the average seasonal, diurnal patterns for SFO for visibility, ceiling and IFR observations. Visibility and ceiling heights and are lowest and IFR observations prior are highest to sunrise or during the nighttime hours. Wind and gust speeds peak in the afternoon to late afternoon range. Figure 6.A.47 displays the hourly, seasonal observations of weather phenomena at SFO. Fog observations are lowest during the afternoon hours. Mist observations are highest in the morning hours whereas haze is highest during the mid-morning to mid-afternoon hours. Figure 6.A.48 displays the diurnal patterns for weather, wind, ceiling height, and visibility impacts. Overall, most impacts occur in the early hours until or after sunrise and are worse for DJF.

6.A.9 Phoenix Sky Harbor (PHX) International Airport Weather Climatology

6.A.9.1 Monthly Weather

Phoenix's location within the Sonoran Desert provides a mostly hot and dry climate. During the summer months, intense solar heating over the dessert southwest creates an area of low pressure of the region thereby changing the wind patterns and bringing moisture to the area. This summertime phenomena is referred sometimes as the "North American Monsoon" (National Weather Service). It is important to note that this creates an increase in moisture, precipitation, and thunderstorms for the region. In addition to increased rain and thunderstorms, dust storms can also occur. Besides the North American Monsoon, large seasonal and daily temperature fluctuations make Phoenix's climate present numerous challenges for aviation.

Figure 6.A.49 displays the average monthly temperature pattern for PHX. High temperatures in the summer months result in high density altitudes despite the lower field elevation resulting in performance issues for aircraft. High temperatures are also likely to impact the health and safety of workers working outside. The increase in dew point and relative humidity is due to the influx of moisture as a result of the North American Monsoon. Visibility shows a decrease in both July and in January and December as result of higher relative humidities. This is reflected in the average number of IFR hours observed. Ceiling shows a decrease in winter months as a result of less solar insolation and another decrease starting in July as a likely result of the North American Monsoon. Figure 6.A.50 shows the increase in thunderstorms and precipitation starting July further aiding the idea of the North American Monsoon. Higher amounts of rain are also seen from December to March. Obscuring phenomena are rare at PHX. However, most obscuring phenomena occur in December and January and again in July and August. Figure 6.A.51 depicts the average monthly weather,

wind, ceiling, and visibility severity impacts. Overall minor, moderate, and severe impacts are low for PHX. However, most impacts occur in either the winter months or the times that coincide with the North American Monsoon.

6.A.9.2 Seasonal, Diurnal Weather

Figure 6.A.52, Figure 6.A.53, and Figure 6.A.54 all displays different aspects of the seasonal, diurnal weather of PHX. Looking at JJA in all three figures, the impacts of the nighttime monsoon thunderstorms can be seen in numerous plots from rain to haze to visibility. Interactions from the mountainous terrain create thunderstorms in the high mountains during the afternoon; as these thunderstorms decay and cool the mid-level environment, cool air descends into the Phoenix area destabilizing the local environment and create the nocturnal thunderstorms. Hourly observations for other season show the typical and expected patterns for PHX and relatively low frequency in which they occur likely mean that weather outside of JJA has major impacts on PHX. However, obscuring phenomena, low visibility, and low ceiling heights could create problems for PHX in the early part of the day.

6.A.10 Miami (MIA) International Airport Weather Climatology

6.A.10.1 Monthly and Seasonal, Diurnal Weather

Miami's southerly location and proximity to the warm waters of the Atlantic Ocean provides a warm climate with few hazards (outside of hurricanes). Figure 6.A.55, Figure 6.A.56, and Figure 6.A.57 all display monthly averages for METAR variables and weather phenomena counts. IFR observations are low and peak in January. Thunderstorm and rain observations peak in the summer months starting in June and decreasing steadily until September. Obscuring

phenomena are have low chances of occurrence throughout the year but fog and mist are most likely to occur in the winter months. Weather impacts occur throughout the year with most severe weather impacts occurring in from June to September. Moderate and severe wind impacts occur most often in the fall months and coincide with the peaks in hurricane season. Severe and moderate ceiling impacts occur most often in the cool season months and visibility impacts can occur year round. Density altitude is not an issue for MIA due to its low elevation and moderate temperatures.

Figure 6.A.58, Figure 6.A.59, and Figure 6.A.60 all display the seasonal, diurnal patterns for MIA. Nothing shocking unexpected is observed. It is important to note that the peak in thunderstorms coincides with the warming of the environmental temperature and that nocturnal thunderstorms do not appear to be a common phenomenon. Also increases in rain coincide with the increases in thunderstorms.

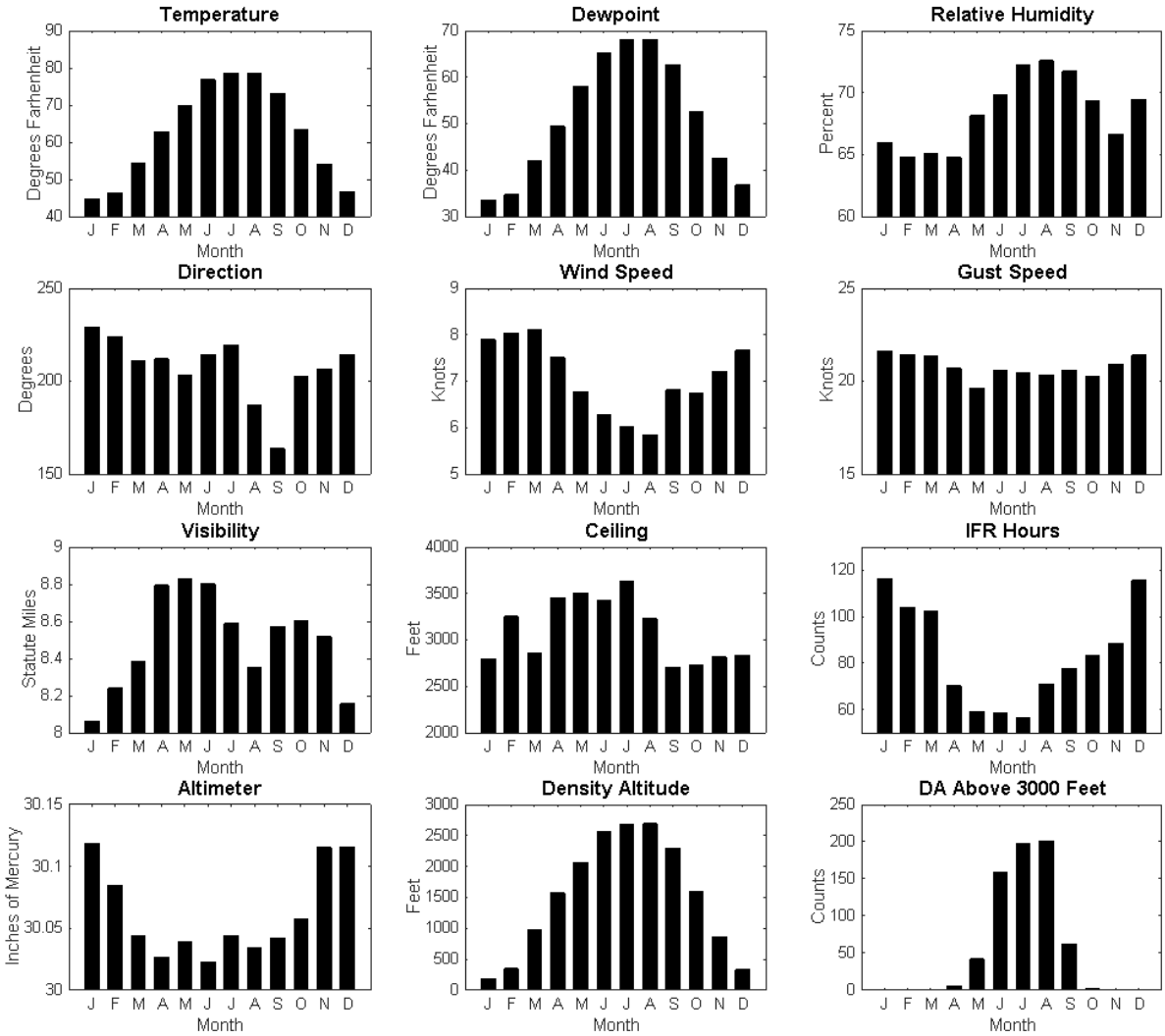


Figure 6.A.1. ATL monthly averages for METAR and derived values.

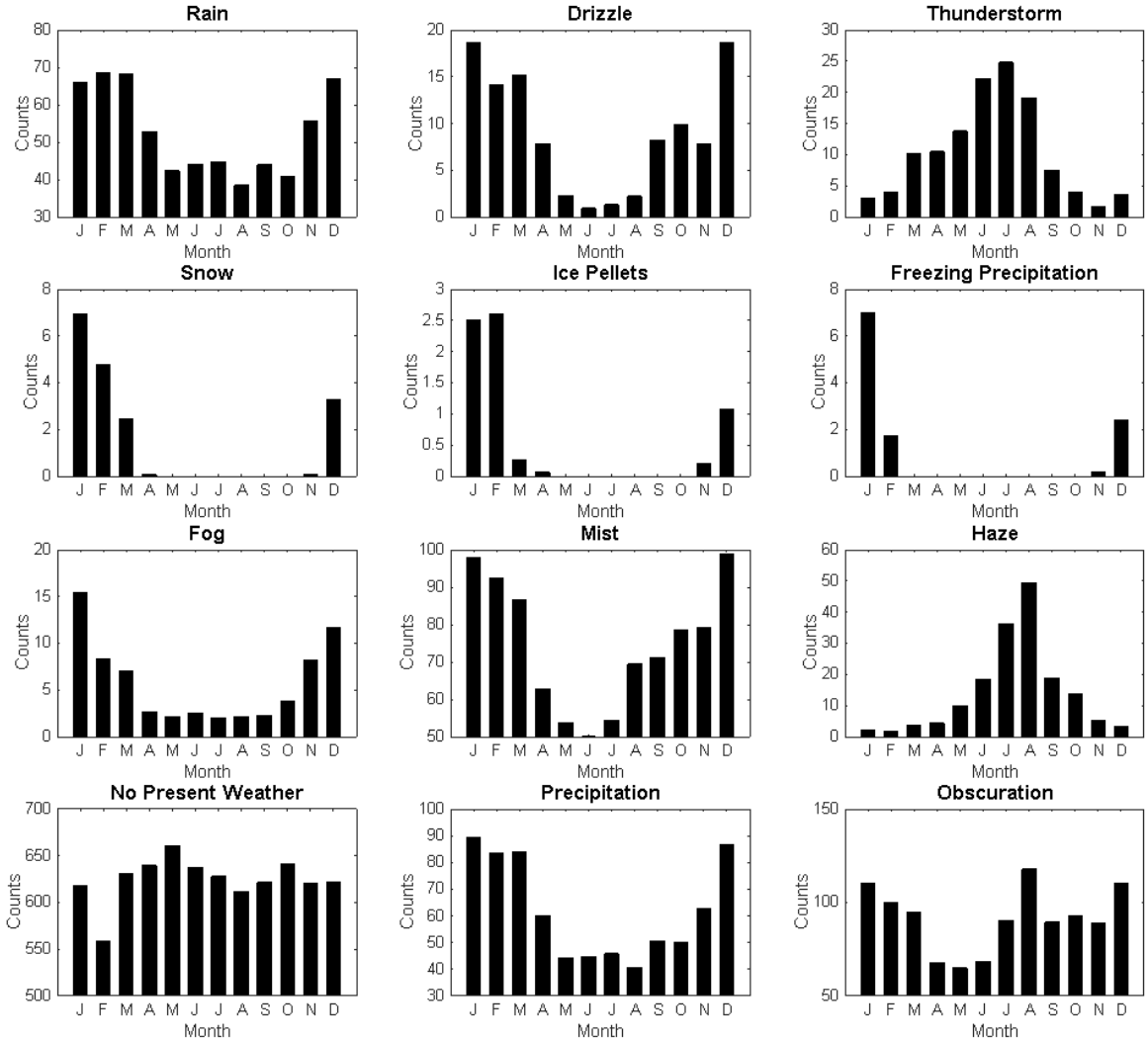


Figure 6.A.2. ATL monthly average counts for observed weather phenomena.

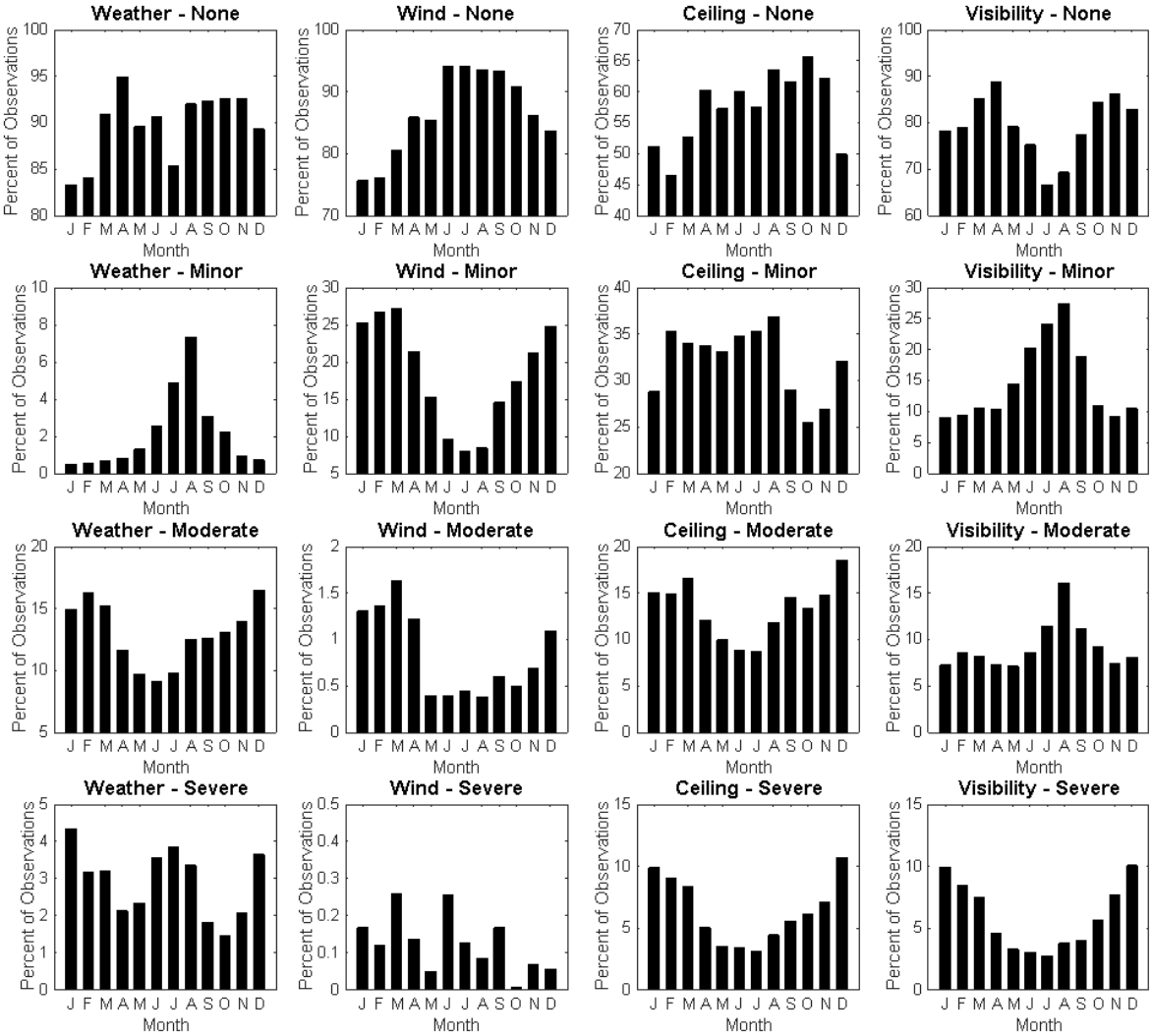


Figure 6.A.3. ATL monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

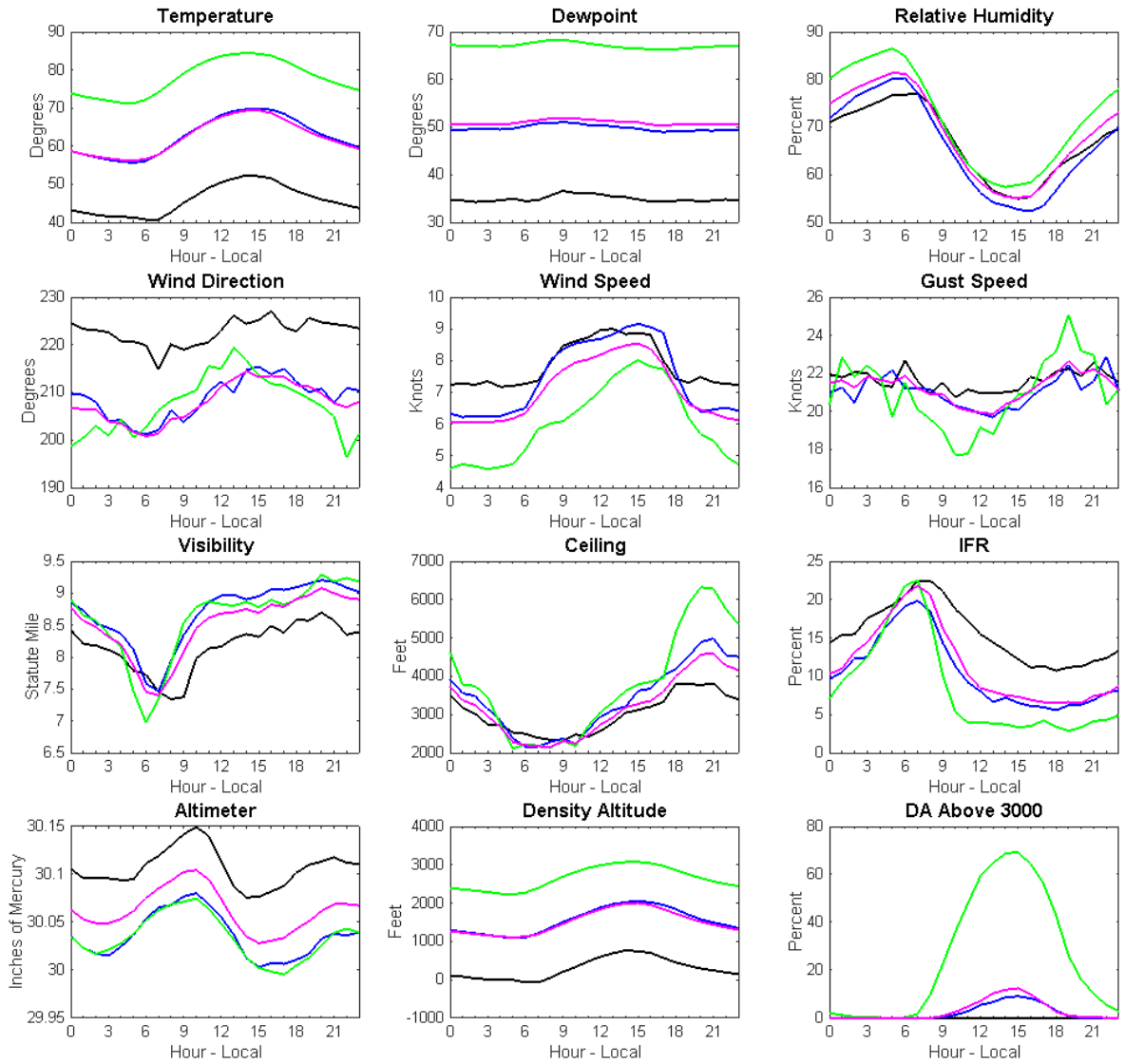


Figure 6.A.4. ATL diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

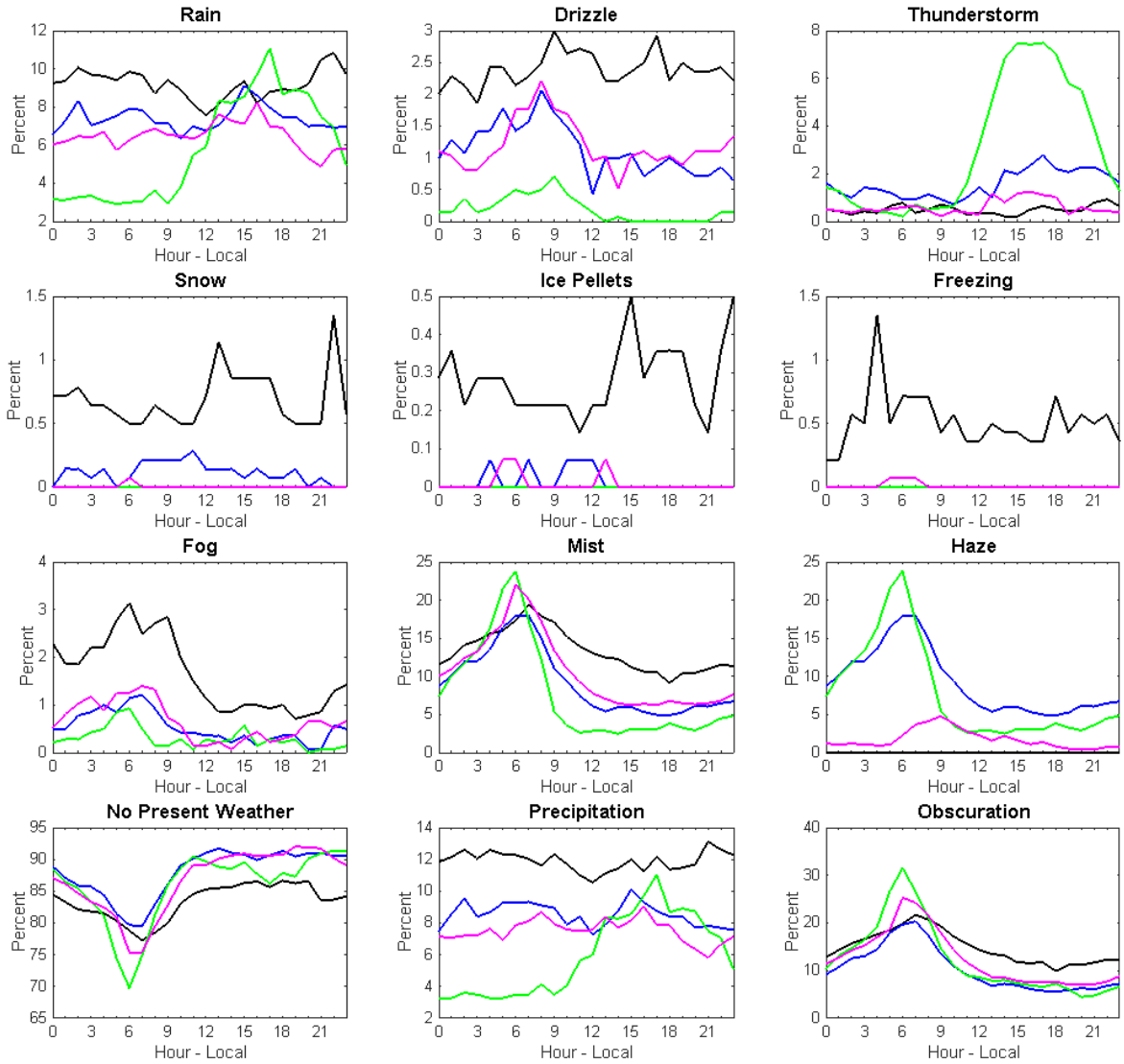


Figure 6.A.5. ATL seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

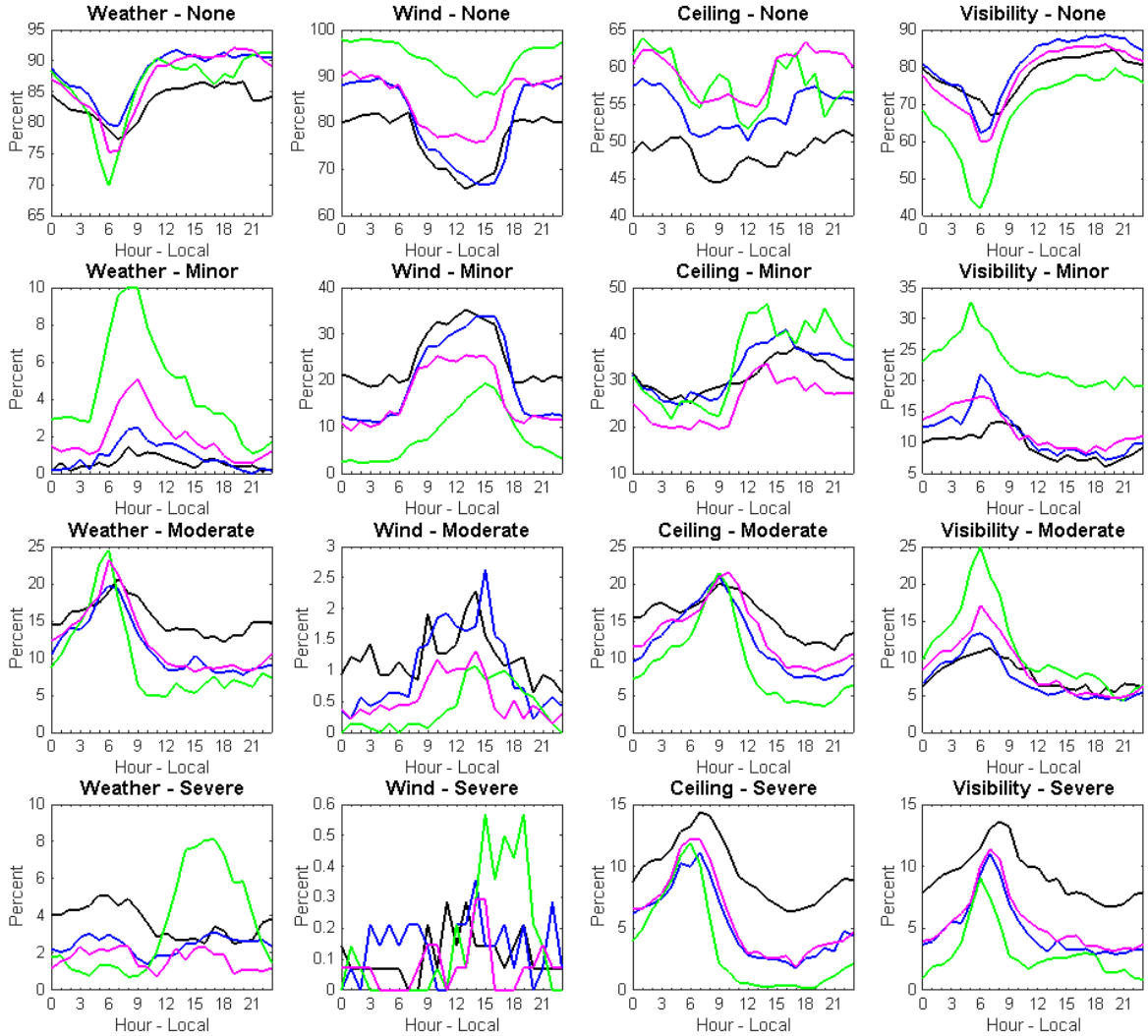


Figure 6.A.6. ATL seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

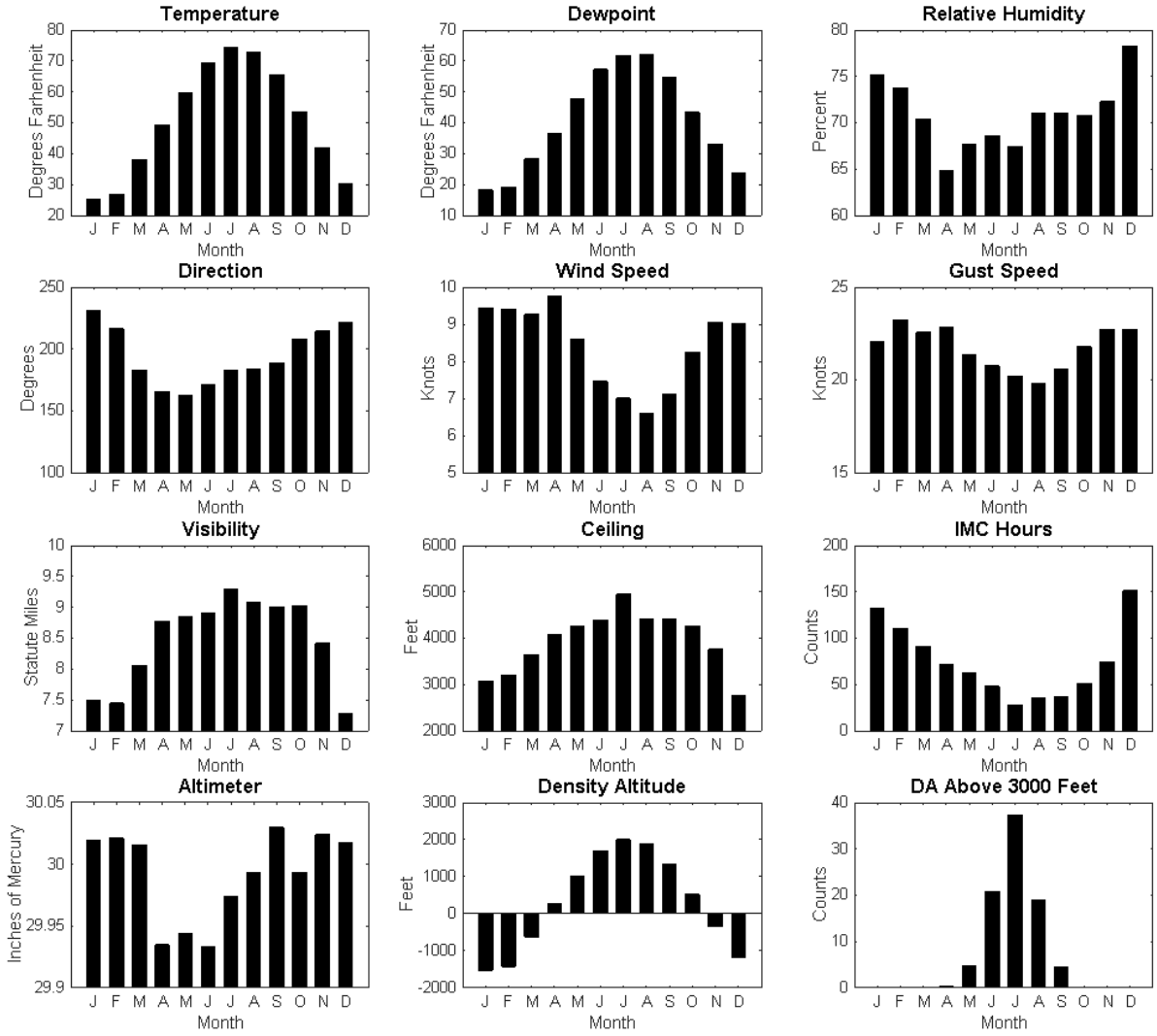


Figure 6.A.7. ATL monthly averages for METAR and derived values.

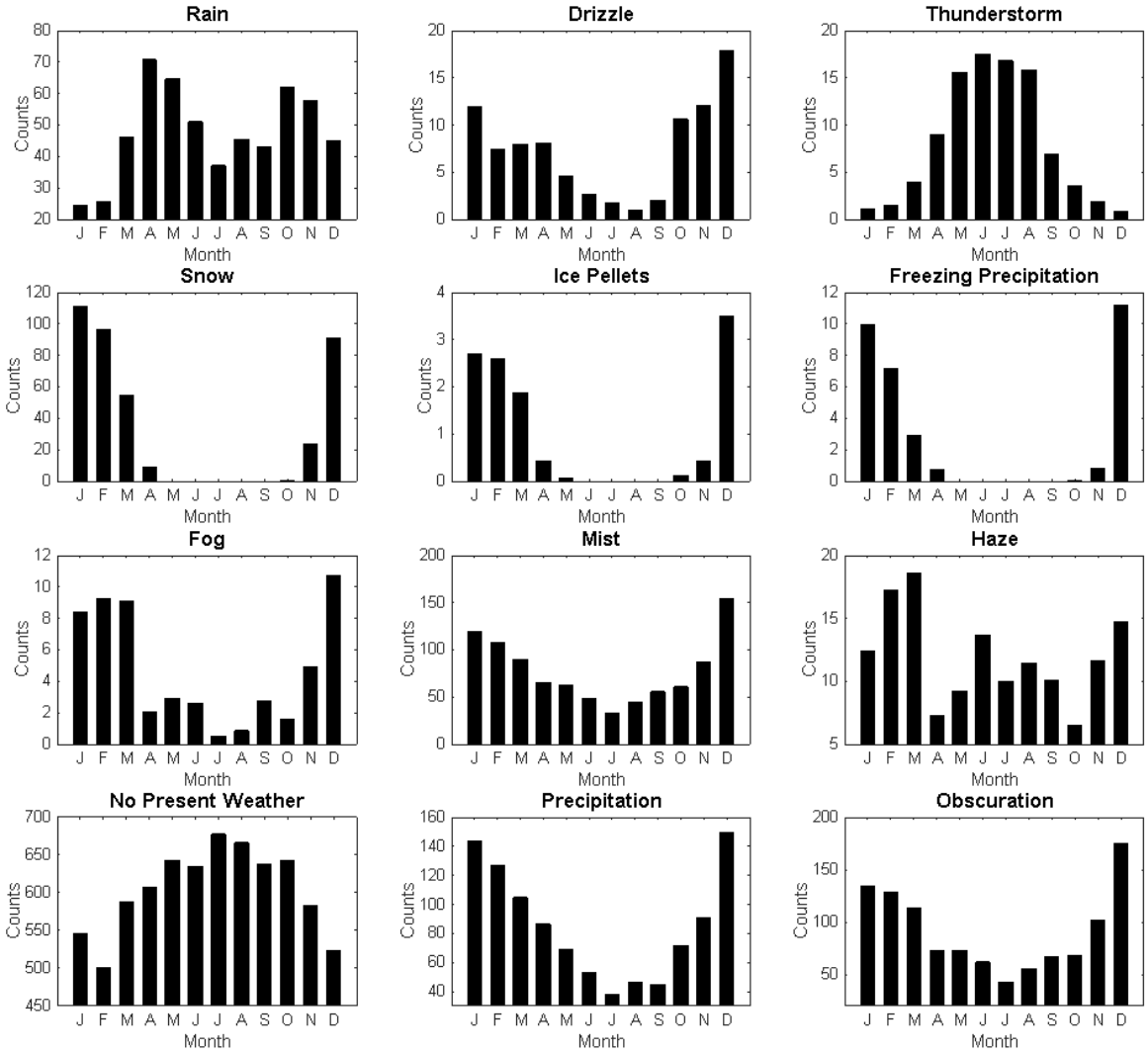


Figure 6.A.8. ORD monthly average counts for observed weather phenomena.

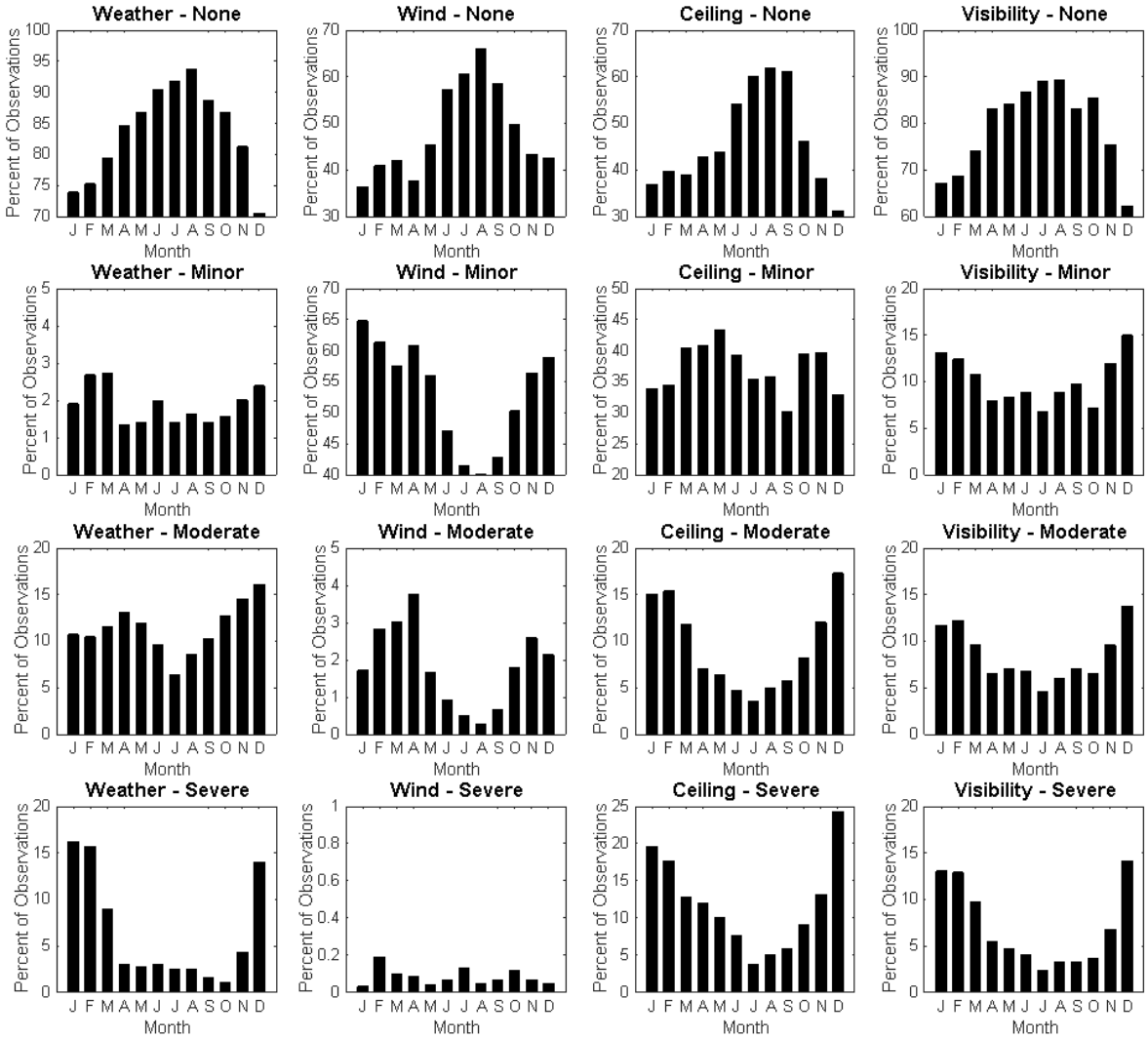


Figure 6.A.9. ORD monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

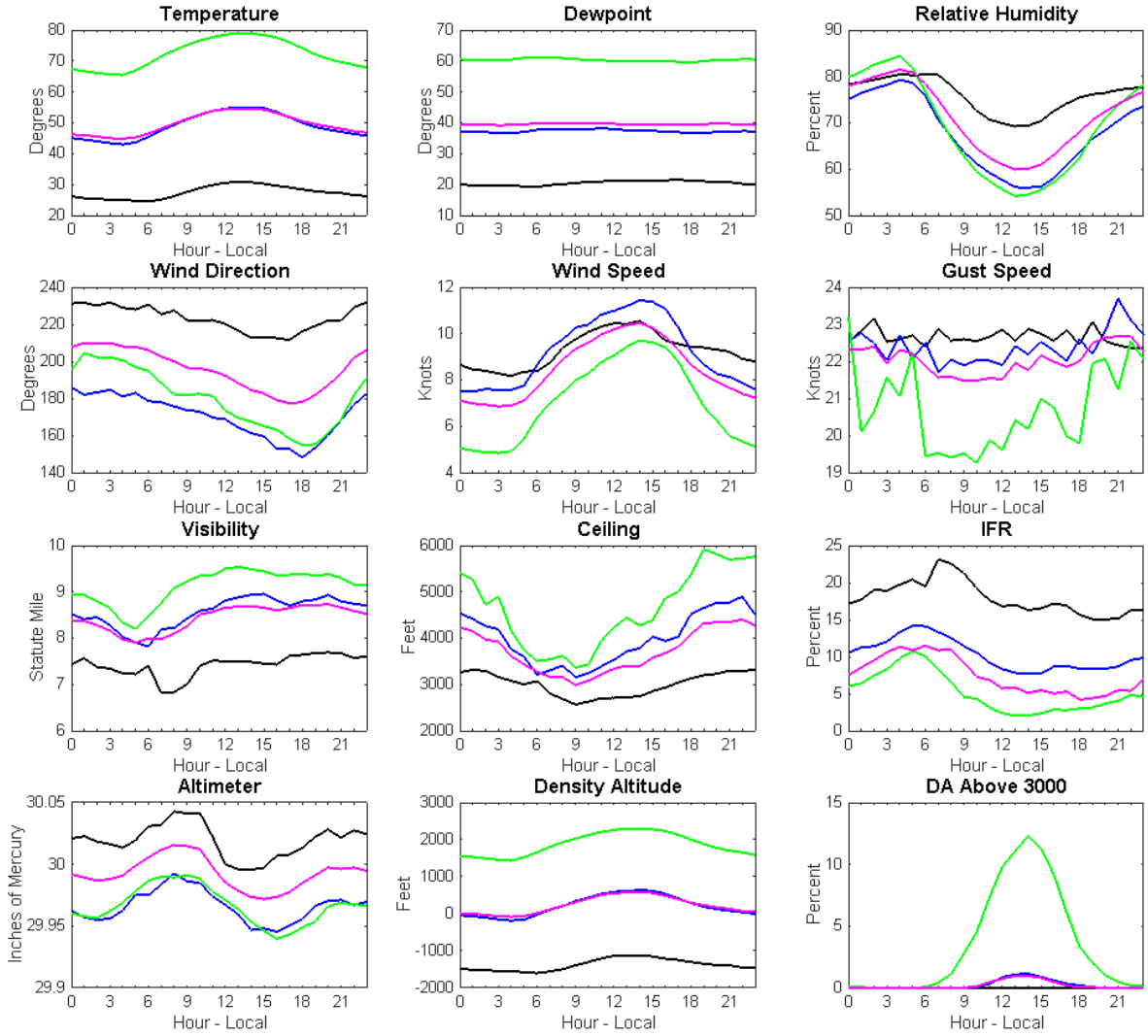


Figure 6.A.10. ORD diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

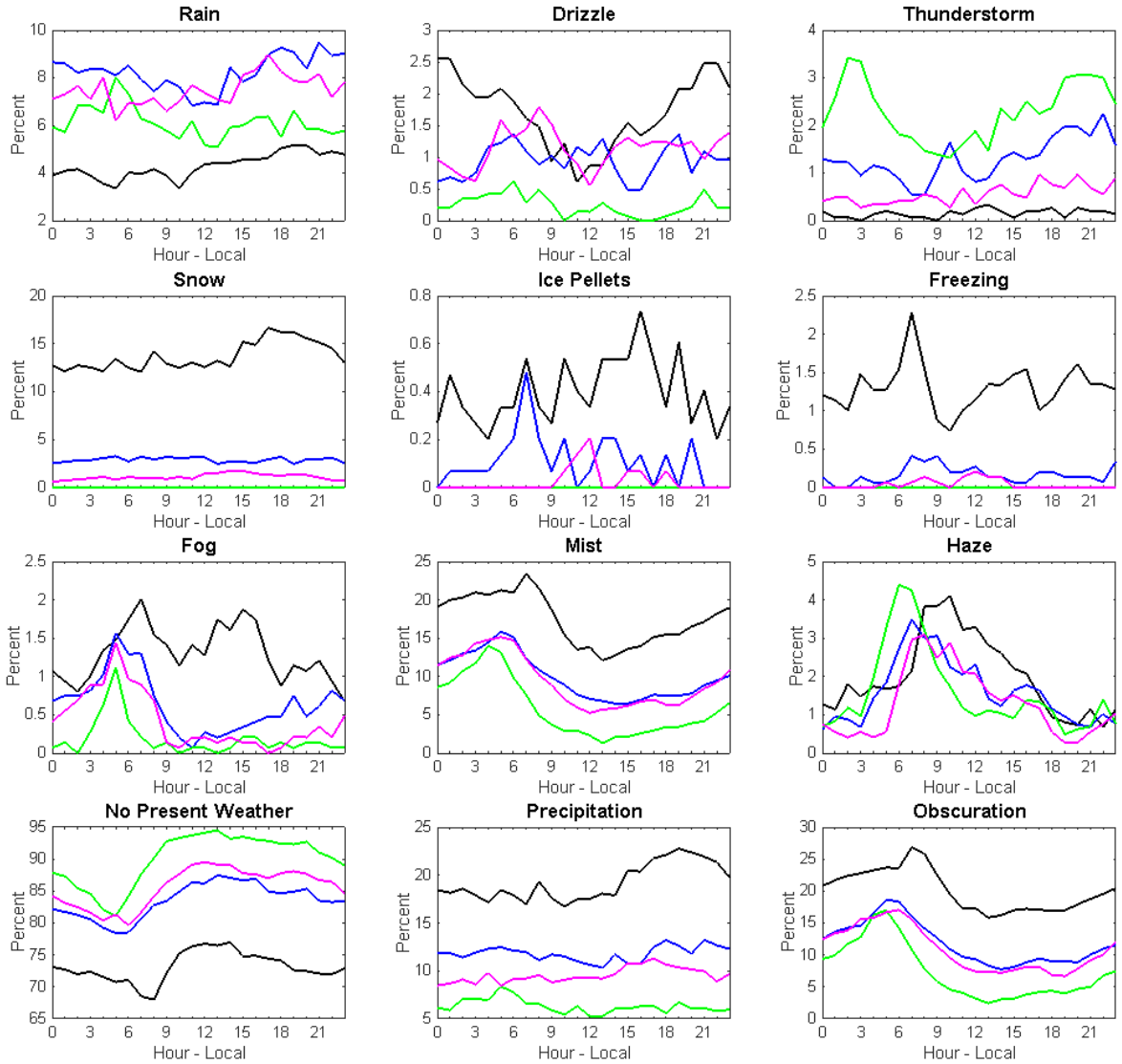


Figure 6.A.11. ORD seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

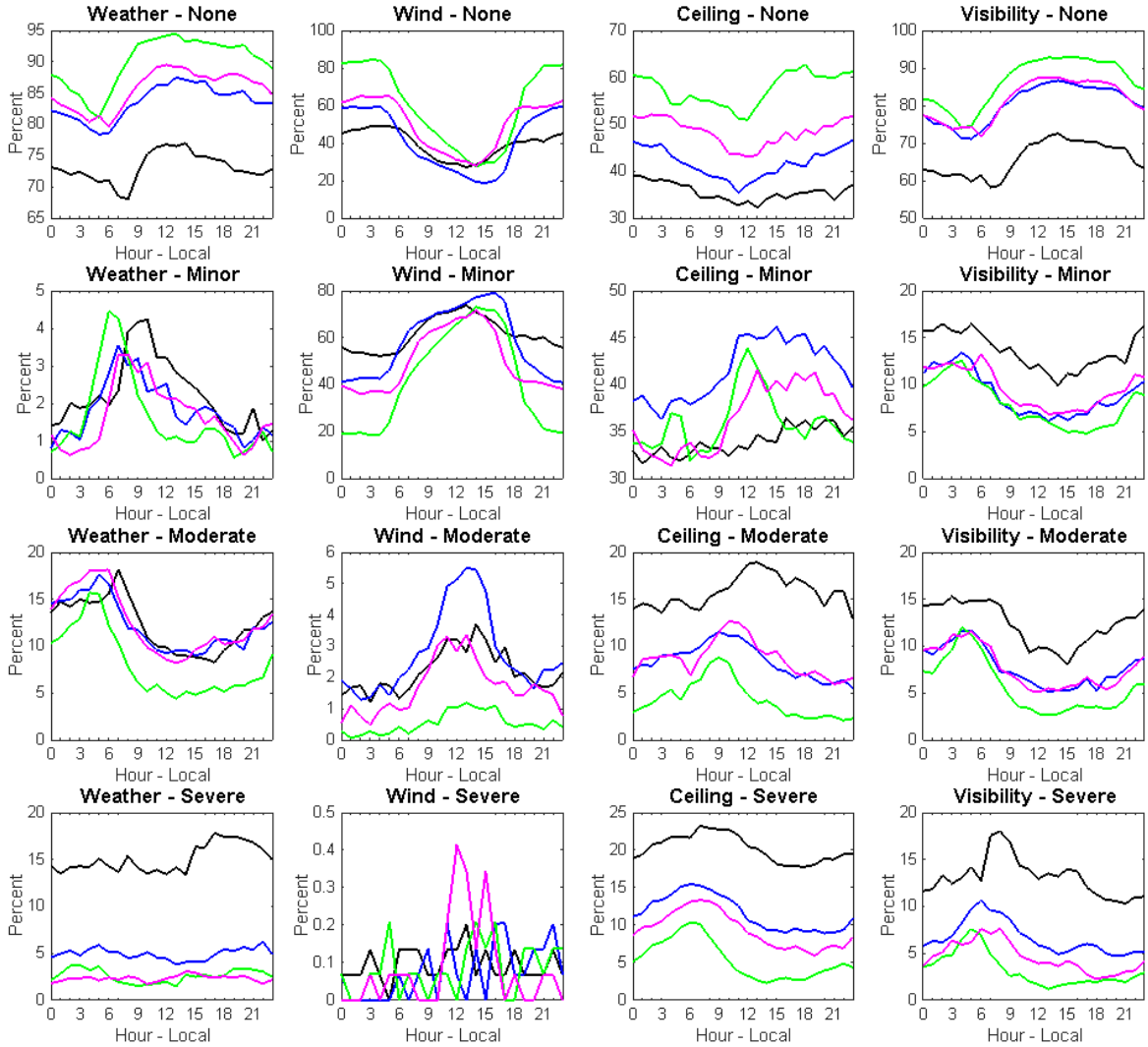


Figure 6.A.12. ORD seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

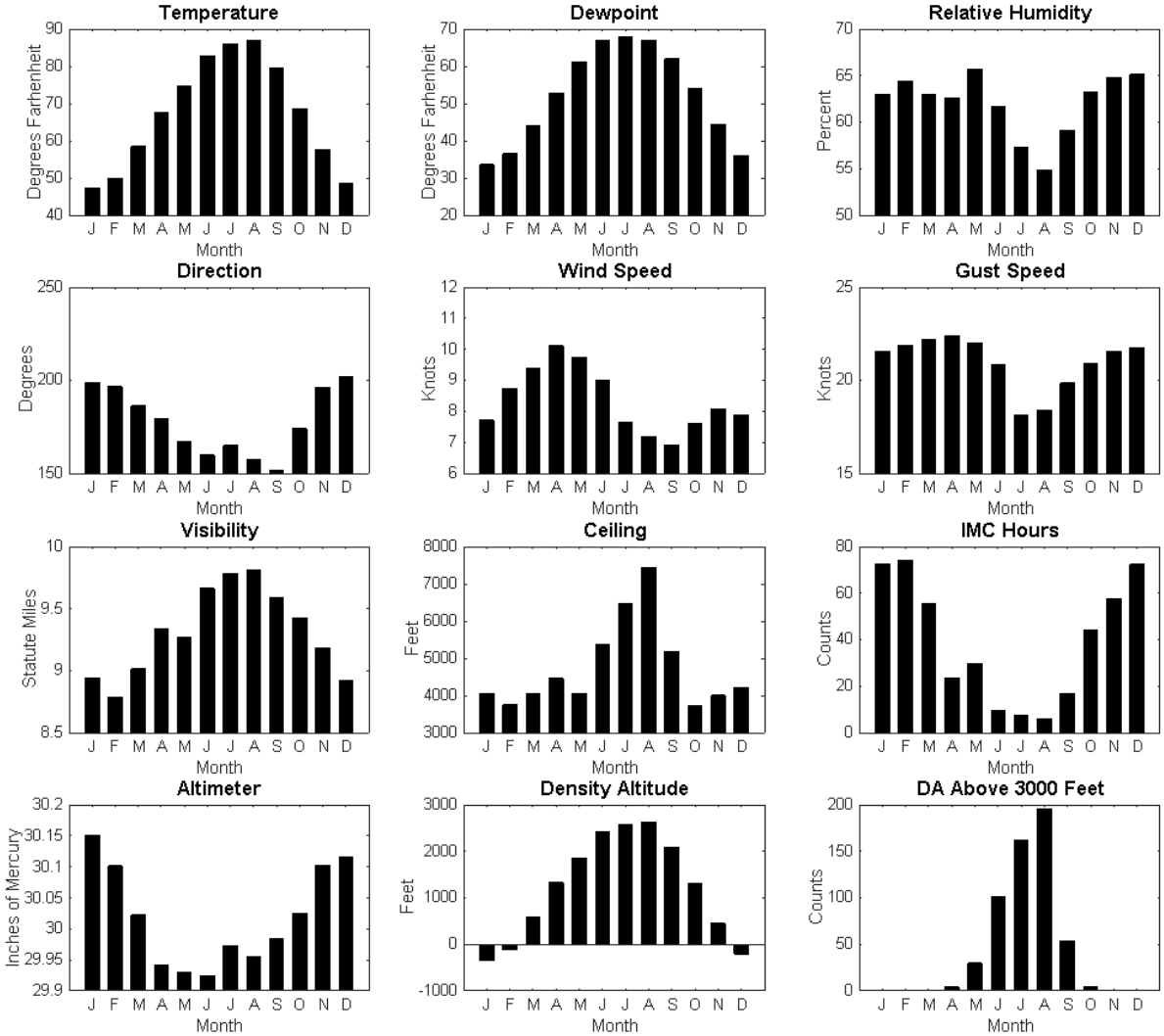


Figure 6.A.13. DAL monthly averages for METAR and derived values.

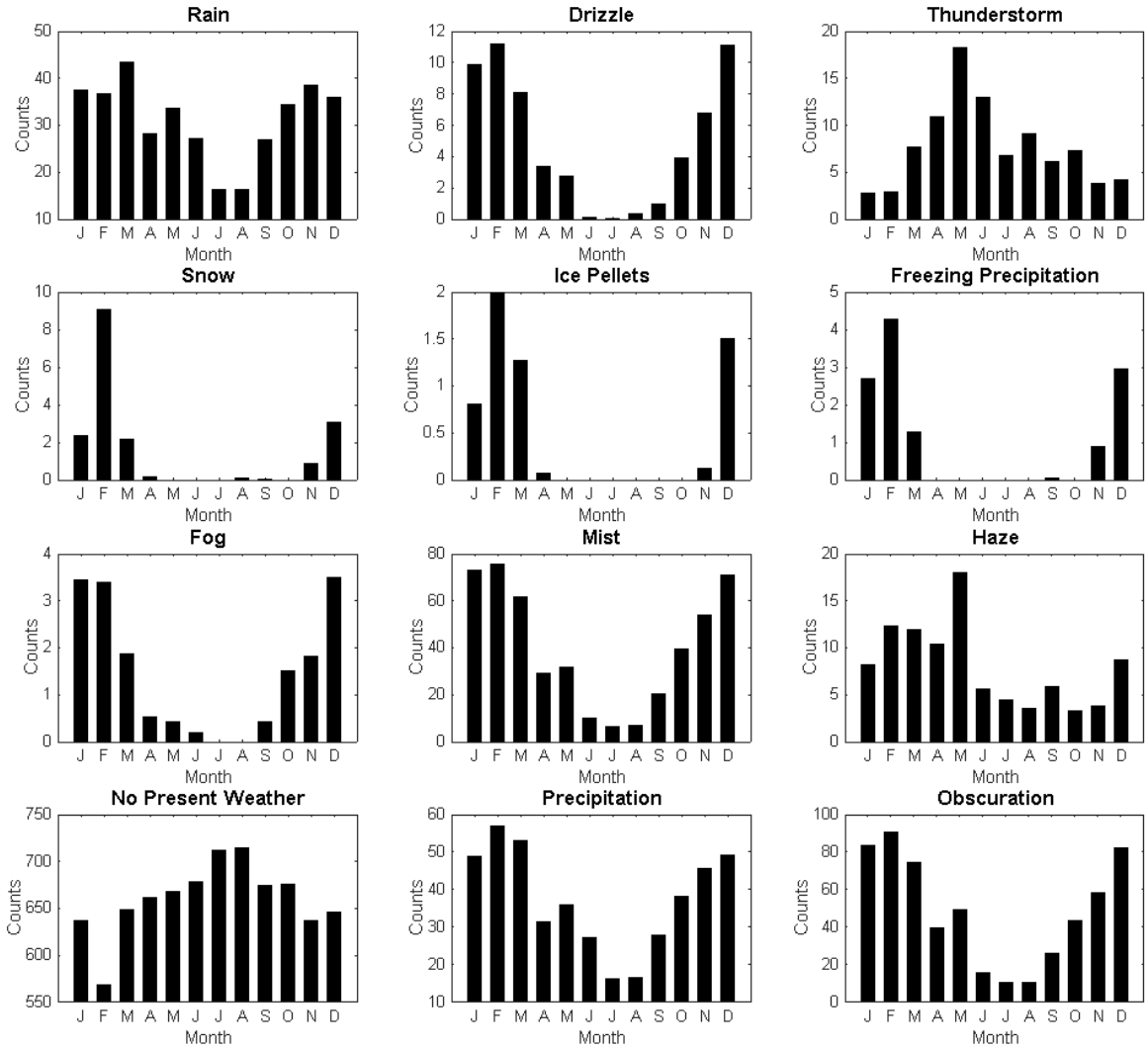


Figure 6.A.14. DAL monthly average counts for observed weather phenomena.

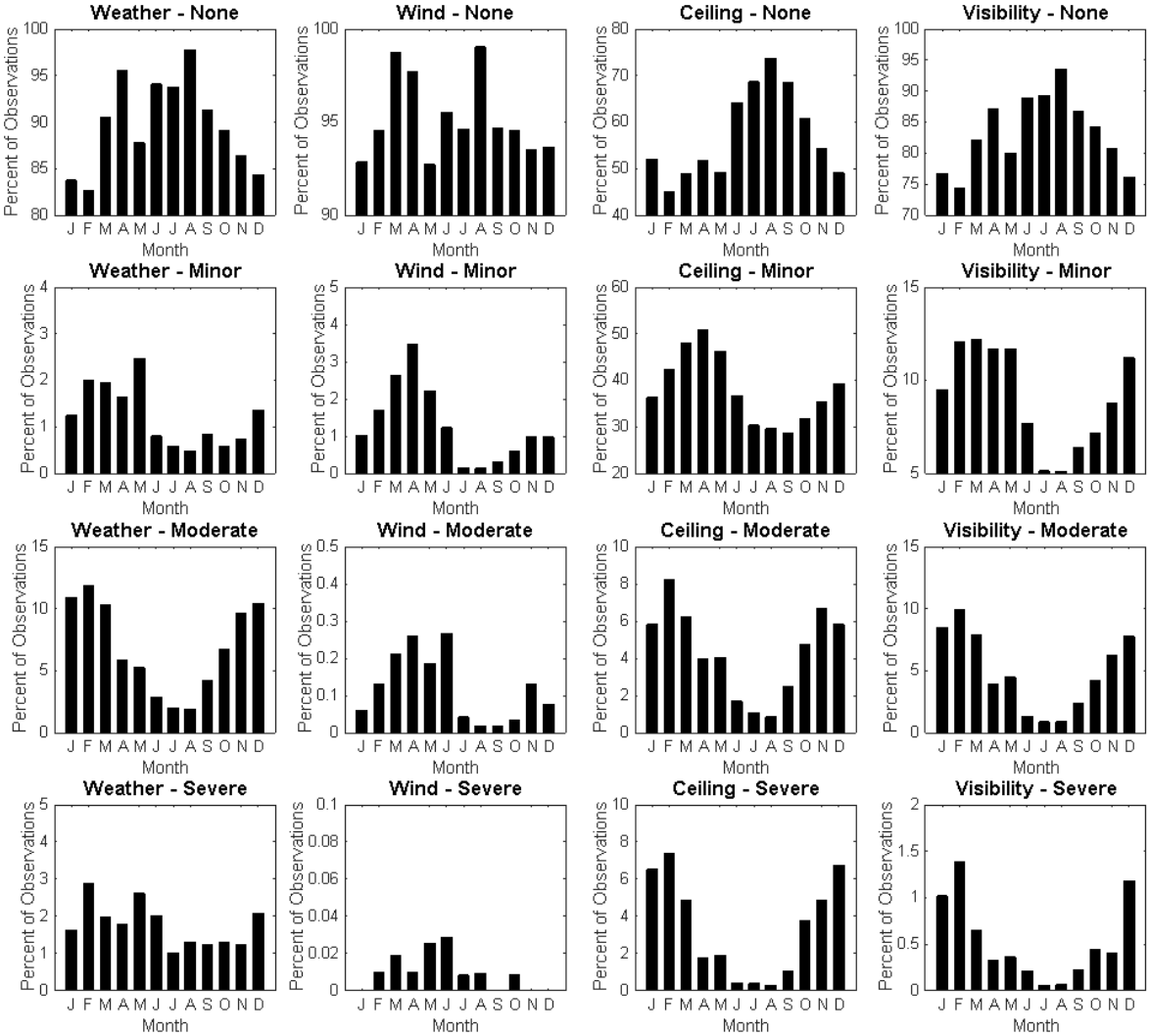


Figure 6.A.15. DAL monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

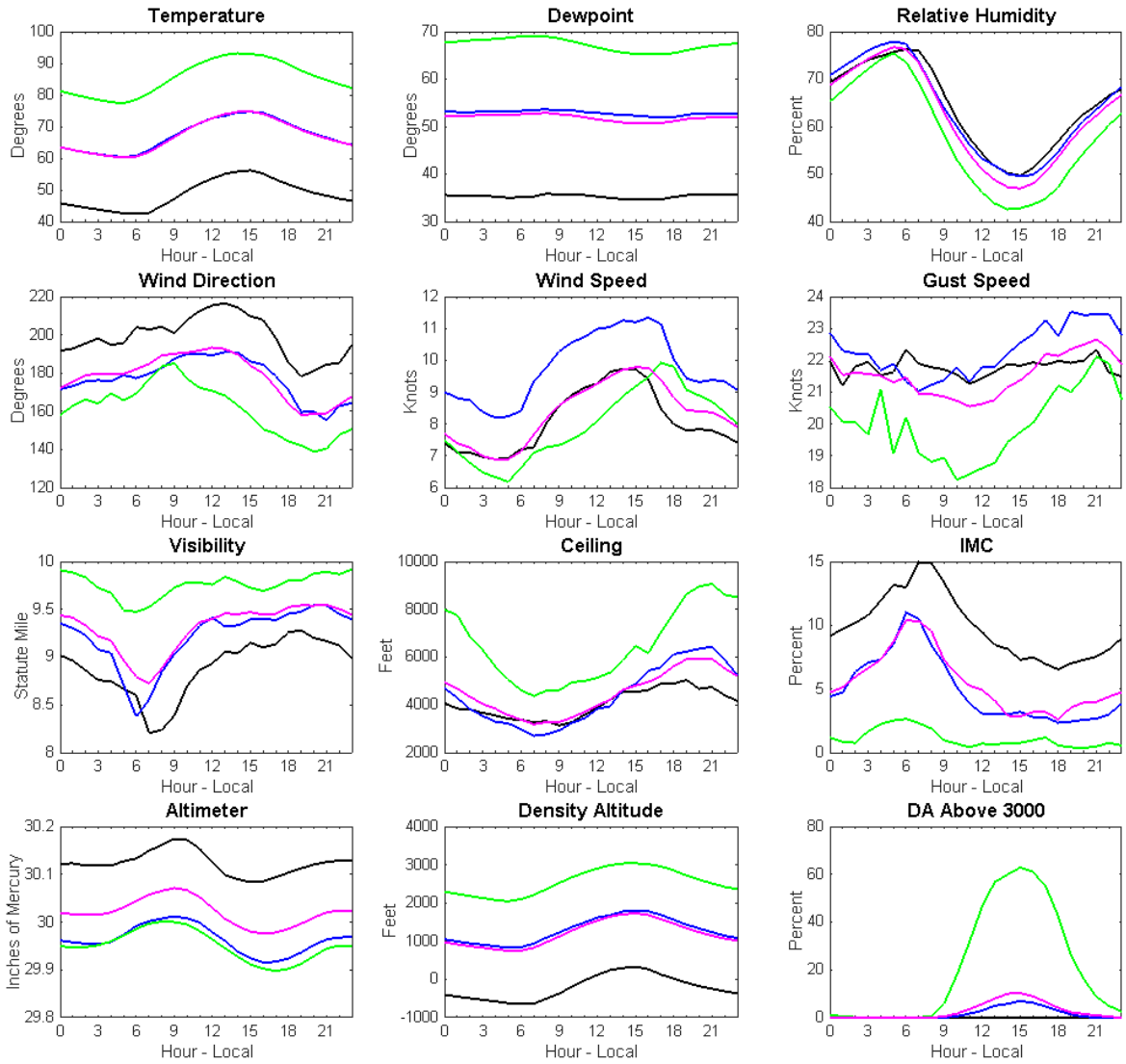


Figure 6.A.16. DAL diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

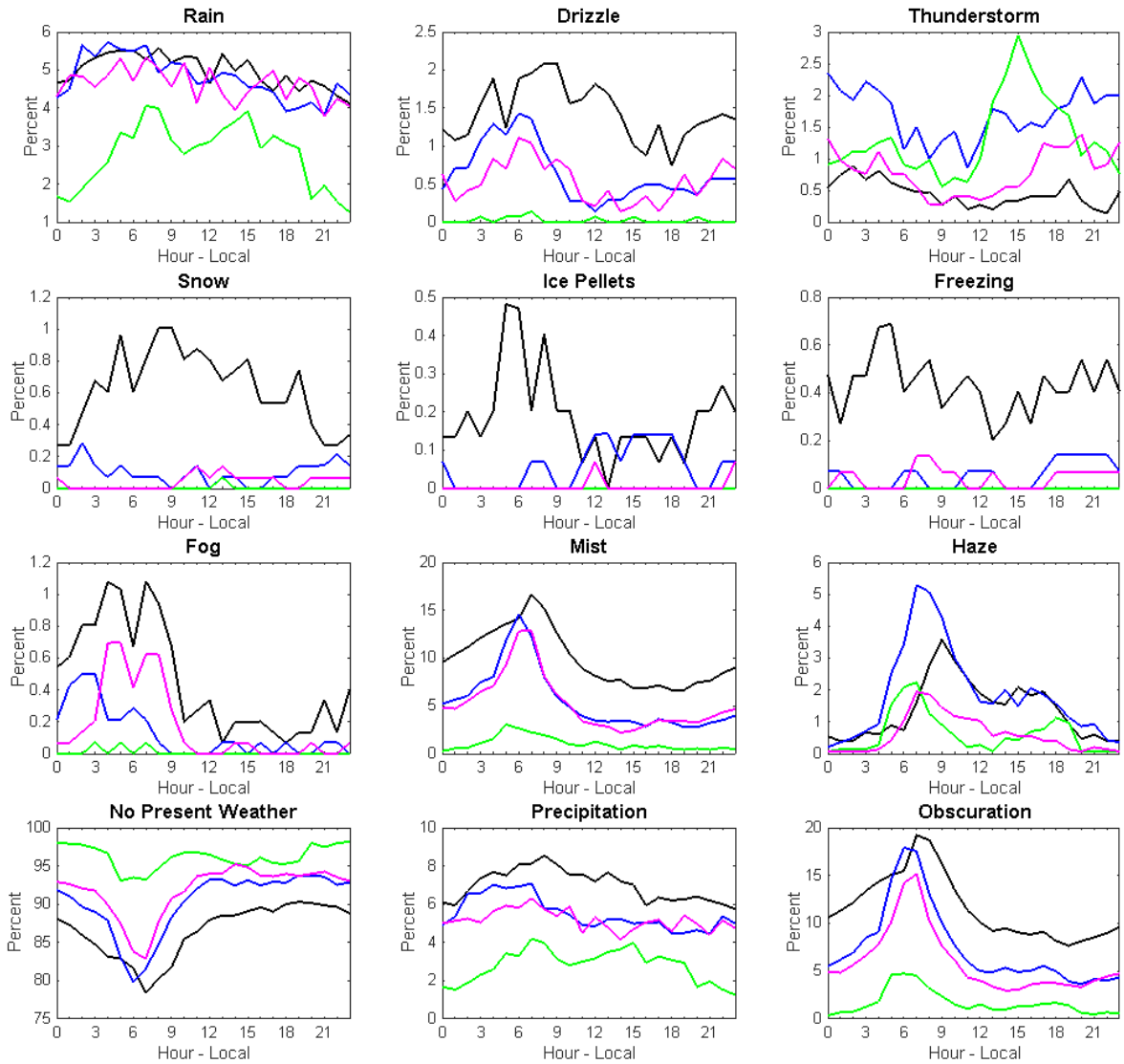


Figure 6.A.17. DAL seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

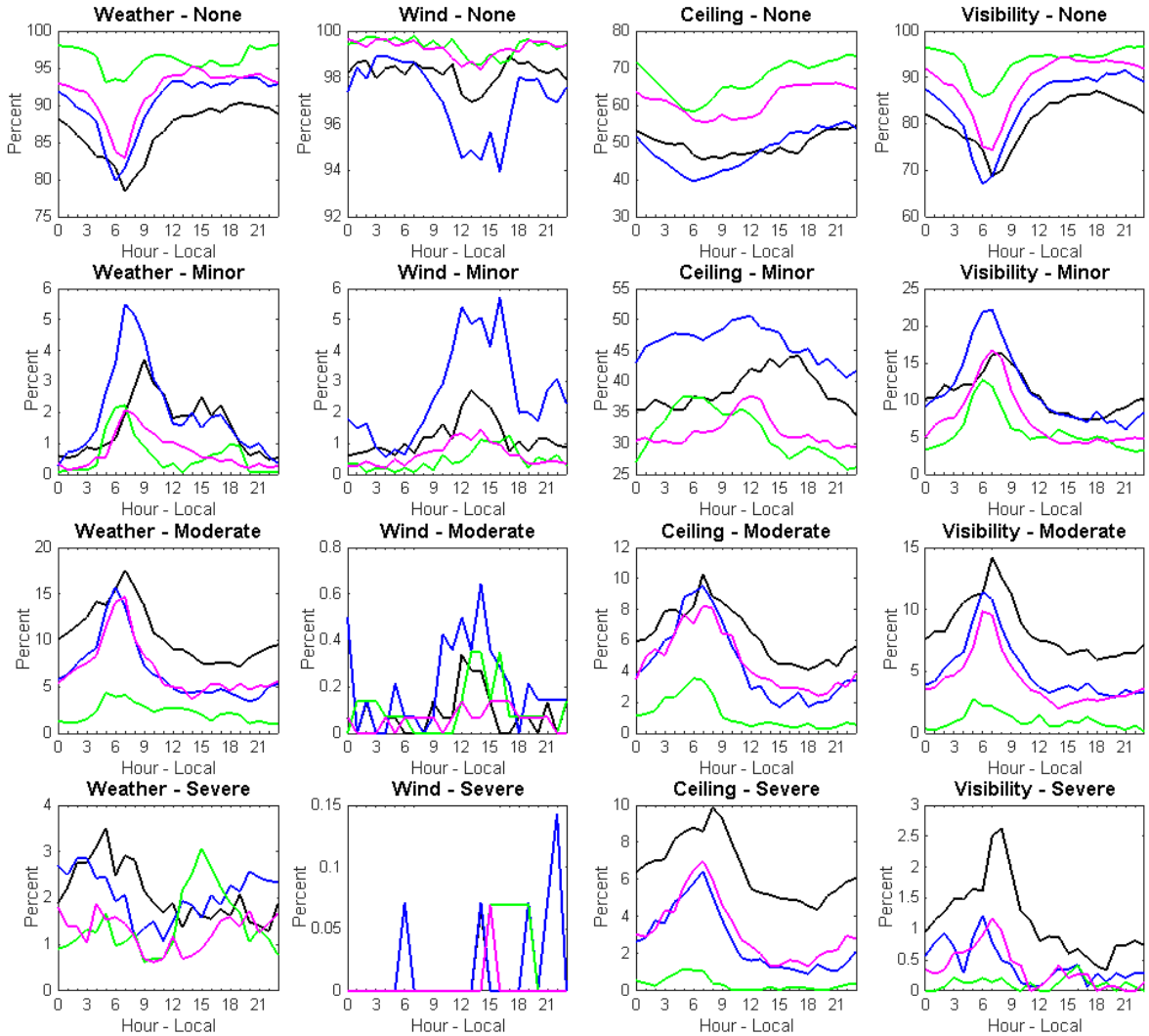


Figure 6.A.18. DAL seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

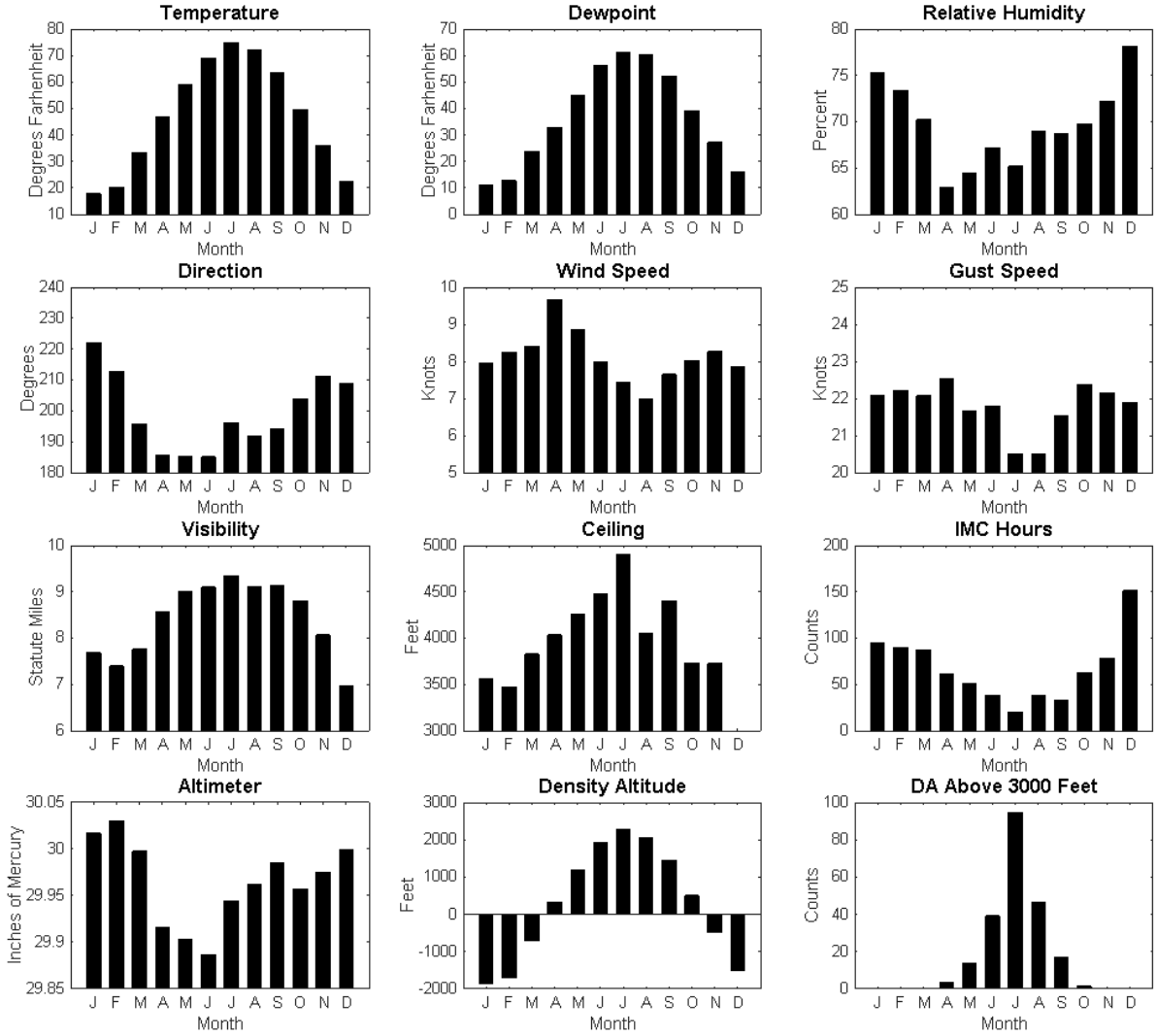


Figure 6.A.19. MSP monthly averages for METAR and derived values.

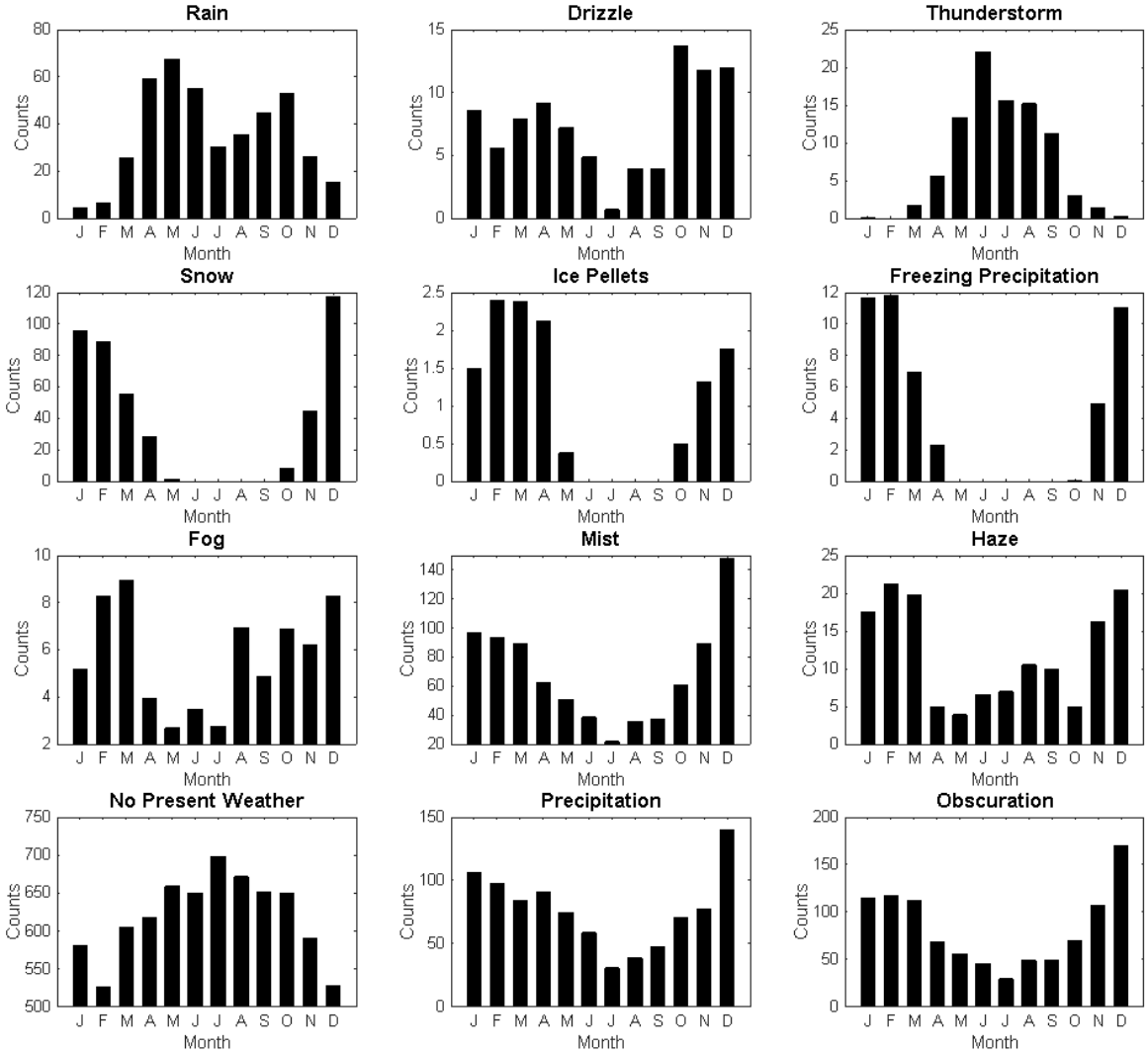


Figure 6.A.20. MSP monthly average counts for observed weather phenomena.

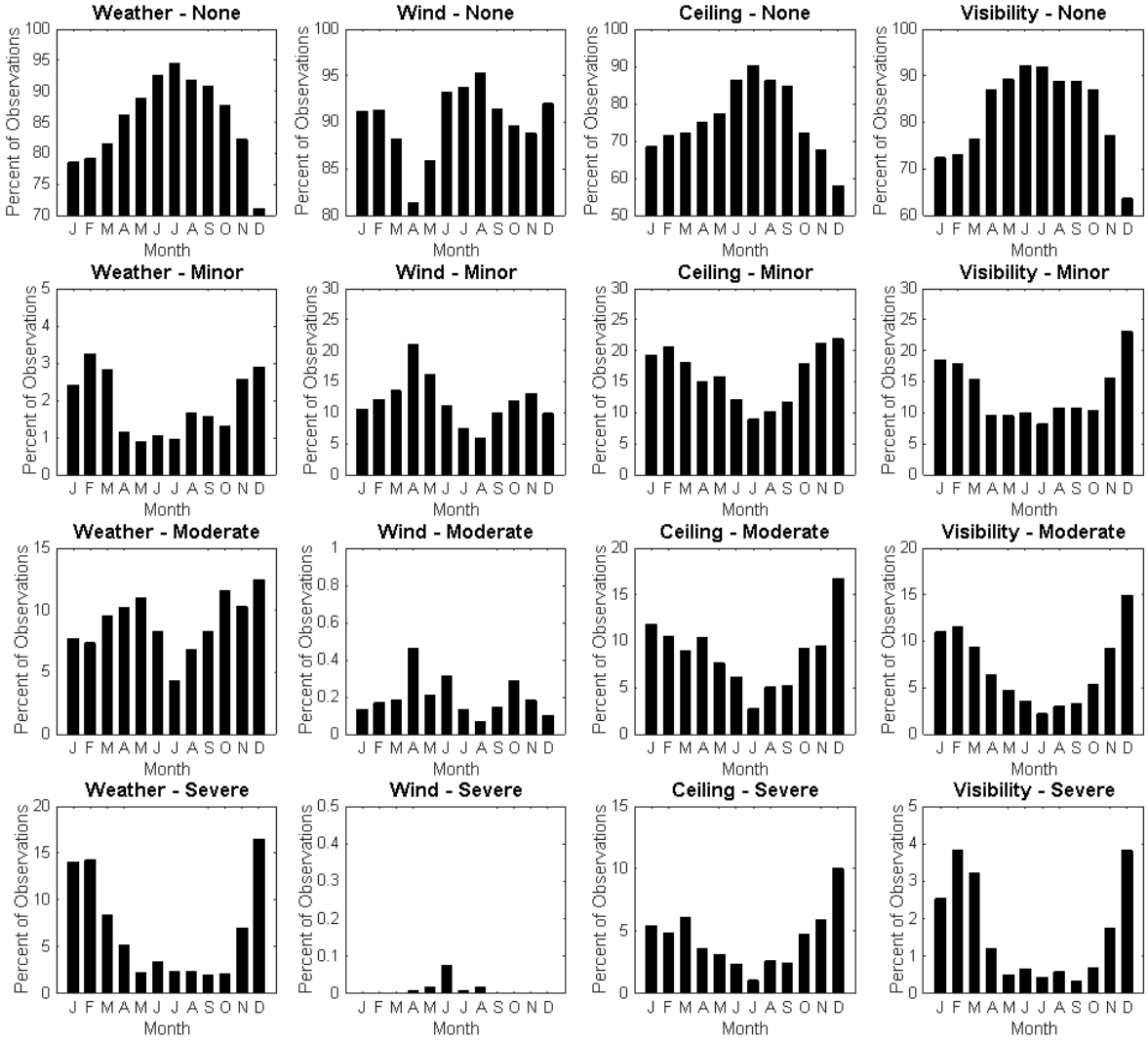


Figure 6.A.21. MSP monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

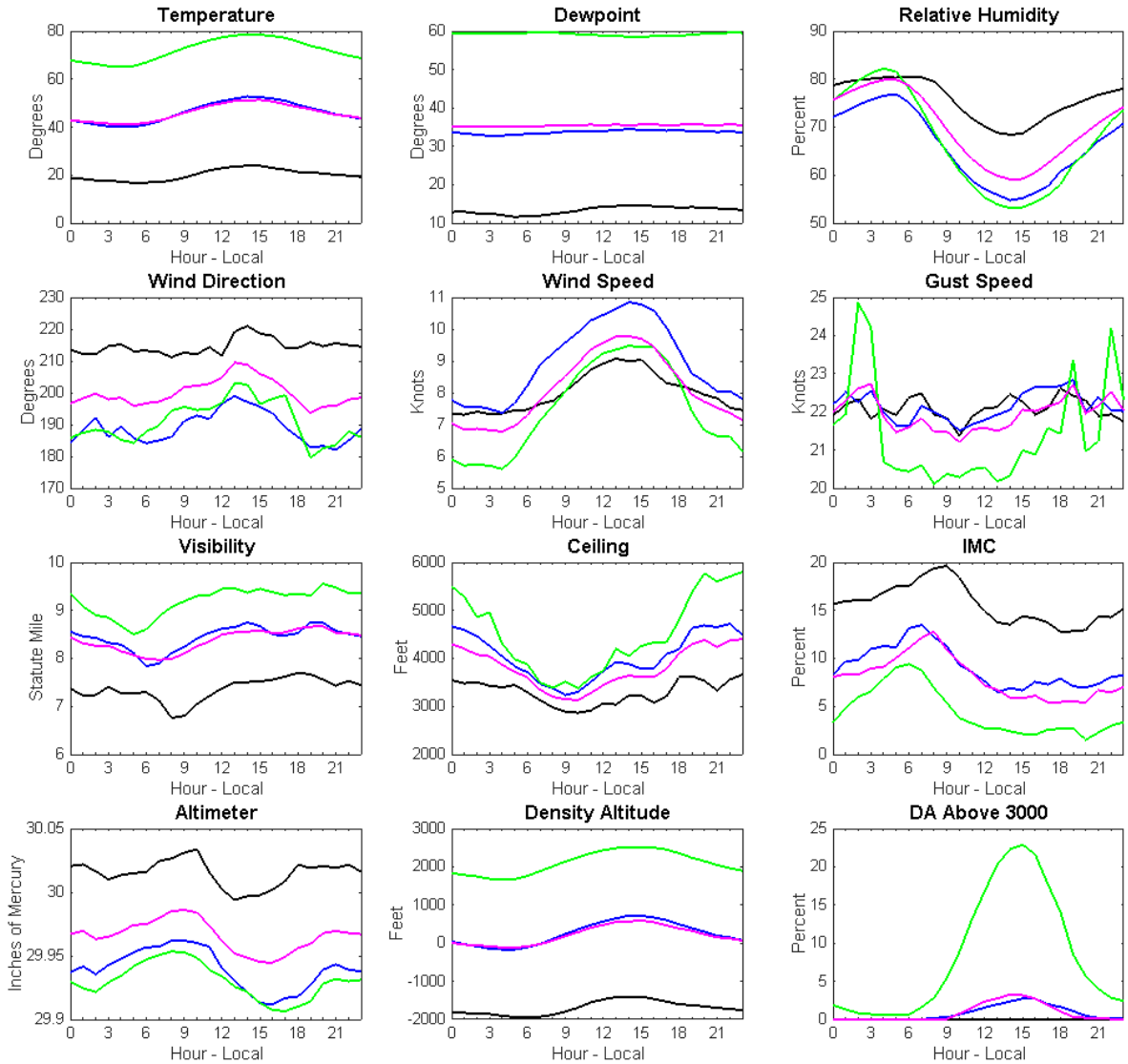


Figure 6.A.22. MSP diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

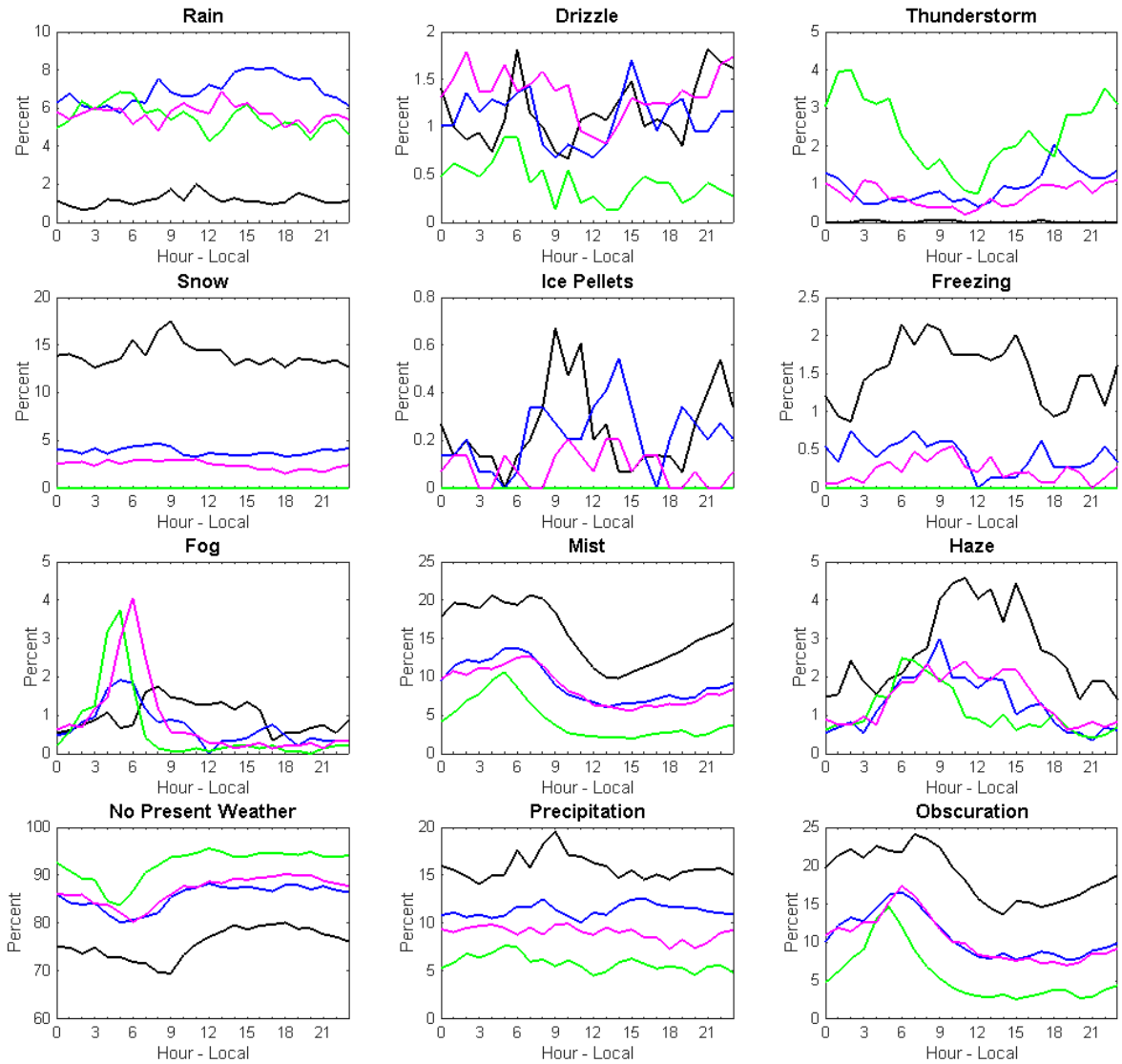


Figure 6.A.23. MSP seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

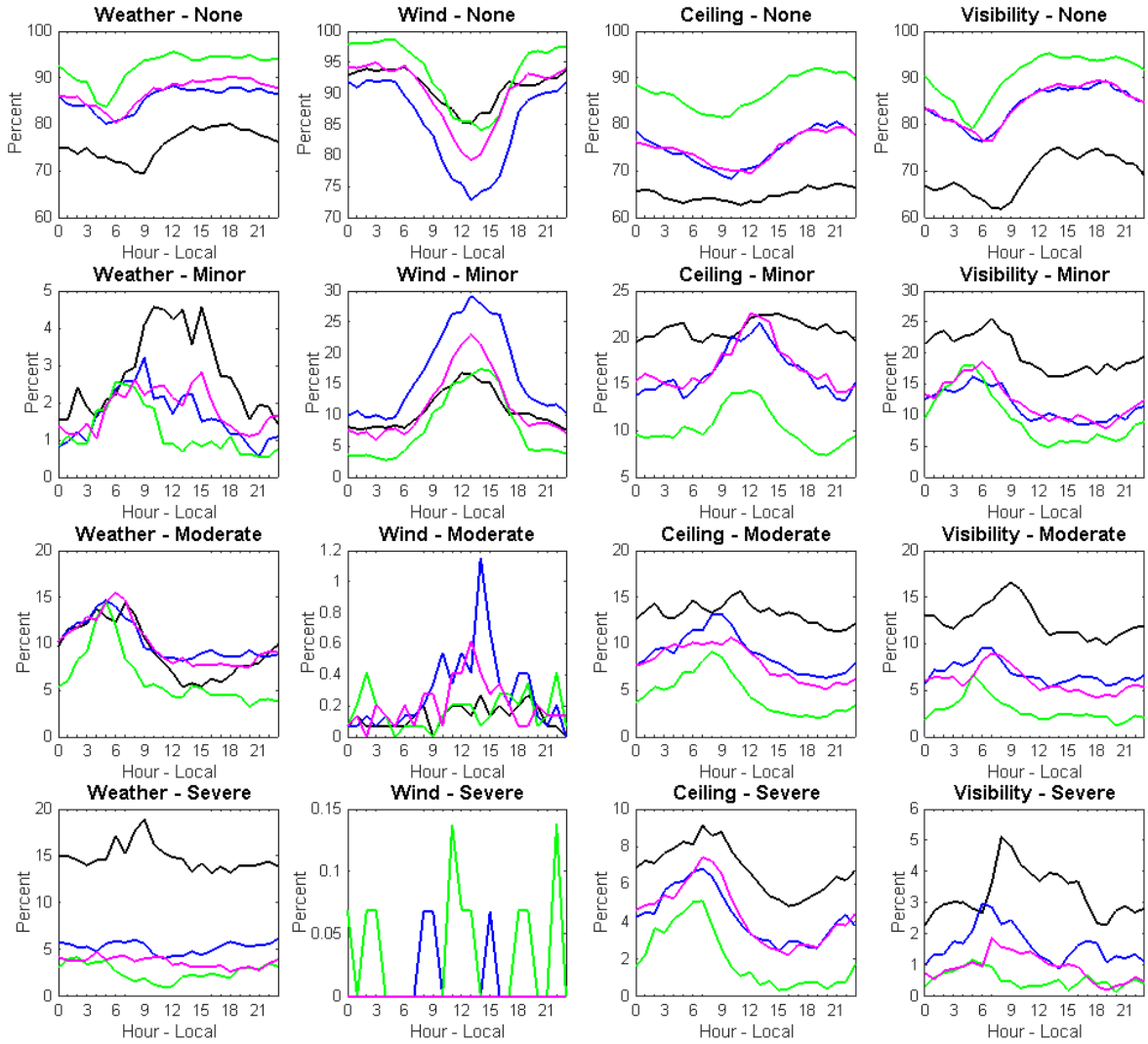


Figure 6.A.24. MSP seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

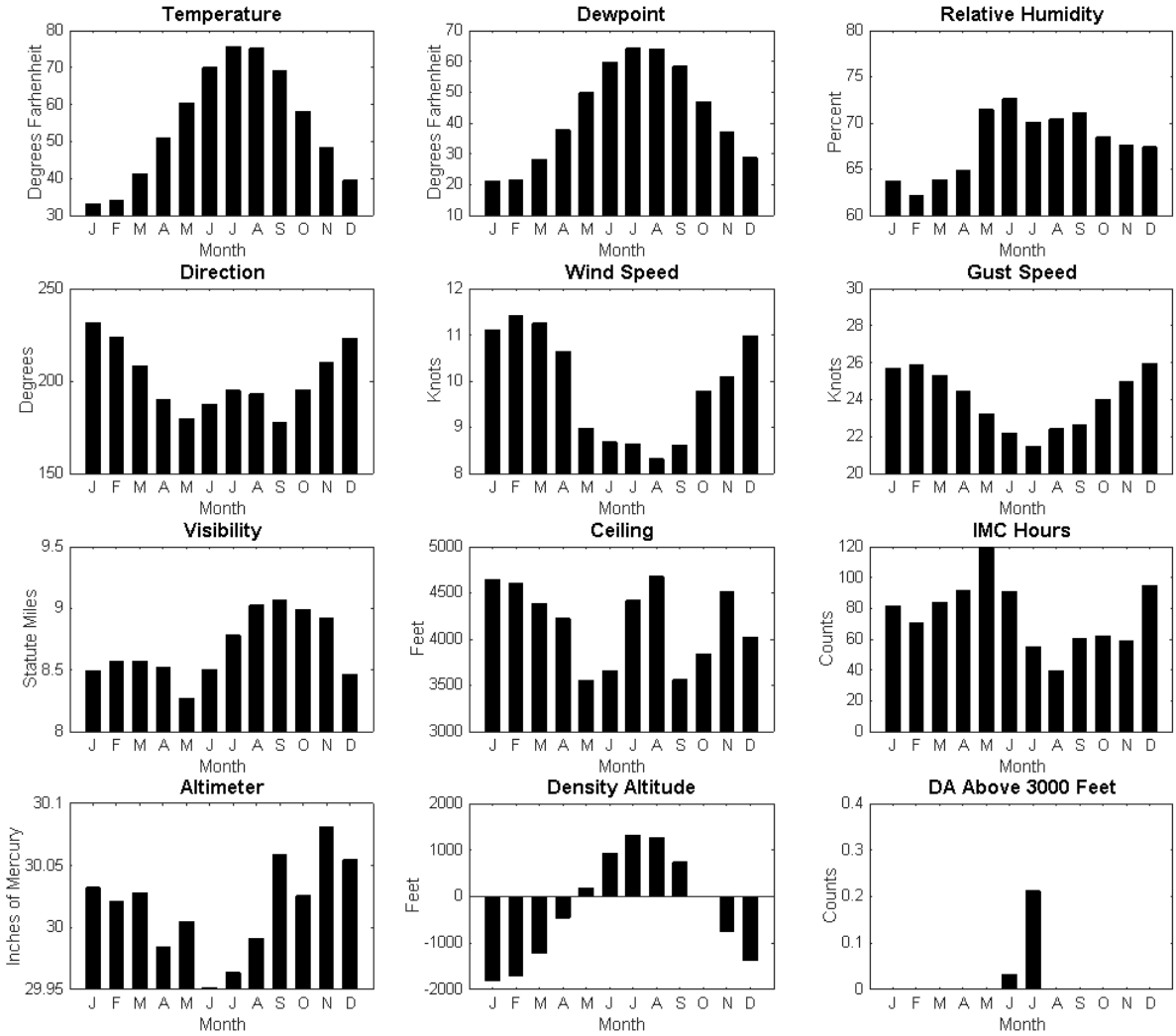


Figure 6.A.25. JFK monthly averages for METAR and derived values.

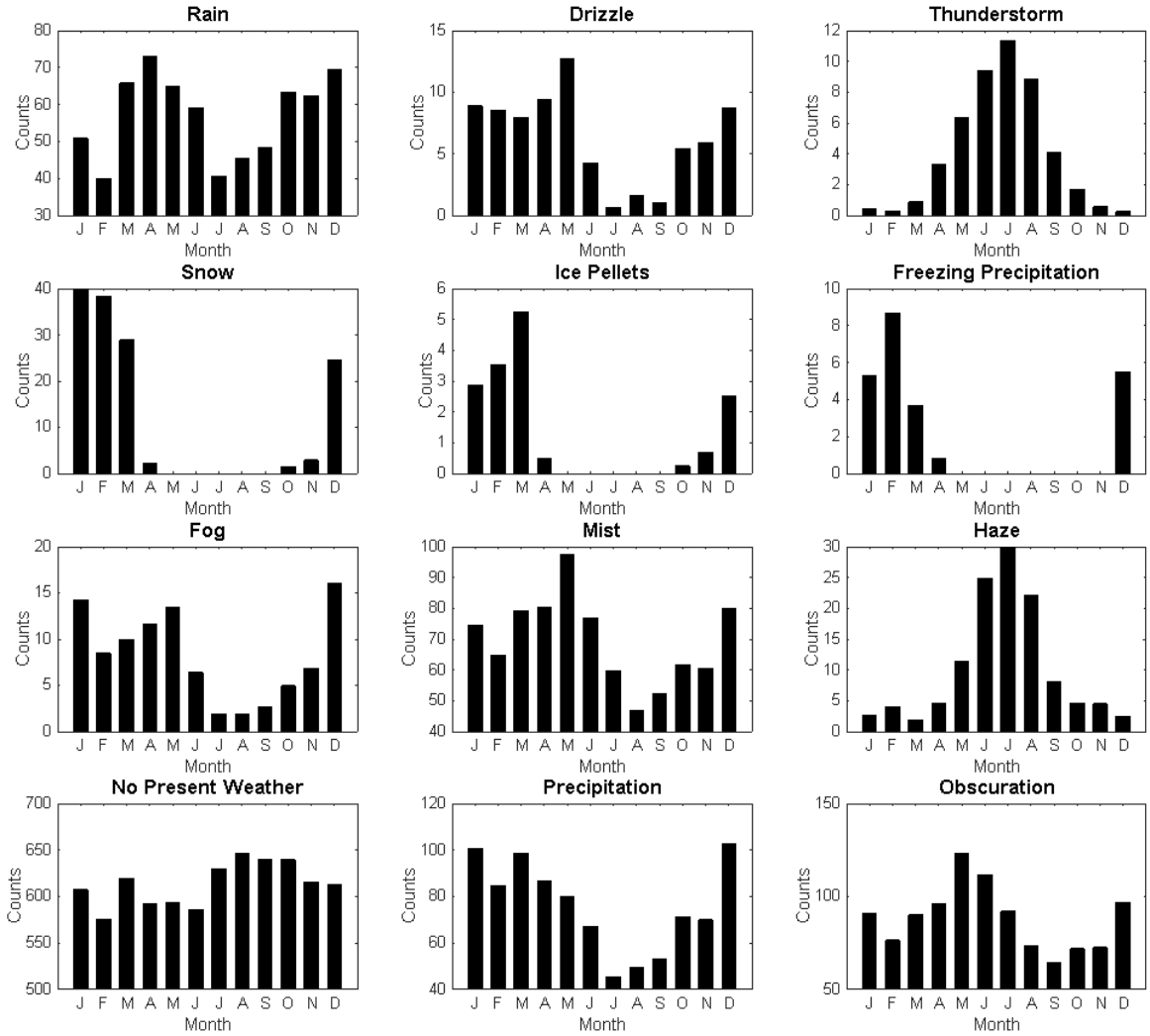


Figure 6.A.26. JFK monthly average counts for observed weather phenomena.

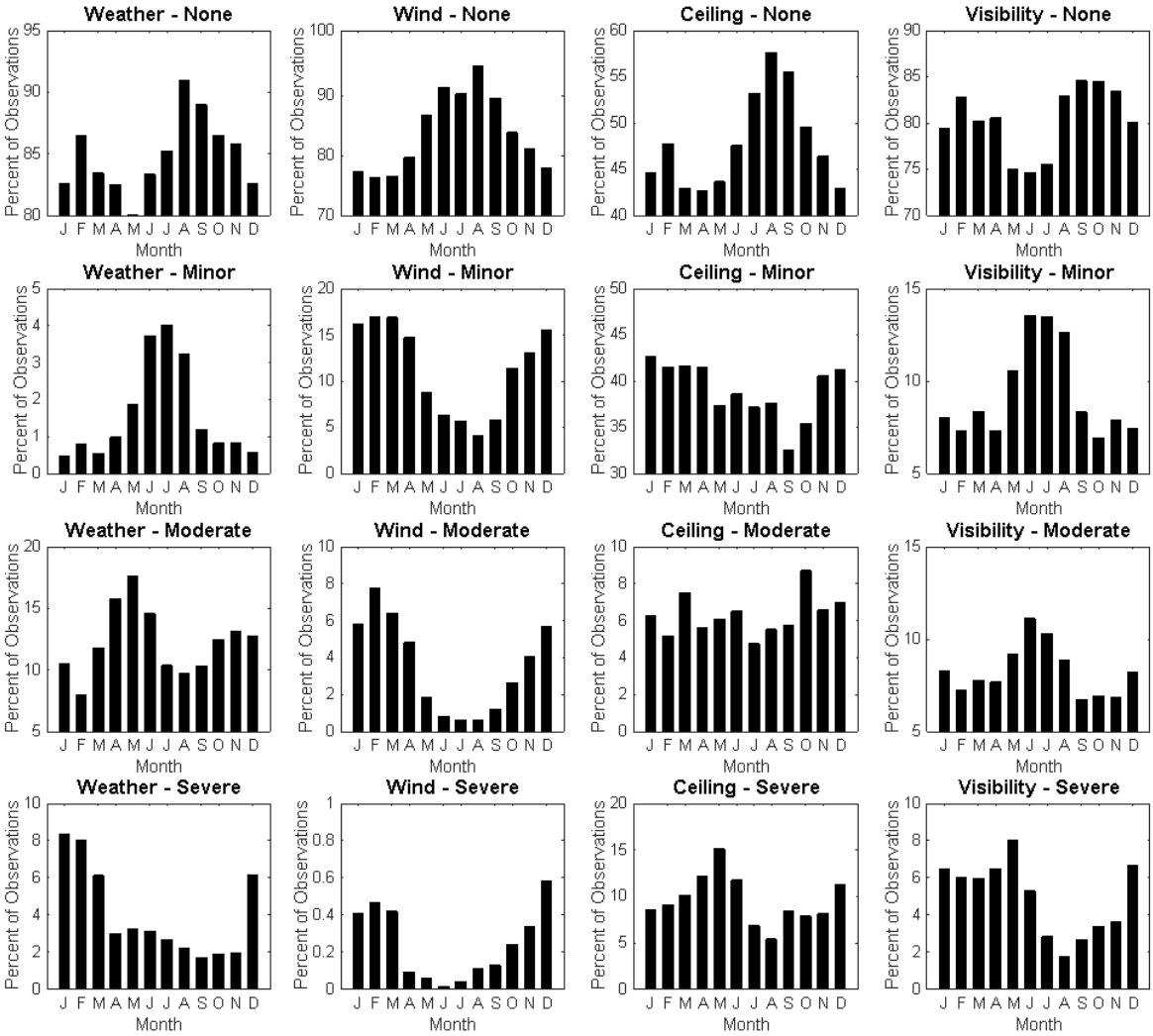


Figure 6.A.27. JFK monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

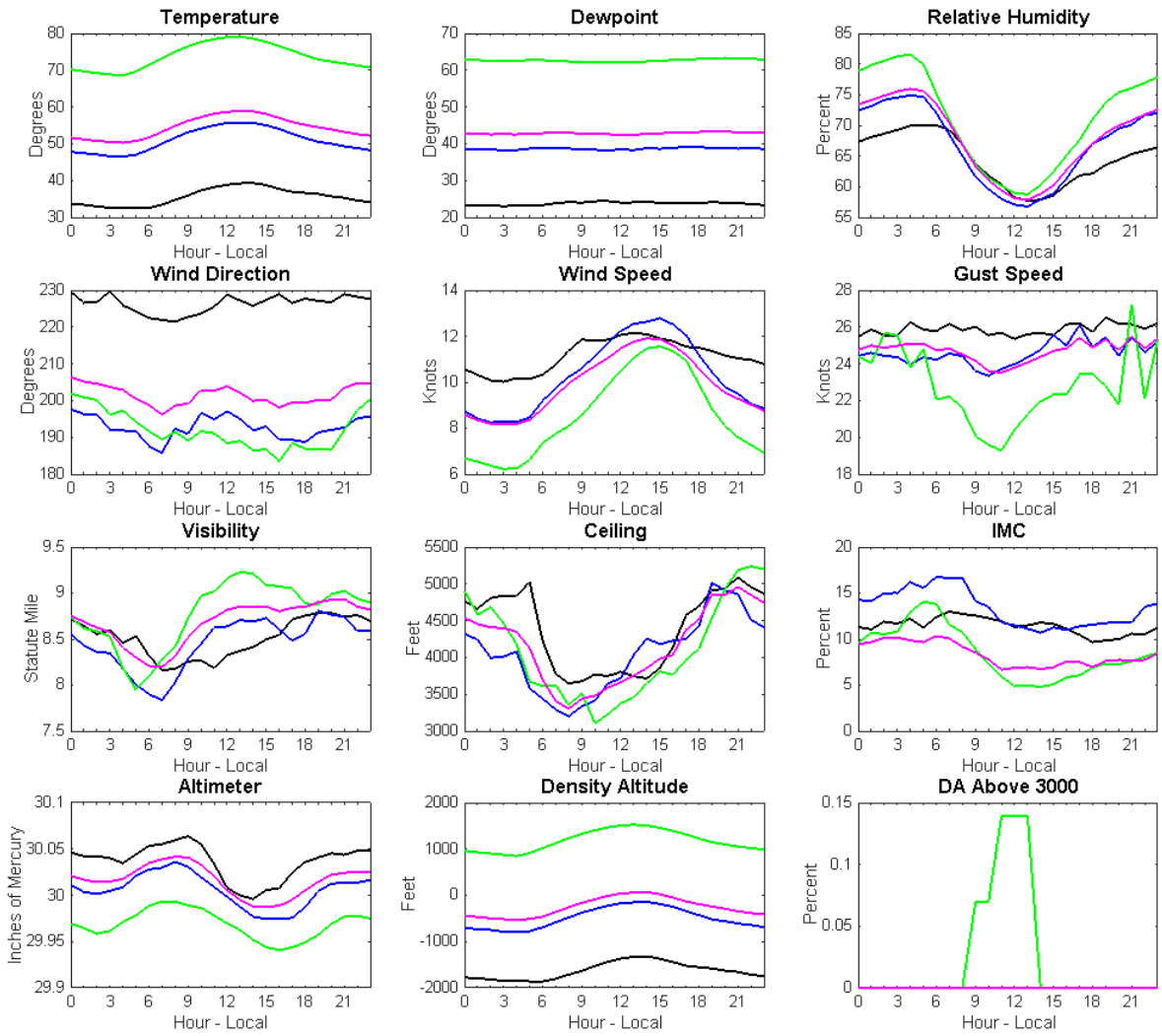


Figure 6.A.28. JFK diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

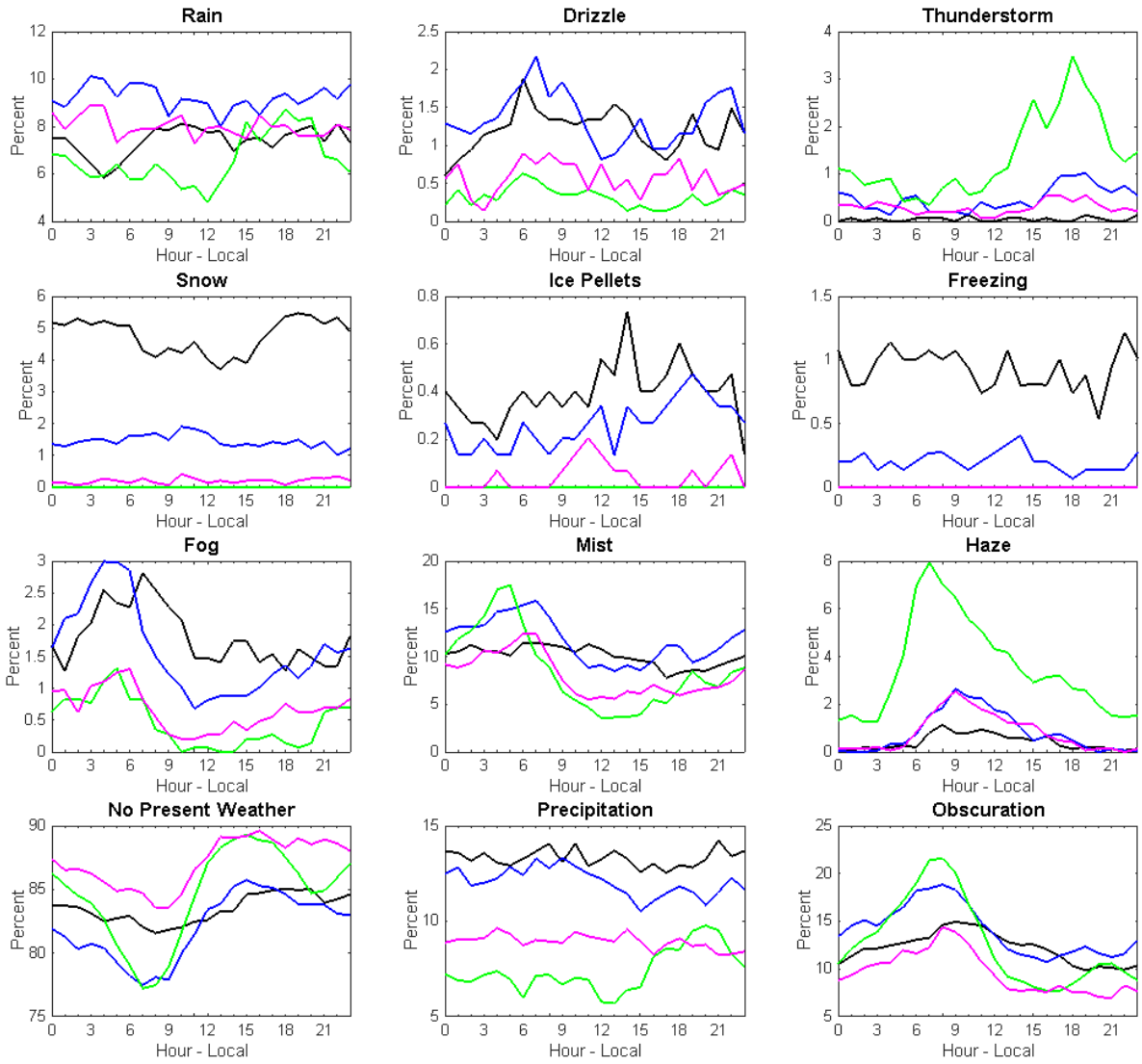


Figure 6.A.29. JFK seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

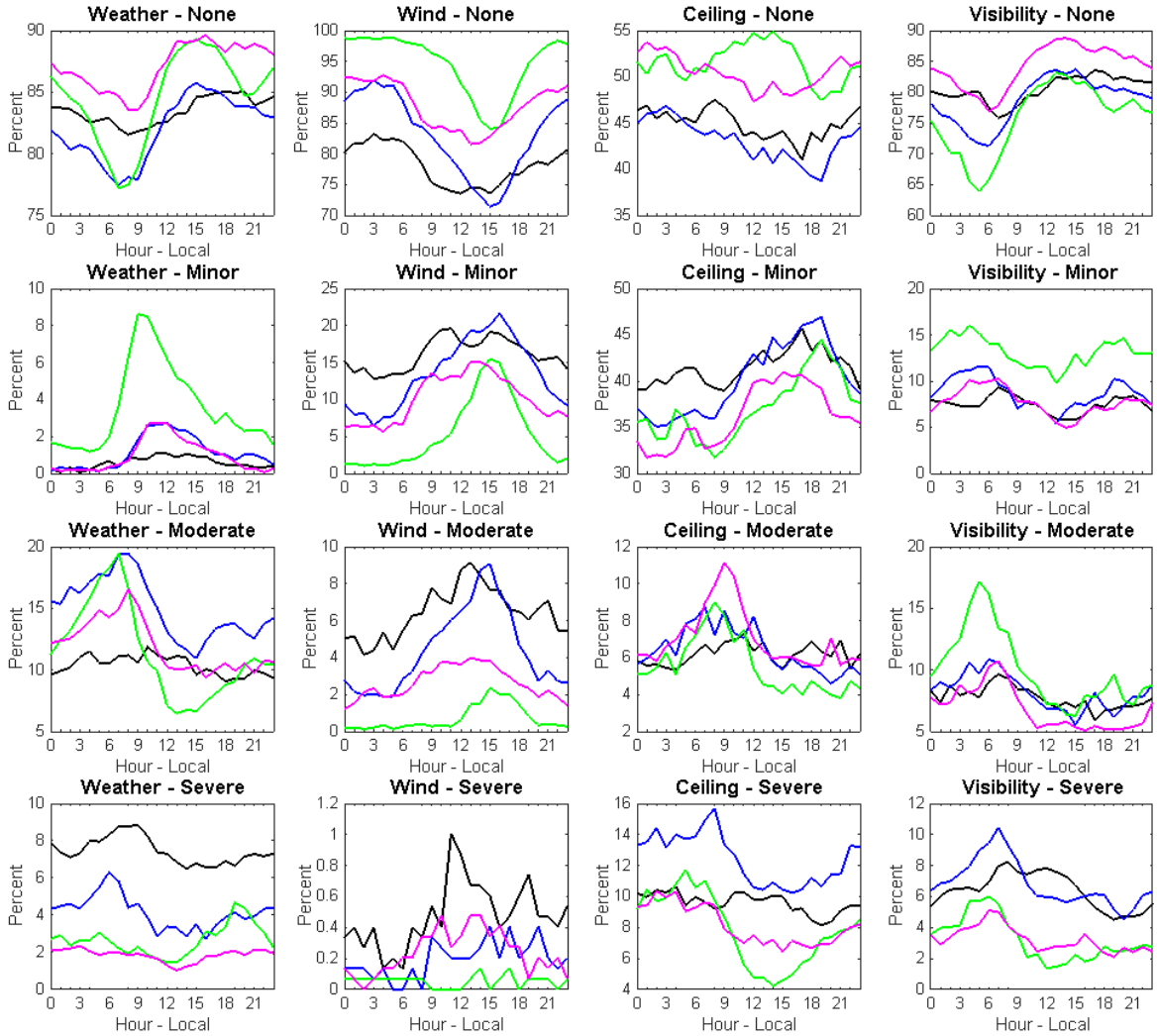


Figure 6.A.30. JFK seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

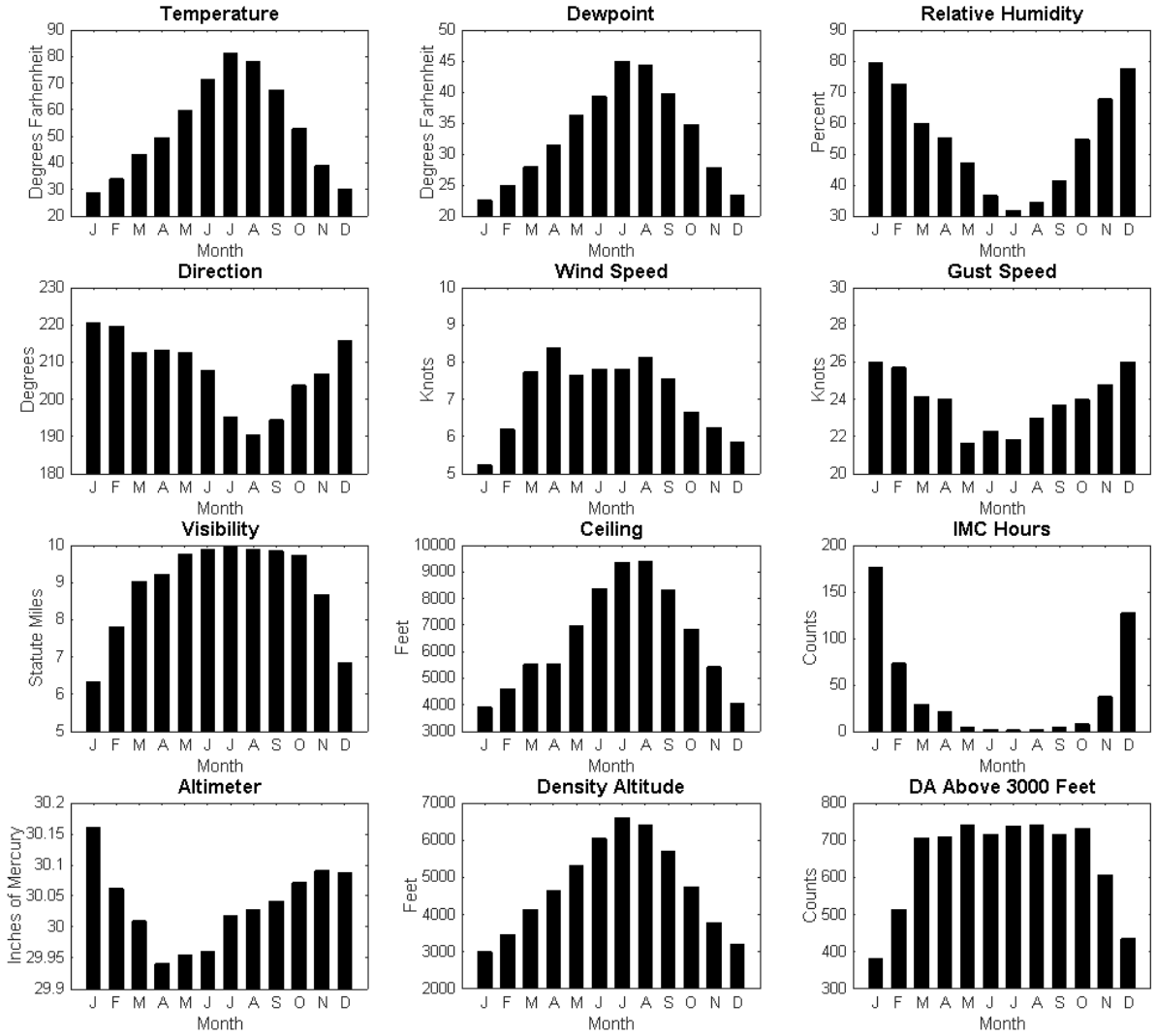


Figure 6.A.31. SLC monthly averages for METAR and derived values.

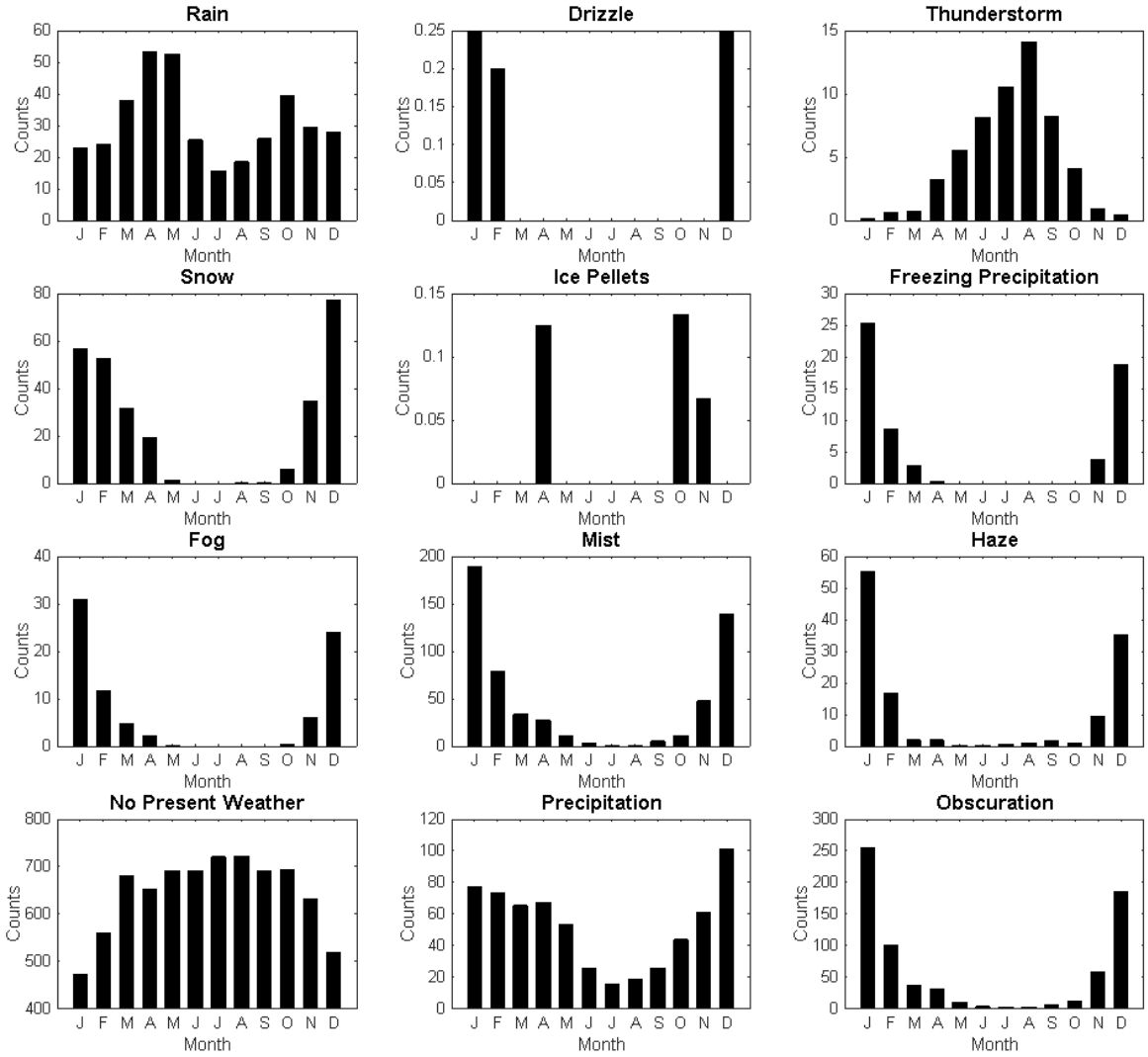


Figure 6.A.32. SLC monthly average counts for observed weather phenomena.

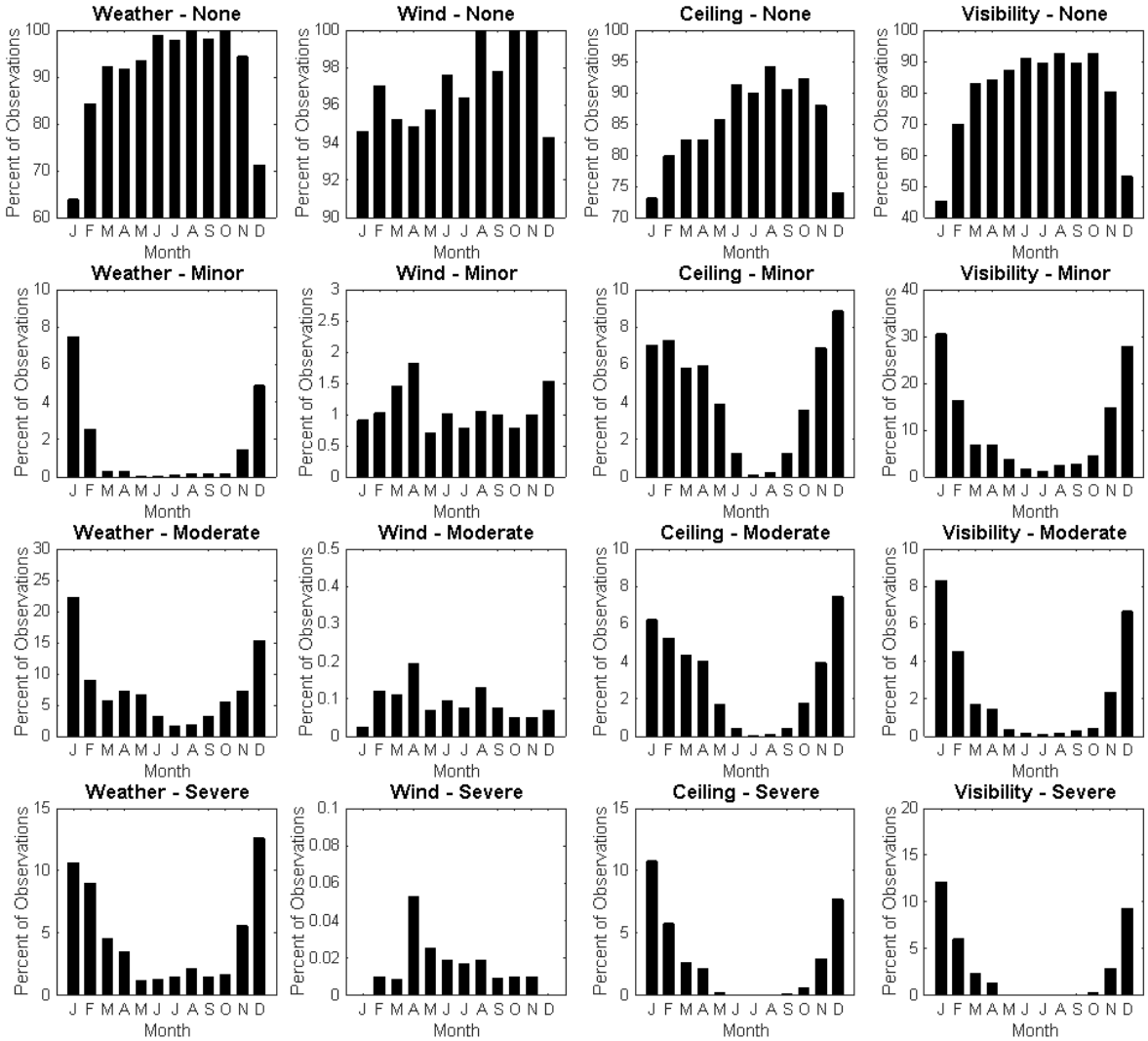


Figure 6.A.33. SLC monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

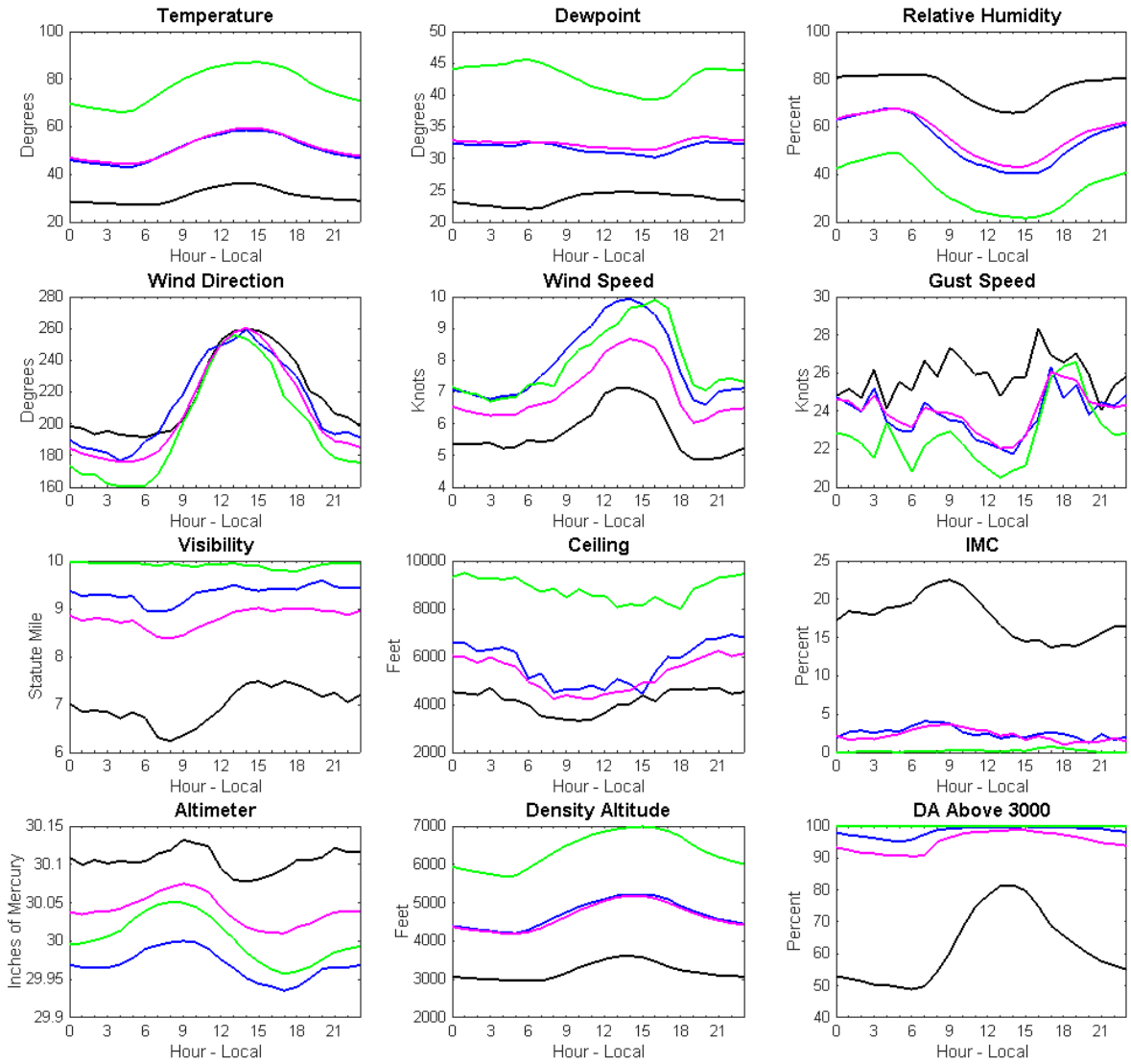


Figure 6.A.34. SLC diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

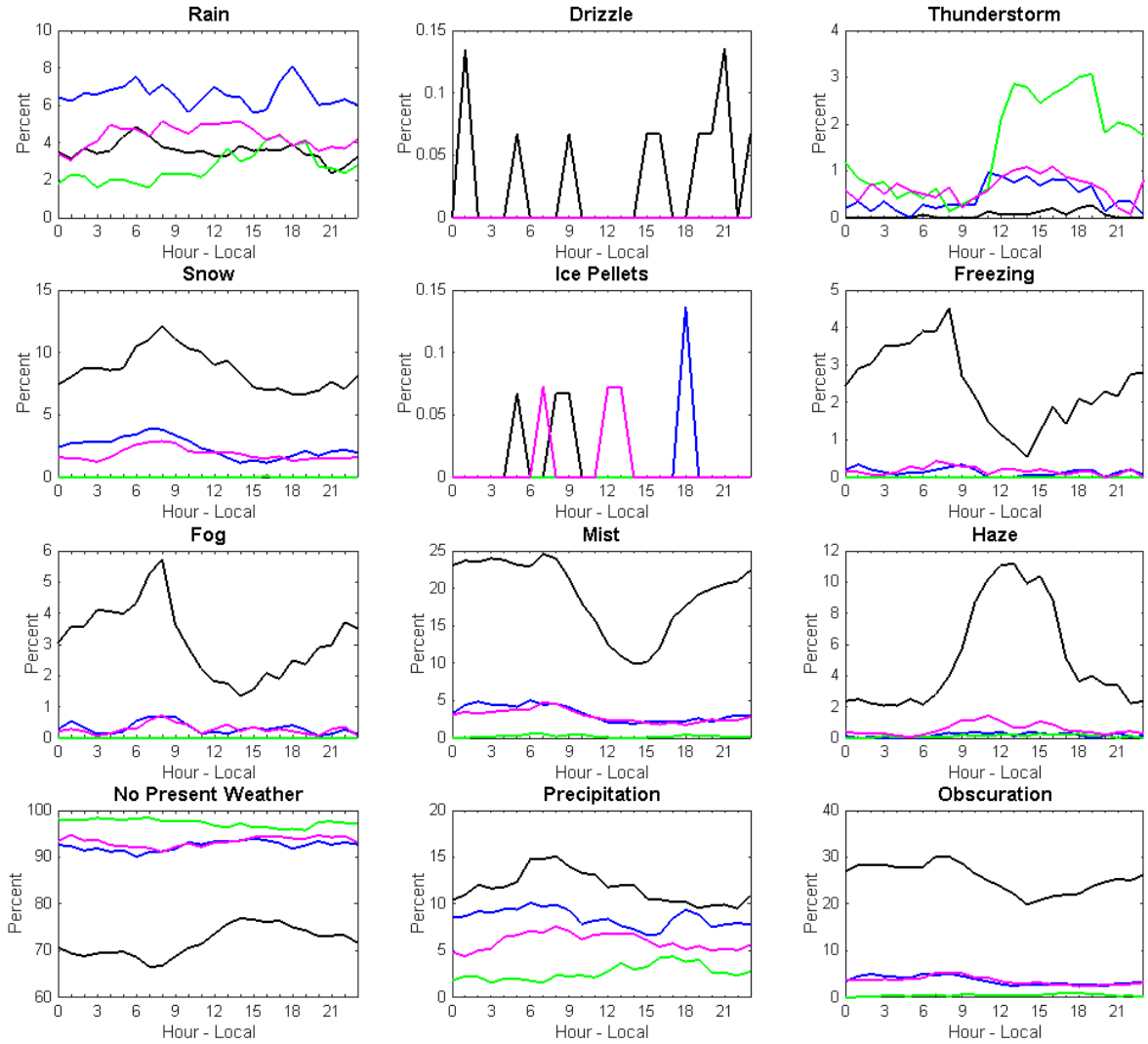


Figure 6.A.35. SLC seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

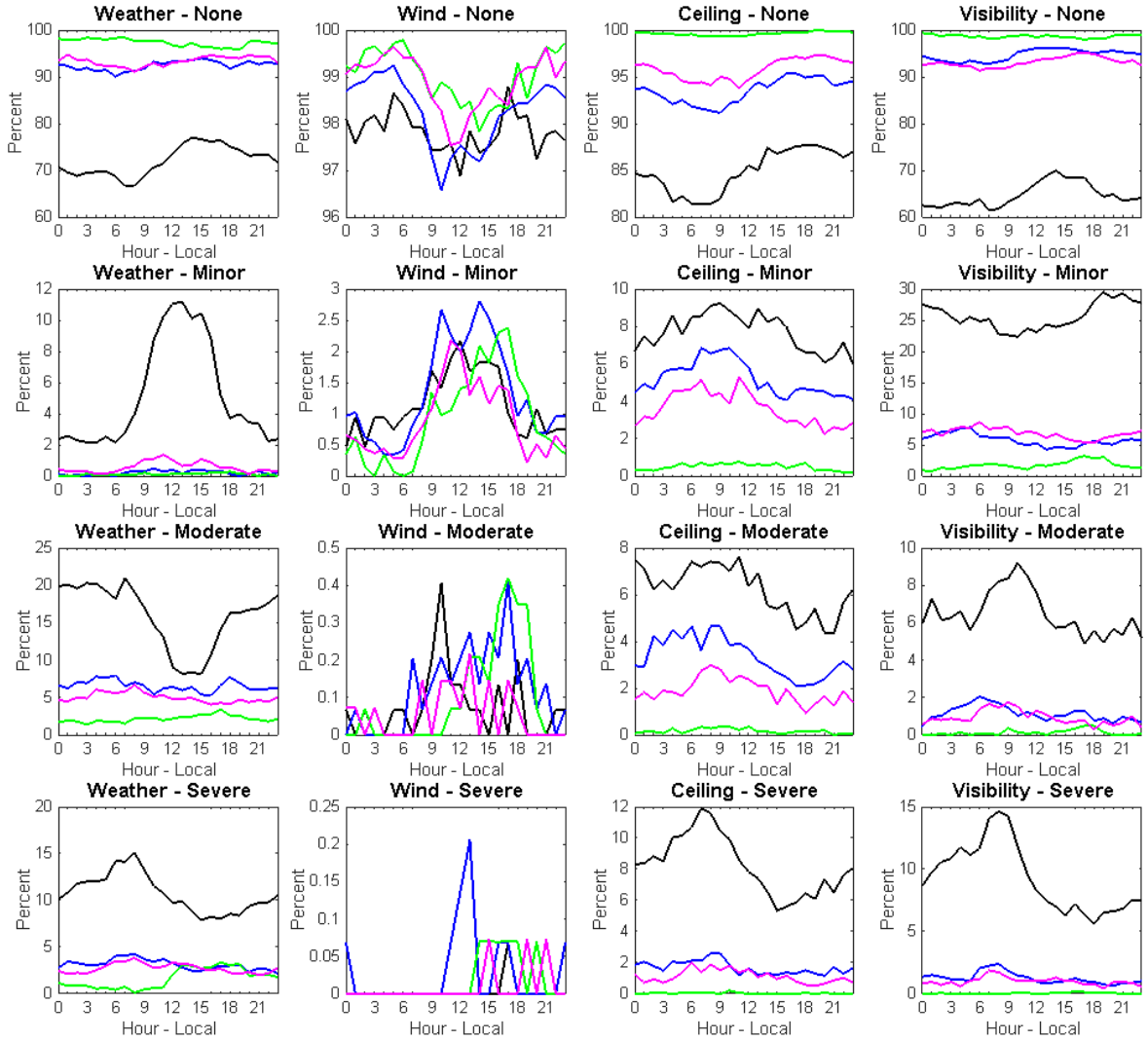


Figure 6.A.36. SLC seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

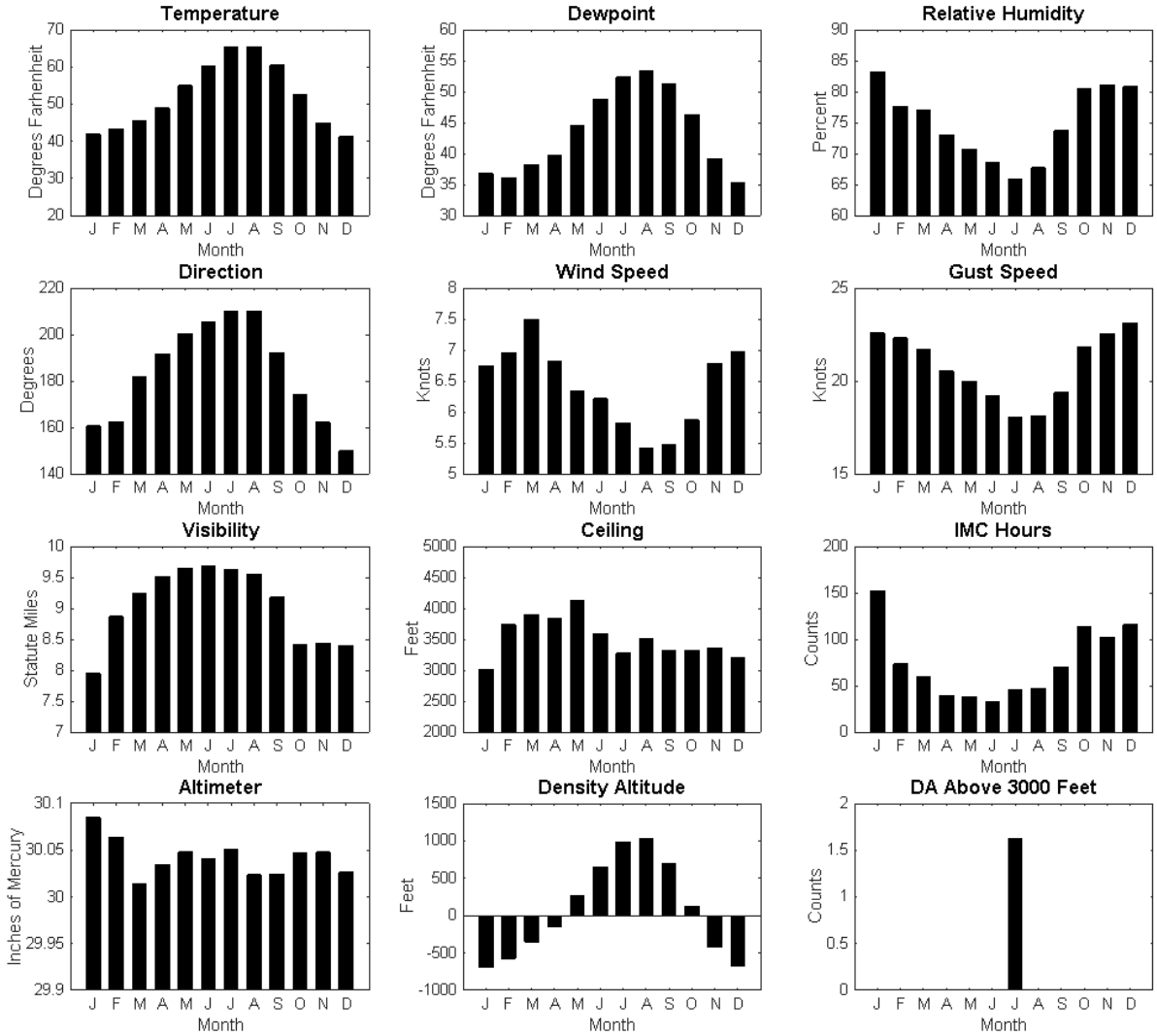


Figure 6.A.37. SEA monthly averages for METAR and derived values.

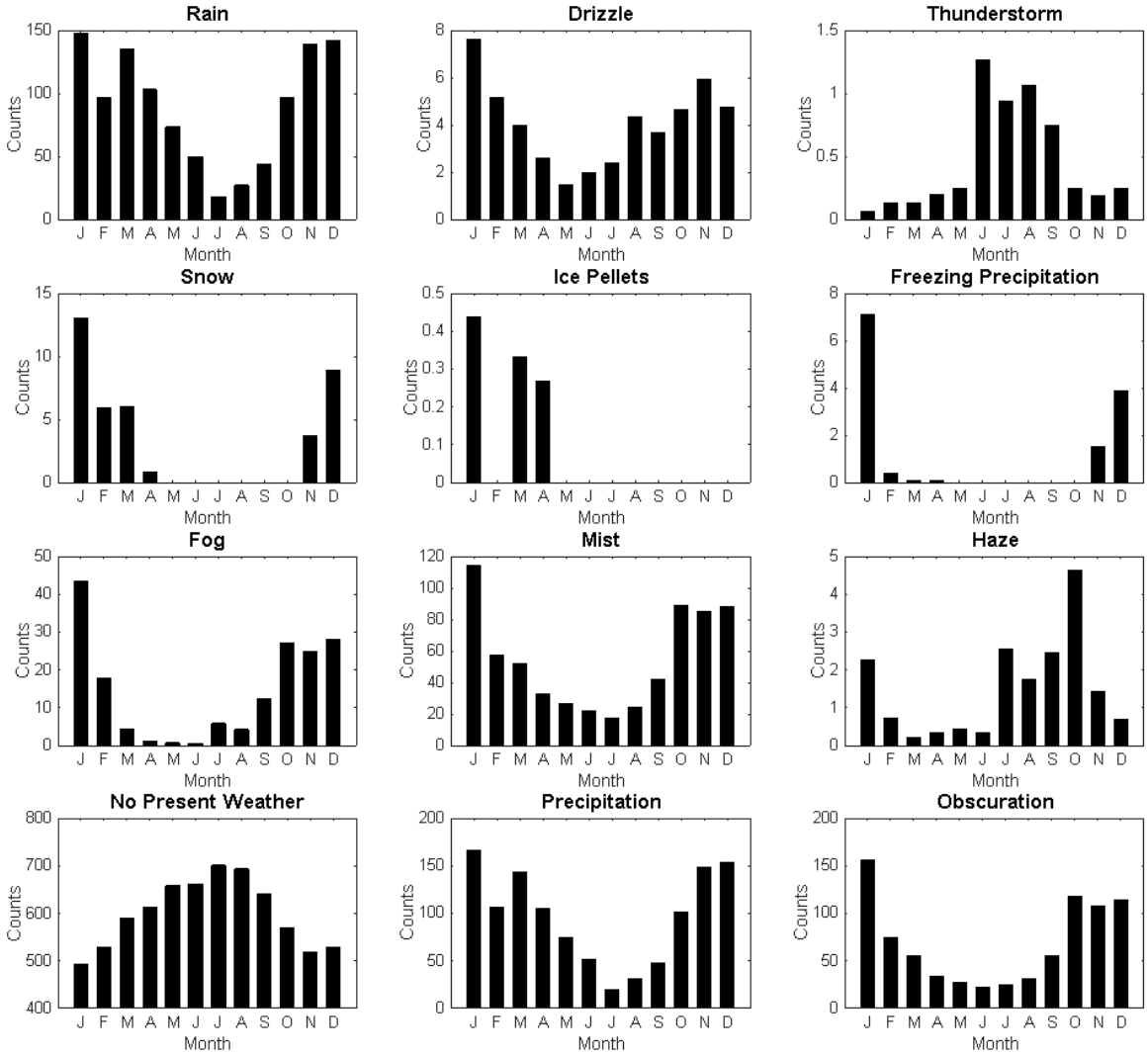


Figure 6.A.38. SEA monthly average counts for observed weather phenomena.

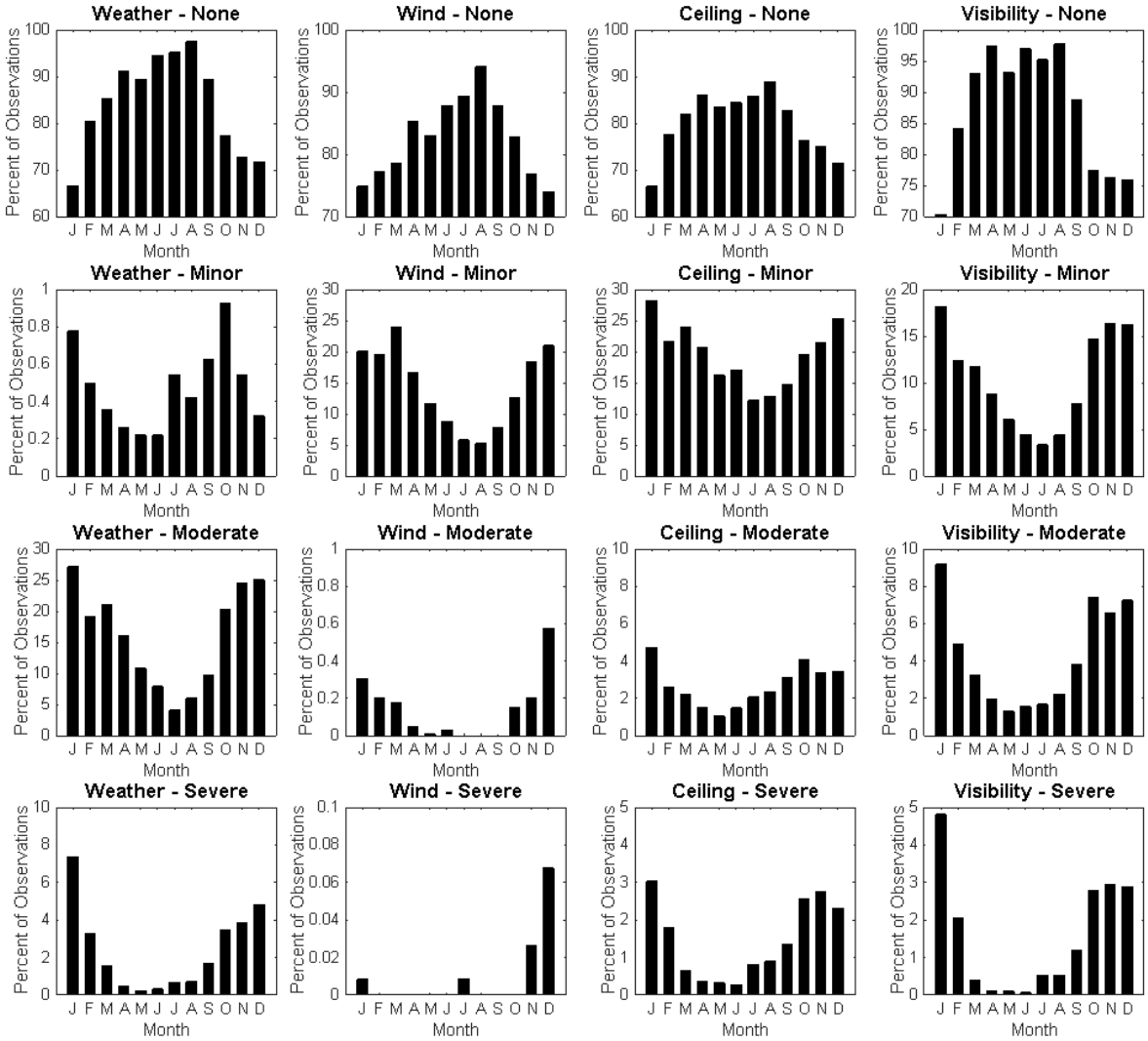


Figure 6.A.39. SEA monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

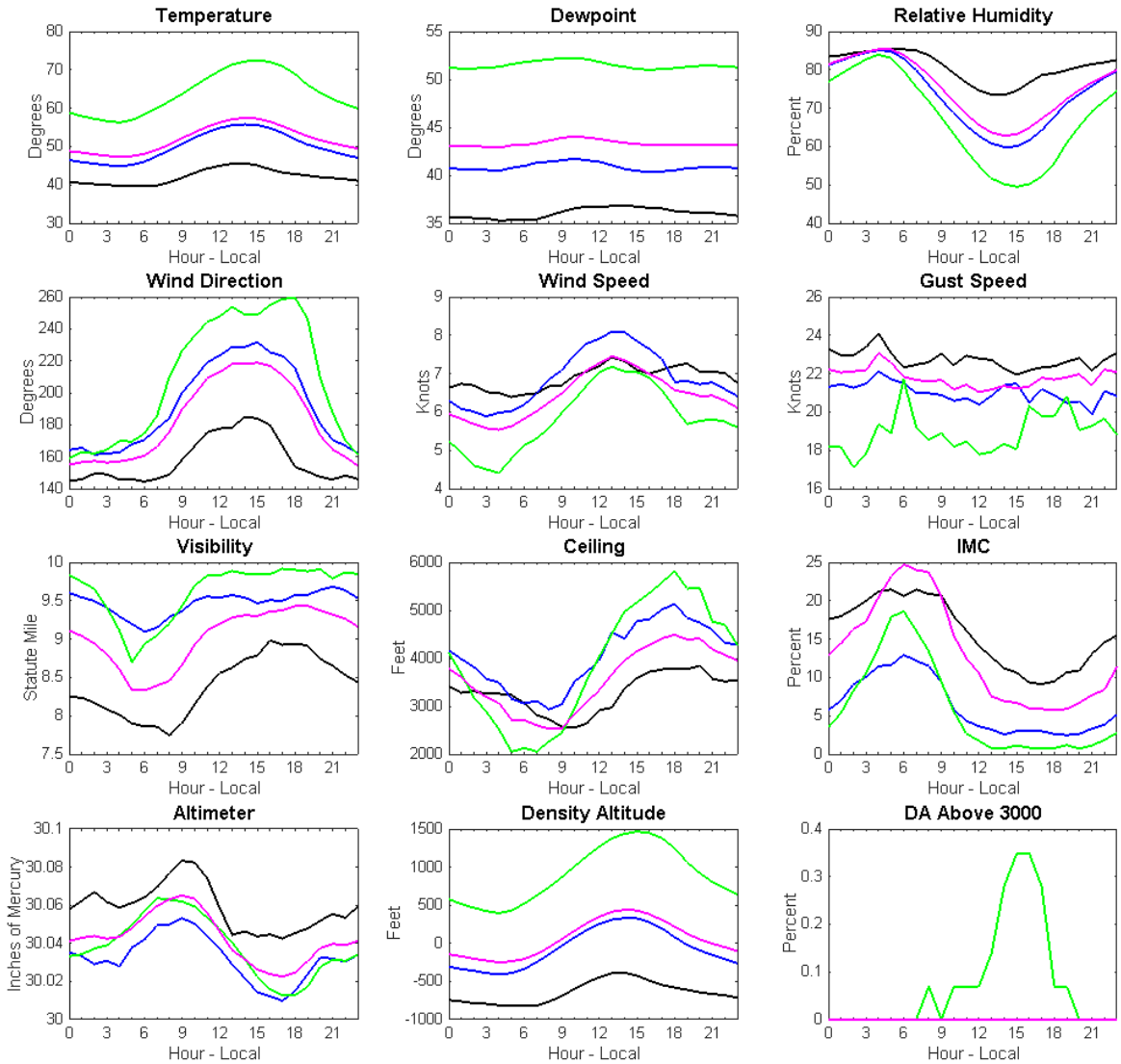


Figure 6.A.40. SEA diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

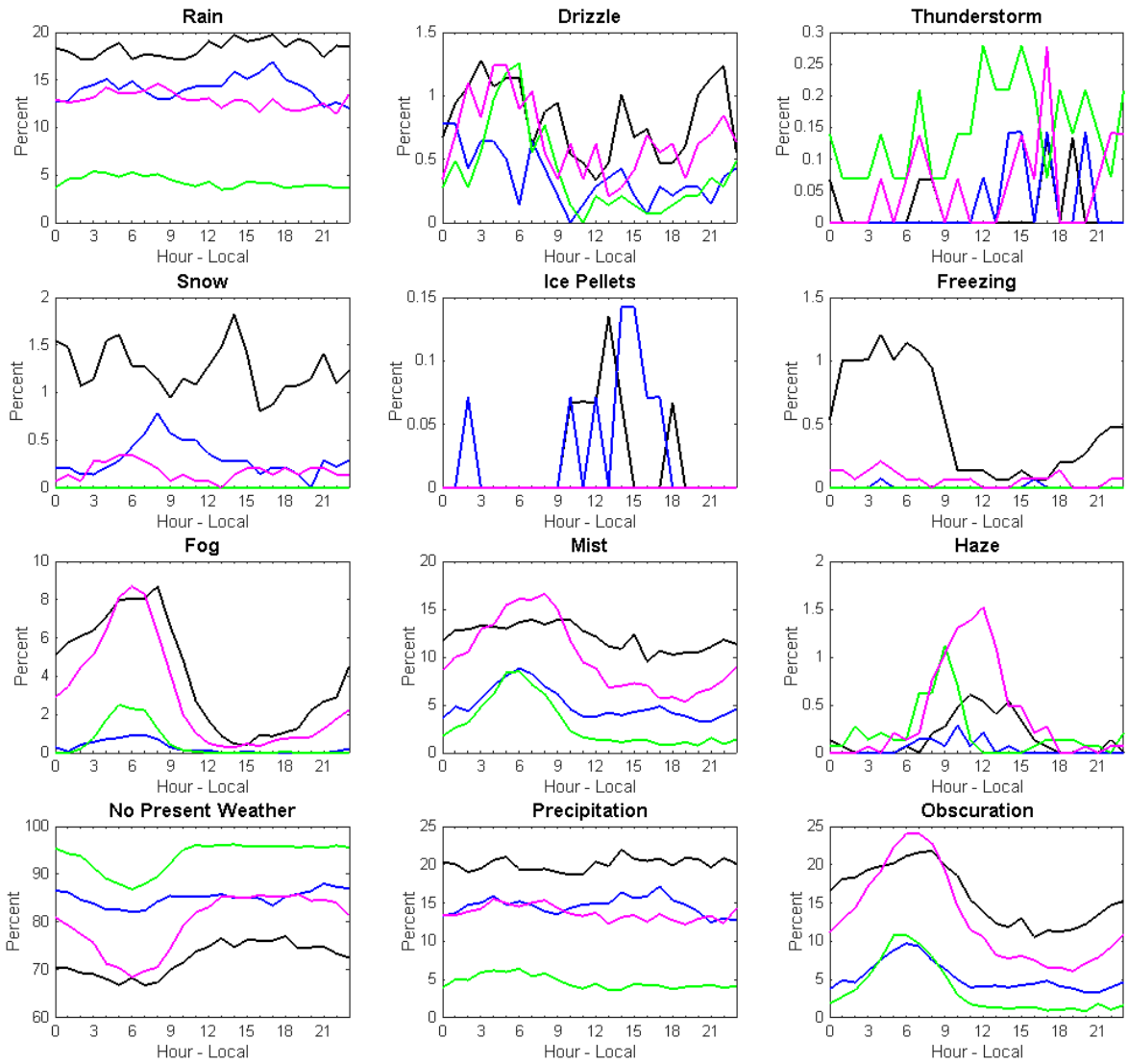


Figure 6.A.41. SEA seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

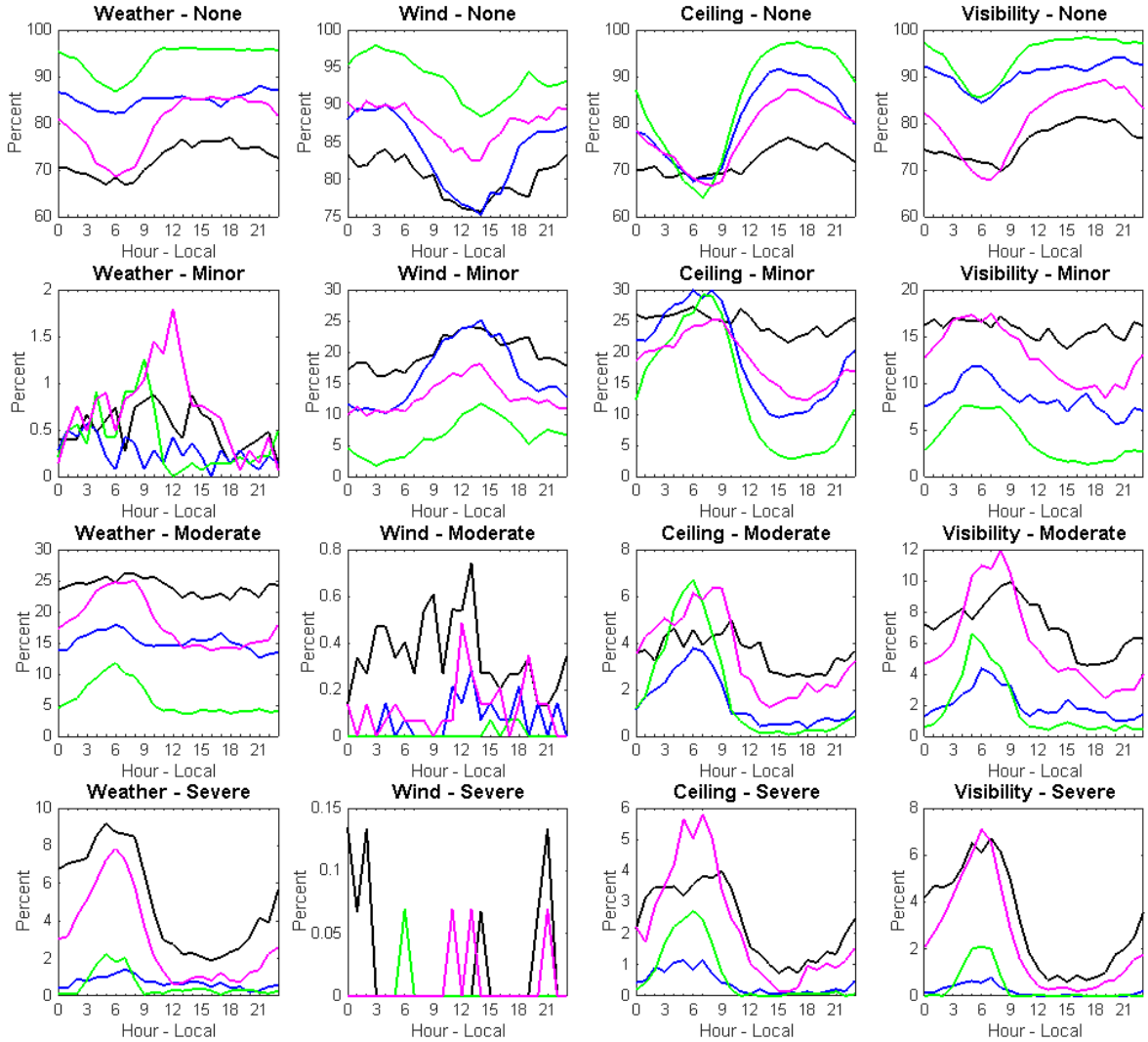


Figure 6.A.42. SEA seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

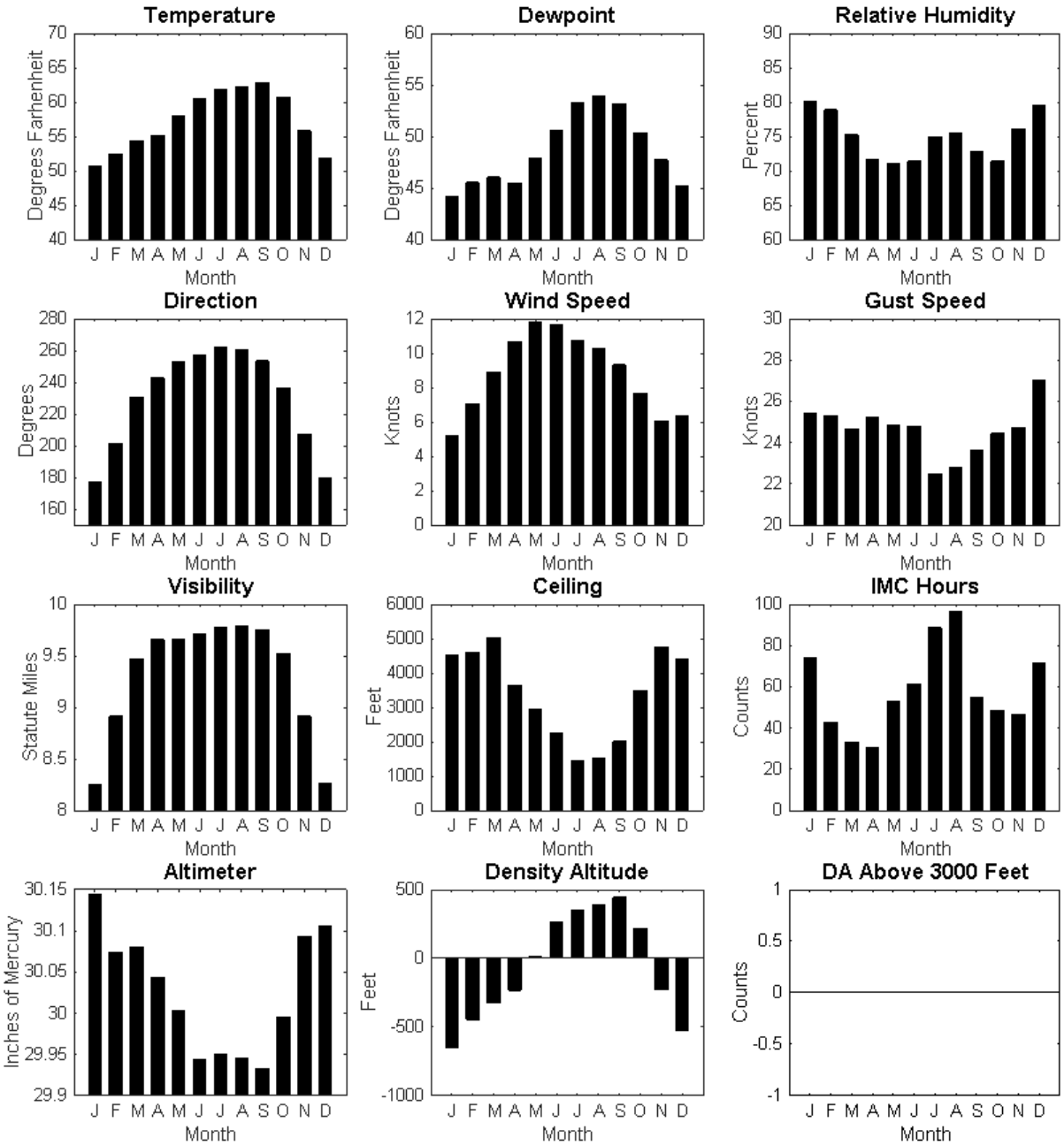


Figure 6.A.43. SFO monthly averages for METAR and derived values.

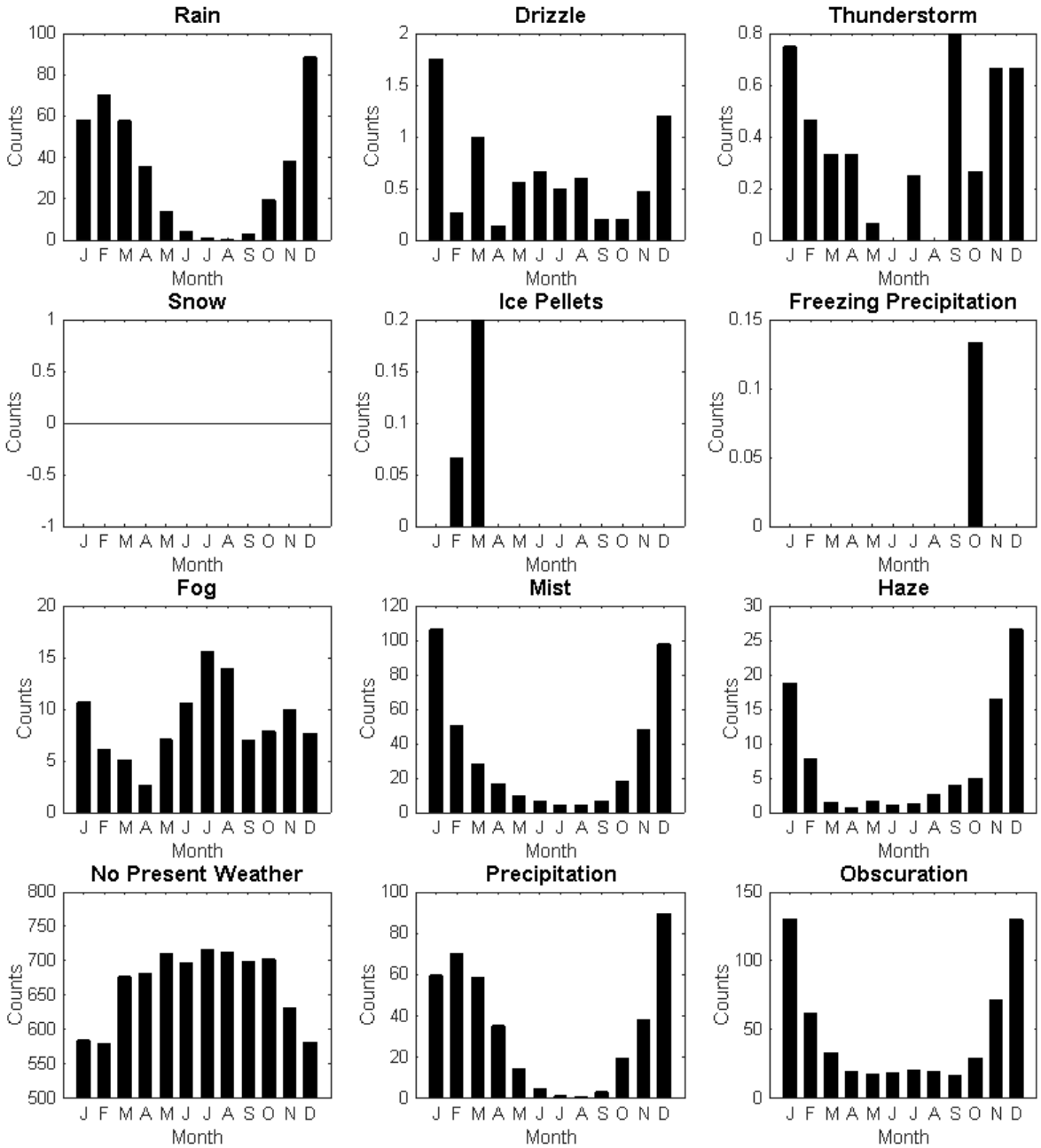


Figure 6.A.44. SFO monthly average counts for observed weather phenomena.

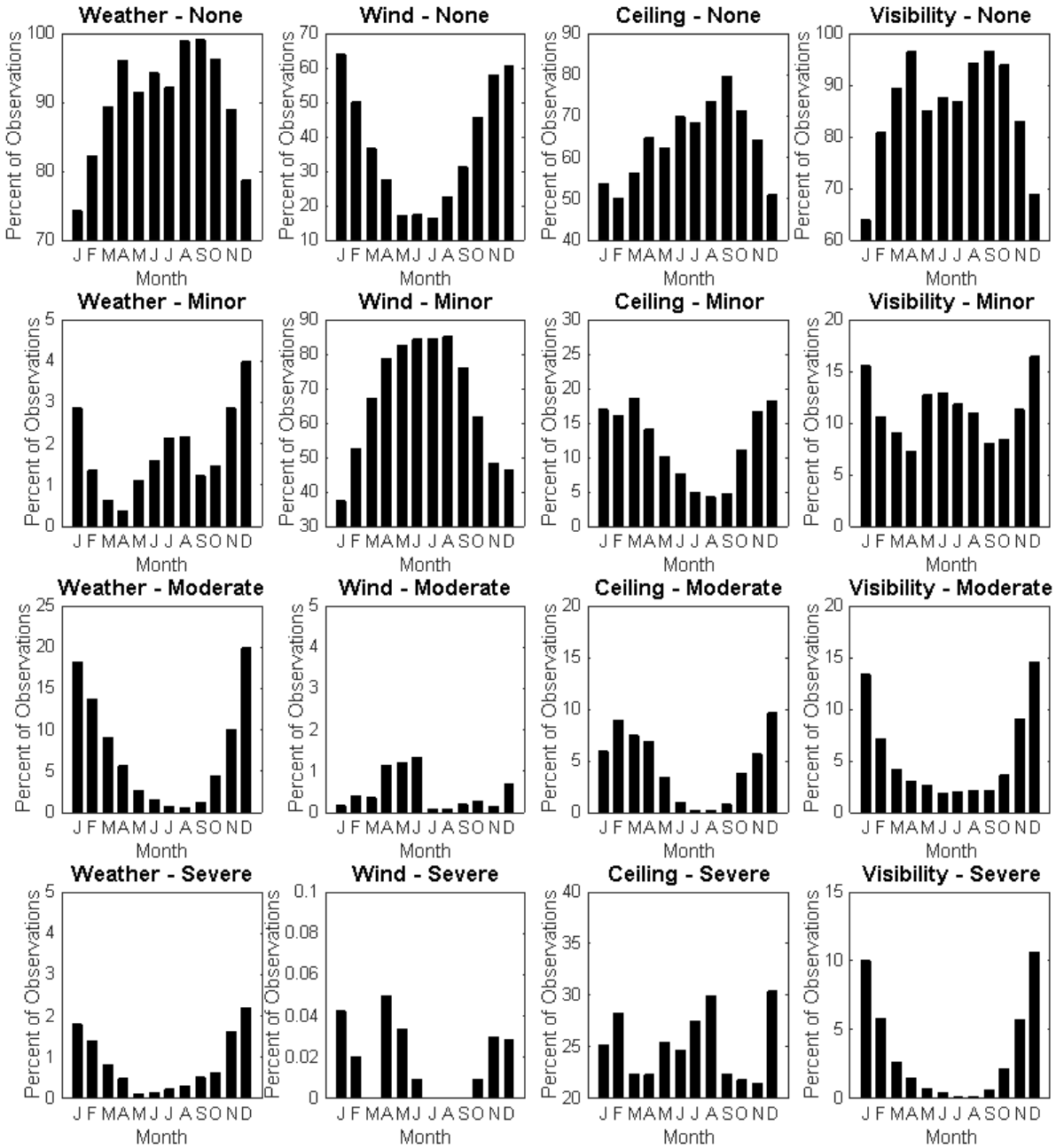


Figure 6.A.45. SFO monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

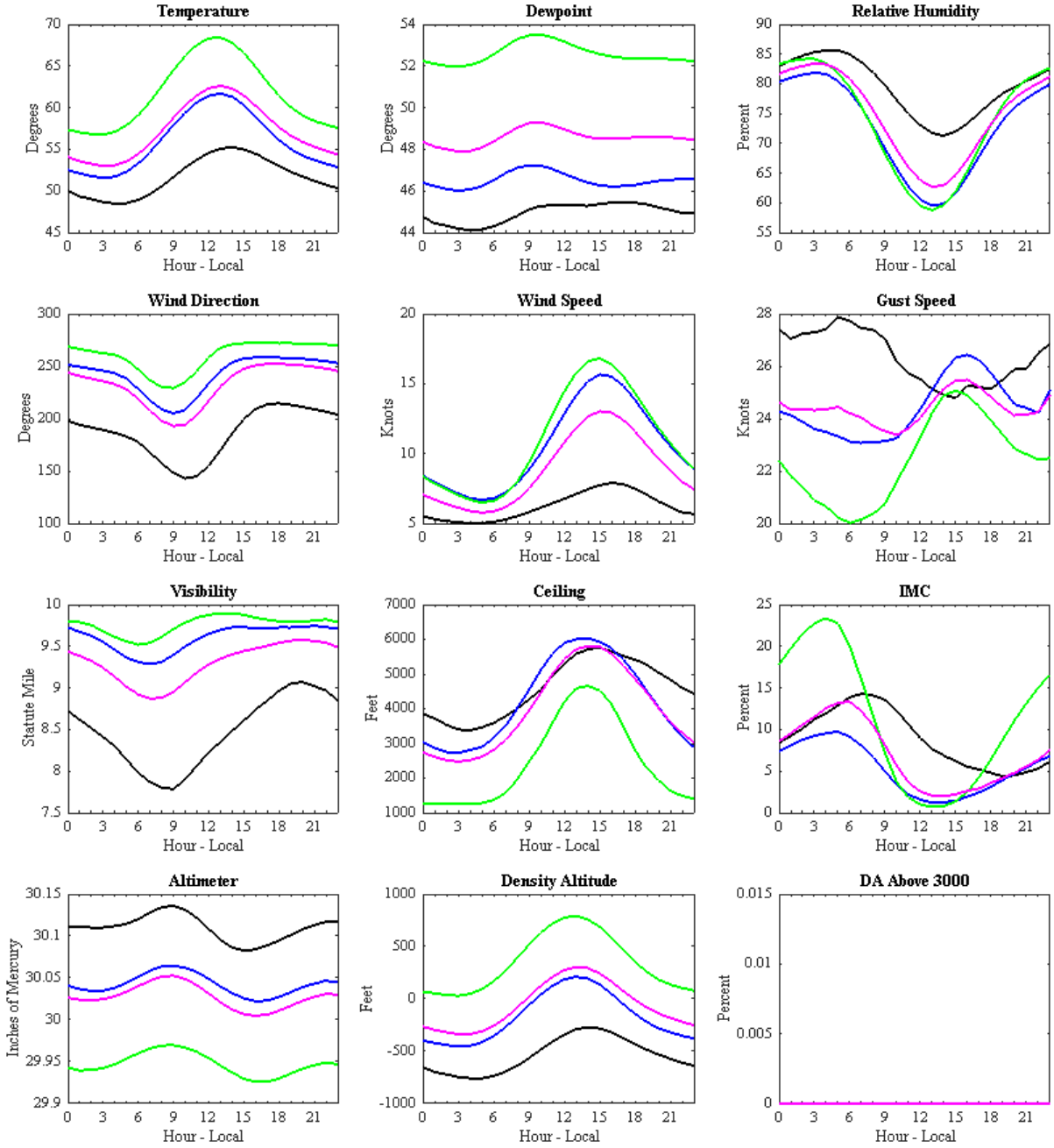


Figure 6.A.46. SFO diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

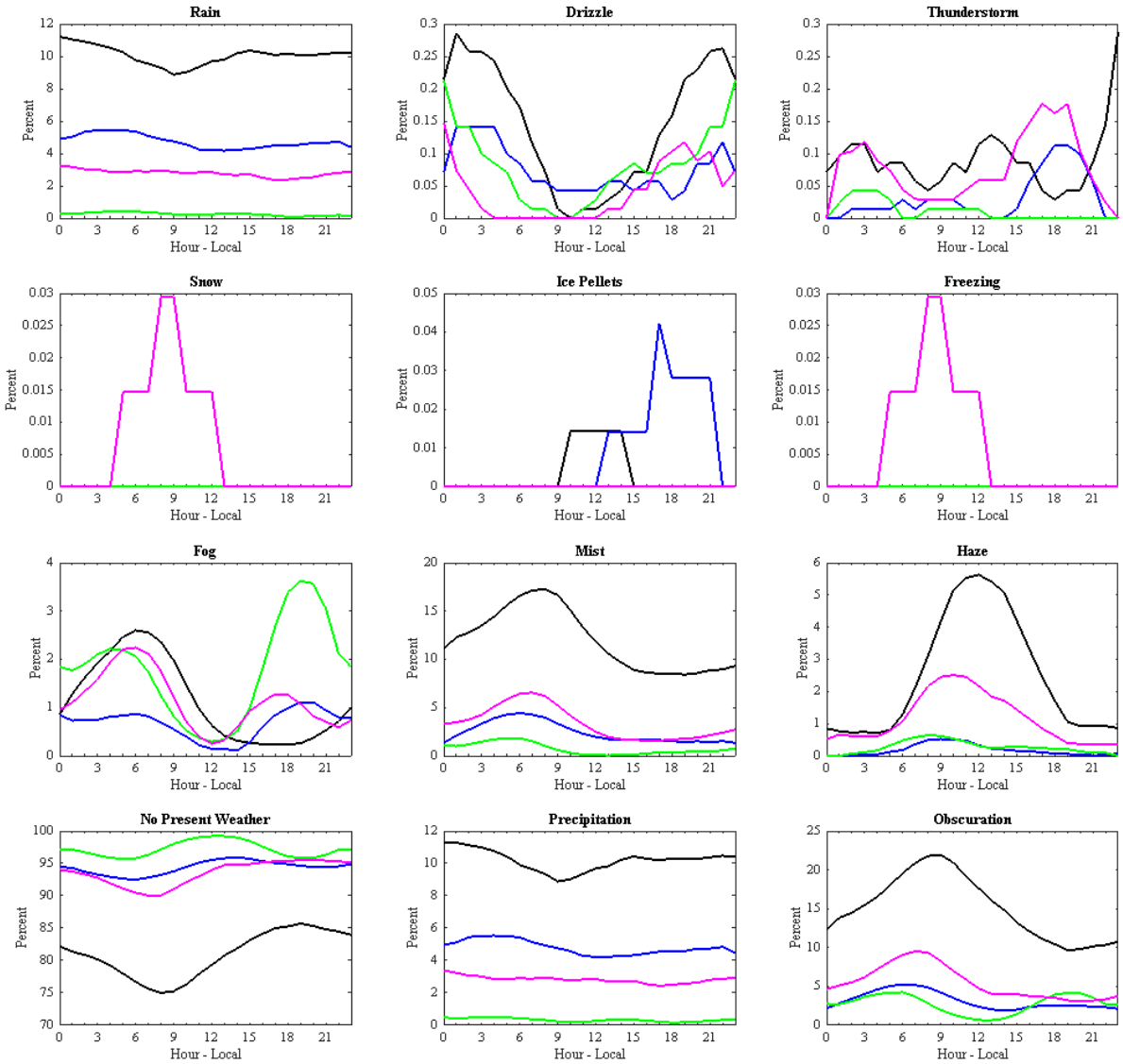


Figure 6.A.47. SFO seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

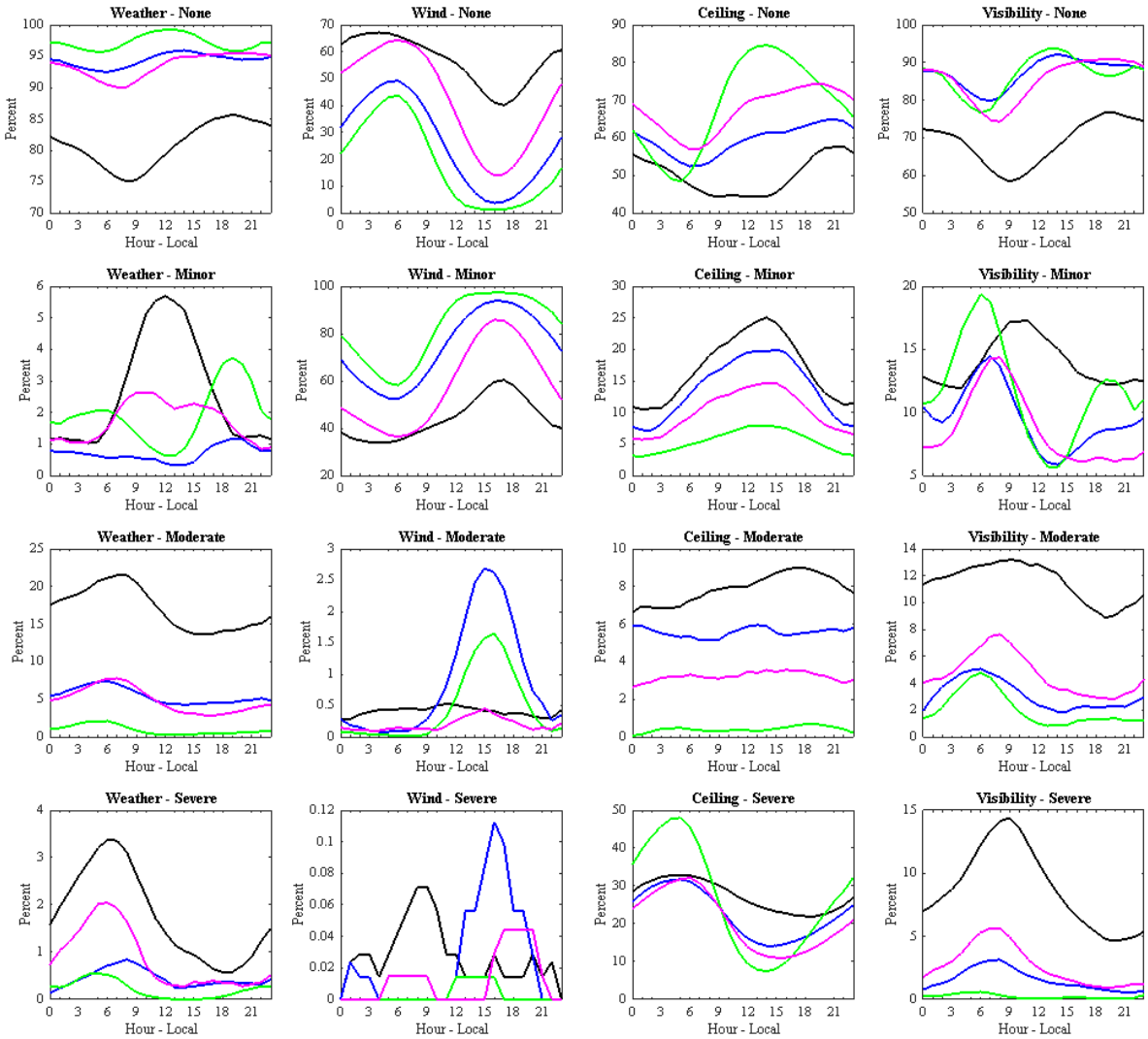


Figure 6.A.48. SFO seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

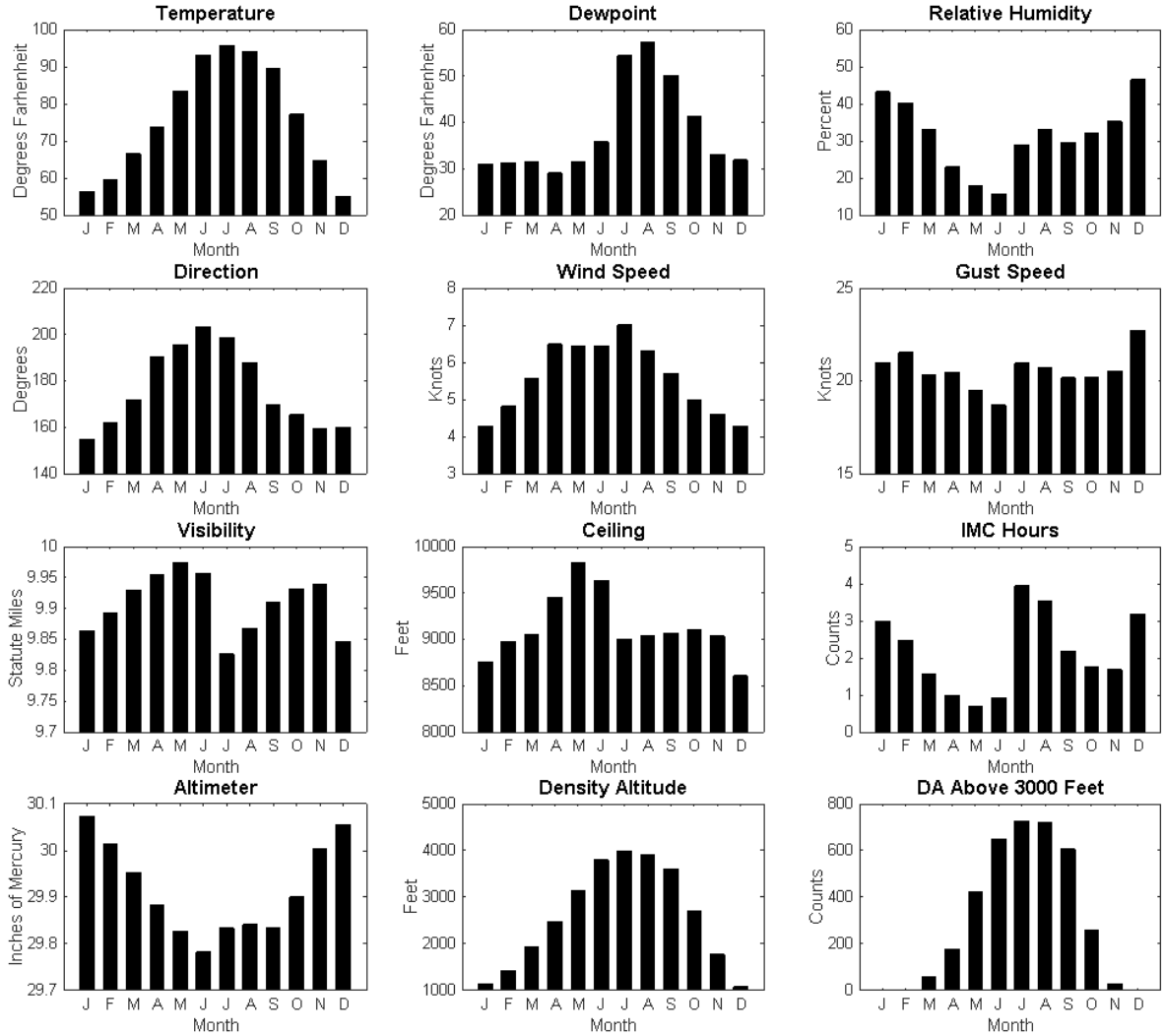


Figure 6.A.49. PHX monthly averages for METAR and derived values.

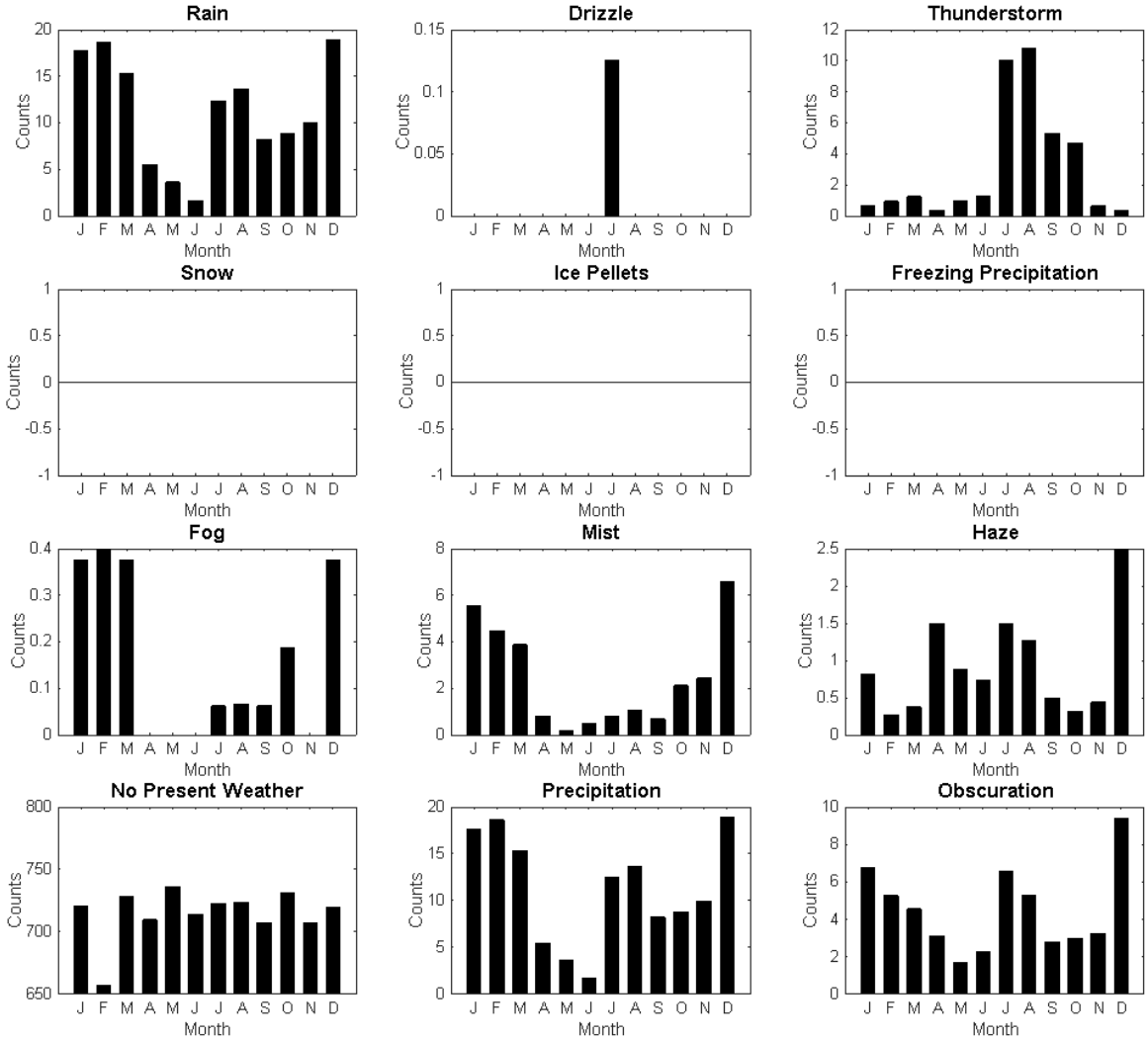


Figure 6.A.50. PHX monthly average counts for observed weather phenomena.

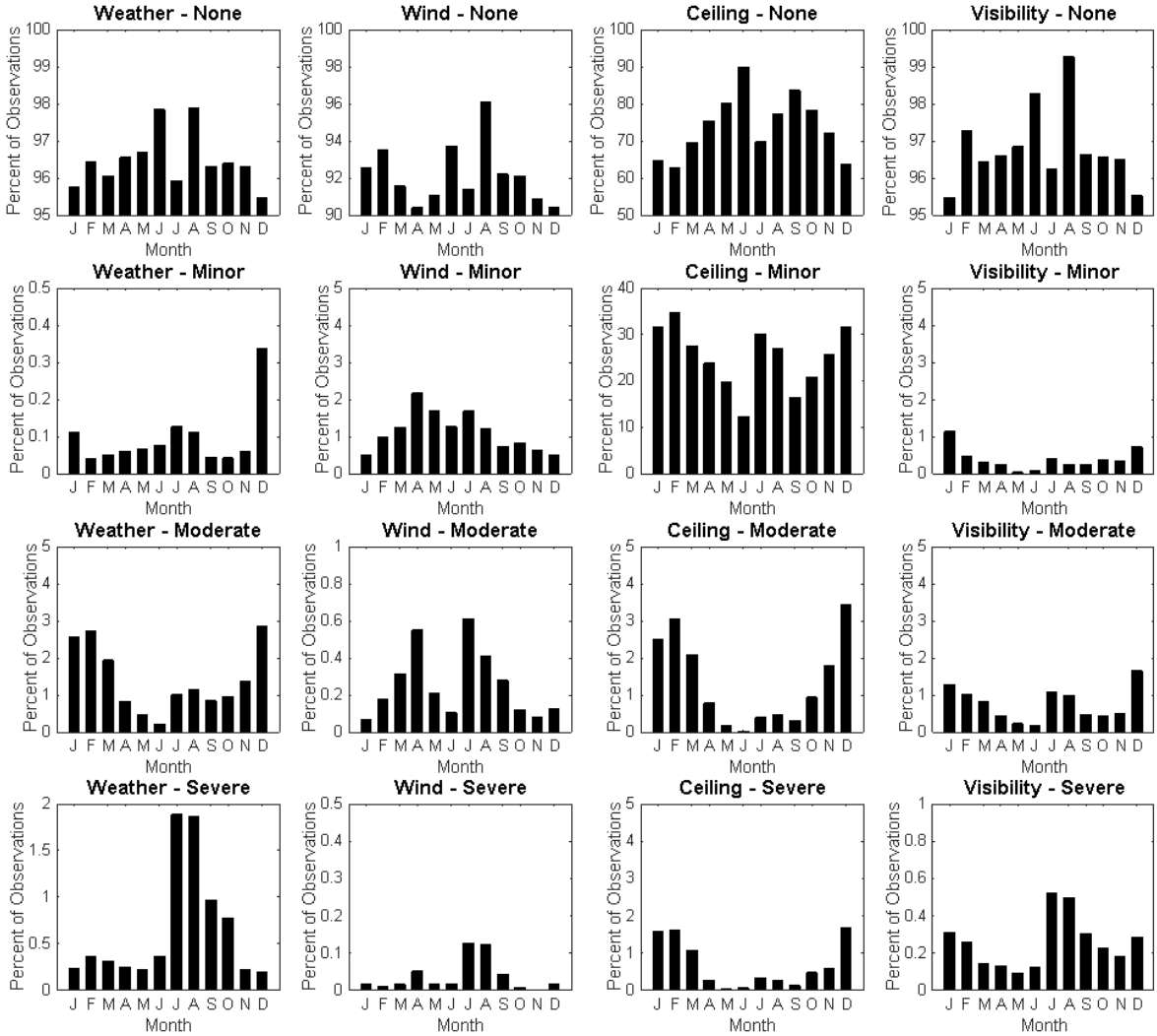


Figure 6.A.51. PHX monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

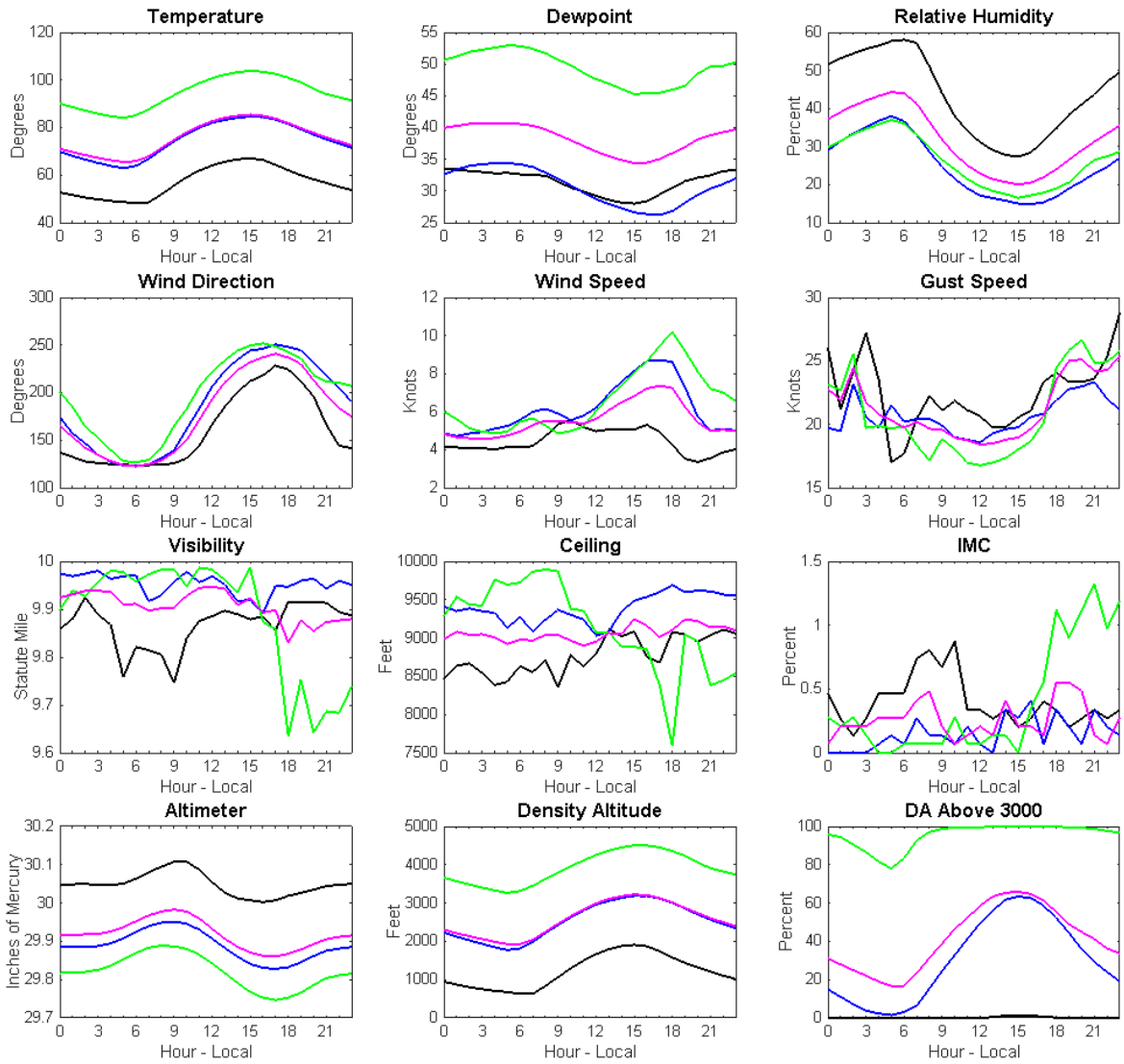


Figure 6.A.52. PHX diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

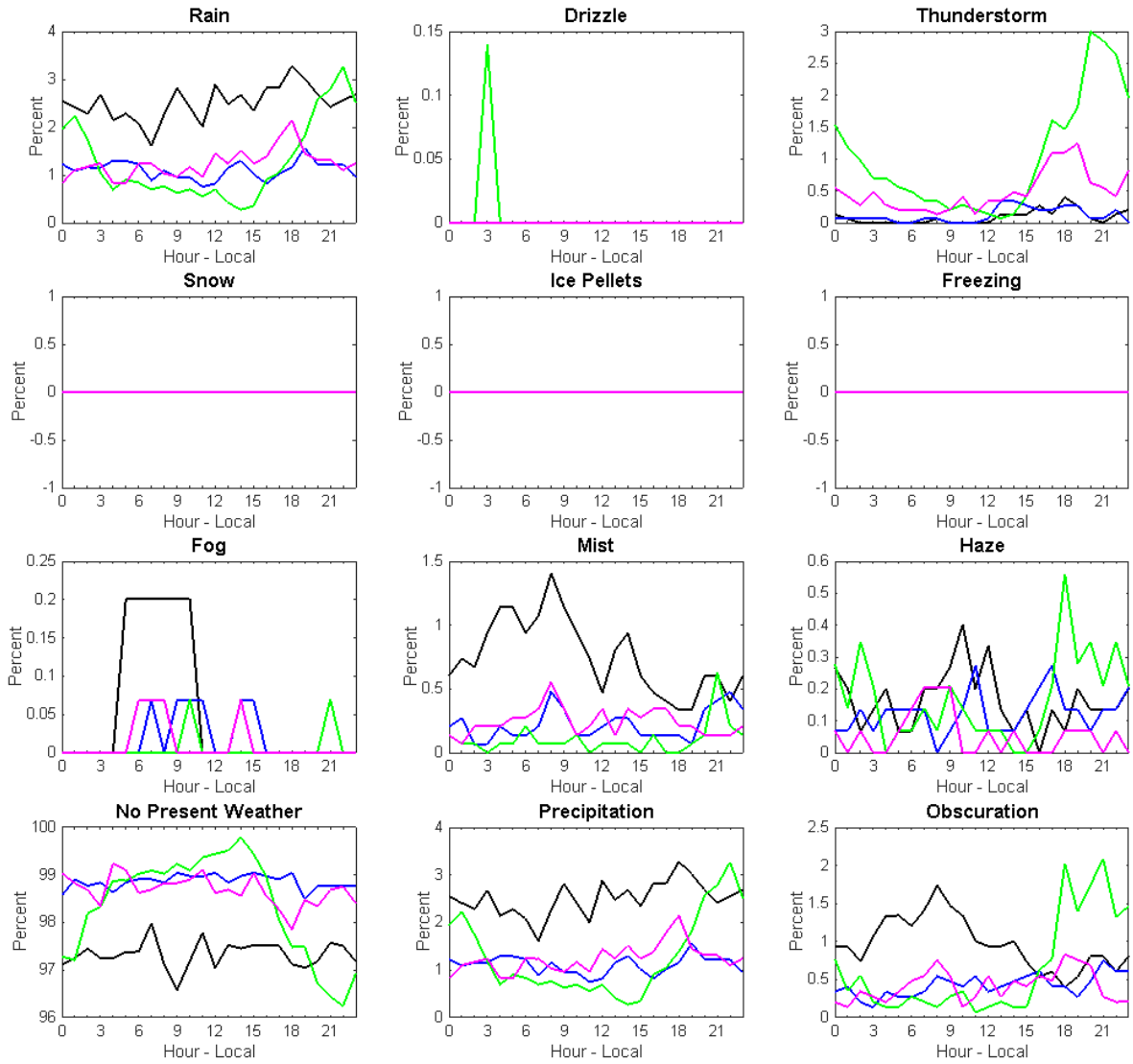


Figure 6.A.53. PHX seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

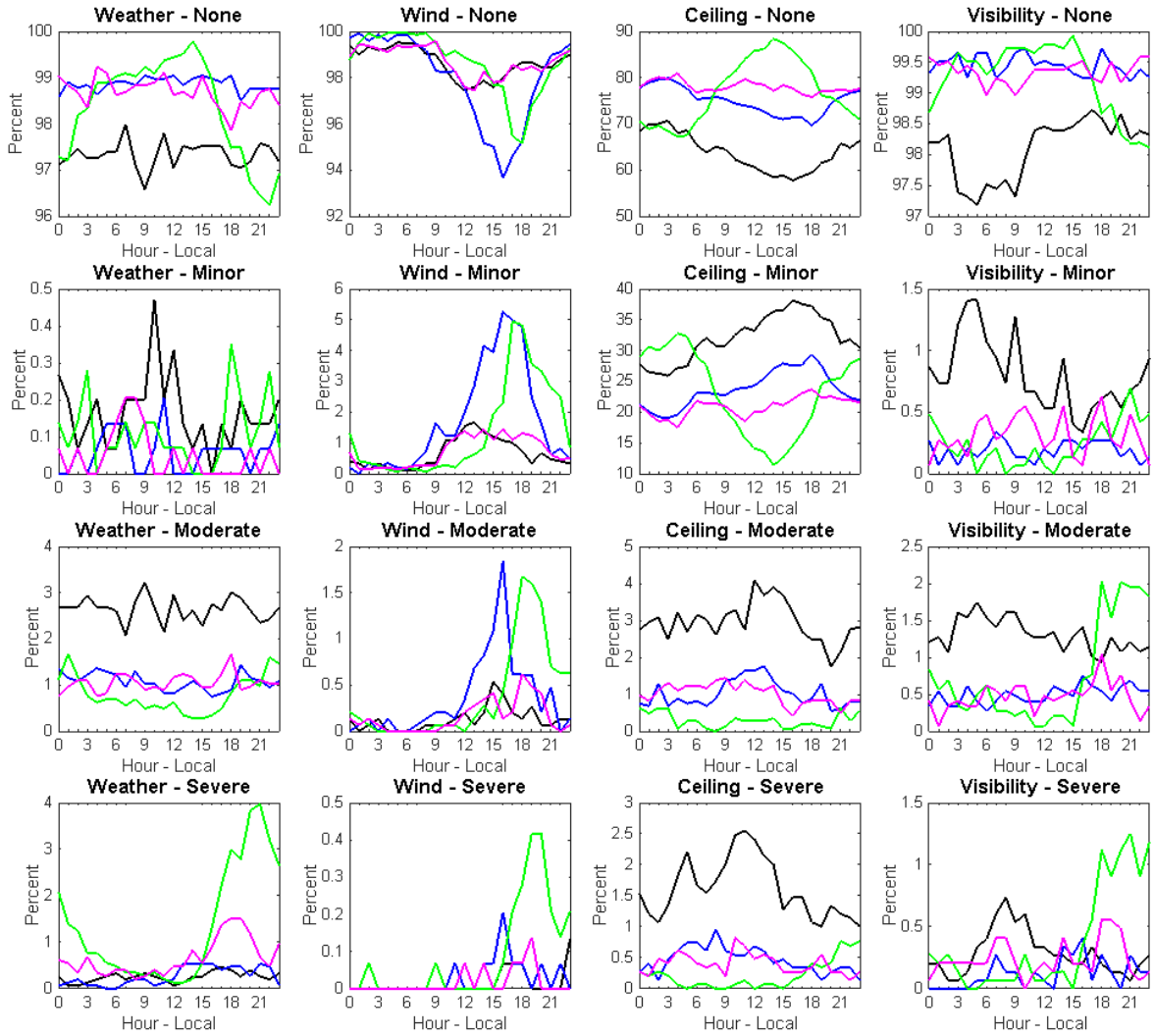


Figure 6.A.54. PHX seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

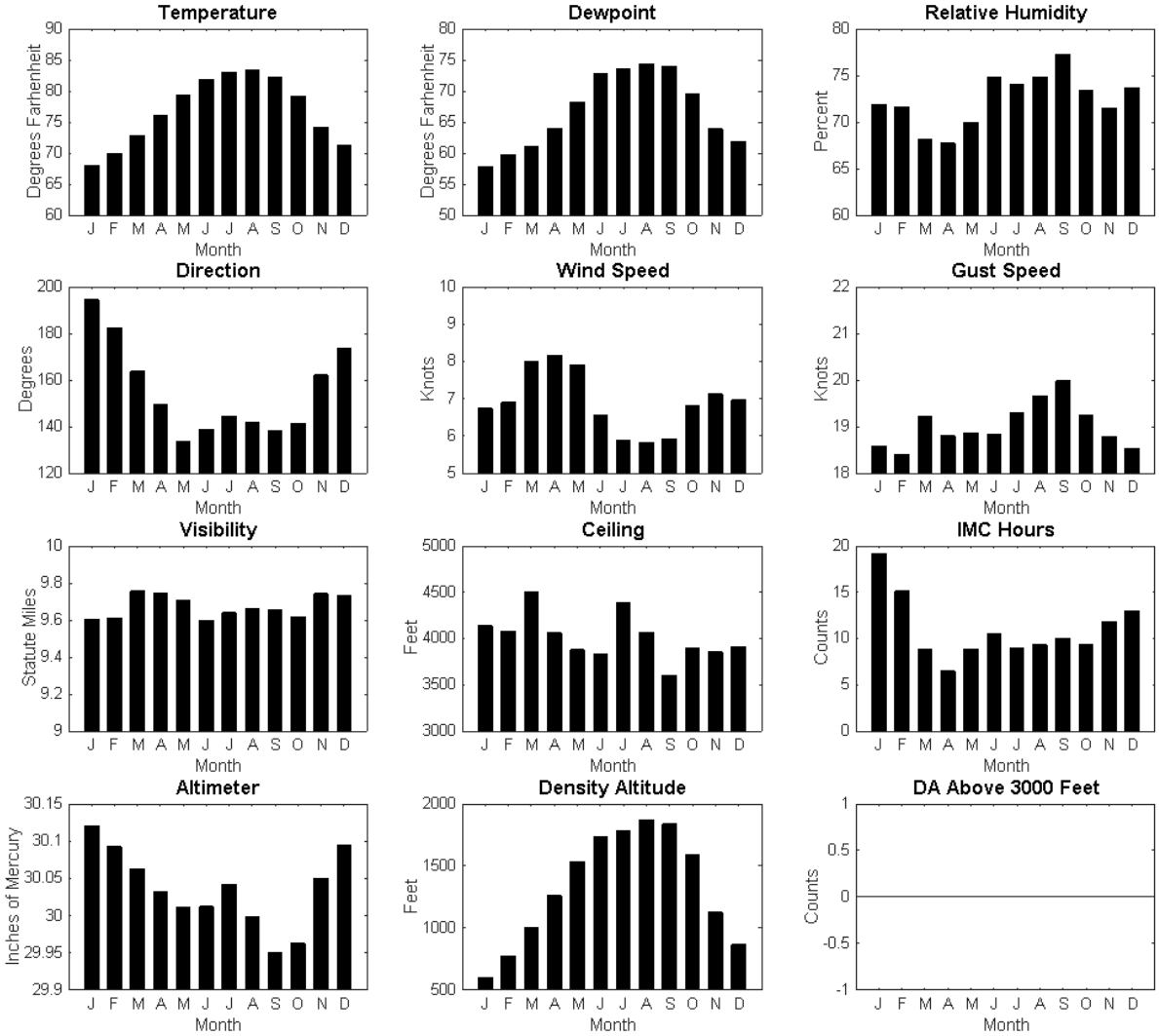


Figure 6.A.55. MIA monthly averages for METAR and derived values.

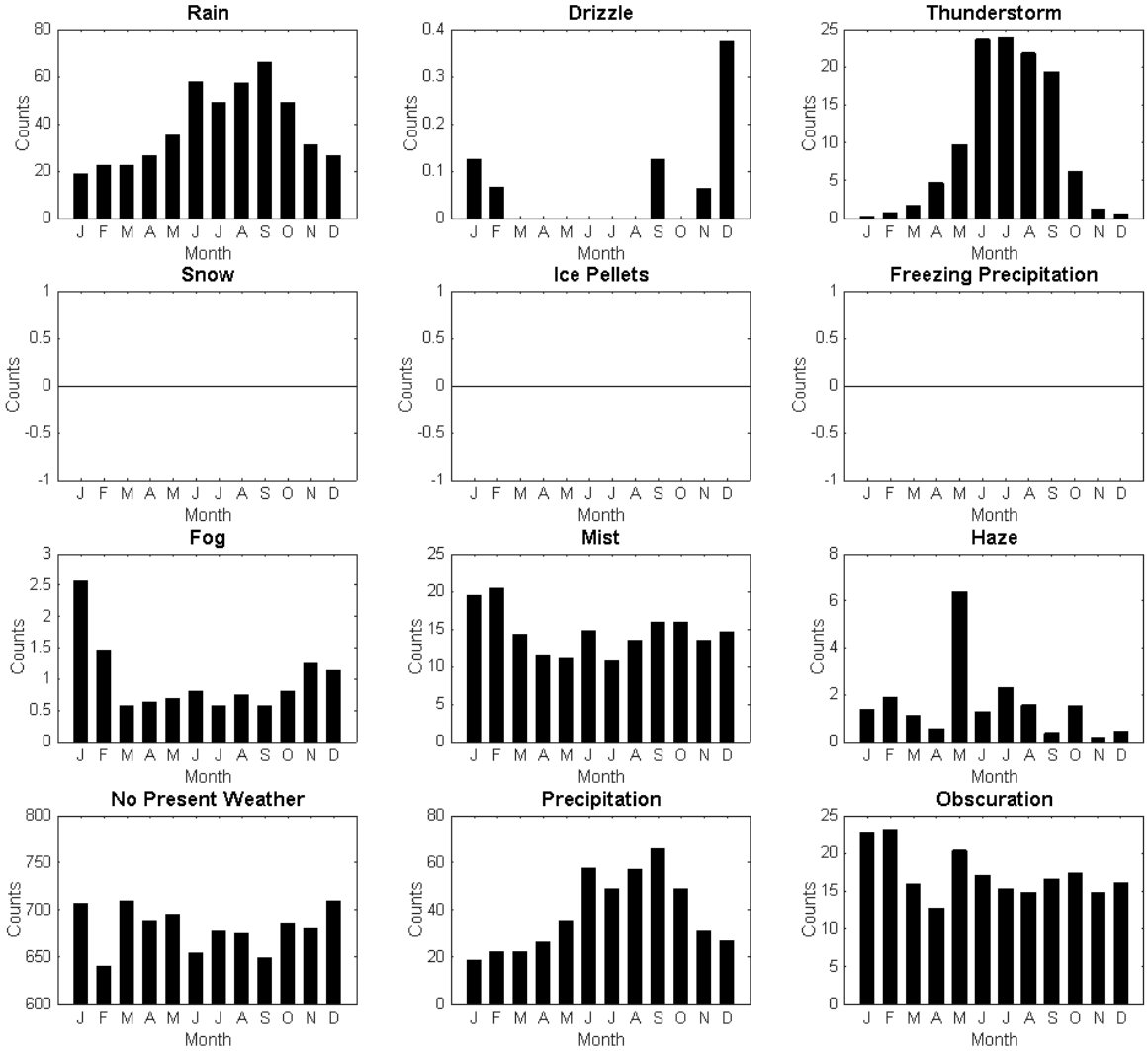


Figure 6.A.56. MIA monthly average counts for observed weather phenomena.

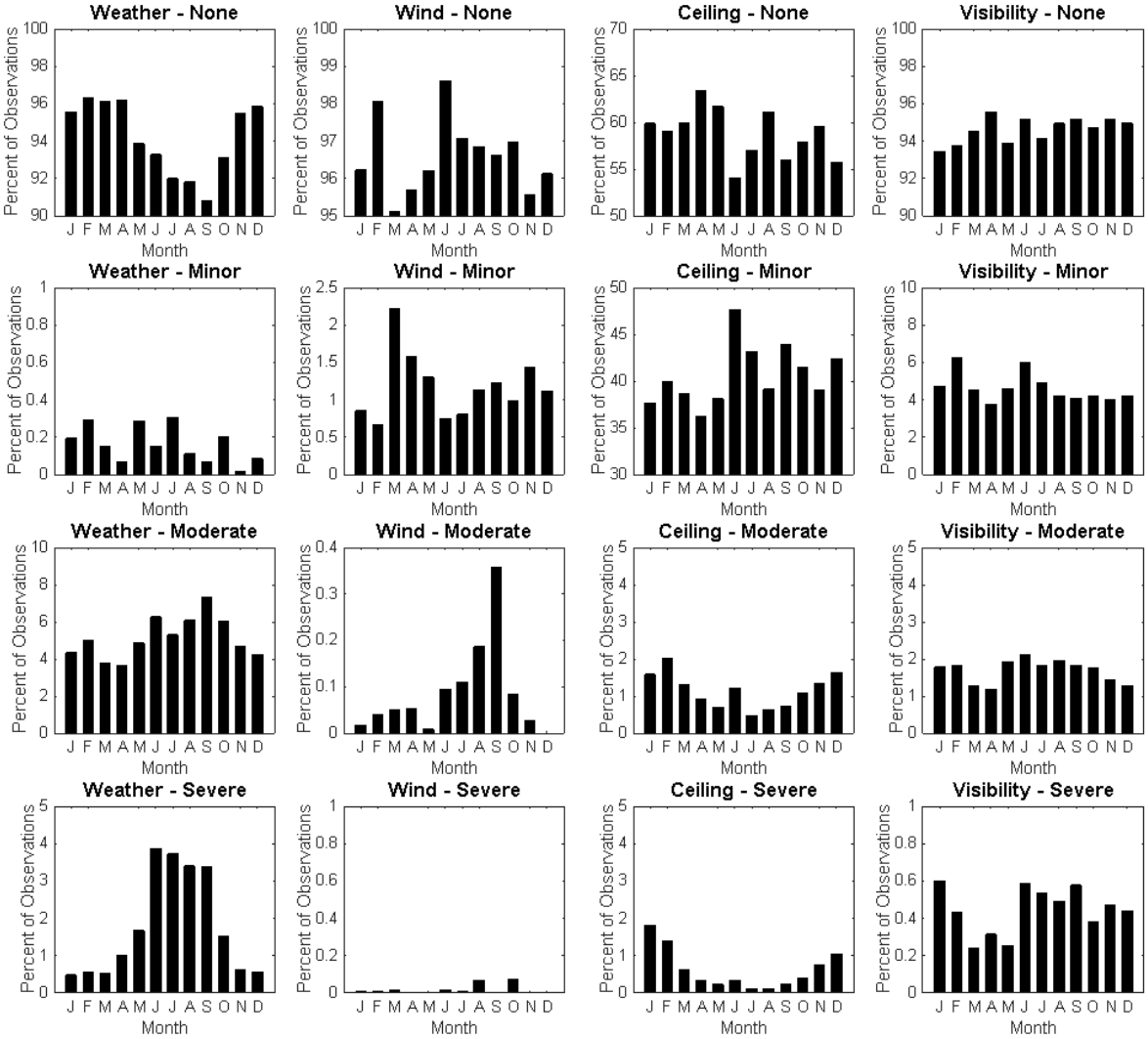


Figure 6.A.57. MIA monthly average percent of observations for weather, wind, ceiling height, and visibility severity impacts.

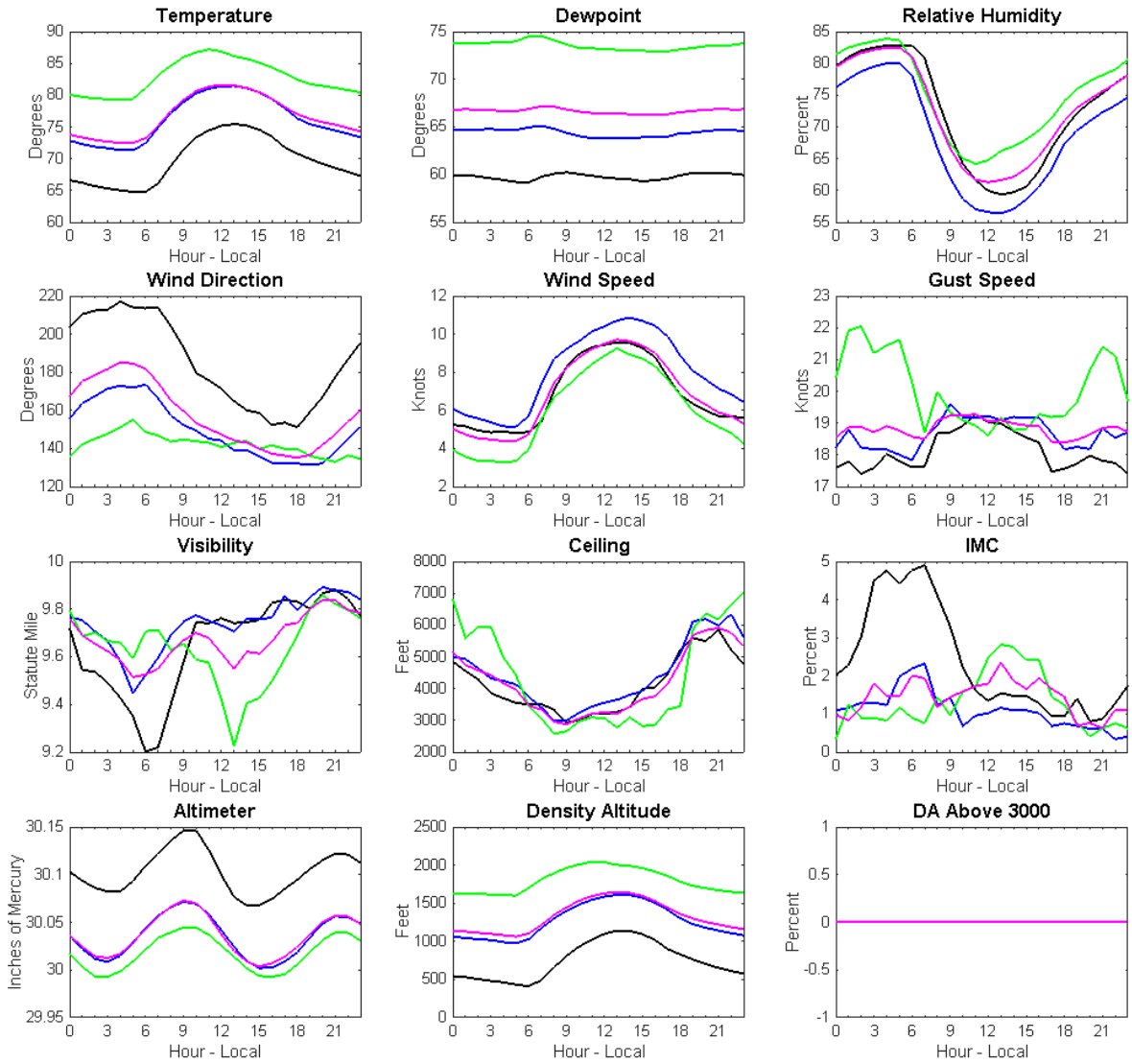


Figure 6.A.58. MIA diurnal, seasonal averages for METAR and derived values. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

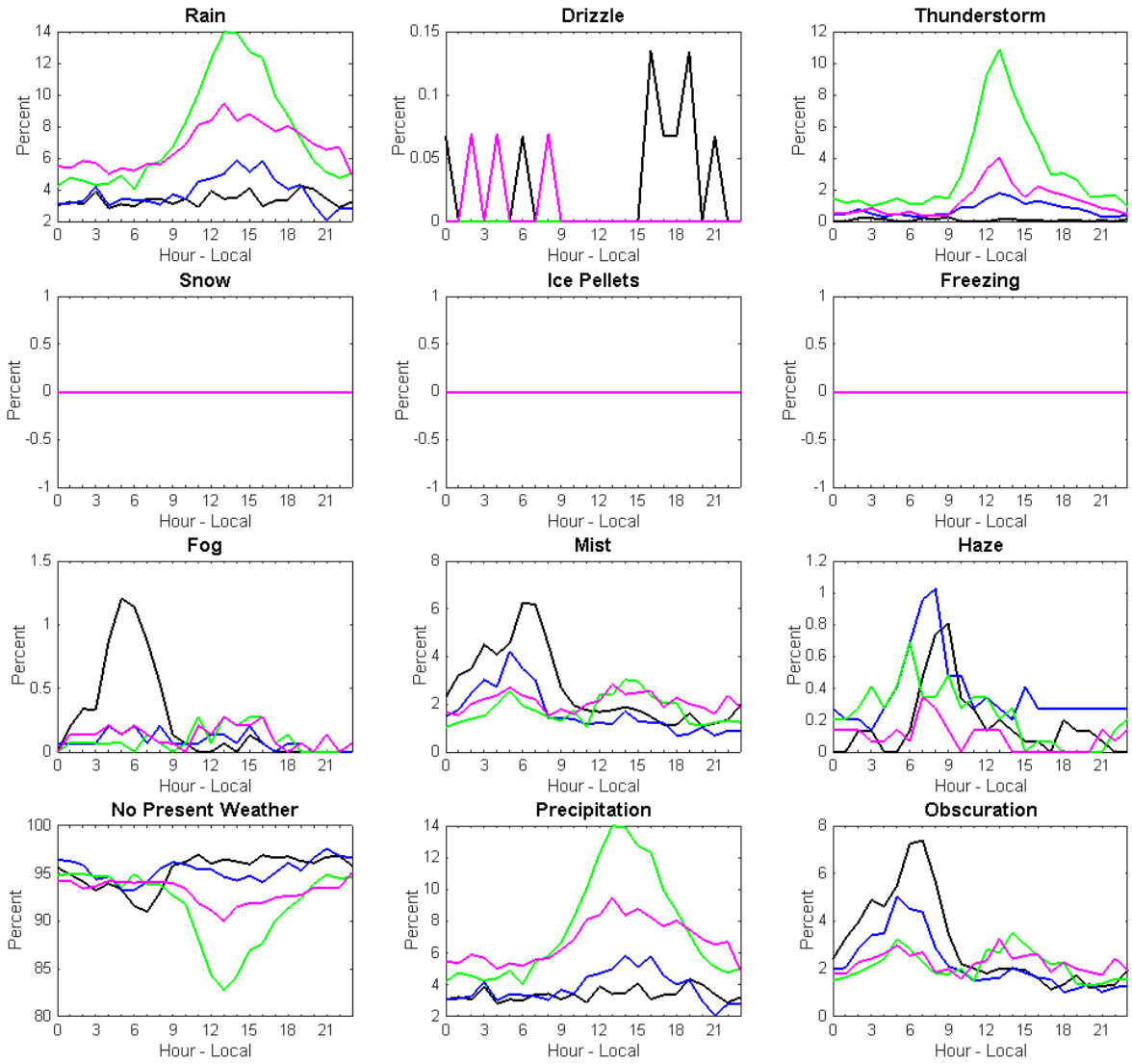


Figure 6.A.59. MIA seasonal, diurnal average percent of observation for observed weather phenomena. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

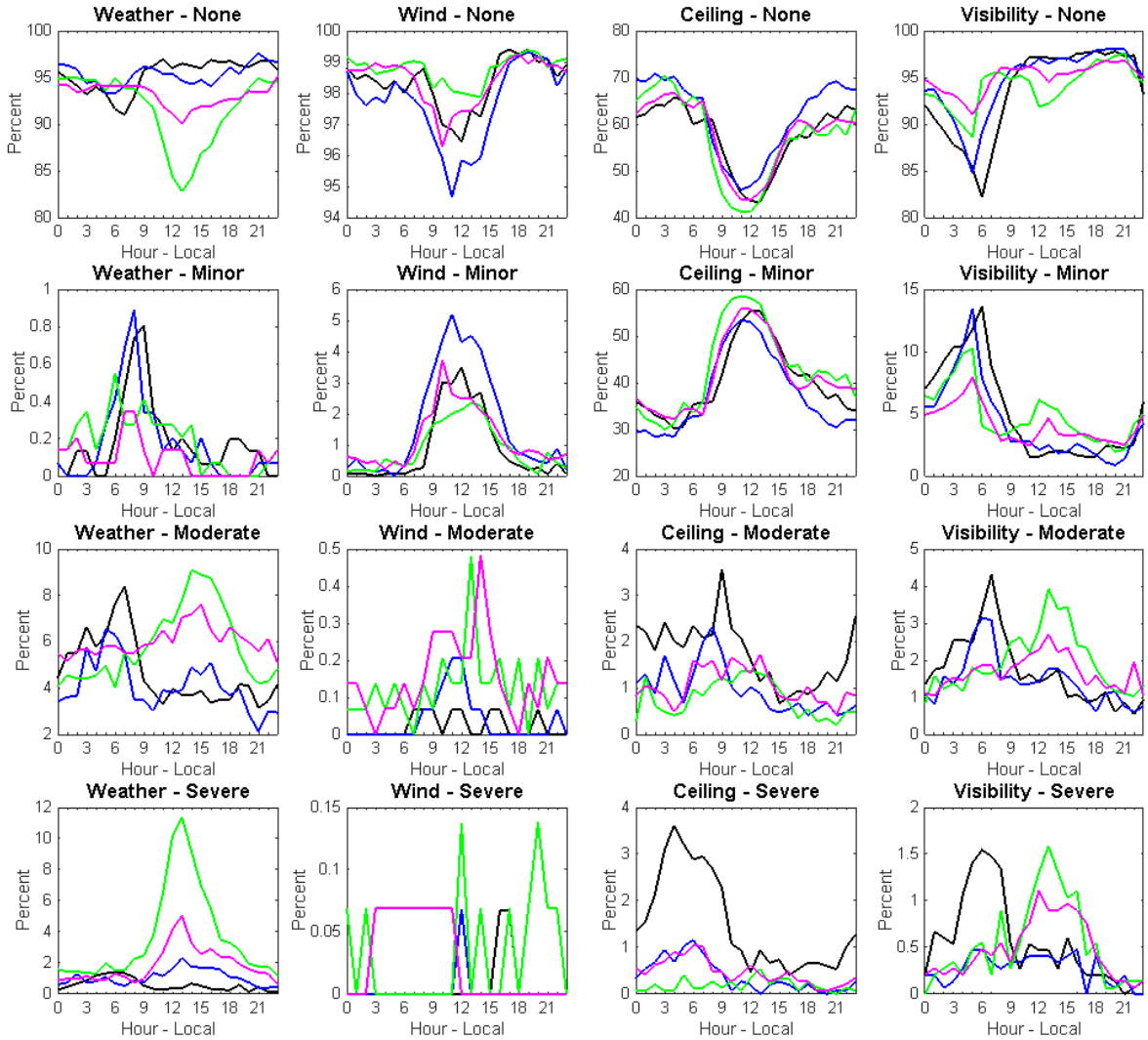


Figure 6.A.60. MIA seasonal, diurnal percent of observations of weather, wind, ceiling height, and visibility impact severity scores. The black line indicates December, January, and February (DJF) season. The blue line indicates the March, April, and May (MAM) season. The green line indicates the June, July, and August (JJA) season. The magenta line indicate the September, October, and November (SON) season.

APPENDIX IV: Aviation Definitions

1. RTO = Rejected Takeoff

2. V1 = The maximum speed in the takeoff at which the pilot must take the first action (e.g., apply brakes, reduce thrust, deploy speed brakes) to stop the airplane within the accelerate-stop distance. V1 also means the minimum speed in the takeoff, following a failure of the critical engine at VEF, at which the pilot can continue the takeoff and achieve the required height above the takeoff surface within the takeoff distance.

3. V2 = Takeoff safety speed. The speed at which the aircraft may safely be climbed with one engine inoperative.

4. VEF = The speed at which the critical engine is assumed to fail during takeoff.

5. VEVENT = The speed at which failure is assumed to fail during takeoff.

6. VLOF = Lift-off speed

7. VR = Rotation speed

* Definitions taken from the CFR Title 14, Chapter 1, Subchapter A, Part 1 “Definitions and Abbreviations”.

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