**Key Scientific Principles By Chapter – Introductory (Primer) Chapters**

Chapter 2

2.1 **Atmospheric pressure** is the weight of the overlying atmospheric gasses, per unit surface area.

2.2 Pressure decreases rapidly with altitude in the lowermost atmosphere, and less rapidly at higher levels (this variation describes an exponential decrease with height).

2.3 Differences in atmospheric pressure across a horizontal distance give rise to the **pressure gradient force**, which accelerates air from high toward low regions of pressure – creating wind.

2.4 On a surface weather chart, **isobars** are drawn as contour lines of constant pressure, typically spaced every 4 mb. The more closely spaced the isobars, the stronger the wind.

2.5 The **Coriolis Effect** arises from the spinning Earth; it deflects air that begins to move, to the right, in the Northern Hemisphere.

2.6 The **geostrophic wind** is a balanced state between the pressure gradient force and Coriolis effect; this wind moves at constant speed, in a straight path, above the surface.

2.7 Horizontal variations in atmospheric temperature, over long distances, give rise to a horizontal pressure gradient force (low pressure is associated with warm air, high pressure with cold, dense air).

2.8 A system of global atmospheric winds, called the **atmospheric general circulation**, arises from a strong imbalance in radiational heating between the equator and poles. There are several components to the general circulation, in the tropics, mid-latitudes and polar regions.

2.9 The tropical **Hadley cells** circulate warm, equatorial air toward the higher latitudes; these cells give rise to tropical easterly winds (trade winds), the ITCZ, subtropical anticyclones, and the subtropical jet stream.

2.10 The **Intertropical Convergence Zone (ITCZ)** is where easterly trade winds from each hemisphere converge, near the equator, causing air to rise. This forms a nearly continuous belt of showers and thunderstorms, often organized into large clusters of storms.

2.11 **Subtropical anticyclones** (high pressure cells) are situated near 30 N and S; these cells are formed by air descending on the periphery of the Hadley cells. As the air descends, it warms and dries, creating large cloud-free zones.

2.12 The **subtropical jet stream** forms in in the upper atmosphere, in each hemisphere; it forms when poleward-moving air, exiting the Hadley cell, becomes deflected toward the east by the Coriolis Effect.

2.13 Mid latitude circulation features of the atmospheric general circulation include: The polar front, polar jet stream, extratropical cyclones and anticyclones.

2.14 The **polar front** is a deep, wave-like discontinuity between tropical and polar air masses, lying across the mid latitudes. Extratropical cyclones frequently develop from waves along this boundary.

2.15 The **polar jet stream** develops along the polar front, at high altitudes. It is maintained by the strong north-south temperature gradient across the polar front. The polar jet constantly develops large meanders (Rossby waves) that are inherently unstable, tied to formation of extratropical cyclones and anticyclones near the surface.

2.16 The upper-atmosphere **polar vortex** and band of deep, **polar easterlies** are found above the Arctic Circle in each hemisphere.

2.17 **Extratropical cyclones** and **anticyclones** are large, transient vortices that migrate from west to east across mid latitudes. Air converges in a counterclockwise spiral around these cyclones, which feature low pressure in their core (“L” on a weather map). Air diverges in a clockwise spiral around anticyclones, with high pressure in the core (“H” on a weather map). These systems bring changeable weather (extremes in temperature, precipitation, fair weather) to most mid-latitude locations.

2.18 Around extratropical cyclones and anticyclones, a type of circular wind called the **gradient wind** develops as a consequence of the pressure gradient, Coriolis effect and **centripetal** (inward-directed) **force**.

2.19 Near the surface, the **friction force** creates an imbalanced flow in the gradient wind, causing air to spiral inward toward the center of an extratropical cyclone, and away from the center of an extratropical anticyclone.

2.20 The principle of **mass conservation** requires that air that spirals inward toward the center of an extratropical cyclone to rise, and air that spirals outward in an extratropical cyclone to draw down air from above.

2.21 The meanders in the jet stream, called Rossby waves, take the form of **troughs** (equatorward-curved segments) and **ridges** (poleward-curved segments). Cold, polar air moves south in a trough, while warm, tropical air moves north in a ridge.

2.22 Air flowing through a trough in the jet stream is **subgeostrophic** (slower than geostrophic). As the air moves away from the trough it accelerates (diverges); this effect draws up air from the surface (via the **principle of mass conservation**), leading to the development of a large region of low pressure, and subsequent formation of an extratropical cyclone.

2.23 Air rising in the core of an extratropical cyclone cools and becomes saturated, leading to widespread cloud cover and precipitation (i.e. a storm) within the cyclone.

2.24 Air flowing through a ridge in the jet stream is **supergeostrophic** (faster than geostrophic). As the air moves away from the ridge it deaccelerates (converges); this effect causes air to descend toward the surface (via the **principle of mass conservation**), leading to the development of a large region of high pressure, and subsequent formation of an extratropical anticyclone.

2.25 Air sinking in the core of an extratropical anticyclone warms and becomes unsaturated, leading to widespread fair weather and generally clear skies.

2.26 In an extratropical cyclone, **fronts** develop in the lower atmosphere where contrasting air masses (i.e. tropical and polar) are drawn together. The warm, buoyant air is forced to ascend vigorously along fronts, developing bands of deep cloud, heavy precipitation, and sometimes severe weather.

2.27 A **tropical cyclone** (**hurricane** in the Atlantic, **typhoon** in the Pacific) is an intense cyclonic vortex in the tropics, with a compact, inner core of extremely low pressure. Very strong winds around the low are in a state of **cyclostrophic balance** between the pressure gradient force and outward-directed **centrifugal force**.

2.28 A **tornado** is the most intense type of cyclonic vortex, typically less than a half-mile across, and generated within a severe, rotating thunderstorm called a **supercell.** Its winds, which may top 300 mph, are in a state of cyclostrophic balance.

2.29 Regional and local wind systems are driven by uneven heating of the atmosphere. These winds include the sea breeze, mountain/valley breeze, nocturnal low-level jet, and North American Monsoon. Under certain conditions, thunderstorms develop along a narrow zone of rising air in each case.

2.30 The **sea breeze** develops between heated land and cooler, adjacent ocean water during the daytime. It is a shallow circulation cell with rising air over the land, and sinking air over the ocean.

2.31 The **mountain/valley breeze** is created by strong heating of sloped, elevated terrain during daytime. Air rises from the valley floor, up the mountain, creating a steady wind. At night, the elevated land cools more strongly than the surrounding air, causing a cold, dense air flow to settle into the valley floor.

2.32 The **nocturnal low level jet** is a wind current of the Great Plains. It is a narrow, elongated ribbon of air that blows moist, unstable air from the Gulf of Mexico northward over the Plains – leading to large complexes of heavily-raining thunderstorms, and frequent severe weather.

2.33 The **North American summer monsoon** is a seasonal (summertime) wind pattern that develops over the U.S. Desert Southwest and adjoining portions of northern Mexico. The large expanse of exceptionally hot air develops a zone of low pressure, which accelerates airflow from the Gulf of California northward. Late afternoon and evening thunderstorms blossom in this unstable air mass across Arizona, New Mexico, Utah, Nevada and Southern California from June through September.

Chapter 3

3.1 **Atmospheric humidity** is any measure of the amount, concentration, ratio or percentage of water vapor in the air.

3.2 **Evaporation** is a change in phase of water from liquid to vapor, requiring the input of heat (**latent heat of evaporation**) from a free water surface, or the air. Evaporation varies as a function of temperature, in an exponential manner i.e. warmer temperatures can evaporate vastly larger amounts of vapor than cooler air.

3.3 **Transpiration** is the diffusion of water vapor into the air from small openings in leaf surfaces from grass, trees, corn stalks, etc.

3.4 Air becomes **saturated** when the maximum amount of water evaporates into the air, from a free water surface; any further increase in vapor mass will lead to condensation.

3.5 Air can become saturated in two ways: (1) cool the air, while holding the amount of water vapor constant; and (2) evaporate additional vapor into the air, while holding air temperature constant.

3.6 The **dew point temperature** is that temperature at which air must be cooled in order to reach saturation. Dew point temperature is proportional to the amount of vapor mass in the air.

3.7 The dew point temperature commonly decreases with increasing latitude and altitude across the U.S., and reaches higher values during the summer than during winter. It is largest along the Gulf Coast states during summer, and lowest at high elevations in the Desert Southwest during winter.

3.8 The **relative humidity** is a percentage expressing how close the air is to saturation. It is the ratio of the amount of vapor in the air, to the maximum amount of vapor if the air were saturated. Relative humidity depends on *both* vapor content and air temperature.

3.9 Throughout a 24-hr period, relative humidity varies strongly with the change in air temperature (assuming constant values of vapor content); it reaches its highest value in the early morning, when the air is coolest, and its lowest value during the late afternoon during high temperature.

3.10 The most common way that air cools to saturation involves the ascent, expansion and **adiabatic cooling** of a humid air parcel. Adiabatic cooling comes about as an expanding parcel loses internal energy. The parcel cools at a rate of 10 C/km of ascent (as long as it remains unsaturated).

3.11 Four ways that moist air can be lifted to saturation include isolated rising bubbles or **thermals**, **orographic lift** (forced ascent up a mountain slope), **frontal uplift**, and **convergence of air** into a region of low pressure.

3.12 Air that has been lifted becomes slightly **supersaturated** before the first condensed cloud droplets form, on the order of 100.1% to 100.5%.

3.13 Condensation describes the phase change of water vapor, in supersaturated air, to liquid cloud droplets. The surrounding air is warmed by the release of **latent heat of condensation.**

3.14 The formation of microscopic cloud (or fog) droplets requires a slight amount of supersaturation and the presence of **cloud condensation nuclei**, which serve as tiny “staring points” upon which a small sphere of liquid water can condense.

3.15 Growth of microscopic cloud droplets to macroscopic, precipitating size occurs rapidly by a chain-reaction (unstable) type of process within the cloud, termed **collision-coalescence** (**warm cloud process**).

3.16 Cloud droplets and rain drops commonly exist in a **supercooled** state, remaining liquid down to temperatures of -40 C.

3.17 Between temperatures of 0 C and -40 C, thick clouds contain a mixture of liquid (supercooled) and frozen forms of precipitation; the layer is termed the **mixed-phase region** and it plays a critical role in the electrification of thunderclouds and formation of hail inside thunderstorms.

3.18 In the very cold, upper regions of a summertime thundercloud, or in the shallow, layered clouds of winter, microscopic ice crystals in sub-freezing air develop when vapor deposits directly onto microscopic **ice condensation nuclei**. This process is termed **vapor deposition**.

3.19 Snowflakes in a sub-freezing cloud commonly develop when ice crystals **aggregate** or clump together, while being jostled by turbulent air motions, settling through the cloud or being lifted by rising air.

3.20 When a mixed phase region of the cloud contains abundant supercooled water, small, conical ice particles called **graupel** develop from a process called **riming** (accretion and instant freezing of liquid water onto a tiny ice grain). Continued growth of graupel to **hailstones** occurs when a strong cloud updraft levitates ice particles within the mixed phase region for long periods of time.

3.21 The **cold cloud processes** in subfreezing clouds, described by vapor deposition, aggregation and riming, lead to a significant production of rain in cloud systems during both summer and winter; the rain forms as descending ice particles (crystals, snowflakes, graupel, hail) melt upon encountering a warm air layer above the surface.

3.22 **Air mass stability** describes the tendency for a deep air mass to spontaneously “overturn” – that is, the tendency for parcels of warm air to rise away from the surface, and keep rising, through a deep layer.

3.23 An **unstable atmosphere** is one in which parcels of warm air can rise to high levels, promoting the formation of convective showers and thunderstorms.

3.24 **Convection** describes vertical currents of air, in which a buoyant thermal or updraft rises through a deep layer, and a downdraft of cooler air sinks back toward the surface. A thunderstorm or **cumulonimbus cloud** is the deepest, most vigorous form of convection in an unstable atmosphere.

3.25 **Convective rain** describes heavy showers, or cloudbursts, generated by deep convective clouds and thunderstorms. This type of rain tends to be spotty (isolated) and intense, lasting only for brief periods (tens of minutes), and characteristic of summertime weather systems across the U.S.

3.26 A **stable atmosphere** is one in which surface-based air parcels lack buoyancy to rise spontaneously; moist parcels may be forced upward, for short distances, reach saturation and form extensive layers of shallow cloud.

3.27 **Stratiform precipitation** describes rain or snow falling from stable, horizontally-oriented cloud layers (**nimbostratus**) that cover widespread areas. The precipitation tends to be moderate or light, and often persists for many hours.

3.28 Atmospheric stability is assessed from weather balloon data. The vertical change of air temperature, called the **atmospheric lapse rate**, is compared to the adiabatic lapse rate of a rising air parcel, at many levels.

3.29 To more completely describe whether a rising air parcel is stable or unstable, the adiabatic lapse rate must be adjusted once the parcel achieves saturation. Above the saturation level, the adiabatic lapse rate changes to -6 C/km (on average), because the cooling due to expansion is partly compensated by the release of latent heat of condensation.

3.30 The atmosphere commonly **destabilizes** (becomes more unstable through a deep air layer) from two processes: (1) strong surface heating from the Sun (mid-late afternoon) or arrival of a warm air mass near the surface; and/or (2) strong cooling or arrival of a cold air mass in the upper air layers.

3.31 During the cool season (October through April), extratropical cyclones are the dominant precipitation-producing weather systems over much of the U.S. These large, traveling storms in a stable atmosphere create regions of stratiform precipitation, often heaviest along fronts.

3.32 Cloud and precipitation features of a typical extratropical cyclone, as seen from satellite or weather radar, include the **comma head**, **cold frontal rainband**, **dry slot**, and **warm frontal rain shield**. Heavy rain and/or thunderstorms occasionally develops in the more unstable **warm sector** of the storm system, ahead of the cold front, and fed by a deep river of moist air termed the **warm conveyor belt**.

3.33 During the warm season (May through September), summertime precipitation-generating weather systems are more convective in nature, developing in an unstable atmosphere. The **Bermuda High**, a subtropical anticyclone located across the Atlantic Ocean, pumps high-dewpoint air across the eastern two thirds of the U.S.

3.34 Convective, flash-flood generating complexes of summertime include **mesoscale convective complexes (MCCs), derechos, squall lines** and clusters of orographic thunderstorms; many of these systems also generate other forms of severe weather including tornadoes, damaging wind gusts and large hail.

Chapter 4

4.1 The **synoptic weather map** is a surface chart showing weather patterns across the U.S., or North America, with all observations analyzed at the same time (typically every 3 hours). The **synoptic scale** captures large-scale weather patterns and air motions, i.e. up to several 100 to a few 1000 km horizontal dimension, over time frames of 12-24+ hours i.e. jet stream waves and extratropical cyclones.

4.2 **Upper air analysis charts** are synoptic maps depicting temperature, humidity and wind patterns, every 12 hours, based on data collected from **radiosonde** launches. Analyzed levels typically include 1.5 km, 3 km, 5.5 km and 10 km.

4.3 The **mesoscale** is an intermediate scale of motion, smaller than synoptic scale, with horizontal dimensions of 10 to a few 100 km, and timescales of 1-6 hours. Mesoscale processes are more difficult to observe, requiring an increased density of observations; common mesoscale weather systems include fronts, hurricanes, squall lines and clusters of thunderstorms.

4.4 **Radiosondes** collect upper atmospheric observations including pressure, temperature, humidity and winds (based on GPS). These balloon-borne instrument packages transmit their data in real-time to a ground receiver.

4.5 Weather and environmental satellites use **remote sensing instruments** to collect information about atmospheric structure, composition, cloud patterns, winds and surface characteristics such as ocean temperature and wind speed.

4.6 **Geostationary weather satellites** orbit the Earth at such a high altitude that their revolution is synchronized with Earth’s spin; they thus view the same portion of the planetary disc. **Polar orbiting satellites** utilize a much lower orbit, and collect data across narrow transects, orbiting the Earth every 90 minutes.

4.7 Satellite remote sensors exploit different energy wavelengths of the **electromagnetic spectrum**, which includes the visible, infrared and microwave channels. Visible light provides high resolution images of clouds over the daylight side of the Earth; infrared provides thermal imaging of cloud tops (and thus cloud top height) during all hours of the day; and microwave can “see” through cloud layers, revealing patterns and intensity of precipitation.

4.8 **Weather radar** is a type of ground-based remote sensing tool. The radar antenna emits rapid, short pulses of microwave energy as it sweeps out an arc through the atmosphere. Precipitation particles (rain drops, snowflakes, hailstones) scatter some of the energy back to the antenna; computers compute the distance to the precipitation and estimate its intensity.

4.9 Most radars use the **Doppler principle** to estimate wind speed and direction, along the radar beam. Pulses of radar energy transmitted at a fixed frequency are phase-shifted toward or away from the radar, based on the horizontal speed of precipitation particles embedded in the moving air.

4.10 Modern radars have acquired **polarimetric capability**, which transmits energy pulses in horizontally and vertically polarized orientations. By comparing how much scattered energy is returned in the horizontal vs. vertical directions, these radars can better discriminate among different types of precipitation i.e. large, oblate (flattened) rain drops vs. spherical hailstones.

4.11 **Lightning detection networks** such as the National Lightning Detection Network (NLDN) can accurately locate and assign precise timing to individual lightning strokes, between cloud and ground, across the U.S. Smaller networks called Lightning Mapping Arrays (LMAs) provide higher resolution measurements over small, experimental areas, and can map total lightning (intracloud plus cloud to ground), lightning power and polarity.

4.12 **Numerical Weather Prediction (NWP)** is the highly advanced science of predicting future weather states using mathematical models of the atmosphere, and run on extremely fast supercomputers. **Data assimilation** – the process of gathering weather observations from a diverse set of measurement platforms and running exacting quality control measures – has become a powerful way of improving the accuracy of the forecast models.

4.13 There a great many types of forecast models run by many government agencies and universities. **Medium-range prediction models** include the U.S. Global Forecast System (GFS) and European Center for Medium Range Weather Forecasting (ECMWF); these are run 2-4 times a day, simulating time periods of 7-10 days.

4.14 The **short range forecast models** trade length of simulation for higher space and time resolution, so mesoscale processes can be more accurately predicted. These models include the U.S. North American Model (NAM) and High Resolution Rapid Refresh (HRRR) models.

4.15 Modern NWP now includes ways to better understand the uncertainty in forecasts. Most models now generate a series of **ensemble forecasts**, which shows how weather patterns respond to slight yet unavoidable errors in the data used to prescribe the starting (initial) state of the models. This is used to establish the degree of confidence in a particular model simulation.

4.16 U.S. weather forecasting falls under the auspices of the **National Weather Service** (NWS), a branch of the National Oceanographic and Atmospheric Administration (NOAA). More than 100 **Weather Service Forecast Offices** (WSFOs) divide the country up into individual forecast zones.

4.17 NOAA has also established several specialty forecast centers, called the **National Centers for Environmental Prediction** (NCEP), which focus on a particular set of weather hazards, providing national coverage. Some of these centers include the **Tropical Prediction Center** (TPC) near Miami, Florida; the **Storm Prediction Center** (SPC) in Norman, Oklahoma; and the **Hydrometeorological Prediction Center** (HPC) in College Park, MD. The TPC tracks and forecasts tropical cyclones; SPC provides national forecasts of severe thunderstorms and tornadoes; and the HPC handles prediction of flash floods, heavy snow and ice.

4.18 NCEP centers such as the SPC issue watches for severe thunderstorms and tornadoes, which cover moderate-sized regions (portions of states) for time periods of 3-6 hours. **Watches** outline the *potential* for severe weather according to a tiered set of probability criteria. **Warnings** are more shorter (20-30 min) products, issued for local regions (portions of an individual county) once actual severe weather has been observed or detected by weather radar. Issuance of warnings is the responsibility of WSFOs.