Recent Advances in Meteorology

Julius Farr

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Introduction

Meteorology is the interdisciplinary scientific study of the atmosphere that focuses on weather processes and short term forecasting (in contrast with climatology). Studies in the field stretch back millennia, though significant progress in meteorology did not occur until the eighteenth century. The nineteenth century saw breakthroughs occur after observing networks developed across several countries. Breakthroughs in weather forecasting were achieved in the latter half of the twentieth century, after the development of the computer.

Meteorological phenomena are observable weather events which illuminate and are explained by the science of meteorology. Those events are bound by the variables that exist in Earth's atmosphere: They are temperature, air pressure, water vapor, and the gradients and interactions of each variable, and how they change in time. The majority of Earth's observed weather is located in the troposphere. Different spatial scales are studied to determine how systems on local, region, and global levels impact weather and climatology. Meteorology, climatology, atmospheric physics, and atmospheric chemistry are sub-disciplines of the atmospheric sciences. Meteorology and hydrology compose the interdisciplinary field of hydrometeorology. Interactions between Earth's atmosphere and the oceans are part of coupled ocean-atmosphere studies. Meteorology has application in many diverse fields such as the military, energy production, transport, agriculture and construction.

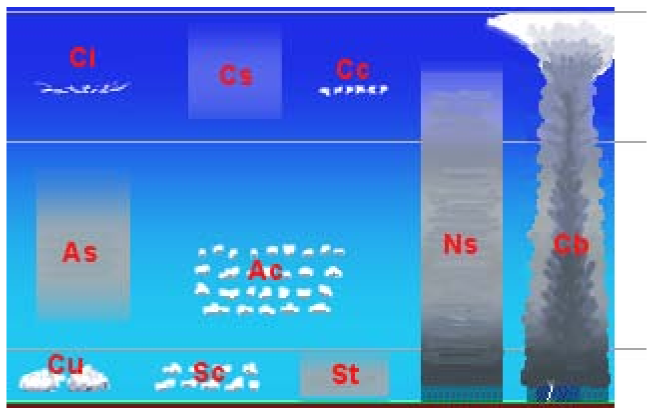
The word "meteorology" is from Greek μετέωρος, *metéōros*, "high in the sky"; and -λογία, *-logia*.

Atmospheric composition research

In 1648, Blaise Pascal rediscovers that atmospheric pressure decreases with height, and deduces that there is a vacuum above the atmosphere. In 1738, Daniel Bernoulli publishes *Hydrodynamics*, initiating the kinetic theory of gases and established the basic laws for the theory of gases. In 1761, Joseph Black discovers that ice absorbs heat without changing its temperature when melting. In 1772, Black's student Daniel Rutherford discovers nitrogen, which he calls *phlogisticated air*, and together they developed the phlogiston theory. In 1777, Antoine Lavoisier discovers oxygen and develops an explanation for combustion. In 1783, in Lavoisier's book *Reflexions sur le phlogistique*, he deprecates the phlogiston theory and proposes a caloric theory. In 1804, Sir John Leslie observes that a matte black surface radiates heat more effectively than a polished surface, suggesting the importance of black body radiation. In 1808, John

Dalton defends caloric theory in *A New System of Chemistry* and describes how it combines with matter, especially gases; he proposes that the heat capacity of gases varies inversely with atomic weight. In 1824, Sadi Carnot analyzes the efficiency of steam engines using caloric theory; he develops the notion of a reversible process and, in postulating that no such thing exists in nature, lays the foundation for the second law of thermodynamics.

Observation networks and weather forecasting



Cloud classification by altitude of occurrence

In 1654, Ferdinando II de Medici establishes the first *weather observing* network, that consisted of meteorological stations in Florence, Cutigliano, Vallombrosa, Bologna, Parma, Milan, Innsbruck, Osnabrück, Paris and Warsaw. Collected data was centrally sent to Florence at regular time intervals. In 1832, an electromagnetic telegraph was created by Baron Schilling. The arrival of the electrical telegraph in 1837 afforded, for the first time, a practical method for quickly gathering surface weather observations from a wide area. This data could be used to produce maps of the state of the atmosphere for a region near the Earth's surface and to study how these states evolved through time. To make frequent weather forecasts based on these data required a reliable network of observations, but it was not until 1849 that the Smithsonian Institution began to establish an observation network across the United States under the leadership of Joseph Henry. Similar observation networks were established in Europe at this time. In 1854, the United Kingdom government appointed Robert FitzRoy to the new office of *Meteorological Statist to the Board of Trade* with the role of gathering weather observations at sea. FitzRoy's office became the United Kingdom Meteorological Office in 1854, the first national meteorological service in the world. The first daily weather forecasts made by FitzRoy's Office were published in *The Times* newspaper in 1860. The following year a system was introduced of hoisting storm warning cones at principal ports when a gale was expected.

Over the next 50 years many countries established national meteorological services. The India Meteorological Department (1875) was established following tropical cyclone and monsoon related famines in the previous decades. The Finnish Meteorological Central Office (1881) was formed from part of Magnetic Observatory of Helsinki University.

Japan's Tokyo Meteorological Observatory, the forerunner of the Japan Meteorological Agency, began constructing surface weather maps in 1883. The United States Weather Bureau (1890) was established under the United States Department of Agriculture. The Australian Bureau of Meteorology (1906) was established by a Meteorology Act to unify existing state meteorological services.

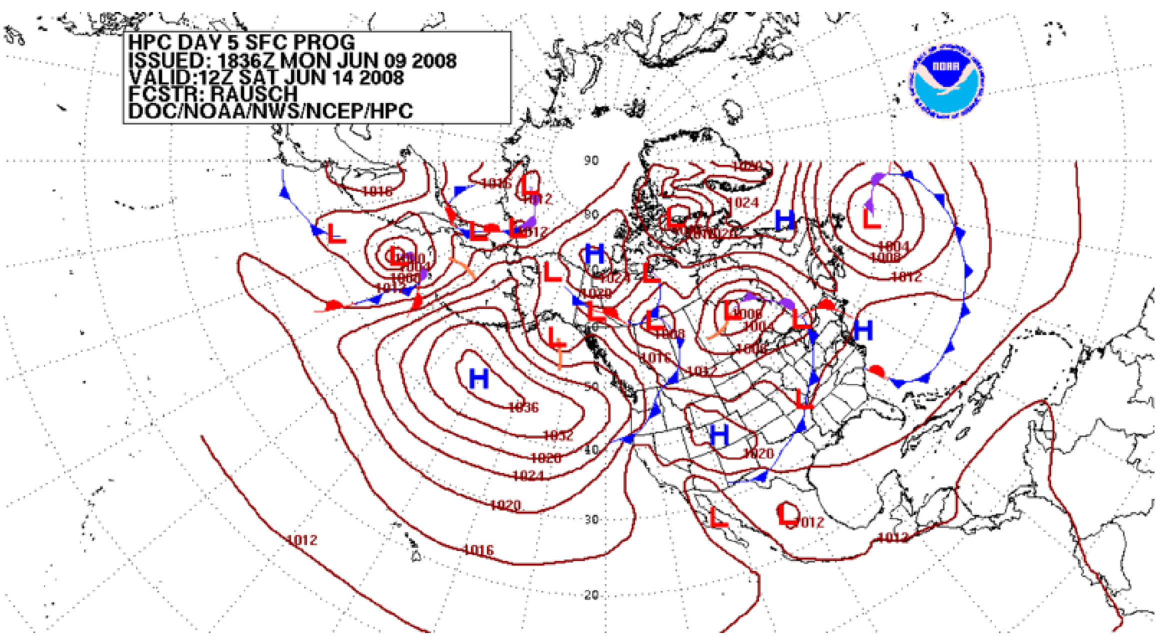
Meteorologists

Meteorologists are scientists who study meteorology. Meteorologists work in government agencies, private consulting and research services, industrial enterprises, utilities, radio and television stations, and in education. In the United States, meteorologists held about 8,800 jobs in 2006.

Meteorologists are best-known for forecasting the weather. Many radio and television weather forecasters are professional meteorologists, while others are merely reporters with no formal meteorological training. The American Meteorological Society and National Weather Association issue "Seals of Approval" to weather broadcasters who meet certain requirements.

Applications

Weather forecasting



Forecast of surface pressures five days into the future for the north Pacific, North America, and north Atlantic ocean.

Weather forecasting is the application of science and technology to predict the state of the atmosphere for a future time and a given location. Human beings have attempted to predict the weather informally for millennia, and formally since at least the nineteenth century. Weather forecasts are made by collecting quantitative data about the current state of the atmosphere and using scientific understanding of atmospheric processes to project how the atmosphere will evolve.

Once an all human endeavor based mainly upon changes in barometric pressure, current weather conditions, and sky condition, forecast models are now used to determine future conditions. Human input is still required to pick the best possible forecast model to base the forecast upon, which involves pattern recognition skills, teleconnections, knowledge of model performance, and knowledge of model biases. The chaotic nature of the atmosphere, the massive computational power required to solve the equations that describe the atmosphere, error involved in measuring the initial conditions, and an incomplete understanding of atmospheric processes mean that forecasts become less accurate as the difference in current time and the time for which the forecast is being made (the *range* of the forecast) increases. The use of ensembles and model consensus help narrow the error and pick the most likely outcome.

There are a variety of end uses to weather forecasts. Weather warnings are important forecasts because they are used to protect life and property. Forecasts based on temperature and precipitation are important to agriculture, and therefore to commodity traders within stock markets. Temperature forecasts are used by utility companies to estimate demand over coming days. On an everyday basis, people use weather forecasts to determine what to wear on a given day. Since outdoor activities are severely curtailed by heavy rain, snow and the wind chill, forecasts can be used to plan activities around these events, and to plan ahead and survive them.

Aviation meteorology

Aviation meteorology deals with the impact of weather on air traffic management. It is important for air crews to understand the implications of weather on their flight plan as well as their aircraft, as noted by the Aeronautical Information Manual:

The effects of ice on aircraft are cumulative-thrust is reduced, drag increases, lift lessens, and weight increases. The results are an increase in stall speed and a deterioration of aircraft performance. In extreme cases, 2 to 3 inches of ice can form on the leading edge of the airfoil in less than 5 minutes. It takes but 1/2 inch of ice to reduce the lifting power of some aircraft by 50 percent and increases the frictional drag by an equal percentage.

Agricultural meteorology

Meteorologists, soil scientists, agricultural hydrologists, and agronomists are persons concerned with studying the effects of weather and climate on plant distribution, crop yield, water-use efficiency, phenology of plant and animal development, and the energy balance of managed and natural ecosystems. Conversely, they are interested in the role of vegetation on climate and weather.

Hydrometeorology

Hydrometeorology is the branch of meteorology that deals with the hydrologic cycle, the water budget, and the rainfall statistics of storms. A hydrometeorologist prepares and issues forecasts of accumulating (quantitative) precipitation, heavy rain, heavy snow, and highlights areas with the potential for flash flooding. Typically the range of knowledge that is required overlaps with climatology, mesoscale and synoptic meteorology, and other geosciences.

Nuclear meteorology

Nuclear meteorology investigates the distribution of radioactive aerosols and gases in the atmosphere.

Maritime meteorology

Maritime meteorology deals with air and wave forecasts for ships operating at sea. Organizations such as the Ocean Prediction Center, Honolulu National Weather Service forecast office, United Kingdom Met Office, and JMA prepare high seas forecasts for the world's oceans.

Chapter-1

History of Meteorology

The **timeline of meteorology** contains events of scientific and technological advancements in the area of atmospheric sciences. The most notable advancements in observational meteorology, weather forecasting, climatology, atmospheric chemistry, and atmospheric physics are listed chronologically. Some historical weather events are included that mark time periods where advancements were made, or even that sparked policy change.

Antiquity

- 600 BC - Thales may qualify as the first Greek meteorologist. He described the water cycle in a fairly accurate way. He also issued the first seasonal crop forecast.

- 400 BC - There is some evidence that Democritus predicted changes in the weather, and that he used this ability to convince people that he could predict other future events.

- 400 BC - Hippocrates writes a treatise called *Airs, Waters and Places*, the earliest known work to include a discussion of weather. More generally, he wrote about common diseases that occur in particular locations, seasons, winds and air.

- 350 BC - Aristotle writes *Meteorology*.

  Although the term **meteorology** is used today to describe a subdiscipline of the atmospheric sciences, Aristotle's work is more general. The work touches upon much of what is known as the earth sciences. In his own words:
  ...all the affections we may call common to air and water, and the kinds and parts of the earth and the affections of its parts.

Aristotle

One of the most impressive achievements in *Meteorology* is his description of what is now known as the hydrologic cycle:

Now the sun, moving as it does, sets up processes of change and becoming and decay, and by its agency the finest and sweetest water is every day carried up and is dissolved into vapour and rises to the upper region, where it is condensed again by the cold and so returns to the earth.

- 250 BC - Archimedes studies the concepts of buoyancy and the hydrostatic principle. Positive buoyancy is necessary for the formation of convective clouds (cumulus, cumulus congestus and cumulonimbus).

- 25 AD - Pomponius Mela, a geographer for the Roman empire, formalizes the climatic zone system.

- c. 80 AD - In his *Lunheng*, the Han Dynasty Chinese philosopher Wang Chong (27-97 AD) dispels the Chinese myth of rain coming from the heavens, and states that rain is evaporated from water on the earth into the air and forms clouds, stating that clouds condense into rain and also form dew, and says when the clothes of people in high mountains are moistened, this is because of the air-suspended rain water. However, Wang Chong supports his theory by quoting a similar one of Gongyang Gao's, the latter's commentary on the *Spring and Autumn Annals*, the Gongyang Zhuan, compiled in the 2nd century BC, showing that the Chinese conception of rain evaporating and rising to form clouds goes back much farther than Wang Chong. Wang Chong wrote:

  As to this coming of rain from the mountains, some hold that the clouds carry the rain with them, dispersing as it is precipitated (and they are right). Clouds and rain are really the same thing. Water evaporating upwards becomes clouds, which condense into rain, or still further into dew.

Middle Ages

- 7th century-St. Isidore of Seville,in his work *De Rerum Natura*, writes about astronomy, cosmology and meteorology. In the chapter dedicated to Meteorology, he discusses the thunder, clouds, rainbows and wind.

- 9th century - Al-Kindi (Alkindus), an Arab naturalist, writes a treatise on meteorology entitled *Risala fi l-Illa al-Failali l-Madd wa l-Fazr* (*Treatise on the Efficient Cause of the Flow and Ebb*), in which he presents an argument on tides which "depends on the changes which take place in bodies owing to the rise and fall of temperature."

- 9th century - Al-Dinawari, a Kurdish naturalist, writes the *Kitab al-Nabat* (*Book of Plants*), in which he deals with the application of meteorology to agriculture during the Muslim Agricultural Revolution. He describes the meteorological character of the sky, the planets and constellations, the Sun and Moon, the lunar phases indicating seasons and rain, the *anwa* (heavenly bodies of rain), and atmospheric phenomena such as winds, thunder, lightning, snow, floods, valleys, rivers, lakes, wells and other sources of water.

- 10th century - Ibn Wahshiyya's *Nabatean Agriculture* discusses the weather forecasting of atmospheric changes and signs from the planetary astral alterations; signs of rain based on observation of the lunar phases, nature of thunder and lightning, direction of sunrise, behaviour of certain plants and animals, and weather forecasts based on the movement of winds; pollenized air and winds; and formation of winds and vapours.

- 1021 - Ibn al-Haytham (Alhazen) introduces the scientific method in his *Book of Optics*. He writes on the atmospheric refraction of light, for example, the cause of morning and evening twilight. He endeavored by use of hyperbola and geometric optics to chart and formulate basic laws on atmospheric refraction. He provides the first correct definition of the twilight, discusses atmospheric refraction, shows that the twilight is due to atmospheric refraction and only begins when the Sun is 19 degrees below the horizon, and uses a complex geometric demonstration to measure the height of the Earth's atmosphere as 52,000 *passuum* (49 miles), which is very close to the modern measurement of 50 miles. He also realized that the atmosphere also reflects light, from his observations of the sky brightening even before the Sun rises.

- 1020s - Ibn al-Haytham publishes his *Risala fi l-Daw'* (*Treatise on Light*) as a supplement to his *Book of Optics*. He discusses the meteorology of the rainbow, the density of the atmosphere, and various celestial phenomena, including the eclipse, twilight and moonlight.

- 1027 - Avicenna publishes *The Book of Healing*, in which Part 2, Section 5, contains his essay on mineralogy and meteorology in six chapters: formation of mountains; the advantages of mountains in the formation of clouds; sources of water; origin of earthquakes; formation of minerals; and the diversity of earth's terrain. He also describes the structure of a meteor, and his theory on the formation of metals combined Jābir ibn Hayyān's sulfur–mercury theory from Islamic alchemy (although he was critical of alchemy) with the mineralogical theories of Aristotle and Theophrastus. His scientific methodology of field observation was also original in the Earth sciences.

- Late 11th century - Abu 'Abd Allah Muhammad ibn Ma'udh, who lived in Al-Andalus, wrote a work on optics later translated into Latin as *Liber de crepisculis*, which was mistakenly attributed to Alhazen. This was a short work containing an estimation of the angle of depression of the sun at the beginning of the morning twilight and at the end of the evening twilight, and an attempt to calculate on the basis of this and other data the height of the atmospheric moisture responsible for the refraction of the sun's rays. Through his experiments, he obtained the accurate value of 18°, which comes close to the modern value.

- 1088 - In his *Dream Pool Essays*, the Chinese scientist Shen Kuo wrote vivid descriptions of tornadoes, that rainbows were formed by the shadow of the sun in rain, occurring when the sun would shine upon it, and the curious common phenomena of the effect of lightning that, when striking a house, would merely scorch the walls a bit but completely melt to liquid all metal objects inside.

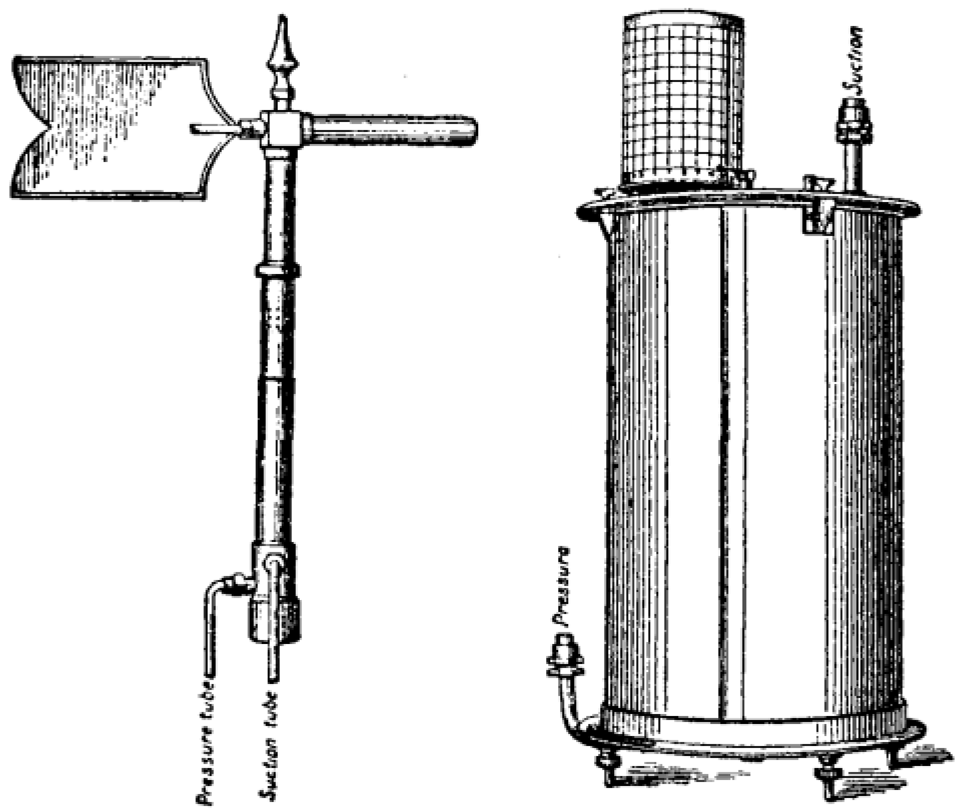
- 1121 - Al-Khazini, a Muslim scientist of Byzantine Greek descent, publishes *The Book of the Balance of Wisdom*, the first study on the hydrostatic balance.

- 13th century-St. Albert the Great is the first to propose that each drop of falling rain had the form of a small sphere, and that this form meant that the rainbow was produced by light interacting with each raindrop.

- Roger Bacon was the first to calculate the angular size of the rainbow. He stated that the rainbow summit can not appear higher than 42 degrees above the horizon.

- Late 13th century-Theoderic of Freiburg and Kamāl al-Dīn al-Fārisī give the first accurate explanations of the primary rainbow, simultaneously but independently.Theoderic also gives the explantion for the secondaty rainbow.

- 1441 - King Sejongs son, Prince Munjong, invented the first standardized rain gauge. These were sent throughout the Joseon Dynasty of Korea as an official tool to assess land taxes based upon a farmer's potential harvest.



Anemometers

- 1450 - Leone Battista Alberti developed a **swinging-plate anemometer**, and is known as the first *anemometer*.

  - Nicolas Cryfts, (Nicolas of Cusa), described the first **hair hygrometer** to measure humidity. The design was drawn by Leonardo da Vinci, referencing Cryfts design in *da Vinci's Codex Atlanticus*.

- 1494 Christopher Columbus experience a tropical cyclone, leads to the first written European account of a hurricane.

17th century

Galileo.

- 1607 - Galileo Galilei constructs a thermoscope. Not only did this device measure temperature, but it represented a paradigm shift. Up to this point, heat and cold were believed to be qualities of Aristotle's elements (fire, water, air, and earth). *Note: There is some controversy about who actually built this first thermoscope. There is some evidence for this device being independently built at several* *different times.* This is the era of the first recorded meteorological observations. As there was no standard measurement, they were of little use until the work of Daniel Gabriel Fahrenheit and Anders Celsius in the 18th century.

Sir Francis Bacon

- 1611 - Johannes Kepler writes the first scientific treatise on snow crystals: "Strena Seu de Nive Sexangula (A New Year's Gift of Hexagonal Snow)".
- 1620 - Francis Bacon (philosopher) analyzes the scientific method in his philosophical work; Novum Organum.
- 1643 - Evangelista Torricelli invents the **mercury barometer**.

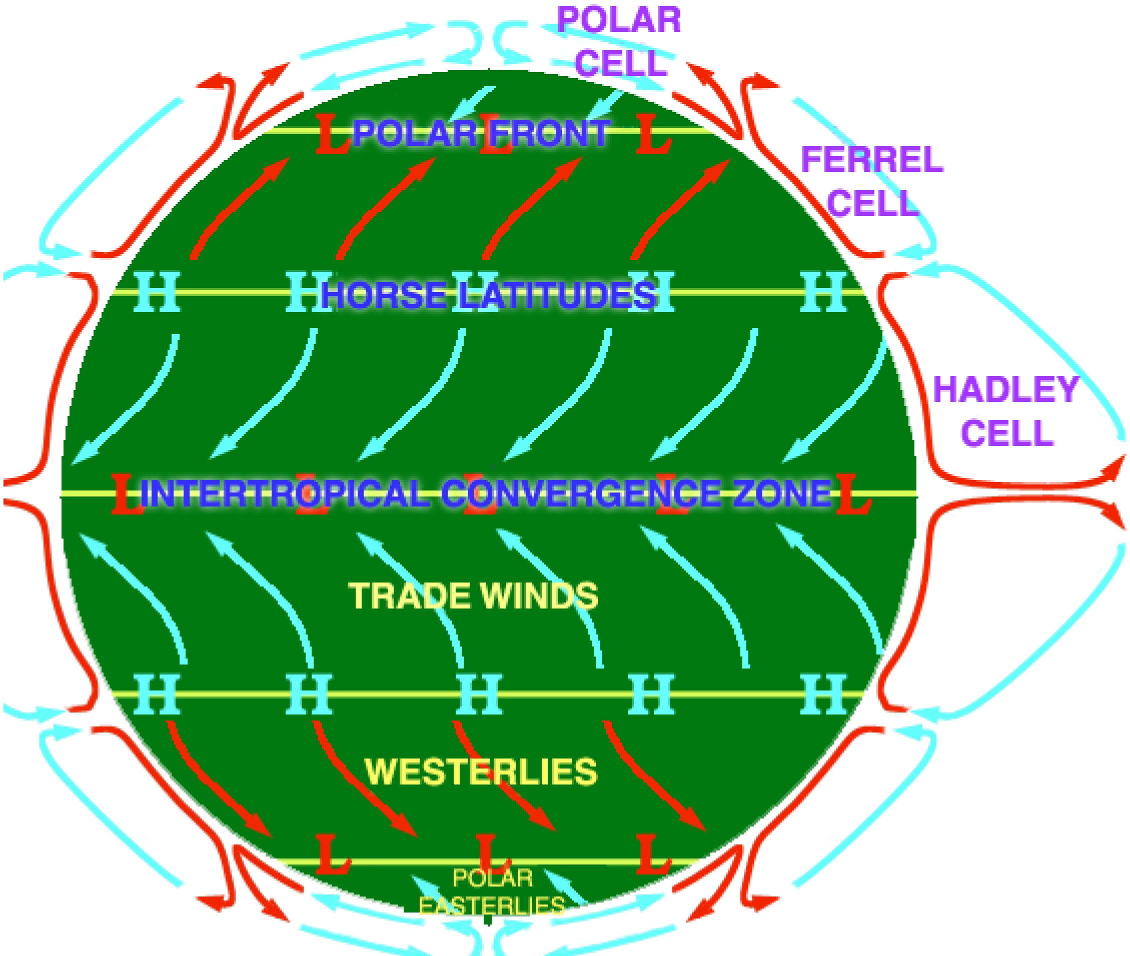
Blaise Pascal.

- 1648 - Blaise Pascal rediscovers that atmospheric pressure decreases with height, and deduces that there is a vacuum above the atmosphere.
- 1654 - Ferdinando II de Medici sponsors the first *weather observing* network, that consisted of meteorological stations in Florence, Cutigliano, Vallombrosa, Bologna, Parma, Milan, Innsbruck, Osnabrück, Paris and Warsaw. Collected data was centrally sent to Accademia del Cimento in Florence at regular time intervals.
- 1662 - Sir Christopher Wren invented the mechanical, self-emptying, **tipping bucket rain gauge**.
- 1667 - Robert Hooke builds another type of anemometer, called a **pressure-plate anemometer**.
- 1686 - Edmund Halley presents a systematic study of the trade winds and monsoons and identifies solar heating as the cause of atmospheric motions.

  - Edmund Halley establishes the relationship between barometric pressure and height above sea level.

18th century

- 1716 - Edmund Halley suggests that aurorae are caused by "magnetic effluvia" moving along the Earth's magnetic field lines.



Global circulation as described by Hadley.

- 1724 - Gabriel Fahrenheit creates reliable scale for measuring temperature with a mercury-type thermometer.
- 1735 - The first *ideal* explanation of global circulation was the study of the Trade winds by George Hadley.
- 1738 - Daniel Bernoulli publishes *Hydrodynamics*, initiating the kinetic theory of gases. He gave a poorly detailed equation of state, but also the basic laws for the theory of gases.
- 1742 - Anders Celsius, a Swedish astronomer, proposed the Celsius temperature scale which led to the current Celsius scale.
- 1743 - Benjamin Franklin is prevented from seeing a lunar eclipse by a hurricane, he decides that cyclones move in a contrary manner to the winds at their periphery.
- 1761 - Joseph Black discovers that ice absorbs heat without changing its temperature when melting.

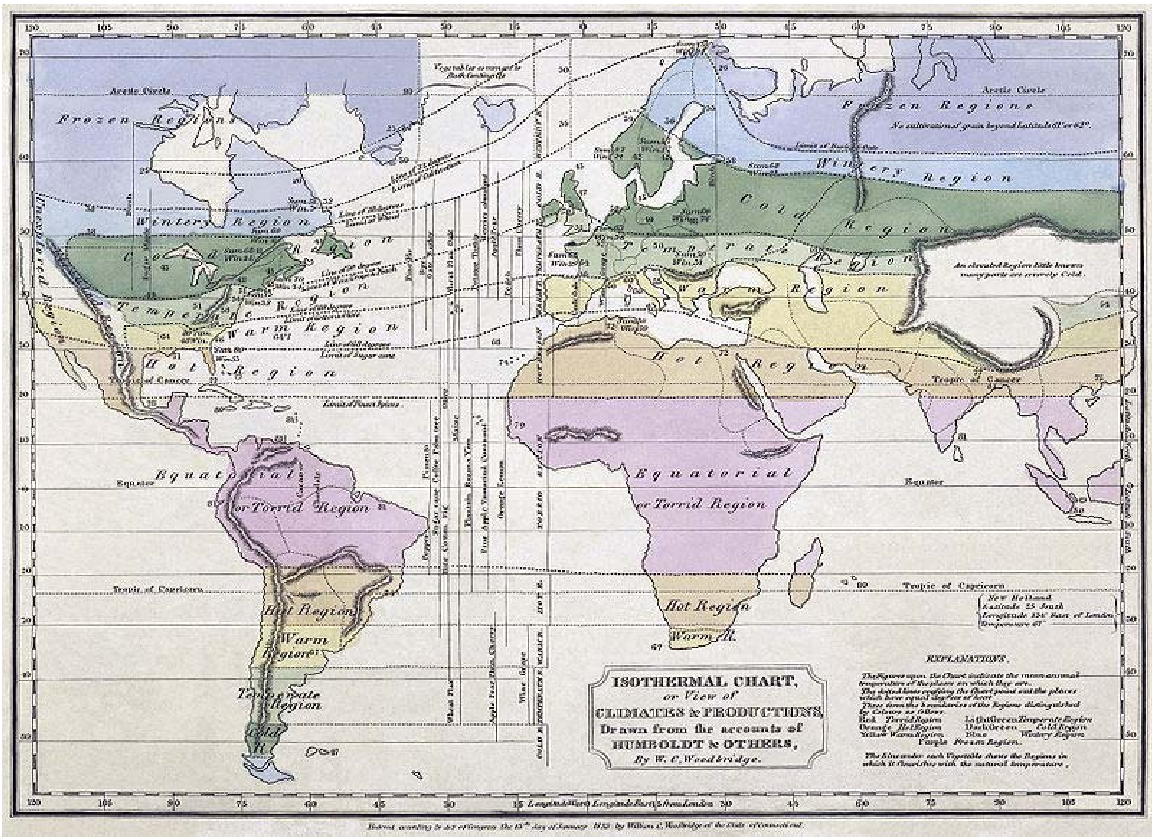
- 1772 - Black's student Daniel Rutherford discovers nitrogen, which he calls *phlogisticated air*, and together they explain the results in terms of the phlogiston theory.
- 1774 - Louis Cotte is put in charge of a "medico-meteorological" network of French veterinarians and country doctors to investigate the relationship between plague and weather. The project continued until 1794.

  - Royal Society begins twice daily observations compiled by Samuel Horsley testing for the influence of winds and of the moon on the barometer readings.

- 1777 - Antoine Lavoisier discovers oxygen and develops an explanation for combustion.
- 1780 - Charles Theodor charters the first international network of meteorological observers known as "Societas Meteorologica Palatina". The project collapses in 1795.
- 1783 - In Lavoisier's book *Reflexions sur le phlogistique*, he deprecates the phlogiston theory and proposes a caloric theory.

  - First hair hygrometer demonstrated. The inventor was Horace-Bénédict de Saussure.

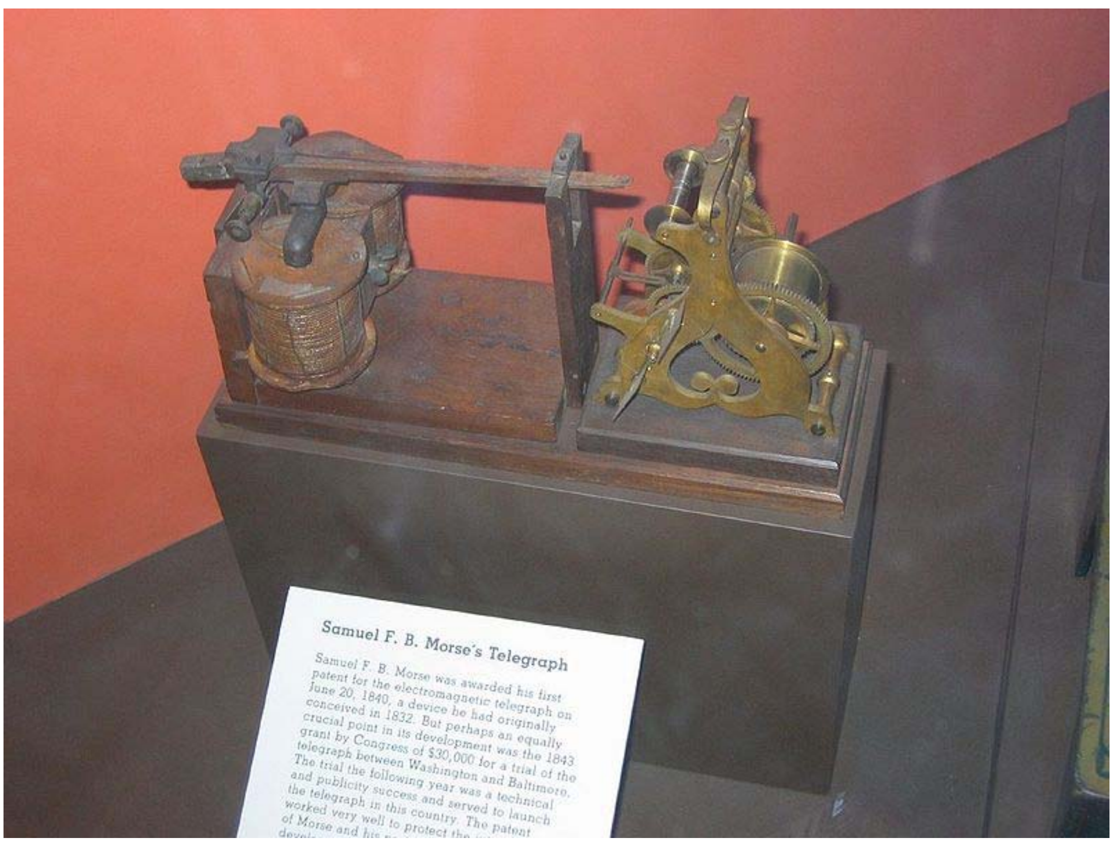
19th century



Isothermal chart of the world created 1823 by William Channing Woodbridge using the work of Alexander von Humboldt.

- 1800 - The Voltaic pile was the first modern electric battery, invented by Alessandro Volta, which led to later inventions like the telegraph.
- 1802-1803 - Luke Howard writes *On the Modification of Clouds* in which he assigns cloud types Latin names.
- 1804 - Sir John Leslie observes that a matte black surface radiates heat more effectively than a polished surface, suggesting the importance of black body radiation.
- 1806 - Francis Beaufort introduces his system for classifying wind speeds.
- 1808 - John Dalton defends caloric theory in *A New System of Chemistry* and describes how it combines with matter, especially gases; he proposes that the heat capacity of gases varies inversely with atomic weight.
- 1810 - Sir John Leslie freezes water to ice artificially.
- 1819 - Pierre Louis Dulong and Alexis Thérèse Petit give the Dulong-Petit law for the specific heat capacity of a crystal.

- 1820 - John Herapath develops some ideas in the kinetic theory of gases but mistakenly associates temperature with molecular momentum rather than kinetic energy; his work receives little attention other than from Joule.
- 1822 - Joseph Fourier formally introduces the use of dimensions for physical quantities in his *Theorie Analytique de la Chaleur*.
- 1824 - Sadi Carnot analyzes the efficiency of steam engines using caloric theory; he develops the notion of a reversible process and, in postulating that no such thing exists in nature, lays the foundation for the second law of thermodynamics.
- 1827 - Robert Brown discovers the Brownian motion of pollen and dye particles in water.
- 1832 - An electromagnetic telegraph was created by Baron Schilling.
- 1834 - Émile Clapeyron popularises Carnot's work through a graphical and analytic formulation.
- 1835 - Gaspard-Gustave Coriolis publishes theoretical discussions of machines with revolving parts and their efficiency, for example the efficiency of waterweels. At the end of the 19th century, meteorologists recognized that the way the Earth's rotation is taken into account in meteorology is analogous to what Coriolis discussed: an example of Coriolis Effect.
- 1836 - An American scientist, Dr. David Alter, invented the first known American electric telegraph in Elderton, Pennsylvania, one year before the much more popular Morse telegraph was invented.



The electrical telegraph owned and built by Samuel Morse.

- 1837 - Samuel Morse independently developed an electrical telegraph, an alternative design that was capable of transmitting over long distances using poor quality wire. His assistant, Alfred Vail, developed the Morse code signalling alphabet with Morse. The first electric telegram using this device was sent by Morse on May 24, 1844 from the U.S. Capitol in Washington, D.C. to the B&O Railroad "outer depot" in Baltimore and sent the message:

  What hath God wrought

- 1839 - The *first commercial* electrical telegraph was constructed by Sir William Fothergill Cooke and entered use on the Great Western Railway. Cooke and Wheatstone patented it in May 1837 as an alarm system.
- 1841 - Elias Loomis the first person known to attempt to devise a theory on frontal zones, and prepared some of the first known weather maps. The idea of fronts did not catch on until expanded upon by the Norwegians in the years following World War I.
- 1843 - John James Waterston fully expounds the kinetic theory of gases, but is ridiculed and ignored.

  - James Prescott Joule experimentally finds the mechanical equivalent of heat.
  - Lucien Vidie invented the aneroid, *from Greek meaning without liquid*, barometer.

- 1846 - Cup anemometer invented by Dr. John Thomas Romney Robinson.
- 1847 - Hermann von Helmholtz publishes a definitive statement of the conservation of energy, the first law of thermodynamics.

  - The Manchester Examiner newspaper organises the first weather reports collected by electrical means.

- 1848 - William Thomson extends the concept of absolute zero from gases to all substances.
- 1849 - Smithsonian Institution begins to establish an observation network across the United States, with 150 observers via telegraph, under the leadership of Joseph Henry.

  - William John Macquorn Rankine calculates the correct relationship between saturated vapour pressure and temperature using his *hypothesis of molecular vortices*.

- 1850 - Rankine uses his *vortex* theory to establish accurate relationships between the temperature, pressure, and density of gases, and expressions for the latent heat of evaporation of a liquid; he accurately predicts the surprising fact that the apparent specific heat of saturated steam will be negative.

- Rudolf Clausius gives the first clear joint statement of the first and second law of thermodynamics, abandoning the caloric theory, but preserving Carnot's principle.

- 1852 - Joule and Thomson demonstrate that a rapidly expanding gas cools, later named the Joule-Thomson effect.
- 1854 - The French astronomer Leverrier showed that a storm in the Black Sea could be followed across Europe and would have been predictable if the telegraph had been used. A service of storm forecasts was established a year later by the Paris Observatory.

  - Rankine introduces his *thermodynamic function*, later identified as entropy.

- 1859 - James Clerk Maxwell discovers the distribution law of molecular velocities.
- 1860 - Robert FitzRoy uses the new telegraph system to gather daily observations from across England and produces the first synoptic charts. He also coined the term "weather forecast" and his were the first ever daily weather forecasts to be published in this year.

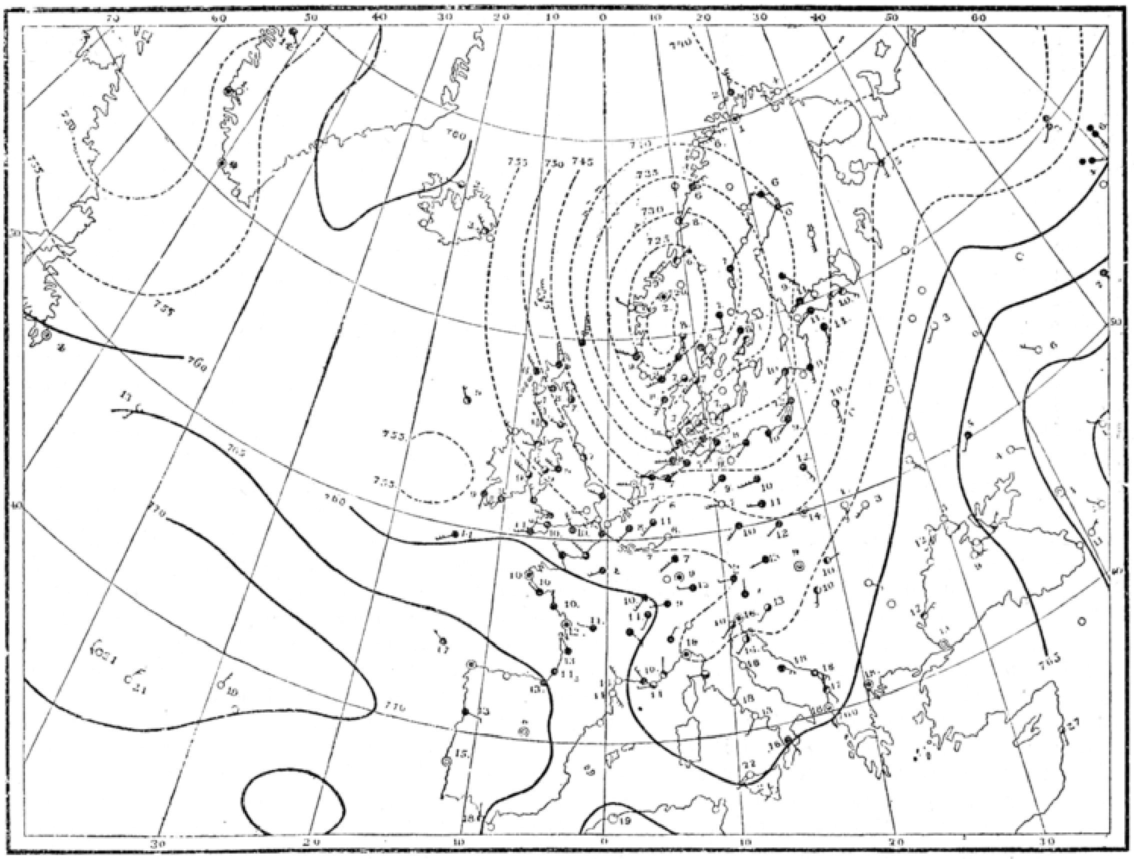
  - After establishment in 1849, 500 U.S. telegraph stations are now making weather observations and submitting them back to the Smithsonian Institution. The observations are later interrupted by the American Civil War.

- 1865 - Josef Loschmidt applies Maxwell's theory to estimate the number-density of molecules in gases, given observed gas viscosities.

  - Manila Observatory founded in the Philippines.

- 1869 - Joseph Lockyer starts the scientific journal Nature.
- 1870 - Benito Vines becomes the head of the Meteorological Observatory at Belen in Havana, Cuba. He develops the first observing network in Cuba and creates some of the first hurricane-related forecasts.
- 1872 - Ludwig Boltzmann states the Boltzmann equation for the temporal development of distribution functions in phase space, and publishes his H-theorem.
- 1873 - International Meteorological Organization formed in Vienna.

  - United States Army Signal Corp, forerunner of the National Weather Service, issues its first hurricane warning.



Väderlekskarta på morgonen den 22 oktober 1874.

Synoptic chart from 1874.

- 1876 - Josiah Willard Gibbs publishes the first of two papers (the second appears in 1878) which discuss phase equilibria, statistical ensembles, the free energy as the driving force behind chemical reactions, and chemical thermodynamics in general.
- 1881 - Finnish Meteorological Central Office was formed from part of Magnetic Observatory of Helsinki University.
- 1889 - India Meteorological Department established following tropical cyclone and monsoon related famines in the previous decades.
- 1890 - US Weather Bureau is created as a civilian operation under the U.S. Department of Agriculture.
- 1892 - William Henry Dines invented another kind of anemometer, called the **pressure-tube (Dines) anemometer**. His device measured the difference in pressure arising from wind blowing in a tube versus that blowing across the tube.

  - The first mention of the term "El Niño" to refer to climate occurs when Captain Camilo Carrilo told the Geographical society congress in Lima that Peruvian sailors named the warm northerly current "El Niño" because it was most noticeable around Christmas.

- 1896 - IMO publishes the first International cloud atlas.

  - Svante Arrhenius proposes carbon dioxide as a key factor to explain the ice ages.

- 1898 - US Weather Bureau established a hurricane warning network at Kingston, Jamaica.

20th century

- 1902 - Richard Assmann and Léon Teisserenc de Bort, two European scientists, independently discovered the stratosphere.
- 1904 - Vilhelm Bjerknes presents the vision that forecasting the weather is feasible based on mathematical methods.
- 1905 - Australian Bureau of Meteorology established by a Meteorology Act to unify existing state meteorological services.
- 1919 - Norwegian Cyclone Model introduced for the first time in meteorological literature. Marks a revolution in the way the atmosphere is conceived and immediately starts leading to improved forecasts. Sakuhei Fujiwhara is the first to note that hurricanes move with the larger scale flow, and later publishes a paper on the Fujiwara Effect in 1921.
- 1920 - Milutin Milanković proposes that long term climatic cycles may be due to changes in the eccentricity of the Earth's orbit and changes in the Earth's obliquity.
- 1922 - Lewis Fry Richardson organises the first numerical weather prediction experiment.
- 1923 - The oscillation effects of ENSO were first *erroneously* described by Sir Gilbert Thomas Walker from whom the Walker circulation takes its name; now an important aspect of the *Pacific ENSO* phenomenon.
- 1924 - Gilbert Walker first coined the term "Southern Oscillation".
- 1930, January 30 - Pavel Molchanov invents and launches the first radiosonde. Named "271120", it was released 13:44 Moscow Time in Pavlovsk, USSR from the Main Geophysical Observatory, reached a height of 7.8 kilometers measuring temperature there (-40.7 °C) and sent the first aerological message to the Leningrad Weather Bureau and Moscow Central Forecast Institute.
- 1935 - IMO decides on the 30 years normal period (1900–1930) to describe the climate.
- 1937 - The U.S. Army Air Forces Weather Service was established (redesignated in 1946 as **AWS**-Air Weather Service).
- 1938 - Guy Stewart Callendar first to propose global warming from carbon dioxide emissions.
- 1939 - Rossby waves were first identified in the atmosphere by Carl-Gustaf Arvid Rossby who explained their motion. Rossby waves are a subset of inertial waves.
- 1941 - Pulsed radar network is implemented in England during World War II. Generally during the war, operators started noticing echoes from weather elements such as rain and snow.

- 1943 – 10 years after flying into the Washington Hoover Airport on mainly instruments during the August 1933 Chesapeake-Potomac hurricane, J. B. Duckworth flies his airplane into a Gulf hurricane off the coast of Texas, proving to the military and meteorological community the utility of weather reconnaissance.
- 1944 - The Great Atlantic Hurricane is caught on radar near the Mid-Atlantic coast, the first such picture noted from the United States.
- 1947 - The Soviet Union launched its first Long Range Ballistic Rocket 18 October, based on the German rocket A4 (V-2). The photographs demonstrated the immense potential of observing weather from space.
- 1948 - First correct tornado prediction by Robert C. Miller and E. J. Fawbush for tornado in Oklahoma.

  - Erik Palmén publishes his findings that hurricanes require surface water temperatures of at least 26°C (80°F) in order to form.

- 1950 - First successful numerical weather prediction experiment. Princeton University, group of Jule Gregory Charney on ENIAC.

  - Hurricanes begin to be named alphabetically with the radio alphabet.
  - **WMO** World Meteorological Organization replaces IMO under the auspice of the United Nations.

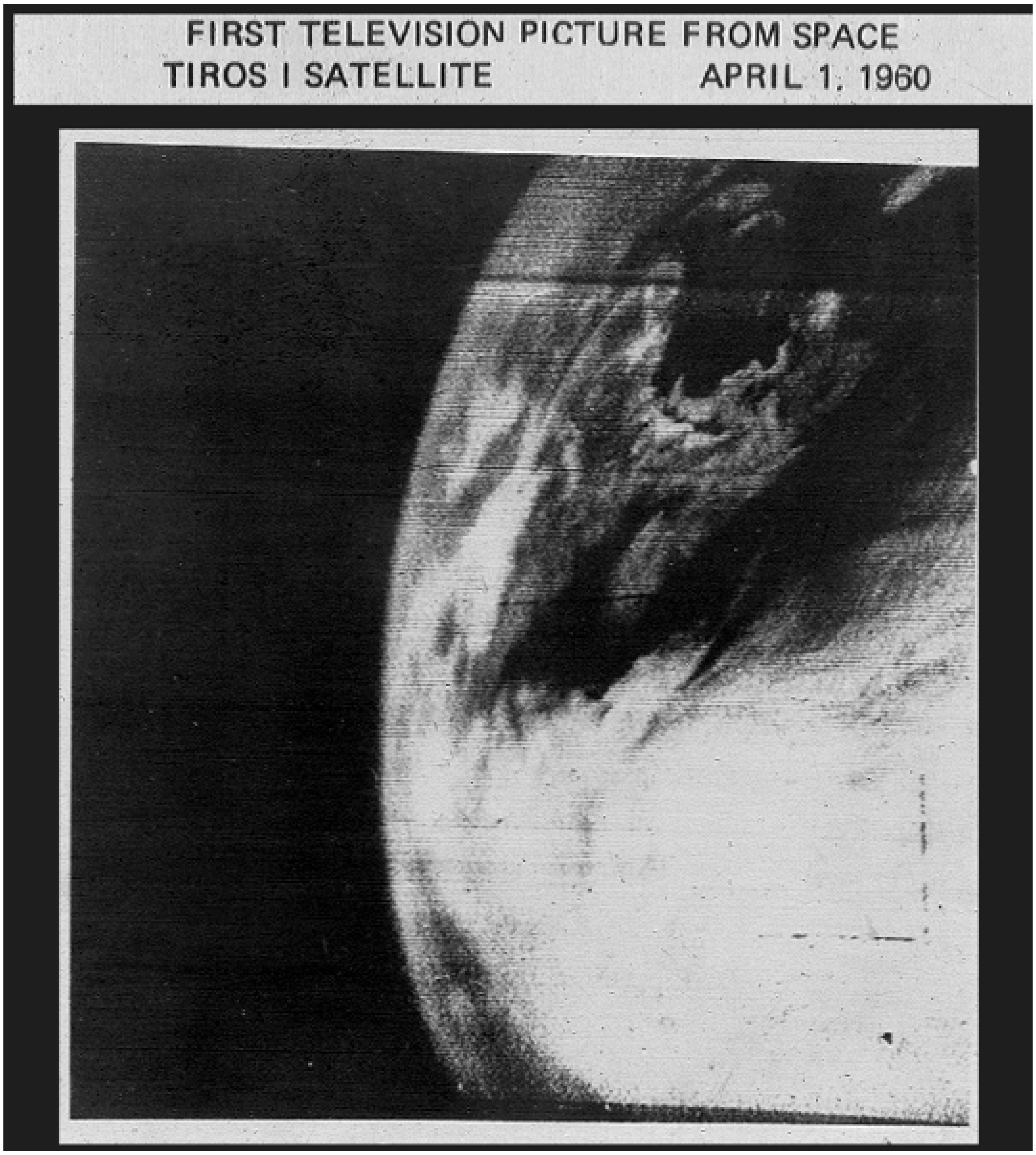
- 1953 - National Hurricane Center (NOAA) creates a system for naming hurricanes using alphabetical lists of women's names.
- 1954 - First routine real-time numerical weather forecasting. The Royal Swedish Air Force Weather Service.

  - A United States Navy rocket captures a picture of an inland tropical depression near the Texas/Mexico border, which leads to a surprise flood event in New Mexico. This convinces the government to set up a weather satellite program.

- 1955 - Norman Phillips at the Institute for Advanced Study in Princeton, New Jersey, runs first Atmospheric General Circulation Model.

  - **NSSP** National Severe Storms Project and **NHRP** National Hurricane Research Projects established. The Miami office of the United States Weather Bureau is designated the main hurricane warning center for the Atlantic Basin.

- 1957-1958 - International Geophysical Year coordinated research efforts in eleven sciences, focused on polar areas during the solar maximum.



The first television image of Earth from space from the TIROS-1 weather satellite.

- 1959 - The first weather satellite, Vanguard 2, was launched on 17 February. It was designed to measure cloud cover, but a poor axis of rotation kept it from collecting a notable amount of useful data.
- 1960 - The first weather satellite to be considered a success was TIROS-1, launched by NASA on 1 April. TIROS operated for 78 days and proved to be much more successful than Vanguard 2. TIROS paved the way for the Nimbus program, whose technology and findings are the heritage of most of the Earth-observing satellites NASA and NOAA have launched since then.
- 1961 - Edward Lorenz accidentally discovers Chaos theory when working on numerical weather prediction.

- 1962 - Keith Browning and Frank Ludlam publish first detailed study of a *supercell* storm (over Wokingham, UK). Project STORMFURY begins its 10-year project of seeding hurricanes with silver iodide, attempting to weaken the cyclones.
- 1968 - A hurricane database for Atlantic hurricanes is created for NASA by Charlie Newmann and John Hope, named HURDAT.
- 1969 - Saffir-Simpson Hurricane Scale created, used to describe hurricane strength on a category range of 1 to 5. Popularized during Hurricane Gloria of 1985 by media.

  - Jacob Bjerknes described ENSO by suggesting that an anomalously warm spot in the eastern Pacific can weaken the east-west temperature difference, causing weakening in the Walker circulation and trade wind flows, which push warm water to the west.

- 1970s Weather radars are becoming more standardized and organized into networks. The number of scanned angles was increased to get a three-dimensional view of the precipitation, which allowed studies of thunderstorms. Experiments with the Doppler effect begin.
- 1970 - **NOAA** National Oceanic and Atmospheric Administration established. Weather Bureau is renamed the National Weather Service.
- 1971 - Ted Fujita introduces the Fujita scale for rating tornadoes.
- 1974 - **AMeDAS** network, developed by Japan Meteorological Agency used for gathering regional weather data and verifying forecast performance, begun operation on November 1, the system consists of about 1,300 stations with automatic observation equipment. These stations, of which more than 1,100 are unmanned, are located at an average interval of 17 km throughout Japan.
- 1975 - The first Geostationary Operational Environmental Satellite, **GOES**, was launched into orbit. Their role and design is to aid in hurricane tracking. Also this year, Vern Dvorak develops a scheme to estimate tropical cyclone intensity from satellite imagery.

  - The first use of a General Circulation Model to study the effects of carbon dioxide doubling. Syukuro Manabe and Richard Wetherald at Princeton University.

- 1980s onwards, networks of weather radars are further expanded in the developed world. Doppler weather radar is becoming gradually more common, adds velocity information.
- 1982 - The first Synoptic Flow experiment is flown around Hurricane Debby to help define the large scale atmospheric winds that steer the storm.
- 1988 - WSR-88D type weather radar implemented in the United States. Weather surveillance radar that uses several modes to detect severe weather conditions.
- 1992 - Computers first used in the United States to draw surface analyses.

- 1997 - The Pacific Decadal Oscillation was named by Steven R. Hare, who noticed it while studying salmon production patterns. Simultaneously the PDO climate pattern was also found by Yuan Zhang.
- 1998 - Improving technology and software finally allows for the digital underlaying of satellite imagery, radar imagery, model data, and surface observations improving the quality of United States Surface Analyses.

  - CAMEX3, a NASA experiment run in conjunction with NOAA's Hurricane Field Program collects detailed data sets on Hurricanes Bonnie, Danielle, and Georges.

- 1999 - Hurricane Floyd induces *fright factor* in some coastal States and causes a massive evacuation from coastal zones from northern Florida to the Carolinas. It comes ashore in North Carolina and results in nearly 80 dead and $4.5 billion in damages mostly due to extensive flooding.

21st century

- 2001 - National Weather Service begins to produce a Unified Surface Analysis, ending duplication of effort at the Tropical Prediction Center, Ocean Prediction Center, Hydrometeorological Prediction Center, as well as the National Weather Service offices in Anchorage, AK and Honolulu, HI.
- 2003 - NOAA hurricane experts issue first experimental Eastern Pacific Hurricane Outlook.
- 2004 - A record number of hurricanes strike Florida in one year, Charley, Frances, Ivan, and Jeanne.
- 2005 - A record 27 named storms occur in the Atlantic. National Hurricane Center runs out of names from its standard list and uses Greek alphabet for the first time.
- 2007 - The Fujita scale is replaced with the Enhanced Fujita Scale for National Weather Service tornado assessments.

In 350 BC, Aristotle wrote *Meteorology*. Aristotle is considered the founder of meteorology. One of the most impressive achievements described in the *Meteorology* is the description of what is now known as the hydrologic cycle. The Greek scientist Theophrastus compiled a book on weather forecasting, called the *Book of Signs*. The work of Theophrastus remained a dominant influence in the study of weather and in weather forecasting for nearly 2,000 years. In 25 AD, Pomponius Mela, a geographer for the Roman Empire, formalized the climatic zone system. Around the 9th century, Al-Dinawari, a Kurdish naturalist, writes the *Kitab al-Nabat* (*Book of Plants*), in which he deals with the application of meteorology to agriculture during the Muslim Agricultural Revolution. He describes the meteorological character of the sky, the planets and constellations, the sun and moon, the lunar phases indicating seasons and rain, the *anwa* (heavenly bodies of rain), and atmospheric phenomena such as winds, thunder, lightning, snow, floods, valleys, rivers, lakes, wells and other sources of water.

Chapter-2

Research of Visual Atmospheric Phenomena

Twilight

Twilight at Baker Beach

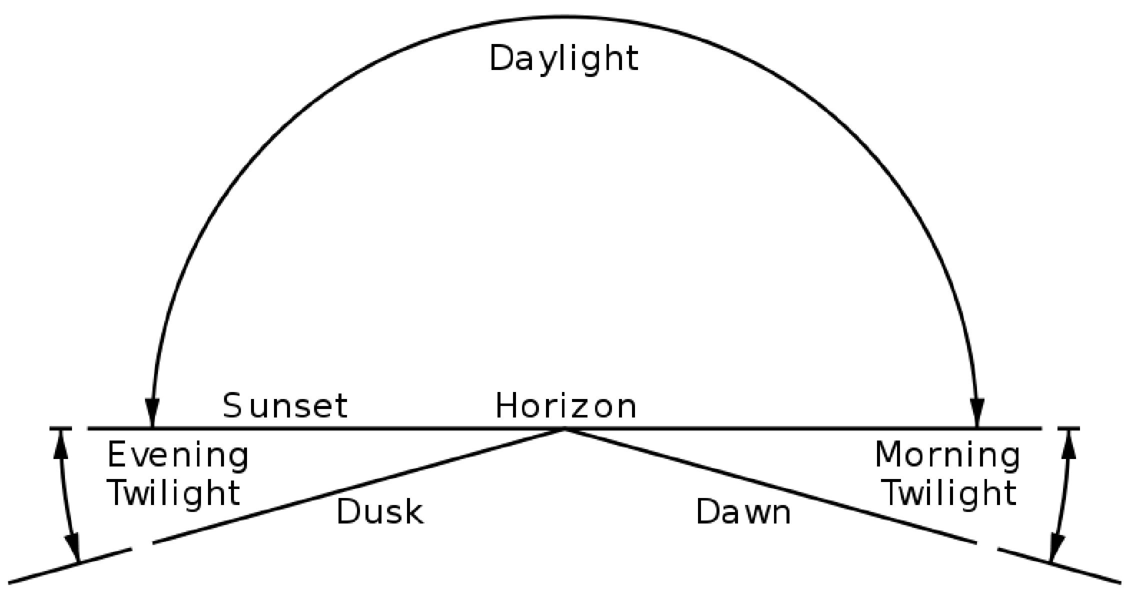
Twilight at Riga Bridge

Figures in silhouette during twilight

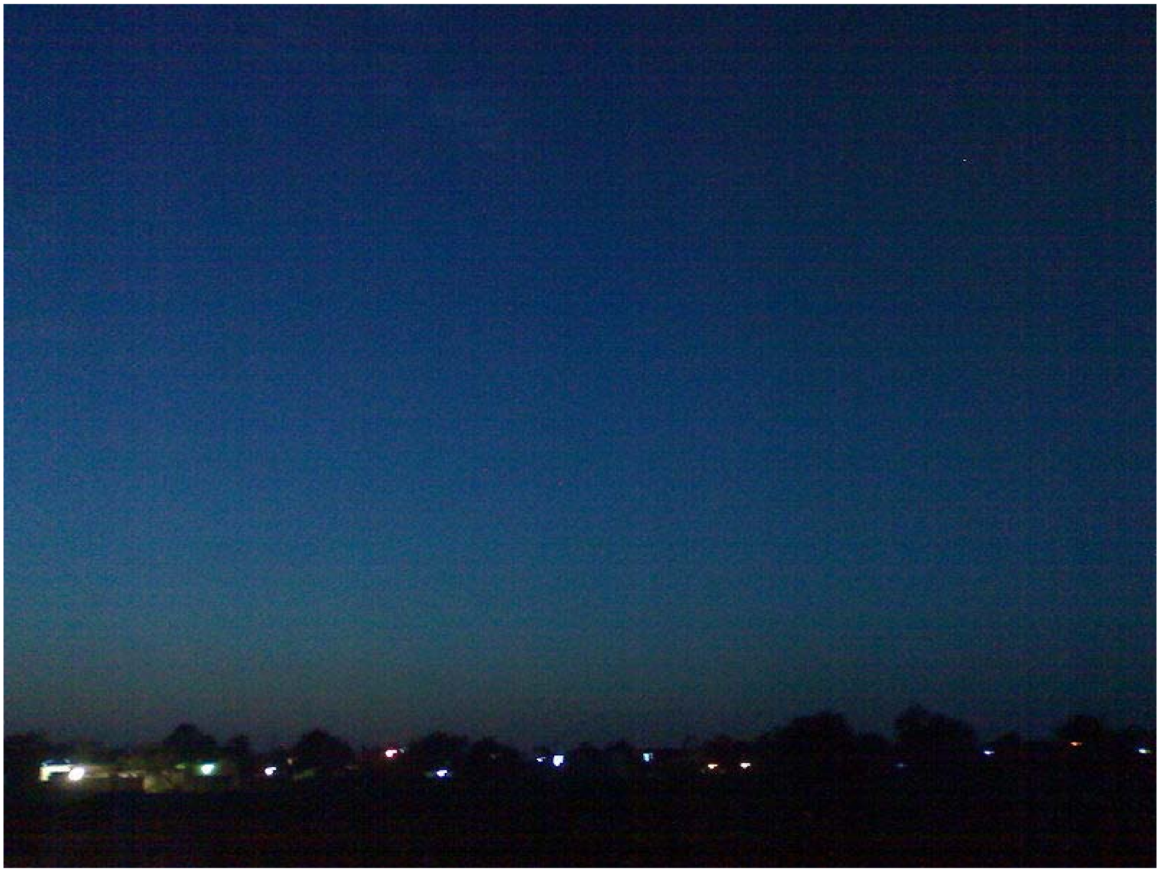
Twilight is the time between dawn and sunrise, and between sunset and dusk. Sunlight scattered in the upper atmosphere illuminates the lower atmosphere, and the surface of the Earth is neither completely lit nor completely dark. The sun itself is not actually visible because it is below the horizon. Owing to the unusual quality of the ambient light at this time, twilight has long been popular with photographers and painters, who refer to it as the "blue hour", after the French expression *l'heure bleue*. Twilight is technically defined as the period before sunrise and after sunset during which there is natural light provided by the upper atmosphere, which receives direct sunlight and scatters part of it towards the Earth's surface.

The collateral adjective of *twilight* is *crepuscular* (for daylight it is *diurnal* and for night, *nocturnal*). The term is most frequently encountered when applied to certain species of insects and mammals that are most active during that time.

Definitions



Description of Twilight



Twilight after Sunset in Parbhani

Twilight is defined according to the solar elevation angle θ_s, which is the position of the geometric center of the sun relative to the horizon. There are three established and widely accepted *subcategories* of twilight: civil twilight (brightest), nautical twilight, and astronomical twilight (darkest).

Definition	Sun's centre relative to mathematical horizon
Day	$-0° 50' \leq \theta_s$
Sun's lower limb at horizon	$\theta_s = -0° 20'$
Center of Sun's disk at horizon	$\theta_s = -0° 35'$
Sun's upper limb at horizon	$\theta_s = -0° 50'$
Civil twilight	$-6° \leq \theta_s < -0° 50'$
Nautical twilight	$-12° \leq \theta_s < -6°$
Astronomical twilight	$-18° \leq \theta_s < -12°$
Night	$\theta_s < -18°$

(For these definitions, an ideal horizon 90° from the zenith is used.)

Civil twilight

Under civil twilight circumstances, the horizon is clearly visible, and terrestrial objects are easily perceptible, without artificial light.

Morning civil twilight (**civil dawn**) begins when the geometric center of the sun is 6° below the horizon and ends at sunrise. Evening civil twilight (**civil dusk**) begins at sunset and ends when the geometric center of the sun reaches 6° below the horizon.

The brightest stars appear during the civil twilight, as well as planets, such as Venus, which is known as the 'morning star' and/or 'evening star'. During this period there is enough light from the sun that artificial sources of light may not be needed to carry on outdoor activities. This concept is sometimes enshrined in laws, for example, when drivers of automobiles must turn on their headlights, when pilots may exercise the rights to fly aircraft, or if the crime of burglary is to be treated as nighttime burglary, which carries stiffer penalties in some jurisdictions. A fixed period (most commonly 30 minutes after sunset or before sunrise) is typically used in such statutes, rather than how many degrees the sun is below the horizon. Civil twilight can also be described as the limit at which twilight illumination is sufficient, under good weather conditions, for terrestrial objects to be clearly distinguished; at the beginning of morning civil twilight, or end of evening civil twilight, the horizon is clearly defined and the brightest stars are visible under good atmospheric conditions.

Nautical twilight

Nautical twilight in Acapulco, with visible stars and horizon

Nautical twilight is the time when the center of the sun is between 6° and 12° below the horizon. In general, nautical twilight ends when navigation via the horizon at sea is no longer possible.

During nautical twilight, sailors can take reliable star sights of well-known stars, using a visible horizon for reference. The end of this period in the evening, or its beginning in the morning, is also the time at which traces of illumination near the sunset or sunrise point of the horizon are very difficult if not impossible to discern (this often being referred to as "first light" before civil dawn and "nightfall" after civil dusk). At the beginning of nautical twilight in the morning (**nautical dawn**), or at the end of nautical twilight in the evening (**nautical dusk**), under good atmospheric conditions and in the absence of other illumination, general outlines of ground objects may be distinguishable, but detailed outdoor operations are not possible, and the horizon is indistinct.

Nautical twilight has military considerations as well. The initialisms **BMNT** (begin morning nautical twilight) and **EENT** (end evening nautical twilight) are used and considered when planning military operations. A military unit may treat BMNT and EENT with heightened security (i.e. a process called "stand to" in which every one assumes their defensive positions). This is partially due to tactics dating back to the French and Indian War (part of the Seven Years' War of 1756-1763), when combatants on both sides would use BMNT and EENT to launch attacks.

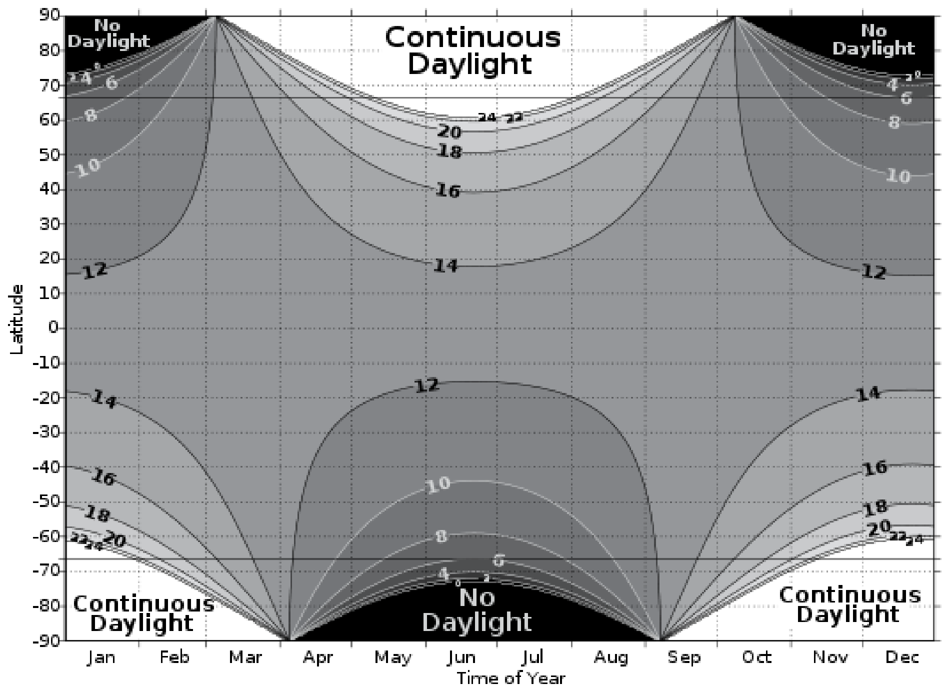
Astronomical twilight

Astronomical twilight at Prague Castle

Astronomical twilight is the time when the center of the Sun is between 12° and 18° below the horizon. From the end of astronomical twilight in the evening to the beginning of astronomical twilight in the morning, the sky (away from urban light pollution) is dark enough for all astronomical observations.

Most casual observers would consider the entire sky already fully dark even when astronomical twilight is just beginning in the evening or just ending in the morning, and astronomers can easily make observations of point sources such as stars, but faint diffuse items such as nebulae and galaxies can only be properly observed beyond the limit of astronomical twilight. Theoretically, the dimmest stars ever visible to the naked eye—those of the sixth magnitude—will appear in the evening once the sun falls more than 18° below the horizon (i.e. when **astronomical dusk** ends) and disappear when the sun moves to within 18° of the horizon in the morning (when **astronomical dawn** begins). However, because of light pollution, some localities—generally those in large cities—may never have the opportunity to view even fourth-magnitude stars, irrespective of the presence of any twilight at all.

Length



The number of daylight hours depends on the latitude and time of year. There are brief times in March and September where continuous daylight exists at locations near both poles.

The length of twilight after sunset and before sunrise is heavily influenced by the latitude of the observer. In the Arctic and Antarctic regions, twilight (if at all) can last for several hours. There is no civil twilight at the poles within a month on either side of the winter solstice. At the poles, civil twilight can be as long as two weeks, while at the equator, it can go from day to night in as little as twenty minutes. This is because at low latitudes the sun's apparent movement is perpendicular to the observer's horizon. As one gets closer to the Arctic and Antarctic circles, the sun's disk moves toward the observer's horizon at a lower angle. The observer's earthly location will pass through the various twilight zones less directly, taking more time.

Within the polar circles, twenty-four hour daylight is encountered in summer and in regions very close to the poles, twilight can last for weeks on the winter side of the equinoxes. Outside the polar circles, where the angular distance from the polar circle is less than the angle which defines twilight (see above), twilight can continue through local midnight near the summer solstice (June in the Northern Hemisphere, December in the Southern Hemisphere). The precise position of the polar circles, and thus of the regions where twilight can continue through local midnight, varies slightly from year to year with Earth's axial tilt. The lowest latitudes at which the various twilights can continue through local midnight are approximately 60.561° (60° 33’ 43”) for civil twilight, 54.561° (54° 33’ 43”) for nautical twilight and 48.561° (48° 33’ 43”) for astronomical twilight.

These are the largest cities, of their respective countries, where the various twilights can continue through local solar midnight:

- Civil twilight from sunset to sunrise: Arkhangelsk, Tampere, Umeå, Trondheim, Mid Yell, Tórshavn, Reykjavik, Nuuk, Whitehorse and Anchorage.

- Nautical twilight from civil dusk to civil dawn: Petropavl, Moscow, Vicebsk, Vilnius, Riga, Tallinn, Wejherowo, Flensburg, Helsinki, Stockholm, Copenhagen, Oslo, Newcastle upon Tyne, Glasgow, Belfast, Letterkenny, Grande Prairie, Juneau, Ushuaia and Puerto Williams.

- Astronomical twilight from nautical dusk to nautical dawn: Hulun Buir, Erdenet, Astana, Samara, Kiev, Minsk, Warsaw, Košice, Zwettl, Prague, Berlin, Paris, Luxembourg city, Brussels, Amsterdam, London, Cardiff, Dublin, Calgary, Vancouver, Cut Bank, International Falls, Bellingham, Rio Gallegos and Punta Arenas.

Although Helsinki, Oslo, Stockholm, Tallinn and Saint Petersburg do not actually receive civil twilight from sunset to sunrise, they do have noticeably lighter skies at night (known as white nights) around the summer solstice.

On other planets

Twilight on Mars is longer than on Earth, lasting for up to two hours before sunrise or after sunset. Dust high in the atmosphere scatters light to the night side of the planet. Similar twilights are seen on Earth following major volcanic eruptions.

Rainbow

Semicircular double rainbow. Supernumerary rainbows on the inside of the primary arc. Shadow of the photographer marks the centre of the rainbow circle (antisolar point).

A **rainbow** is an optical and meteorological phenomenon that causes a spectrum of light to appear in the sky when the Sun shines on to droplets of moisture in the Earth's atmosphere. It takes the form of a multicoloured arc, with red on the outer part of the arc and violet on the inner section.

A rainbow spans a continuous spectrum of colours; the distinct bands are an artifact of human colour vision. The most commonly cited and remembered sequence, in English, is Newton's sevenfold red, orange, yellow, green, blue, indigo and violet (popularly memorized by mnemonics like Roy G. Biv). Rainbows can be caused by other forms of water than rain, including mist, spray, and dew.

Rainbows may also form in mist, such as that of a waterfall

Rainbow with a faint reflected rainbow in the lake

Visibility

Rainbows may also form in the spray created by waves (called *spray bows*)

Rainbows can be observed whenever there are water drops in the air and sunlight shining from behind at a low altitude angle. The most spectacular rainbow displays happen when half the sky is still dark with raining clouds and the observer is at a spot with clear sky in the direction of the sun. The result is a luminous rainbow that contrasts with the darkened background.

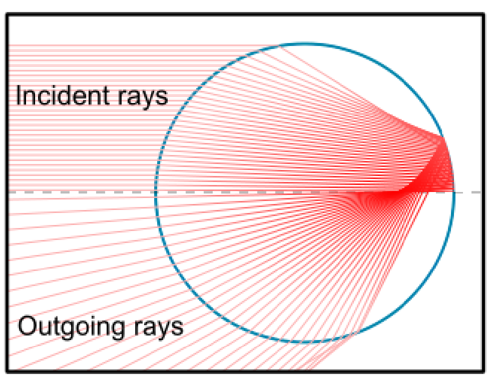
The rainbow effect is also commonly seen near waterfalls or fountains. In addition, the effect can be artificially created by dispersing water droplets into the air during a sunny day. Rarely, a moonbow, lunar rainbow or nighttime rainbow, can be seen on strongly moonlit nights. As human visual perception for colour is poor in low light, moonbows are often perceived to be white. It is difficult to photograph the complete semicircle of a rainbow in one frame, as this would require an angle of view of 84°. For a 35 mm camera, a lens with a focal length of 19 mm or less wide-angle lens would be required. Now that powerful software for stitching several images into a panorama is available, images of the entire arc and even secondary arcs can be created fairly easily from a series of overlapping frames. From an aeroplane, one has the opportunity to see the whole circle of the rainbow, with the plane's shadow in the centre. This phenomenon can be confused with the glory, but a glory is usually much smaller, covering only 5–20°.

At good visibility conditions (for example, a dark cloud behind the rainbow), the second arc can be seen, with inverse order of colours. At the background of the blue sky, the second arc is barely visible.

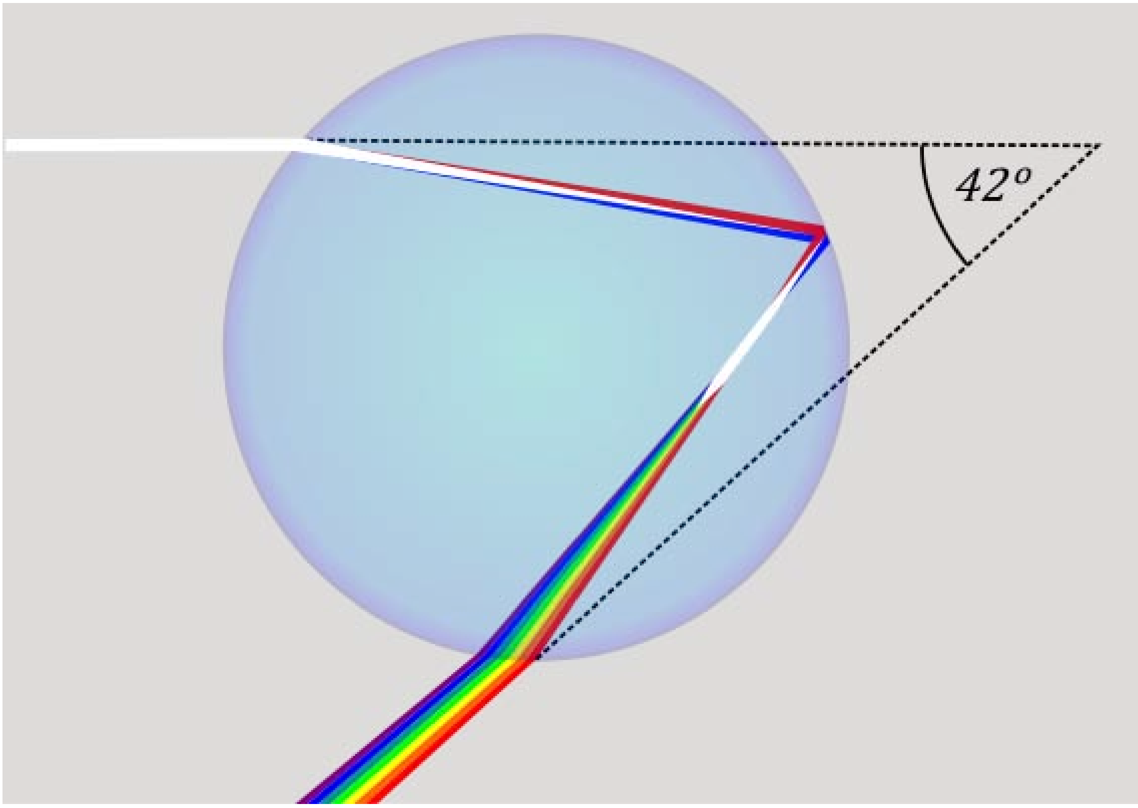
Scientific explanation

The light is first refracted entering the surface of the raindrop, reflected off the back of the drop, and again refracted as it leaves the drop. The overall effect is that the incoming light is reflected back over a wide range of angles, with the most intense light at an angle of 40–42°. The angle is independent of the size of the drop, but does depend on its refractive index. Seawater has a higher refractive index than rain water, so the radius of a "rainbow" in sea spray is smaller than a true rainbow. This is visible to the naked eye by a misalignment of these bows. The amount by which light is refracted depends upon its wavelength, and hence its colour. Blue light (shorter wavelength) is refracted at a greater angle than red light, but due to the reflection of light rays from the back of the droplet, the blue light emerges from the droplet at a smaller angle to the original incident white light ray than the red light. You may then think it is strange that the pattern of colours in a rainbow has red on the outside of the arc and blue on the inside. However, when we examine this issue more closely, we realise that if the red light from one droplet is seen by an observer, then the blue light from that droplet will not be seen because it is on a different path from the red light: a path which is not incident with the observer's eyes. The blue light seen in this rainbow will therefore come from a *different droplet*, which must be below that whose red light can be observed.

Contrary to popular belief, the light at the back of the raindrop does not undergo total internal reflection, and some light does emerge from the back. However, light coming out the back of the raindrop does not create a rainbow between the observer and the Sun because spectra emitted from the back of the raindrop do not have a maximum of intensity, as the other visible rainbows do, and thus the colours blend together rather than forming a rainbow.



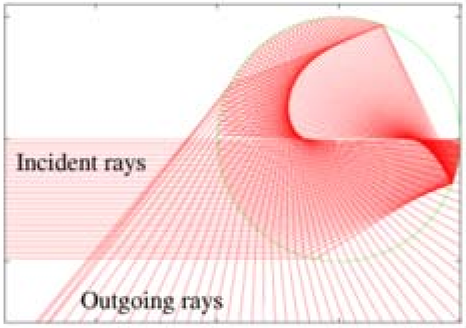
Light rays enter a raindrop from one direction (typically a straight line from the Sun), reflect off the back of the raindrop, and fan out as they leave the raindrop. The light leaving the rainbow is spread over a wide angle, with a maximum intensity at 40.89–42°.



White light separates into different colours on entering the raindrop because red light is refracted by a lesser angle than blue light. On leaving the raindrop, the red rays have turned through a smaller angle than the blue rays, producing a rainbow.

A rainbow does not actually exist at a particular location in the sky. Its apparent position depends on the observer's location and the position of the Sun. All raindrops refract and reflect the sunlight in the same way, but only the light from some raindrops reaches the observer's eye. This light is what constitutes the rainbow for that observer. The position of a rainbow in the sky is always in the opposite direction of the Sun with respect to the observer, and the interior is always slightly brighter than the exterior. The bow is centred on the shadow of the observer's head, or more exactly at the antisolar point (which is below the horizon during the daytime), appearing at an angle of 40–42° to the line between the observer's head and its shadow. As a result, if the Sun is higher than 42°, then the rainbow is below the horizon and usually cannot be seen as there are not usually sufficient raindrops between the horizon (that is: eye height) and the ground, to contribute. Exceptions occur when the observer is high above the ground, for example in an aeroplane (see above), on top of a mountain, or above a waterfall.

Variations



Some light reflects twice inside the raindrop before exiting to the viewer. When the incident light is very bright, this can be seen as a secondary rainbow, brightest at 50–53°.

A double rainbow features reversed colours in the outer (secondary) bow, with the dark Alexander's band between the bows.

Frequently, a dim secondary rainbow is seen outside the primary bow. Secondary rainbows are caused by a double reflection of sunlight inside the raindrops, and appear at an angle of 50–53°. As a result of the second reflection, the colours of a secondary rainbow are inverted compared to the primary bow, with blue on the outside and red on the inside. The secondary rainbow is fainter than the primary because more light escapes from two reflections compared to one and because the rainbow itself is spread over a greater area of the sky. The dark area of unlit sky lying between the primary and secondary bows is called Alexander's band, after Alexander of Aphrodisias who first described it.

A third, or tertiary, rainbow can be seen on rare occasions, and a few observers have reported seeing quadruple rainbows in which a dim outermost arc had a rippling and pulsating appearance. These rainbows would appear on the same side of the sky as the Sun, making them hard to spot. One type of tertiary rainbow carries with it the appearance of a secondary rainbow immediately outside the primary bow. The closely spaced outer bow has been observed to form dynamically at the same time that the outermost (tertiary) rainbow disappears. During this change, the two remaining rainbows have been observed to merge into a band of white light with a blue inner and red outer band. This particular form of doubled rainbow is not like the classic double rainbow due to both spacing of the two bows and that the two bows share identical normal colour positioning before merging. With both bows, the inner colour is blue and the outer colour is red.

Higher-order rainbows were described by Felix Billet (1808–1882) who depicted angular positions up to the 19th-order rainbow, a pattern he called "rose". In the laboratory, it is possible to observe higher-order rainbows by using extremely bright and well collimated light produced by lasers. A sixth-order rainbow was first observed by K. Sassan in 1979 using a HeNe laser beam and a pendant water drop. Up to the 200th-order rainbow was reported by Ng et al. in 1998 using a similar method but an argon ion laser beam.

Supernumerary rainbow

A contrast-enhanced photograph of a supernumerary rainbow, with additional green and purple arcs inside the primary bow.

A **supernumerary rainbow**—also known as a **stacker rainbow**—is an infrequent phenomenon, consisting of several faint rainbows on the inner side of the primary rainbow, and very rarely also outside the secondary rainbow. Supernumerary rainbows are slightly detached and have pastel colour bands that do not fit the usual pattern.

It is not possible to explain their existence using classical geometric optics. The alternating faint rainbows are caused by interference between rays of light following slightly different paths with slightly varying lengths within the raindrops. Some rays are in phase, reinforcing each other through constructive interference, creating a bright band; others are out of phase by up to half a wavelength, canceling each other out through destructive interference, and creating a gap. Given the different angles of refraction for rays of different colours, the patterns of interference are slightly different for rays of different colours, so each bright band is differentiated in colour, creating a miniature rainbow. Supernumerary rainbows are clearest when raindrops are small and of similar size. The very existence of supernumerary rainbows was historically a first indication of the wave nature of light, and the first explanation was provided by Thomas Young in 1804.

Reflected rainbow, reflection rainbow

Reflection rainbow and normal rainbow, at sunset

When a rainbow appears above a body of water, two complementary mirror bows may be seen below and above the horizon, originating from different light paths. Their names are slightly different. A **reflected rainbow** will appear as a mirror image in the water surface below the horizon, if the surface is quiet. The sunlight is first deflected by the raindrops, and then reflected off the body of water, before reaching the observer. The reflected rainbow is frequently visible, at least partially, even in small puddles.

Where sunlight reflects off a body of water before reaching the raindrops, it may produce a **reflection rainbow**, if the water body is large, quiet over its entire surface, and close to the rain curtain. The reflection rainbow appears above the horizon. It intersects the normal rainbow at the horizon, and its arc reaches higher in the sky, with its centre as high above the horizon as the normal rainbow's centre is below it. Due to the combination of requirements, a reflection rainbow is rarely visible.

Six (or even eight) bows may be distinguished if the reflection of the reflection bow, and the secondary bow with its reflections happen to appear simultaneously.

Circumhorizontal arc

The circumhorizontal arc is sometimes referred to by the misnomer "fire rainbow". As it originates in ice crystals, it is not a rainbow but a halo.

Rainbows on Titan

It has been suggested that rainbows might exist on Saturn's moon Titan, as it has a wet surface and humid clouds. The radius of a Titan rainbow would be about 49° instead of 42°, because the fluid in that cold environment is methane instead of water. A visitor might need infrared goggles to see the rainbow, as Titan's atmosphere is more transparent for those wavelengths.

Scientific history

The Greek philosopher Aristotle (384–322 BCE) was first to devote serious attention to the rainbow. After Aristotle's death, much rainbow theory consisted of reaction to his work, although not all of this was uncritical.

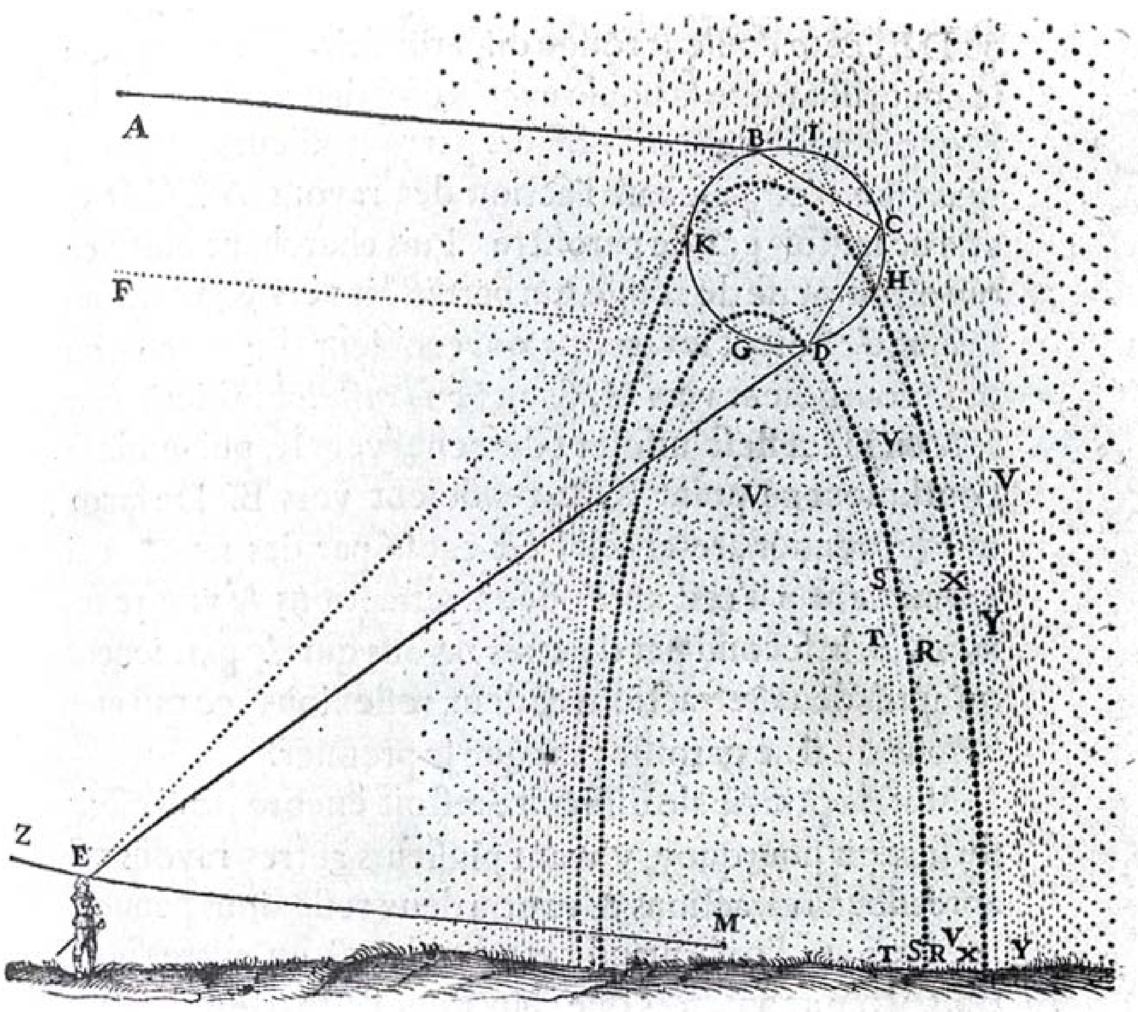
The Arab physicist and polymath, Ibn al-Haytham (Alhazen; 965–1039), attempted to provide a scientific explanation for the rainbow phenomenon. In his *Maqala fi al-Hala wa Qaws Quzah* (*On the Rainbow and Halo*), he "explained the formation of rainbow as an image, which forms at a concave mirror. If the rays of light coming from a farther light source reflect to any point on axis of the concave mirror, they form concentric circles in that point. When it is supposed that the sun as a farther light source, the eye of viewer as a point on the axis of mirror and a cloud as a reflecting surface, then it can be observed the concentric circles are forming on the axis." He was not able to verify this because his theory that "light from the sun is reflected by a cloud before reaching the eye" did not allow for a possible experimental verification. This explanation was later repeated by Averroes, and, though incorrect, provided the groundwork for the correct explanations later given by Kamāl al-Dīn al-Fārisī (1267–ca. 1319/1320) and Theodoric of Freiberg (c.1250–1310). Ibn al-Haytham supported the Aristotelian views that the rainbow is caused by reflection alone and that its colours are not real like object colours.

Ibn al-Haytham's contemporary, the Persian philosopher and polymath Ibn Sīnā (Avicenna; 980–1037), provided an alternative explanation, writing "that the bow is not formed in the dark cloud but rather in the very thin mist lying between the cloud and the sun or observer. The cloud, he thought, serves simply as the background of this thin substance, much as a quicksilver lining is placed upon the rear surface of the glass in a mirror. Ibn Sīnā would change the place not only of the bow, but also of the colour formation, holding the iridescence to be merely a subjective sensation in the eye." This explanation, however, was also incorrect. Ibn Sīnā's account accepts many of Aristotle's arguments on the rainbow.

In Song Dynasty China (960–1279), a polymathic scholar-official named Shen Kuo (1031–1095) hypothesized—as a certain Sun Sikong (1015–1076) did before him—that rainbows were formed by a phenomenon of sunlight encountering droplets of rain in the air. Paul Dong writes that Shen's explanation of the rainbow as a phenomenon of atmospheric refraction "is basically in accord with modern scientific principles."

The Persian astronomer, Qutb al-Din al-Shirazi (1236–1311), gave a fairly accurate explanation for the rainbow phenomenon. This was elaborated on by his student, Kamāl al-Dīn al-Fārisī (1260–1320), who gave a more mathematically satisfactory explanation of the rainbow. He "proposed a model where the ray of light from the sun was refracted twice by a water droplet, one or more reflections occurring between the two refractions." He verified this through extensive experimentation using a transparent sphere filled with water and a camera obscura. As he noted in his *Kitab Tanqih al-Manazir* (*The Revision of the Optics*), al-Farisi used a large clear vessel of glass in the shape of a sphere, which was filled with water, in order to have an experimental large-scale model of a rain drop. He then placed this model within a camera obscura that has a controlled aperture for the introduction of light. He projected light unto the sphere and ultimately deducted through several trials and detailed observations of reflections and refractions of light that the colours of the rainbow are phenomena of the decomposition of light. His research had resonances with the studies of his contemporary Theodoric of Freiberg (without any contacts between them; even though they both relied on Aristotle's and Ibn al-Haytham's legacy), and later with the experiments of Descartes and Newton in dioptrics (for instance, Newton conducted a similar experiment at Trinity College, though using a prism rather than a sphere).

In Europe, Ibn al-Haytham's *Book of Optics* was translated into Latin and studied by Robert Grosseteste. His work on light was continued by Roger Bacon, who wrote in his *Opus Majus* of 1268 about experiments with light shining through crystals and water droplets showing the colours of the rainbow. In addition, Bacon was the first to calculate the angular size of the rainbow. He stated that the rainbow summit can not appear higher than 42° above the horizon. Theodoric of Freiberg is known to have given an accurate theoretical explanation of both the primary and secondary rainbows in 1307. He explained the primary rainbow, noting that "when sunlight falls on individual drops of moisture, the rays undergo two refractions (upon ingress and egress) and one reflection (at the back of the drop) before transmission into the eye of the observer". He explained the secondary rainbow through a similar analysis involving two refractions and two reflections.



René Descartes' sketch of how primary and secondary rainbows are formed

Descartes' 1637 treatise, *Discourse on Method*, further advanced this explanation. Knowing that the size of raindrops did not appear to affect the observed rainbow, he experimented with passing rays of light through a large glass sphere filled with water. By measuring the angles that the rays emerged, he concluded that the primary bow was caused by a single internal reflection inside the raindrop and that a secondary bow could be caused by two internal reflections. He supported this conclusion with a derivation of the law of refraction (subsequently, but independently of, Snell) and correctly calculated the angles for both bows. His explanation of the colours, however, was based on a mechanical version of the traditional theory that colours were produced by a modification of white light.

Isaac Newton demonstrated that white light was composed of the light of all the colours of the rainbow, which a glass prism could separate into the full spectrum of colours, rejecting the theory that the colours were produced by a modification of white light. He also showed that red light gets refracted less than blue light, which led to the first scientific explanation of the major features of the rainbow. Newton's corpuscular theory of light was unable to explain supernumerary rainbows, and a satisfactory explanation was not found until Thomas Young realised that light behaves as a wave under certain conditions, and can interfere with itself.

Young's work was refined in the 1820s by George Biddell Airy, who explained the dependence of the strength of the colours of the rainbow on the size of the water droplets. Modern physical descriptions of the rainbow are based on Mie scattering, work published by Gustav Mie in 1908. Advances in computational methods and optical theory continue to lead to a fuller understanding of rainbows. For example, Nussenzveig provides a modern overview.

Chapter-3

Beaufort Scale

Force 12 at sea.

The **Beaufort Scale** is an empirical measure for describing wind speed based mainly on observed sea conditions. Its full name is the **Beaufort Wind Force Scale**.

History

The scale was created in 1806 by Sir Francis Beaufort, an Irish-born British admiral and hydrographer. The scale that carries Beaufort's name had a long and complex evolution, from the previous work of others, to when Beaufort was a top administrator in the Royal Navy in the 1830s. In the early 19th Century, naval officers made regular weather observations, but there was no standard scale and so they could be very subjective - one man's "stiff breeze" might be another's "soft breeze". Beaufort succeeded in standardizing the scale.

The initial scale of thirteen classes (zero to twelve) did not reference wind speed numbers but related qualitative wind conditions to effects on the sails of a man-of-war, then the main ship of the Royal Navy, from "just sufficient to give steerage" to "that which no canvas sails could withstand." At zero, all his sails would be up; at six, half of his sails would have been taken down; and at twelve, all sails would be stowed away.

The scale was made a standard for ship's log entries on Royal Navy vessels in the late 1830s and was adapted to non-naval use from the 1850s, with scale numbers corresponding to cup anemometer rotations. In 1906, to accommodate the growth of steam power, the descriptions were changed to how the sea, not the sails, behaved and extended to land observations. Rotations to scale numbers were standardized only in 1923. George Simpson, Director of the UK Meteorological Office, was responsible for this and for the addition of the land-based descriptors. The measure was slightly altered some decades later to improve its utility for meteorologists. Today, many countries have abandoned the scale and use the metric-based units m/s or km/h instead, but the severe weather warnings given to public are still approximately the same as when using the Beaufort scale.

The Beaufort scale was extended in 1946, when Forces 13 to 17 were added. However, Forces 13 to 17 were intended to apply only to special cases, such as tropical cyclones. Nowadays, the extended scale is only used in Taiwan and mainland China, which are often affected by typhoons.

Wind speed on the 1946 Beaufort scale is based on the empirical formula:

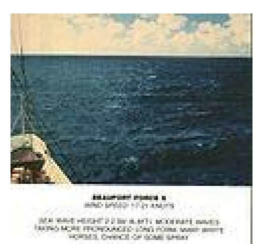
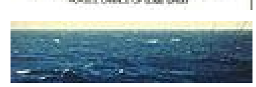
$$v = 0.836\, B^{3/2} \text{ m/s}$$

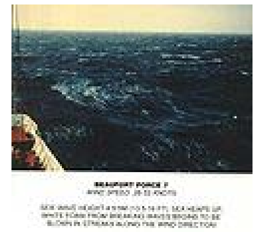
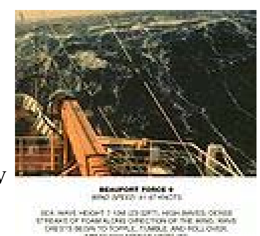
where v is the equivalent wind speed at 10 meters above the sea surface and B is Beaufort scale number. For example, $B = 9.5$ is related to 24.5 m/s which is equal to the lower limit of "10 Beaufort". Using this formula the highest winds in hurricanes would be 23 in the scale.

Today, hurricane force winds are sometimes described as Beaufort scale 12 through 16, very roughly related to the respective category speeds of the Saffir-Simpson Hurricane Scale, by which actual hurricanes are measured, where Category 1 is equivalent to Beaufort 12. However, the extended Beaufort numbers above 13 do not match the Saffir-Simpson Scale. Category 1 tornadoes on the Fujita and TORRO scales also begin roughly at the end of level 12 of the Beaufort scale but are indeed independent scales.

Note that wave heights in the scale are for conditions in the open ocean, not along the shore.

The modern scale

Beaufort number	Description	Wind speed	Wave height	Sea conditions	Land conditions	Sea state photo
0	Calm	< 1 km/h < 1 mph < 1 kn < 0.3 m/s	0 m 0 ft	Flat.	Calm. Smoke rises vertically.	
1	Light air	1.1–5.5 km/h 1–3 mph 1–2 kn 0.3–1.5 m/s	0–0.2 m 0–1 ft	Ripples without crests.	Smoke drift indicates wind direction, still wind vanes.	
2	Light breeze	5.6–11 km/h 4–7 mph 3–6 kn 1.6–3.4 m/s	0.2–0.5 m 1–2 ft	Small wavelets. Crests of glassy appearance, not breaking	Wind felt on exposed skin. Leaves rustle, vanes begin to move.	
3	Gentle breeze	12–19 km/h 8–12 mph 7–10 kn 3.4–5.4 m/s	0.5–1 m 2–3.5 ft	Large wavelets. Crests begin to break; scattered whitecaps	Leaves and small twigs constantly moving, light flags extended.	
4	Moderate breeze	20–28 km/h 13–17 mph 11–15 kn 5.5–7.9 m/s	1–2 m 3.5–6 ft	Small waves with breaking crests. Fairly frequent white horses.	Dust and loose paper raised. Small branches begin to move.	
5	Fresh breeze	29–38 km/h 18–24 mph 16–20 kn 8.0–10.7 m/s	2–3 m 6–9 ft	Moderate waves of some length. Many white horses. Small amounts of spray.	Branches of a moderate size move. Small trees in leaf begin to sway.	
6	Strong breeze	39–49 km/h	3–4 m	Long waves begin to form.	Large branches in motion. Whistling heard	

		25–30 mph 21–26 kn 10.8–13.8 m/s	9–13 ft	White foam crests are very frequent. Some airborne spray is present.	in overhead wires. Umbrella use becomes difficult. Empty plastic garbage cans tip over.	
7	High wind, Moderate gale, Near gale	50–61 km/h 31–38 mph 27–33 kn 13.9–17.1 m/s	4–5.5 m 13–19 ft	Sea heaps up. Some foam from breaking waves is blown into streaks along wind direction. Moderate amounts of airborne spray.	Whole trees in motion. Effort needed to walk against the wind.	
8	Gale, Fresh gale	62–74 km/h 39–46 mph 34–40 kn 17.2–20.7 m/s	5.5–7.5 m 18–25 ft	Moderately high waves with breaking crests forming spindrift. Well-marked streaks of foam are blown along wind direction. Considerable airborne spray.	Some twigs broken from trees. Cars veer on road. Progress on foot is seriously impeded.	
9	Strong gale	75–88 km/h 47–54 mph 41–47 kn 20.8–24.4 m/s	7–10 m 23–32 ft	High waves whose crests sometimes roll over. Dense foam is blown along wind direction. Large amounts of airborne spray may begin to reduce visibility.	Some branches break off trees, and some small trees blow over. Construction/temporary signs and barricades blow over.	
10	Storm, Whole gale	89–102 km/h 55–63 mph 48–55 kn 24.5–28.4 m/s	9–12.5 m 29–41 ft	Very high waves with overhanging crests. Large patches of foam from wave crests give the sea a white appearance. Considerable tumbling of waves with heavy impact. Large amounts of airborne spray reduce visibility.	Trees are broken off or uprooted, saplings bent and deformed. Poorly attached asphalt shingles and shingles in poor condition peel off roofs.	

11	Violent storm	103–117 km/h 64–72 mph 56–63 kn 28.5–32.6 m/s	11.5–16 m 37–52 ft	Exceptionally high waves. Very large patches of foam, driven before the wind, cover much of the sea surface. Very large amounts of airborne spray severely reduce visibility.	Widespread damage to vegetation. Many roofing surfaces are damaged; asphalt tiles that have curled up and/or fractured due to age may break away completely.	
12	Hurricane-force	≥ 118 km/h ≥ 73 mph ≥ 64 kn ≥ 32.7 m/s	≥ 14 m ≥ 46 ft	Huge waves. Sea is completely white with foam and spray. Air is filled with driving spray, greatly reducing visibility.	Very widespread damage to vegetation. Some windows may break; mobile homes and poorly constructed sheds and barns are damaged. Debris may be hurled about.	

The scale is used in the Shipping Forecasts broadcast on BBC Radio 4 in the United Kingdom.

This scale is also widely used in China, Taiwan, Hong Kong and Macau, however with some differences between them. Taiwan uses the Beaufort scale with the extension to 17 noted above. China also switched to this extended version without prior notice on the morning of May 15, 2006, and the extended scale was immediately put to use for Typhoon Chanchu. Hong Kong and Macau however keep using Force 12 as the maximum.

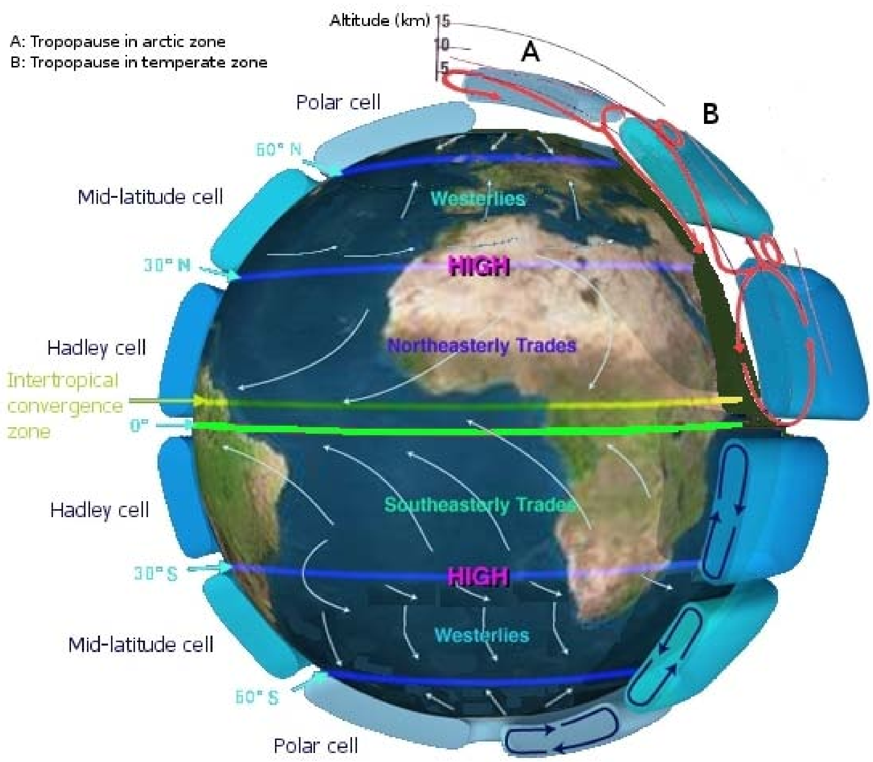
In the United States, winds of force 6 or 7 result in the issuance of a small craft advisory, with force 8 or 9 winds bringing about a gale warning, force 10 or 11 a storm warning ("a tropical storm warning" being issued instead of the latter two if the winds relate to a tropical cyclone), and force 12 a hurricane force wind warning (or hurricane warning if related to a tropical cyclone). A set of red warning flags (daylight) and red warning lights (night time) is displayed at shore establishments which coincide with the various levels of warning.

In Canada, maritime winds forecast to be in the range of 6 to 7 are designated as "strong"; 8 to 9 "gale force"; 10 to 11 "storm force"; 12 "hurricane force". Appropriate wind warnings are issued by Environment Canada's Meteorological Service of Canada: strong wind warning, gale (force wind) warning, storm (force wind) warning and hurricane force wind warning. These designations were standardized nationally in 2008, whereas "light wind" can refer to 0 to 12 or 0 to 15 knots and "moderate wind" 12 to 19 or 16 to 19 knots, depending on regional custom, definition or practice. Prior to 2008, a "strong wind warning" would have been referred to as a "small craft warning" by Environment Canada, similar to US terminology. (Canada and the USA have the Great Lakes in common.)

However, there being no generally accepted definition of "small craft", and to have consistency between wind speed ranges and their associated warnings, the term "strong wind warning" has become the national Canadian norm.

Chapter-4

Prevailing Winds

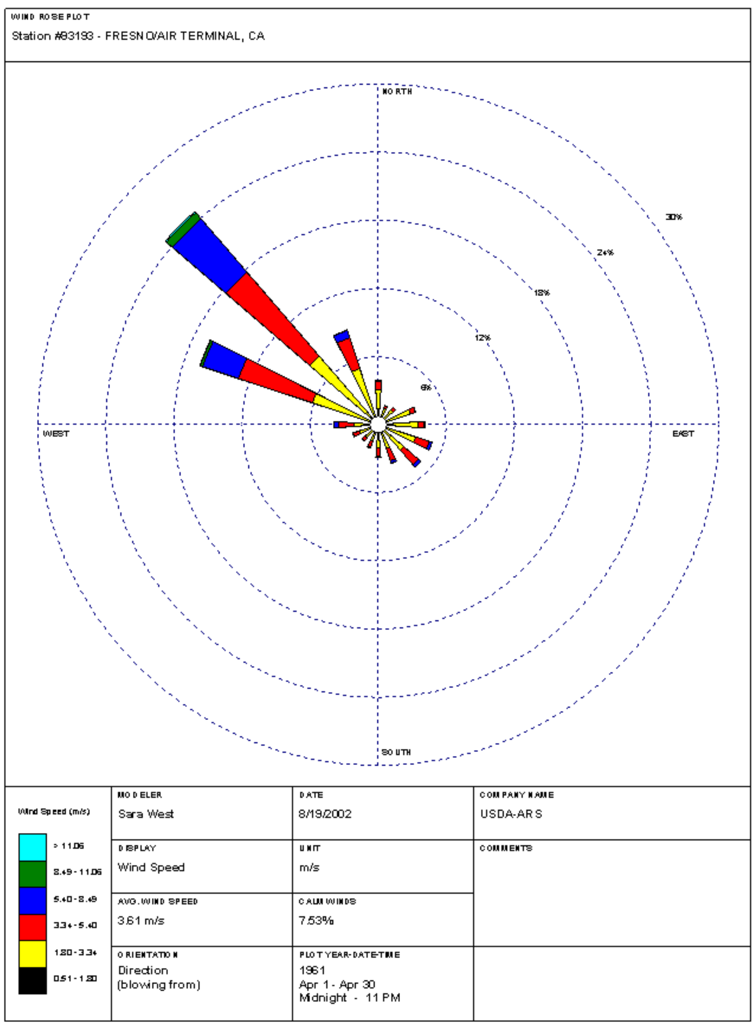


Winds are part of Earth's atmospheric circulation

In meteorology, **prevailing winds** are winds that blow predominantly from a single general direction over a particular point on the Earth's surface. The **dominant winds** are the trends in direction of wind with the highest speed over a particular point on the Earth's surface. A region's prevailing and dominant winds are often affected by global patterns of movement in the Earth's atmosphere. In general, easterly flow exists at low and high latitudes globally. In the mid-latitudes, westerly winds are the rule and their strength is at the mercy of the polar cyclone. In areas where winds tend to be light, the sea breeze/land breeze cycle is the most important to the prevailing wind; in areas which have variable terrain, mountain and valley breezes dominate the wind pattern. Highly elevated surfaces can induce a thermal low, which then augments the environmental wind flow.

Wind roses are tools used to determine the direction of the prevailing wind. Knowledge of the prevailing wind allows the development of prevention strategies for soil erosion of agricultural land, such as across the Great Plains. Sand dunes can orient themselves along, or perpendicular, to the prevailing wind regime within coastal and desert locations. Insects drift along with the prevailing wind, while birds are able to fly more independently of the prevailing wind. Prevailing winds in mountainous locations can lead to significant rainfall gradients within the topography, ranging from wet across windward-facing slopes to desert-like conditions along their lee slopes.

Determination for a location

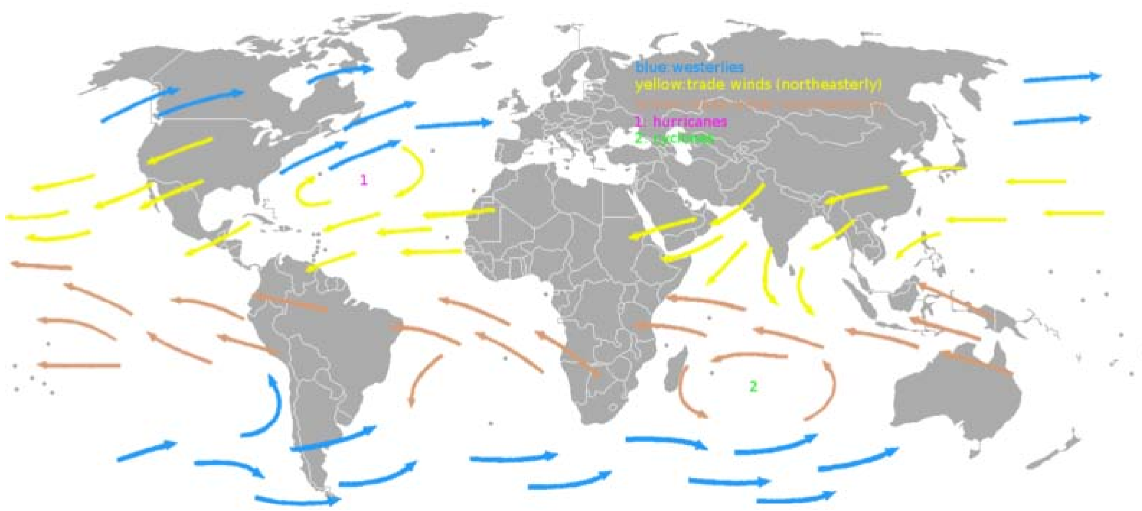


Wind rose plot for Fresno Air Terminal (FAT), Fresno, California for the period 1961-1990

A wind rose is a graphic tool used by meteorologists to give a succinct view of how wind speed and direction are typically distributed at a particular location. Presented in a polar coordinate grid, the wind rose shows the frequency of winds blowing from particular directions. The length of each spoke around the circle is related to the frequency that the wind blows from a particular direction per unit time. Each concentric circle represents a different frequency, emanating from zero at the center to increasing frequencies at the outer circles. A wind rose plot may contain additional information, in that each spoke is broken down into color-coded bands that show wind speed ranges. Wind roses typically use 8 or 16 cardinal directions, such as north (N), NNE, NE, etc., although they may be subdivided into as many as 32 directions.

Climatology

Trades and their impact



The westerlies (blue arrows) and trade winds (yellow arrows)

The **trade winds** (also called **trades**) are the prevailing pattern of easterly surface winds found in the tropics, within the lower portion of the Earth's atmosphere, in the lower section of the troposphere near the Earth's equator. The trade winds blow predominantly from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere, strengthening during the winter and when the Arctic oscillation is in its warm phase. Historically, the trade winds have been used by captains of sailing ships to cross the world's oceans for centuries; and enabled European empire expansion into the Americas, and trade routes to become established across the Atlantic and Pacific oceans.

In meteorology, the trade winds act as the steering flow for tropical storms that form over the Atlantic, Pacific, and south Indian Oceans and make landfall in North America, Southeast Asia, and India, respectively. Trade winds also steer African dust westward across the Atlantic ocean into the Caribbean sea, as well as portions of southeast North America. Shallow cumulus clouds are seen within trade wind regimes, which are capped from becoming taller by a trade wind inversion, which is caused by descending air aloft from within the subtropical ridge. The weaker the trade winds become, the more rainfall can be expected within neighboring landmasses.

History

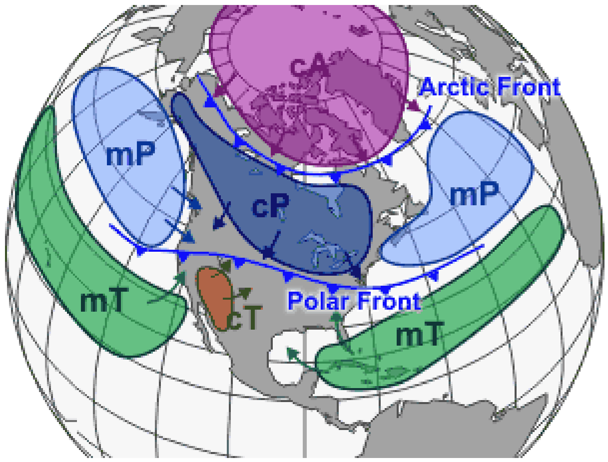
A Spanish galleon

The term *trade winds* originally derives from the early fourteenth century late Middle English word 'trade' meaning "path" or "track." The Portuguese recognized the importance of the trade winds in navigation in the Atlantic ocean as early as the 15th century. The full wind circulation, which included both the trade wind easterlies and higher-latitude Westerlies, was not known across the Pacific ocean until 1565.

The captain of a ship seeks a course along which the winds can be expected to blow in the direction of travel. During the Age of Sail the pattern of prevailing winds made various points of the globe easy or difficult to access, and therefore had a direct impact on European empire-building and thus on modern political geography. For example, Manila galleons could not sail into the wind at all.

By the 18th century the importance of the trade winds to England's merchant fleet for crossing the Atlantic Ocean had led both the general public and etymologists to identify the name with a later meaning of 'trade', "(foreign) commerce". Between 1847 and 1849, Matthew Fontaine Maury collected enough information to create wind and current charts for the world's oceans.

Cause



General distribution of air masses near North America. The green region labeled mT describes a maritime tropical air mass, which is the type of air mass within the belt of the trade winds.

As part of the Hadley cell circulation, surface air flows toward the equator while the flow aloft is towards the poles. A low-pressure area of calm, light variable winds near the equator is known as the doldrums, equatorial trough, intertropical front, or the Intertropical Convergence Zone. When located within a monsoon region, this zone of low pressure and wind convergence is also known as the monsoon trough. Around 30° in both hemispheres air begins to descend toward the surface in subtropical high-pressure belts known as subtropical ridges. The sinking air is relatively dry because as it descends, the temperature increases but the absolute humidity remains constant, which lowers the relative humidity of the air mass. This air mass is dry and subsident, or sinking through the troposphere, and sometimes reaches the ground. When this warm, dry air reaches the surface it is known as a superior air mass. The superior air normally resides over the top of maritime tropical air masses over oceans, forming a warmer and drier layer over the more moderate maritime tropical air mass below. When the temperature increases with height, it is known as a temperature inversion. When it occurs within a trade wind regime, it is known as a trade wind inversion.

The surface air that flows from these subtropical high-pressure belts toward the Equator is deflected toward the west in both hemispheres by the Coriolis effect. These winds blow predominantly from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. Because winds are named for the direction from which the wind is blowing, these winds are called the northeast trade winds in the Northern Hemisphere and the southeast trade winds in the Southern Hemisphere. The trade winds meet at the doldrums.

As they blow across tropical regions, air masses heat up over lower latitudes due to more direct sunlight. Those that develop over land (continental) are drier and hotter than those that develop over oceans (maritime), and travel northward on the western periphery of the subtropical ridge. Maritime tropical air masses are sometimes referred to as trade air masses. The one region of the Earth which has an absence of trade winds is the north Indian ocean.

Weather effects

Nā Pali coast, Kaua'i, showing trade wind cumuli

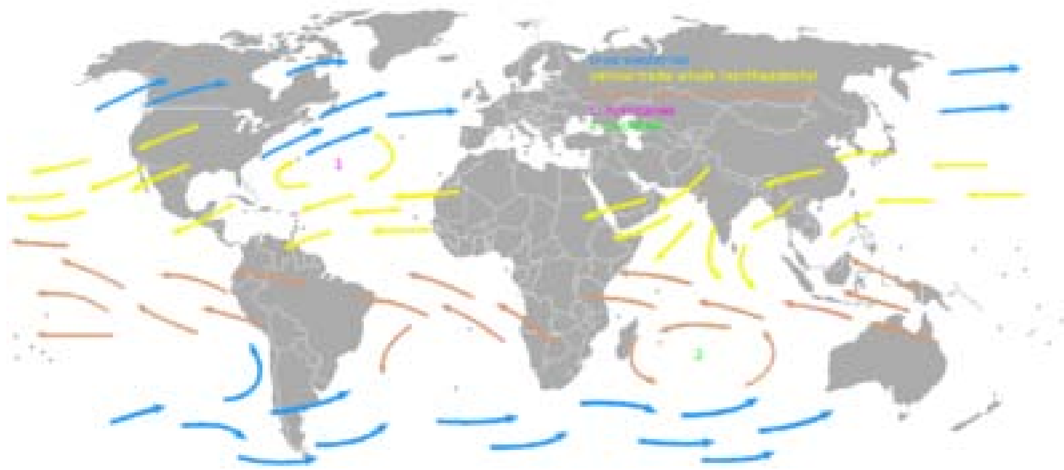
Clouds which form above regions within trade wind regimes are typically composed of cumulus which extend no more than 4 kilometres (13,000 ft) in height, and are capped from being taller by the trade wind inversion. Trade winds originate more from the direction of the poles (northeast in the Northern Hemisphere, southeast in the Southern Hemisphere) during the cold season, and are stronger in the winter than the summer. As an example, the windy season in the Guianas, which lie at low latitudes in South America, occurs between January and April. When the phase of the Arctic oscillation (AO) is warm, trade winds are stronger within the tropics. The cold phase of the AO leads to weaker trade winds. When the trade winds are weaker, more extensive areas of rain fall upon landmasses within the tropics, such as Central America.

During mid-summer in the Northern Hemisphere (July), the westward-moving trade winds south of the northward-moving subtropical ridge expand northwestward from the Caribbean sea into southeastern North America. When dust from the Sahara moving around the southern periphery of the ridge travels over land, rainfall is suppressed and the sky changes from a blue to a white appearance which leads to an increase in red sunsets. Its presence negatively impacts air quality by adding to the count of airborne particulates. Over 50% of the African dust that reaches the United States affects Florida. Since 1970, dust outbreaks have worsened due to periods of drought in Africa. There is a large variability in the dust transport to the Caribbean and Florida from year to year. Dust events have been linked to a decline in the health of coral reefs across the Caribbean and Florida, primarily since the 1970s.

The trade winds (also called trades) are the prevailing pattern of easterly surface winds found in the tropics near the Earth's equator, south of the subtropical ridge. These winds blow predominantly from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. The trade winds act as the steering flow for tropical cyclones that form over world's oceans, guiding their path westward. Trade winds also steer African dust westward across the Atlantic ocean into the Caribbean sea, as well as portions of southeast North America.

Westerlies and their impact

Effect of prevailing wind on a coniferous tree, western Turkey.



The westerlies and trade winds

The **Westerlies**, **anti-trades**, or **Prevailing Westerlies**, are the prevailing winds in the middle latitudes between 35 and 65 degrees latitude, blowing from the high pressure area in the horse latitudes towards the poles. These prevailing winds blow from the west to the east, and steer extratropical cyclones in this general manner. Tropical cyclones which cross the subtropical ridge axis into the Westerlies recurve due to the increased westerly flow. The winds are predominantly from the southwest in the Northern Hemisphere and from the northwest in the Southern Hemisphere.

The Westerlies are strongest in the winter hemisphere and times when the pressure is lower over the poles, while they are weakest in the summer hemisphere and when pressures are higher over the poles. The Westerlies are particularly strong, especially in the southern hemisphere, where there is less land in the middle latitudes to cause the flow pattern to amplify, or become more north-south oriented, which slows the Westerlies down. The strongest westerly winds in the middle latitudes can come in the Roaring Forties, between 40 and 50 degrees latitude. The Westerlies play an important role in carrying the warm, equatorial waters and winds to the western coasts of continents, especially in the southern hemisphere because of its vast oceanic expanse.

Behavior

If the Earth were a non-rotating planet, solar heating would cause winds across the mid-latitudes to blow in a poleward direction, away from the subtropical ridge. However, the Coriolis effect caused by the rotation of Earth causes winds to steer to the right of what would otherwise be expected across the Northern Hemisphere, and left of what would be expected in the Southern Hemisphere. This is why winds across the Northern Hemisphere tend to blow from the southwest, but they tend to be from the northwest in the Southern Hemisphere. When pressures are lower over the poles, the strength of the Westerlies increases, which has the effect of warming the mid-latitudes. This occurs when the Arctic oscillation is positive, and during winter low pressure near the poles is stronger than it would be during the summer. When it is negative and pressures are higher over the poles, the flow is more meridional, blowing from the direction of the pole towards the equator, which brings cold air into the mid-latitudes.

Throughout the year, the Westerlies vary in strength with the polar cyclone. As the cyclone reaches its maximum intensity in winter, the Westerlies increase in strength. As the cyclone reaches its weakest intensity in summer, the Westerlies weaken. An example of the impact of the Westerlies is when dust plumes, originating in the Gobi desert combine with pollutants and spread large distances downwind, or eastward, into North America. The Westerlies can be particularly strong, especially in the Southern Hemisphere, where there is less land in the middle latitudes to cause the progression of west to east winds to slow down. In the Southern hemisphere, because of the stormy and cloudy conditions, it is usual to refer to the Westerlies as the Roaring Forties, Furious Fifties and Shrieking Sixties according to the varying degrees of latitude.

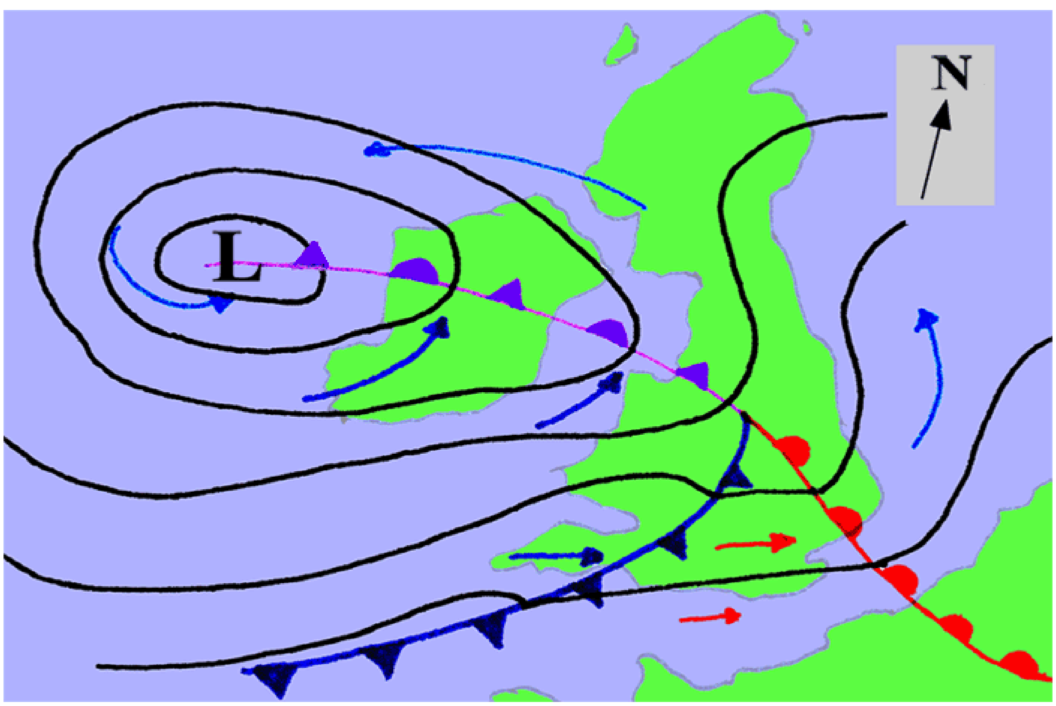
Impact on ocean currents

Benjamin Franklin's map of the Gulf Stream

Due to persistent winds from west to east on the poleward sides of the subtropical ridges located in the Atlantic and Pacific oceans, ocean currents are driven in a similar manner in both hemispheres. The currents in the Northern Hemisphere are weaker than those in the Southern Hemisphere due to the differences in strength between the Westerlies of each hemisphere. The process of western intensification causes currents on the western boundary of an ocean basin to be stronger than those on the eastern boundary of an ocean. These western ocean currents transport warm, tropical water polewards toward the polar regions. Ships crossing both oceans have taken advantage of the ocean currents for centuries.

The Antarctic Circumpolar Current (ACC), or the West Wind Drift, is an ocean current that flows from west to east around Antarctica. The ACC is the dominant circulation feature of the Southern Ocean and, at approximately 125 Sverdrups, the largest ocean current. In the northern hemisphere, the Gulf Stream, part of the North Atlantic Subtropical Gyre, has led to the development of strong cyclones of all types at the base of the Westerlies, both within the atmosphere and within the ocean. The Kuroshio (Japanese for "Black Tide") is a strong western boundary current in the western north Pacific Ocean, similar to the Gulf Stream, which has also contributed to the depth of ocean storms in that region.

Extratropical cyclones



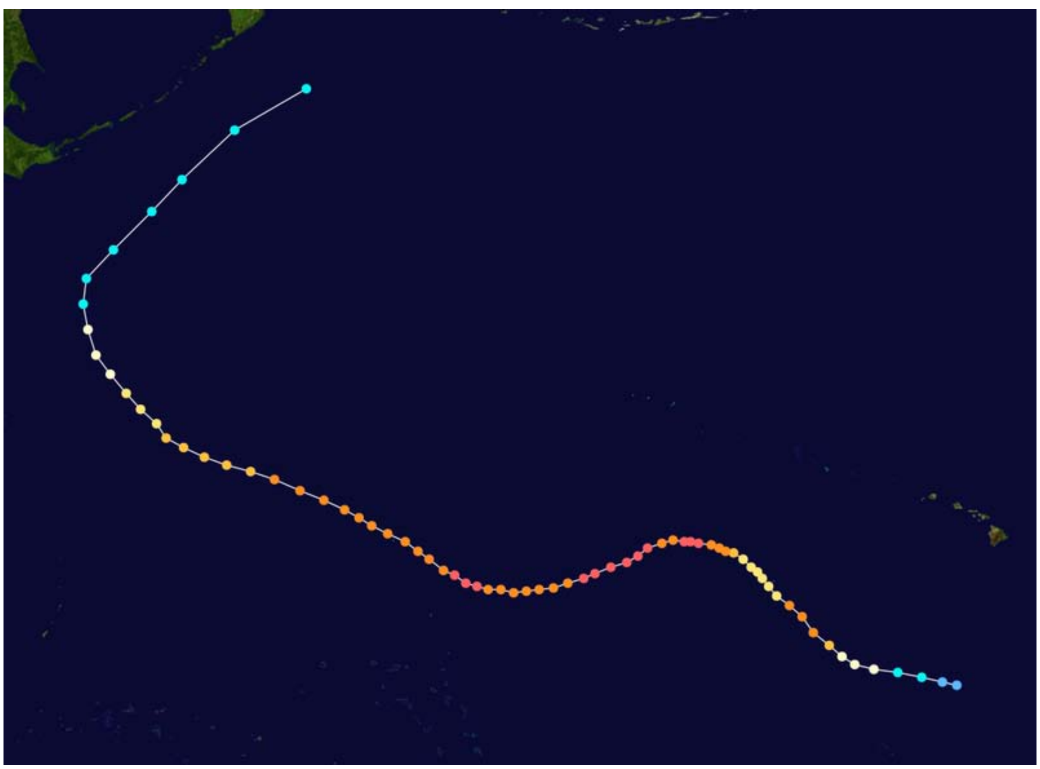
A fictitious synoptic chart of an extratropical cyclone affecting the UK and Ireland. The blue arrows between isobars indicate the direction of the wind, while the "L" symbol denotes the centre of the "low". Note the occluded, cold and warm frontal boundaries.

An extratropical cyclone is a synoptic scale low pressure weather system that has neither tropical nor polar characteristics, being connected with fronts and horizontal gradients in temperature and dew point otherwise known as "baroclinic zones".

The descriptor "extratropical" refers to the fact that this type of cyclone generally occurs outside of the tropics, in the middle latitudes of the planet, where the Westerlies steer the system generally from west to east. These systems may also be described as "mid-latitude cyclones" due to their area of formation, or "post-tropical cyclones" where extratropical transition has occurred, and are often described as "depressions" or "lows" by weather forecasters and the general public. These are the everyday phenomena which along with anti-cyclones, drive the weather over much of the Earth.

Although extratropical cyclones are almost always classified as baroclinic since they form along zones of temperature and dewpoint gradient, they can sometimes become barotropic late in their life cycle when the temperature distribution around the cyclone becomes fairly uniform along the radius from the center of low pressure. An extratropical cyclone can transform into a subtropical storm, and from there into a tropical cyclone, if it dwells over warm waters and develops central convection, which warms its core and causes temperature and dewpoint gradients near their centers to fad.

Interaction with tropical cyclones



Storm track of Typhoon Ioke, showing recurvature off the Japanese coast in 2006

When a tropical cyclone crosses the subtropical ridge axis, normally through a break in the high-pressure area caused by a system traversing the Westerlies, its general track around the high-pressure area is deflected significantly by winds moving towards the general low-pressure area to its north. When the cyclone track becomes strongly poleward with an easterly component, the cyclone has begun *recurvature,* entering the Westerlies. A typhoon moving through the Pacific Ocean towards Asia, for example, will recurve offshore of Japan to the north, and then to the northeast, if the typhoon encounters southwesterly winds (blowing northeastward) around a low-pressure system passing over China or Siberia. Many tropical cyclones are eventually forced toward the northeast by extratropical cyclones in this manner, which move from west to east to the north of the subtropical ridge. An example of a tropical cyclone in recurvature was Typhoon Ioke in 2006, which took a similar trajectory.

The westerlies or the prevailing westerlies are the prevailing winds in the middle latitudes between 35 and 65 degrees latitude, blow from west to east to the north of the high pressure area known as the subtropical ridge in the horse latitudes. These prevailing winds blow from the west to the east, and steer extratropical cyclones in this general manner. The winds are predominantly from the southwest in the Northern Hemisphere and from the northwest in the Southern Hemisphere. They are strongest in the winter when the pressure is lower over the poles, such as when the polar cyclone is strongest, and weakest during the summer when the polar cyclone is weakest and when pressures are higher over the poles.

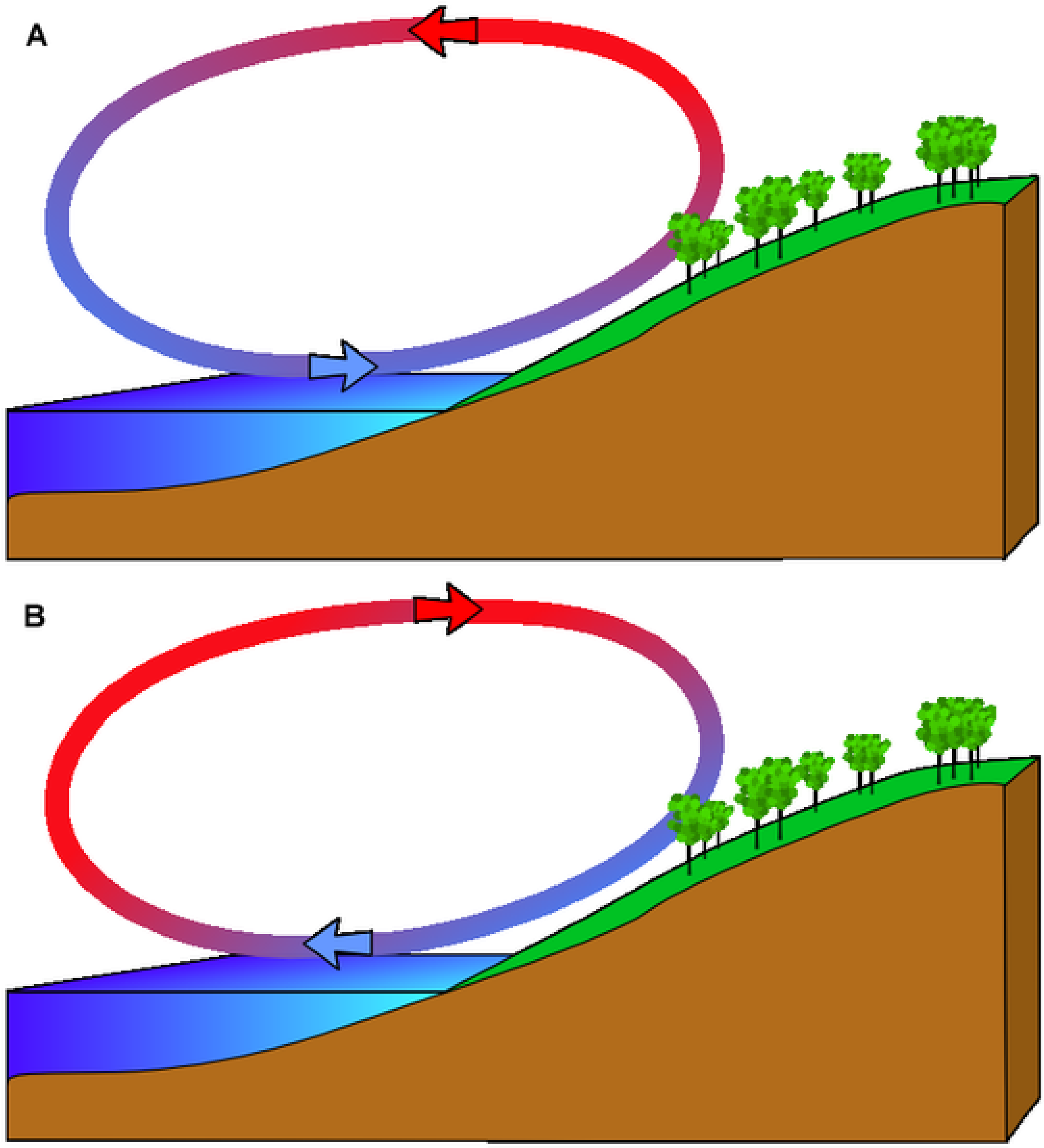
Together with the trade winds, the westerlies enabled a round-trip trade route for sailing ships crossing the Atlantic and Pacific oceans, as the westerlies lead to the development of strong ocean currents in both hemispheres. The westerlies can be particularly strong, especially in the southern hemisphere, where there is less land in the middle latitudes to cause the flow pattern to amplify, which slows the winds down. The strongest westerly winds in the middle latitudes are called the Roaring Forties, between 40 and 50 degrees south latitude, within the Southern Hemisphere. The westerlies play an important role in carrying the warm, equatorial waters and winds to the western coasts of continents, especially in the southern hemisphere because of its vast oceanic expanse.

Polar easterlies

The polar easterlies (also known as Polar Hadley cells) are the dry, cold prevailing winds that blow from the high-pressure areas of the polar highs at the north and South poles towards the low-pressure areas within the westerlies at high latitudes. Unlike trade winds and the westerlies, these prevailing winds blow from the east to the west, and are often weak and irregular. Due to the low sun angle, cold air builds up and subsides at the pole creating surface high-pressure areas, forcing an equatorward outflow of air; that outflow is deflected westward by the Coriolis effect.

Local considerations

Sea and land breezes

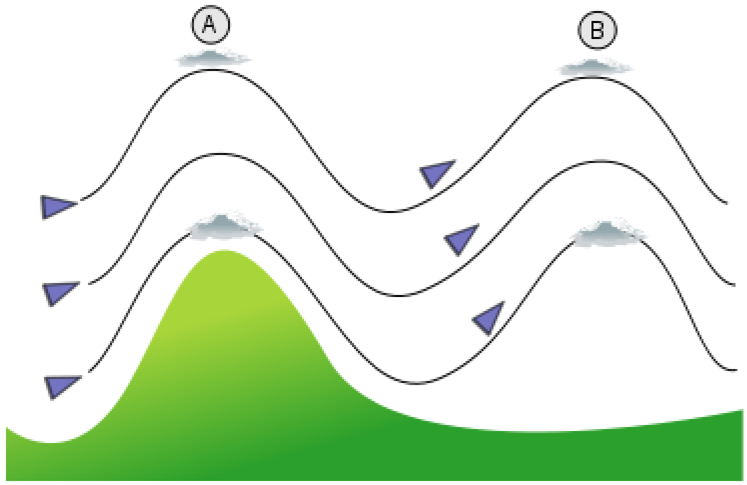


A: Sea breeze, B: Land breeze

In areas where the wind flow is light, sea breezes and land breezes are important factors in a location's prevailing winds. The sea is warmed by the sun to a greater depth than the land due to its greater specific heat. The sea therefore has a greater capacity for absorbing heat than the land, so the surface of the sea warms up more slowly than the land's surface. As the temperature of the surface of the land rises, the land heats the air above it. The warm air is less dense and so it rises. This rising air over the land lowers the sea level pressure by about 0.2%. The cooler air above the sea, now with higher sea level pressure, flows towards the land into the lower pressure, creating a cooler breeze near the coast.

The strength of the sea breeze is directly proportional to the temperature difference between the land mass and the sea. If an offshore wind of 8 knots (15 km/h) exists, the sea breeze is not likely to develop. At night, the land cools off more quickly than the ocean due to differences in their specific heat values, which forces the daytime sea breeze to dissipate. If the temperature onshore cools below the temperature offshore, the pressure over the water will be lower than that of the land, establishing a land breeze, as long as an onshore wind is not strong enough to oppose it.

Circulation in elevated regions

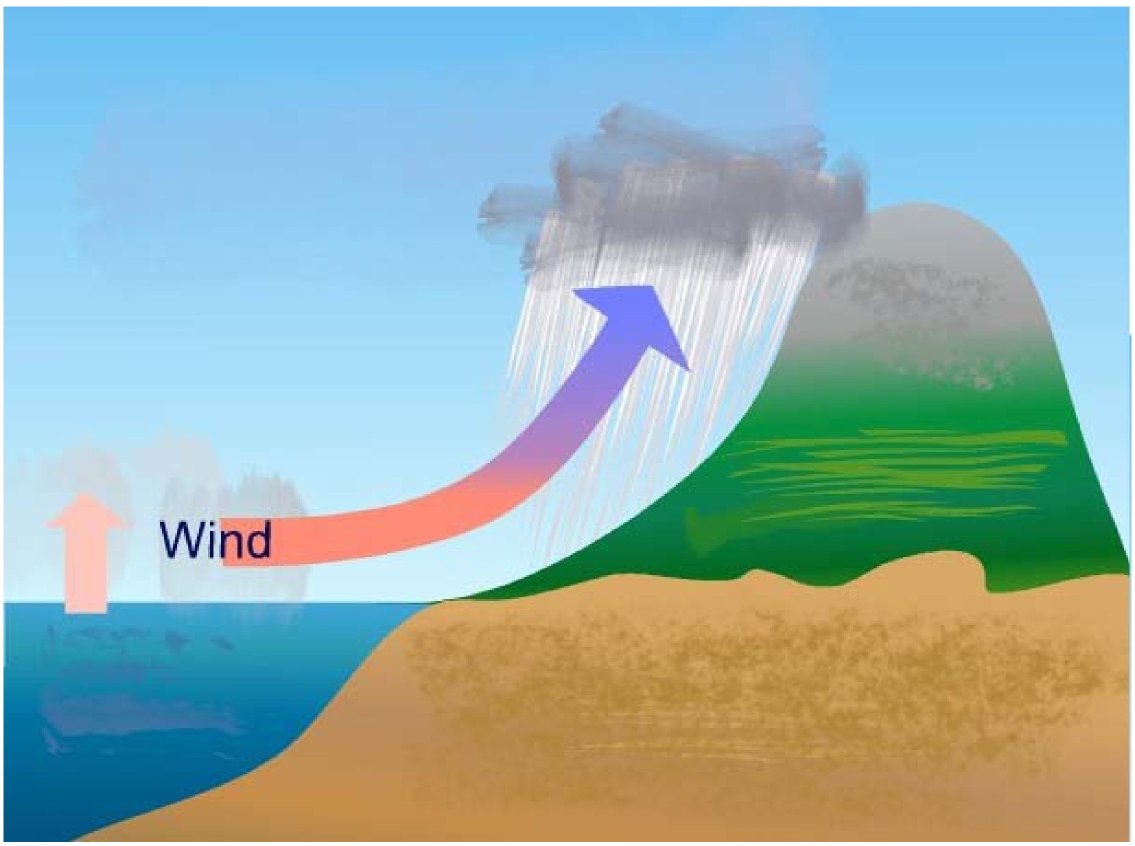


Mountain wave schematic. The wind flows towards a mountain and produces a first oscillation (A). A second wave occurs further away and higher. The lenticular clouds form at the peak of the waves (B).

Over elevated surfaces, heating of the ground exceeds the heating of the surrounding air at the same altitude above sea level, creating an associated thermal low over the terrain and enhancing any thermal lows which would have otherwise existed, and changing the wind circulation of the region. In areas where there is rugged topography that significantly interrupts the environmental wind flow, the wind This barrier jet can increase the low level wind by 45 percent. In mountainous areas, local distortion of the airflow is more severe. Jagged terrain combines to produce unpredictable flow patterns and turbulence, such as rotors. Strong updrafts, downdrafts and eddies develop as the air flows over hills and down valleys. Wind direction changes due to the contour of the land. If there is a pass in the mountain range, winds will rush through the pass with considerable speed due to the Bernoulli principle that describes an inverse relationship between speed and pressure. The airflow can remain turbulent and erratic for some distance downwind into the flatter countryside. These conditions are dangerous to ascending and descending airplanes.

Daytime heating and nighttime cooling of the hilly slopes lead to day to night variations in the airflow, similar to the relationship between sea breeze and land breeze. At night, the sides of the hills cool through radiation of the heat. The air along the hills becomes cooler and denser, blowing down into the valley, drawn by gravity. This is known a katabatic wind or mountain breeze. If the slopes are covered with ice and snow, the katabatic wind will blow during the day, carrying the cold dense air into the warmer, barren valleys. The slopes of hills not covered by snow will be warmed during the day. The air that comes in contact with the warmed slopes becomes warmer and less dense and flows uphill. This is known as an anabatic wind or valley breeze.

Effect on precipitation



Orographic precipitation

Orographic precipitation occurs on the windward side of mountains and is caused by the rising air motion of a large-scale flow of moist air across the mountain ridge, resulting in adiabatic cooling and condensation. In mountainous parts of the world subjected to consistent winds (for example, the trade winds), a more moist climate usually prevails on the windward side of a mountain than on the leeward or downwind side. Moisture is removed by orographic lift, leaving drier air on the descending and generally warming, leeward side where a rain shadow is observed.

In South America, the Andes mountain range blocks Pacific moisture that arrives in that continent, resulting in a desertlike climate just downwind across western Argentina. The Sierra Nevada range creates the same effect in North America forming the Great Basin and Mojave Deserts.

Effect on nature

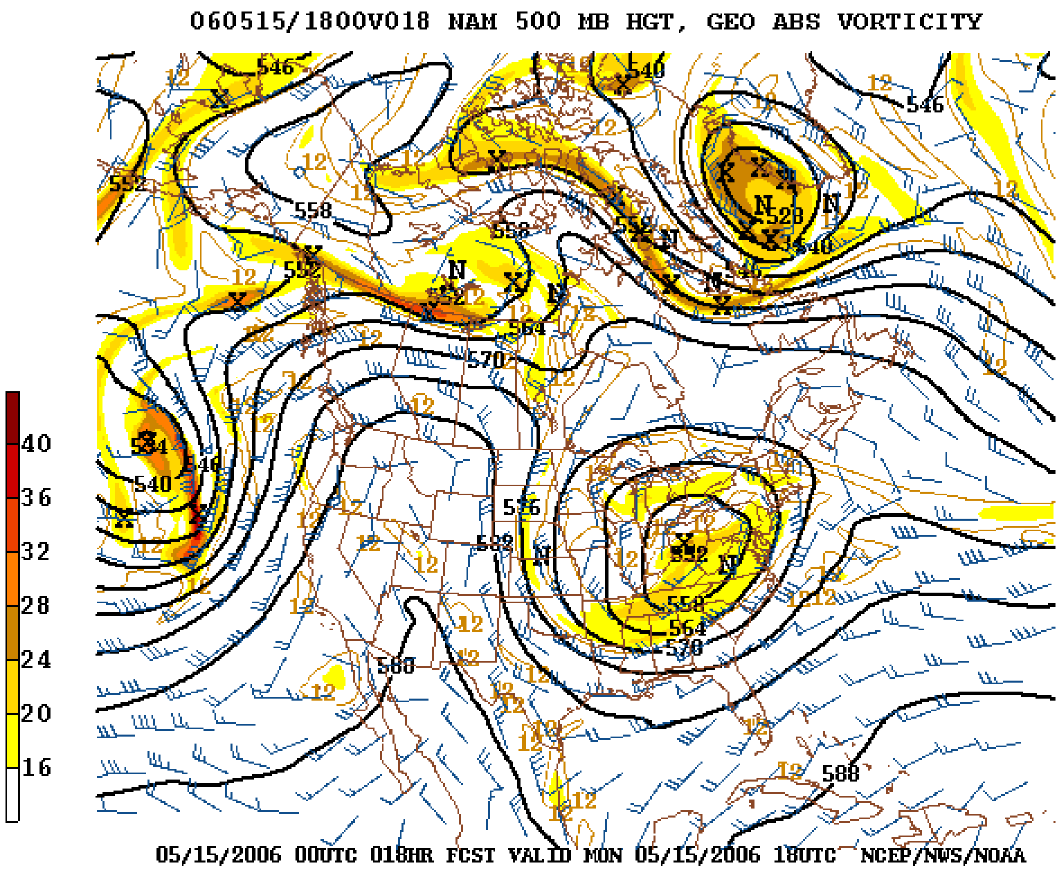
Sand blowing off a crest in the Kelso Dunes of the Mojave Desert, California.

Insects, also known as arthropods, are swept along by the prevailing winds, while birds follow their own course. As such, fine line patterns within weather radar imagery, associated with converging winds, are dominated by insect returns. In the Great Plains, soil erosion of agricultural land is a significant problem, and is mainly driven by the prevailing wind. Because of this, wind barrier strips have been developed to minimize this type of erosion. The strips can be in the form of soil ridges, crop strips, crops rows, or trees which act as wind breaks. They are oriented at a right angle to the wind in order to be most effective. In regions with minimal vegetation, such as coastal and desert areas, transverse sand dunes orient themselves perpendicular to the prevailing wind direction, while longitudinal dunes orient themselves parallel to the prevailing winds.

Chapter-5

Numerical Weather Prediction and Weather Forecasting

Numerical Weather Prediction



An example of 500 mbar geopotential height prediction from a numerical weather prediction model

Numerical weather prediction uses current weather conditions as input into mathematical models of the atmosphere to predict the weather. Although the first efforts to accomplish this were done in the 1920s, it wasn't until the advent of the computer and computer simulation that it was feasible to do in real-time. Manipulating the huge datasets and performing the complex calculations necessary to do this on a resolution fine enough to make the results useful requires the use of some of the most powerful supercomputers in the world. A number of forecast models, both global and regional in scale, are run to help create forecasts for nations worldwide. Use of model ensemble forecasts helps to define the forecast uncertainty and extend weather forecasting farther into the future than would otherwise be possible.

Physical overview

The atmosphere is a fluid. The basic idea of numerical weather prediction is to sample the state of the fluid at a given time and use the equations of fluid dynamics and thermodynamics to estimate the state of the fluid at some time in the future.

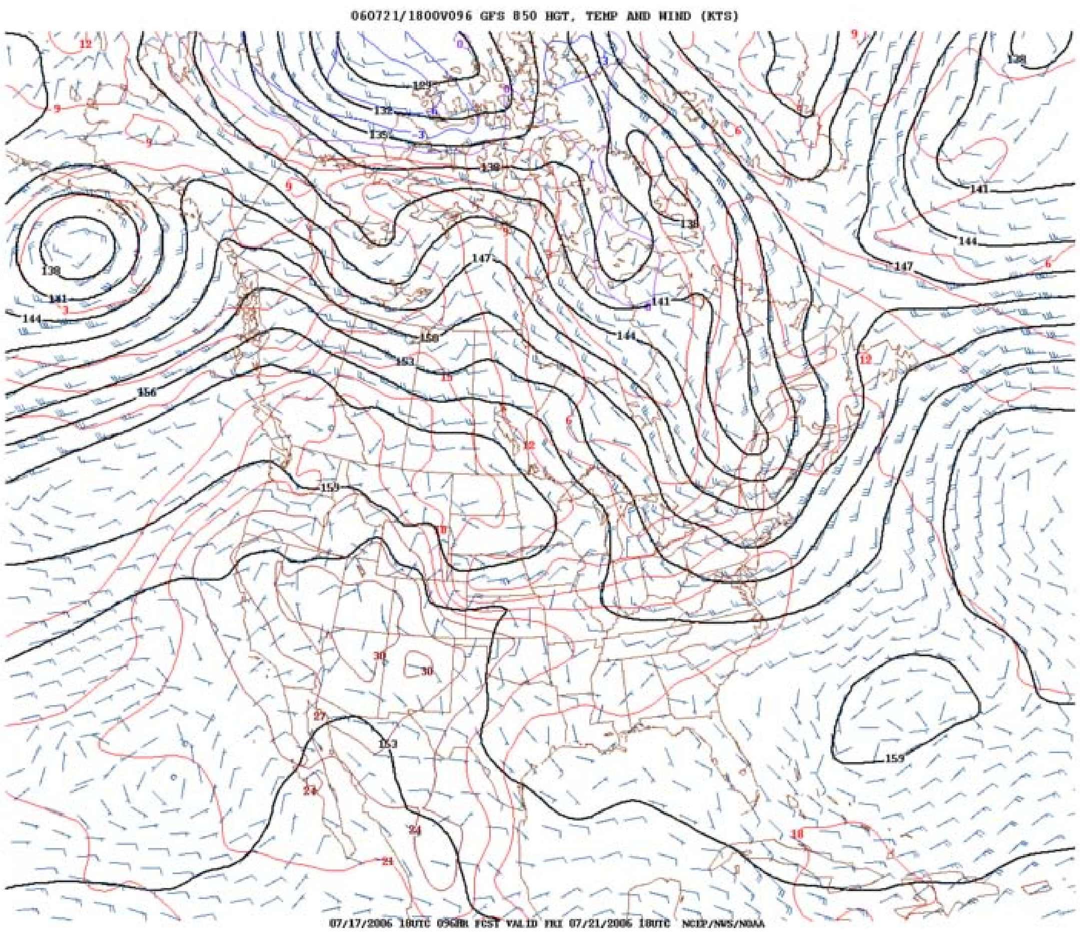
History

British mathematician Lewis Fry Richardson first proposed numerical weather prediction in 1922. Richardson attempted to perform a numerical forecast but it was not successful. The first successful numerical prediction was performed in 1950 by a team composed of the American meteorologists Jule Charney, Philip Thompson, Larry Gates, and Norwegian meteorologist Ragnar Fjörtoft and applied mathematician John von Neumann, using the ENIAC digital computer. They used a simplified form of atmospheric dynamics based on the barotropic vorticity equation. This simplification greatly reduced demands on computer time and memory, so that the computations could be performed on the relatively primitive computers available at the time. Later models used more complete equations for atmospheric dynamics and thermodynamics.

Operational numerical weather prediction (i.e., routine predictions for practical use) began in 1955 under a joint project by the U.S. Air Force, Navy, and Weather Bureau.

Definition of a forecast model

A model, in this context, is a computer program that produces meteorological information for future times at given positions and altitudes. The horizontal domain of a model is either *global*, covering the entire Earth, or *regional*, covering only part of the Earth. Regional models also are known as *limited-area* models.

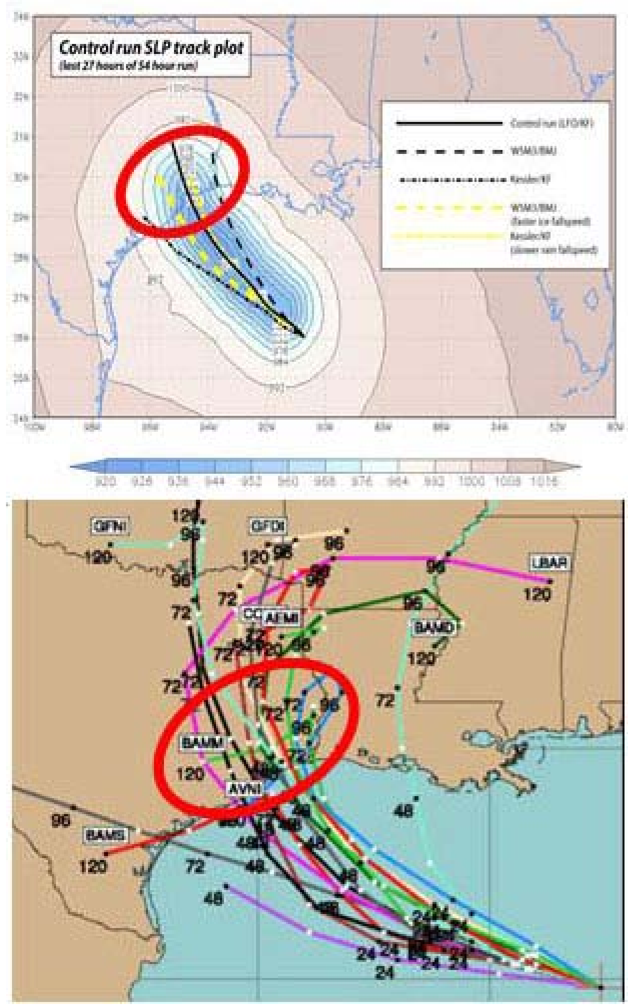


A 96-hour forecast of 850 mbar geopotential height and temperature from the Global Forecast System

The forecasts are computed using mathematical equations for the physics and dynamics of the atmosphere. These equations are nonlinear and are impossible to solve exactly. Therefore, numerical methods obtain approximate solutions. Different models use different solution methods. Some global models use spectral methods for the horizontal dimensions and finite difference methods for the vertical dimension, while regional models and other global models usually use finite-difference methods in all three dimensions. Regional models also can use finer grids to explicitly resolve smaller-scale meteorological phenomena, since they do not have to solve equations for the whole globe.

Models are *initialized* using observed data from a variety of sources e.g radiosondes, weather satellites, aircraft and surface weather observations. The irregularly spaced observations are processed by data assimilation and objective analysis methods, which perform quality control and obtain values at locations usable by the model's mathematical algorithms (usually an evenly spaced grid). The data are then used in the model as the starting point for a forecast. Commonly, the set of equations used is known as the primitive equations. These equations are initialized from the analysis data and rates of change are determined. The rates of change predict the state of the atmosphere a short time into the future. The equations are then applied to this new atmospheric state to find new rates of change, and these new rates of change predict the atmosphere at a yet further time into the future. This *time stepping* procedure is continually repeated until the solution reaches the desired forecast time. The length of the time step is related to the distance between the points on the computational grid. Time steps for global climate models may be on the order of tens of minutes, while time steps for regional models may be a few seconds to a few minutes.

Ensembles



Top: WRF model simulation of Hurricane Rita tracks. *Bottom*: The spread of NHC multi-model ensemble forecast.

As proposed by Edward Lorenz in 1963, it is impossible to definitively predict the state of the atmosphere, owing to the chaotic nature of the fluid dynamics equations involved. Furthermore, existing observation networks have limited spatial and temporal resolution, especially over large bodies of water such as the Pacific Ocean, which introduces uncertainty into the true initial state of the atmosphere. To account for this uncertainty, stochastic or "ensemble" forecasting is used, involving multiple forecasts created with different model systems, different physical parametrizations, or varying initial conditions. The ensemble forecast is usually evaluated in terms of the ensemble mean of a forecast variable, and the ensemble spread, which represents the degree of agreement between various forecasts in the ensemble system, known as ensemble members. A common misconception is that low spread amongst ensemble members necessarily implies more confidence in the ensemble mean. Although a *spread-skill relationship* sometimes exists, the relationship between ensemble spread and skill varies substantially depending on such factors as the forecast model and the region for which the forecast is made.

A meteorologist at the console of the IBM 7090 in the Joint Numerical Weather Prediction Unit. c. 1965

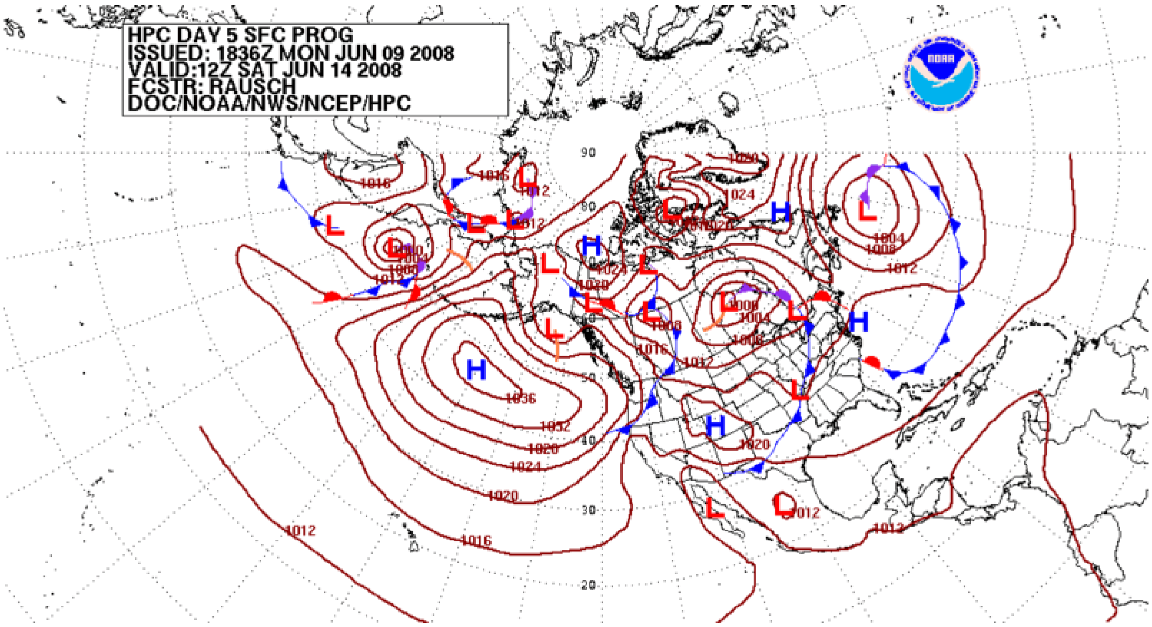
In 1904, Norwegian scientist Vilhelm Bjerknes first argued in his paper *Weather Forecasting as a Problem in Mechanics and Physics* that it should be possible to forecast weather from calculations based upon natural laws.

It was not until later in the 20th century that advances in the understanding of atmospheric physics led to the foundation of modern numerical weather prediction. In 1922, Lewis Fry Richardson published "Weather Prediction By Numerical Process", after finding notes and derivations he worked on as an ambulance driver in World War I. He described therein how small terms in the prognostic fluid dynamics equations governing atmospheric flow could be neglected, and a finite differencing scheme in time and space could be devised, to allow numerical prediction solutions to be found. Richardson envisioned a large auditorium of thousands of people performing the calculations and passing them to others. However, the sheer number of calculations required was too large to be completed without the use of computers, and the size of the grid and time steps led to unrealistic results in deepening systems. It was later found, through numerical analysis, that this was due to numerical instability.

Starting in the 1950s, numerical forecasts with computers became feasible. The first weather forecasts derived this way used barotropic (that means, single-vertical-level) models, and could successfully predict the large-scale movement of midlatitude Rossby waves, that is, the pattern of atmospheric lows and highs.

In the 1960s, the chaotic nature of the atmosphere was first observed and mathematically described by Edward Lorenz, founding the field of chaos theory. These advances have led to the current use of ensemble forecasting in most major forecasting centers, to take into account uncertainty arising from the chaotic nature of the atmosphere. In recent years, climate models have been developed that feature a resolution comparable to older weather prediction models. These climate models are used to investigate long-term climate shifts, such as what effects might be caused by human emission of greenhouse gases.

Weather forecasting



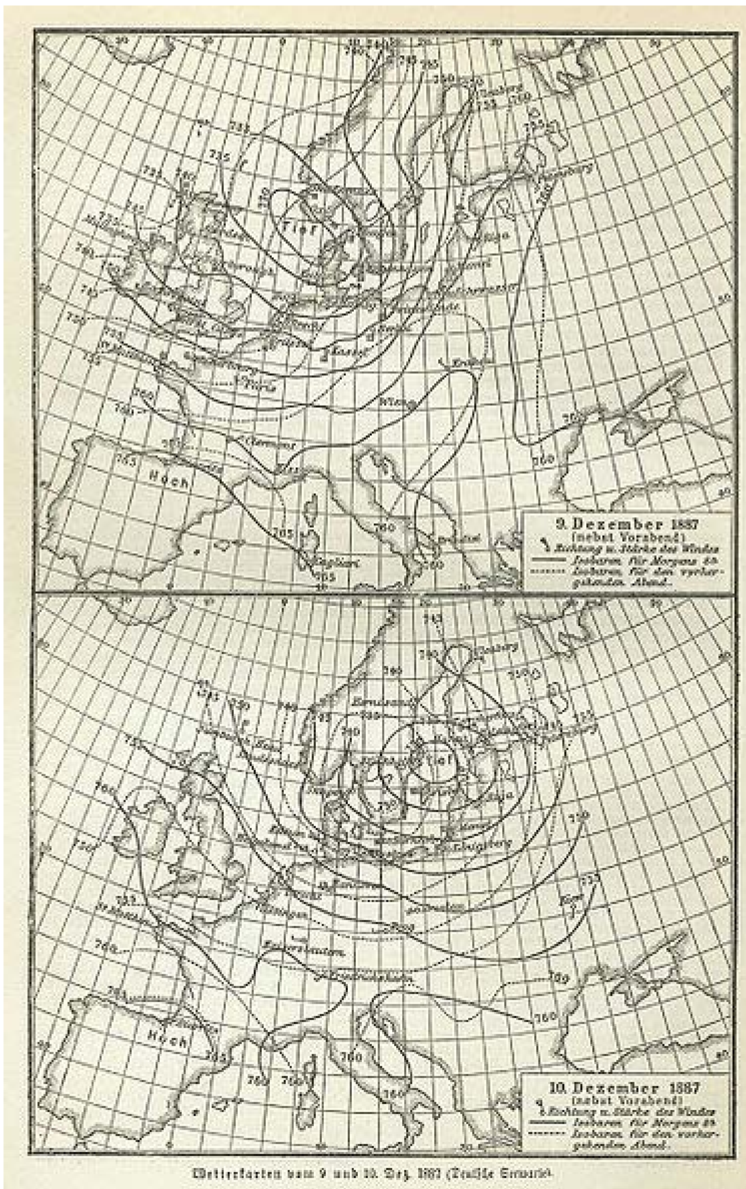
Forecast of surface pressures five days into the future for the north Pacific, North America, and north Atlantic ocean.

Weather forecasting is the application of science and technology to predict the state of the atmosphere for a future time and a given location. Human beings have attempted to predict the weather informally for millennia, and formally since at least the nineteenth century. Weather forecasts are made by collecting quantitative data about the current state of the atmosphere and using scientific understanding of atmospheric processes to project how the atmosphere will evolve.

Once an all-human endeavor based mainly upon changes in barometric pressure, current weather conditions, and sky condition, forecast models are now used to determine future conditions. Human input is still required to pick the best possible forecast model to base the forecast upon, which involves pattern recognition skills, teleconnections, knowledge of model performance, and knowledge of model biases. The chaotic nature of the atmosphere, the massive computational power required to solve the equations that describe the atmosphere, error involved in measuring the initial conditions, and an incomplete understanding of atmospheric processes mean that forecasts become less accurate as the difference in current time and the time for which the forecast is being made (the *range* of the forecast) increases. The use of ensembles and model consensus help narrow the error and pick the most likely outcome.

There are a variety of end uses to weather forecasts. Weather warnings are important forecasts because they are used to protect life and property. Forecasts based on temperature and precipitation are important to agriculture, and therefore to traders within commodity markets. Temperature forecasts are used by utility companies to estimate demand over coming days. On an everyday basis, people use weather forecasts to determine what to wear on a given day. Since outdoor activities are severely curtailed by heavy rain, snow and the wind chill, forecasts can be used to plan activities around these events, and to plan ahead and survive them.

History



Weather map of Europe, 10 December 1887

For millennia people have tried to forecast the weather. In 650 BC, the Babylonians predicted the weather from cloud patterns as well as astrology. In about 340 BC, Aristotle described weather patterns in *Meteorologica*. Later, Theophrastus compiled a book on weather forecasting, called the *Book of Signs*. Chinese weather prediction lore extends at least as far back as 300 BC, which was also around the same time ancient Indian astronomers developed weather-prediction methods. In 904 AD, Ibn Wahshiyya's *Nabatean Agriculture* discussed the weather forecasting of atmospheric changes and signs from the planetary astral alterations; signs of rain based on observation of the lunar phases; and weather forecasts based on the movement of winds.

Ancient weather forecasting methods usually relied on observed patterns of events, also termed pattern recognition. For example, it might be observed that if the sunset was particularly red, the following day often brought fair weather. This experience accumulated over the generations to produce weather lore. However, not all of these predictions prove reliable, and many of them have since been found not to stand up to rigorous statistical testing.

It was not until the invention of the electric telegraph in 1835 that the modern age of weather forecasting began. Before this time, it was not widely practicable to transport information about the current state of the weather any faster than a steam train (and the train also was a very new technology at that time). The telegraph allowed reports of weather conditions from a wide area to be received almost instantaneously by the late 1840s. This allowed forecasts to be made by knowing what the weather conditions were like further upwind. The two men most credited with the birth of forecasting as a science were Francis Beaufort (remembered chiefly for the Beaufort scale) and his protégé Robert Fitzroy (developer of the Fitzroy barometer). Both were influential men in British naval and governmental circles, and though ridiculed in the press at the time, their work gained scientific credence, was accepted by the Royal Navy, and formed the basis for all of today's weather forecasting knowledge. To convey information accurately, it became necessary to have a standard vocabulary describing clouds; this was achieved by means of a series of classifications and, in the 1890s, by pictorial cloud atlases.

Great progress was made in the science of meteorology during the 20th century. The possibility of numerical weather prediction was proposed by Lewis Fry Richardson in 1922, though computers did not exist to complete the vast number of calculations required to produce a forecast before the event had occurred. Practical use of numerical weather prediction began in 1955, spurred by the development of programmable electronic computers.

In the United States, the first public radio forecasts were made in 1925 by Edward B. "E.B." Rideout, on WEEI, the Edison Electric Illuminating station in Boston. Rideout came from the U.S. Weather Bureau, as did WBZ weather forecaster G. Harold Noyes in 1931. Television forecasts followed with Jimmie Fidler in Cincinnati in 1940 or 1947 on the DuMont Television Network. The Weather Channel is a 24-hour cable network that began broadcasting in May 1982.

How models create forecasts

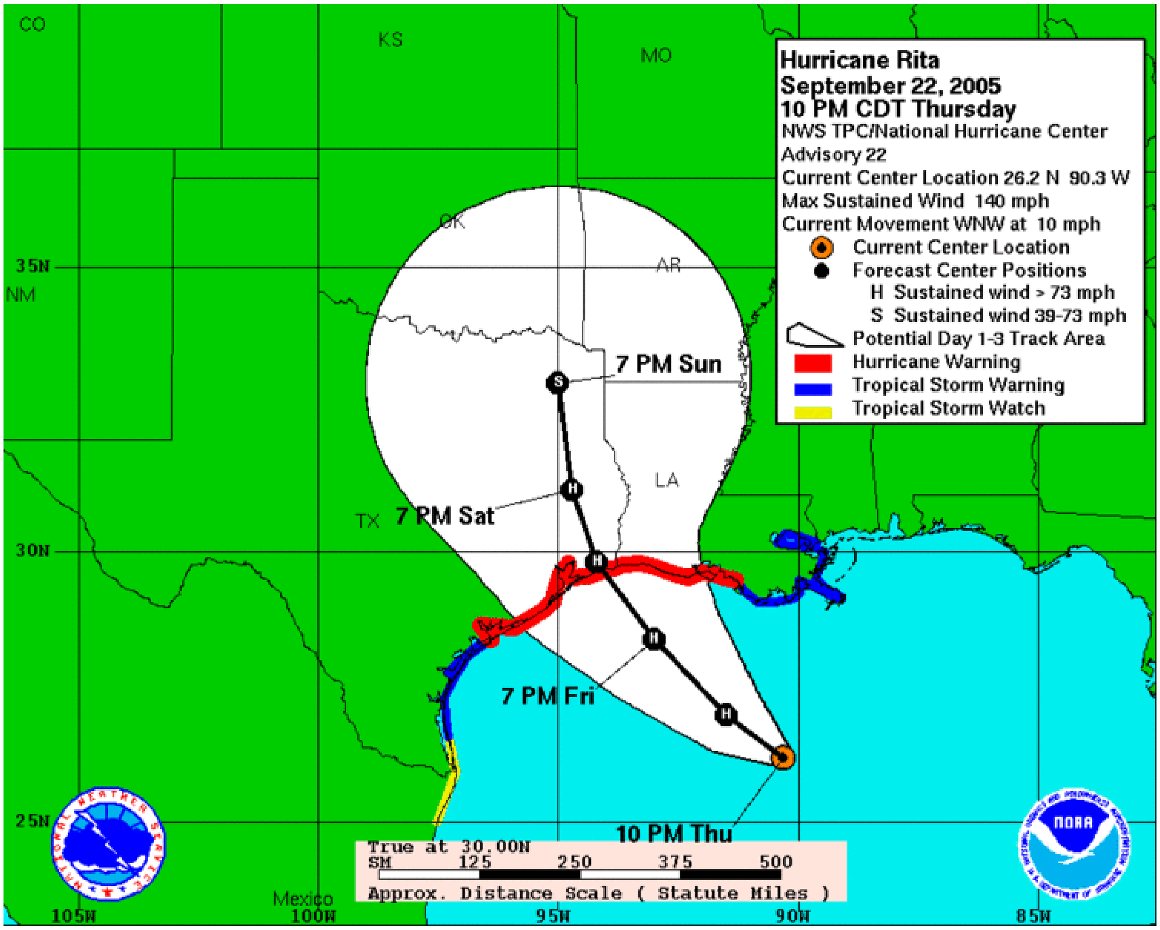
Data collection

Surface weather observations of atmospheric pressure, temperature, wind speed and direction, humidity, precipitation are made near the Earth's surface by trained observers, automatic weather stations or buoys. The World Meteorological Organization acts to standardize the instrumentation, observing practices and timing of these observations worldwide. Stations either report hourly in METAR reports, or every six hours in SYNOP reports.

Measurements of temperature, humidity and wind above the surface are found by launching radiosondes on weather balloons. Data are usually obtained from near the surface to the middle of the stratosphere, about 21 km (13 mi). In recent years, data transmitted from commercial airplanes through the Aircraft Meteorological Data Relay (AMDAR) system has also been incorporated into upper air observation, primarily in numerical models.

Increasingly, data from weather satellites are being used because of their almost global coverage. Although their visible light images are very useful for forecasters to see development of clouds, little of this information can be used by numerical weather prediction models. The infrared (IR) data however can be used as it gives information on the temperature at the surface and cloud tops. Individual clouds can also be tracked from one time to the next to provide information on wind direction and strength at the clouds steering level. Both polar orbiting and geostationary satellites provide soundings of temperature and moisture throughout the depth of the atmosphere. Compared with similar data from radiosondes, the satellite data has the advantage of global coverage, however at a lower accuracy and resolution.

Meteorological radar provide information on precipitation location and intensity, which can be used to estimate precipitation accumulations over time. Additionally, if a Pulse Doppler weather radar is used then wind speed and direction can be determined.



Modern weather predictions aid in timely evacuations and potentially save lives and property damage

Data assimilation and analysis

During the data assimilation process, information gained from the observations is used in conjunction with a numerical model's most recent forecast for the time that observations were made, since this contains information from previous observations. This is used to produce a three-dimensional representation of the temperature, moisture and wind called a meteorological analysis. This is the model's estimate of the current state of the atmosphere.

Numerical weather prediction

Numerical weather prediction models are computer simulations of the atmosphere. They take the analysis as the starting point and evolve the state of the atmosphere forward in time using physics and fluid dynamics. The complicated equations which govern how the state of a fluid changes with time require supercomputers to solve them. The output from the model provides the basis of the weather forecast.

Model output post processing

The raw output is often modified before being presented as the forecast. This can be in the form of statistical techniques to remove known biases in the model, or of adjustment to take into account consensus among other numerical weather forecasts. MOS or model output statistics is a technique used to interpret numerical model output and produce site-specific guidance. This guidance is presented in coded numerical form, and can be obtained for nearly all National Weather Service reporting stations in the United States.

Techniques

Persistence

The simplest method of forecasting the weather, persistence, relies upon today's conditions to forecast the conditions tomorrow. This can be a valid way of forecasting the weather when it is steady state, such as during the summer season in the tropics. This method of forecasting strongly depends upon the presence of a stagnant weather pattern. It can be useful in both short range forecasts and long range forecasts.

Use of a barometer

Using barometric pressure and the pressure tendency (the change of pressure over time) has been used in forecasting since the late 19th century. The larger the change in pressure, especially if more than 3.5 hPa (0.10 inHg), the larger the change in weather can be expected. If the pressure drop is rapid, a low pressure system is approaching, and there is a greater chance of rain. Rapid pressure rises are associated with improving weather conditions, such as clearing skies.

Looking at the sky

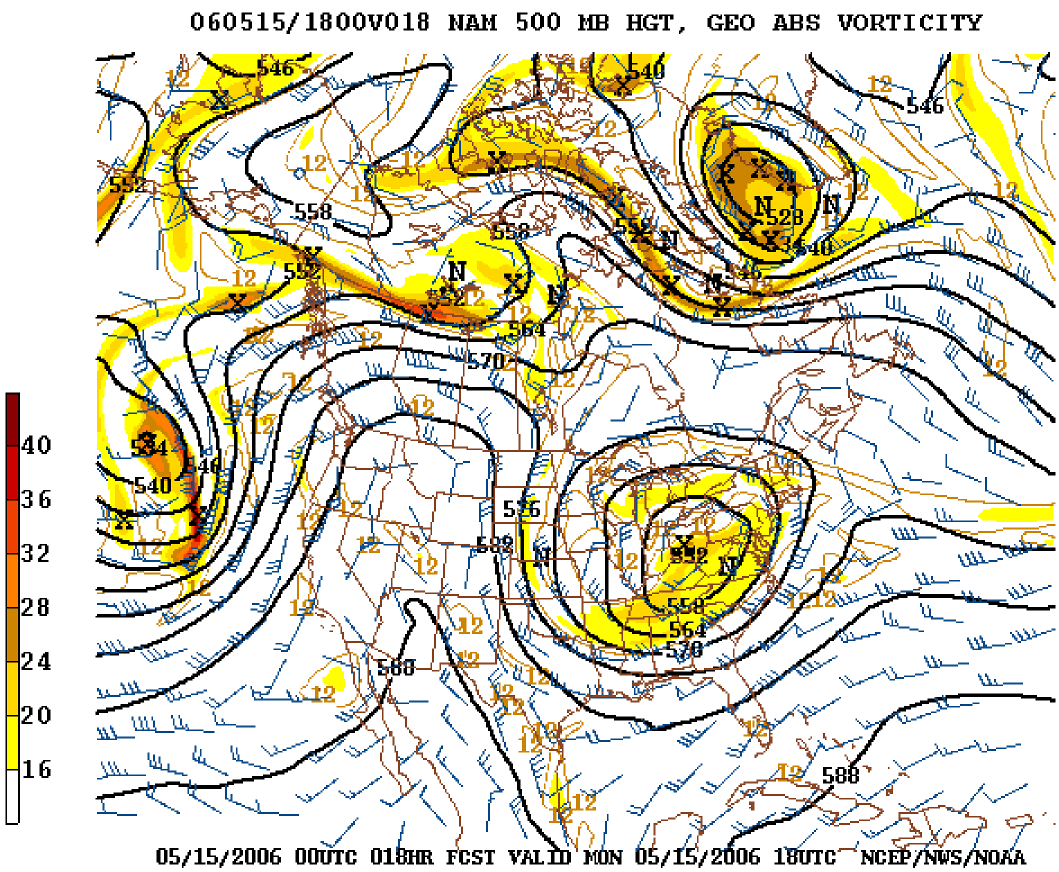
Marestail shows moisture at high altitude, signalling the later arrival of wet weather.

Along with pressure tendency, use of the sky condition is one of more important weather parameters that can be used to forecast weather in mountainous areas. Thickening of cloud cover or the invasion of a higher cloud deck is indicative of rain in the near future. Morning fog portends fair conditions, as rainy conditions are preceded by wind or clouds which prevent fog formation. The approach of a line of thunderstorms could indicate the approach of a cold front. Cloud-free skies are indicative of fair weather for the near future. The use of sky cover in weather prediction has led to various weather lore over the centuries.

Nowcasting

The forecasting of the weather within the next six hours is often referred to as **nowcasting**. In this time range it is possible to forecast smaller features such as individual showers and thunderstorms with reasonable accuracy, as well as other features too small to be resolved by a computer model. A human given the latest radar, satellite and observational data will be able to make a better analysis of the small scale features present and so will be able to make a more accurate forecast for the following few hours.

Use of forecast models



An example of 500 mbar geopotential height prediction from a numerical weather prediction model

In the past, the human forecaster was responsible for generating the entire weather forecast based upon available observations. Today, human input is generally confined to choosing a model based on various parameters, such as model biases and performance. Using a consensus of forecast models, as well as ensemble members of the various models, can help reduce forecast error. However, regardless how small the average error becomes with any individual system, large errors within any particular piece of guidance are still possible on any given model run. Humans are required to interpret the model data into weather forecasts that are understandable to the end user. Humans can use knowledge of local effects which may be too small in size to be resolved by the model to add information to the forecast. While increasing accuracy of forecast models implies that humans may no longer be needed in the forecast process at some point in the future, there is currently still a need for human intervention.

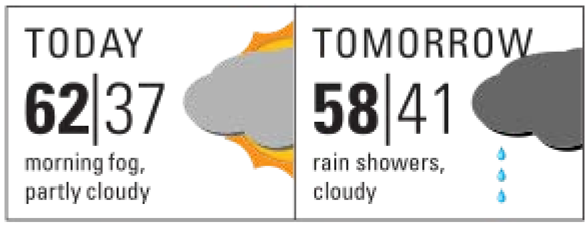
Analog technique

The Analog technique is a complex way of making a forecast, requiring the forecaster to remember a previous weather event which is expected to be mimicked by an upcoming event. What makes it a difficult technique to use is that there is rarely a perfect analog for an event in the future. Some call this type of forecasting pattern recognition. It remains a useful method of observing rainfall over data voids such as oceans, as well as the forecasting of precipitation amounts and distribution in the future. A similar technique is used in medium range forecasting, which is known as teleconnections, when systems in other locations are used to help pin down the location of another system within the surrounding regime. An example of teleconnections are by using El Niño-Southern Oscillation (ENSO) related phenomena.

- Analog model – A model based on similarities between the system under study and another system or process.
- Analytical model – A model that uses classic methods such as calculus or algebra to solve a series of equations.
- Conceptual model – A simplified representation of the system being examined.
- Continuous model – A model that uses continuous simulation, as opposed to a single-event model.
- Deterministic model – A model that produces the same output for a given input without consideration for risk or uncertainty.
- Empirical model – A model represented by simplified processes based on observation, measurements, or practical experience rather than solely on principles or theory. A lumped model is an example.
- Explicit model – A numerical model that uses parameter values or unknown variables at the beginning of a time step in the computational algorithms.
- Implicit model – A numerical model that uses parameter values or unknown variables at the end of a time step in the computational algorithms.
- Mass balance model – A model based on the conservation of mass and focuses on balancing inputs and outputs from the model area. Also known as a zero-dimensional model.
- Numerical model – A model that uses a numerical method to solve a series of equations, as opposed to an analytical model. The results from numerical models are often approximations, while analytic models produce exact solutions.
- One-dimensional model – A model that includes only one space dimension.
- Pseudo-deterministic model – A semi-distributed model.

- Stochastic mathematical model – A model that includes statistical elements and produces a set of outputs for a given set of inputs. The output represents a set of expected values.
- Two-dimensional model – A model that includes two space dimensions, usually horizontal and vertical averaging.

Public uses



An example of a two-day weather forecast in the visual style that an American newspaper might use. Temperatures are given in Fahrenheit.

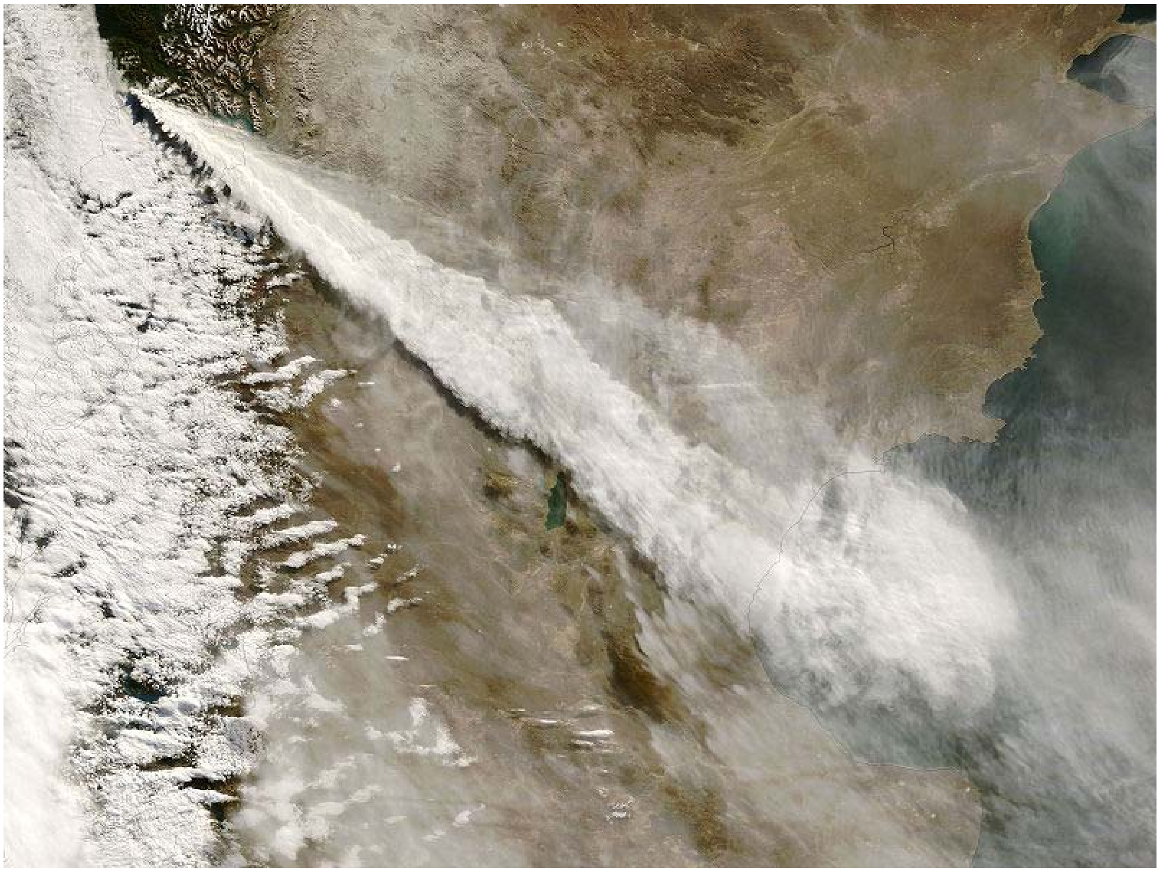
Most end users of forecasts are members of the general public. Thunderstorms can create strong winds and dangerous lightning strikes that can lead to deaths, power outages, and widespread hail damage. Heavy snow or rain can bring transportation and commerce to a stand-still, as well as cause flooding in low-lying areas. Excessive heat or cold waves can sicken or kill those with inadequate utilities, and droughts can impact water usage and destroy vegetation.

Several countries employ government agencies to provide forecasts and watches/warnings/advisories to the public in order to protect life and property and maintain commercial interests. Knowledge of what the end user needs from a weather forecast must be taken into account to present the information in a useful and understandable way. Examples include the National Oceanic and Atmospheric Administration's National Weather Service (NWS) and Environment Canada's Meteorological Service (MSC). Traditionally, newspaper, television, and radio have been the primary outlets for presenting weather forecast information to the public. Increasingly, the internet is being used due to the vast amount of specific information that can be found. In all cases, these outlets update their forecasts on a regular basis.

Severe weather alerts and advisories

A major part of modern weather forecasting is the severe weather alerts and advisories which the national weather services issue in the case that severe or hazardous weather is expected. This is done to protect life and property. Some of the most commonly known of severe weather advisories are the severe thunderstorm and tornado warning, as well as the severe thunderstorm and tornado watch. Other forms of these advisories include winter weather, high wind, flood, tropical cyclone, and fog. Severe weather advisories and alerts are broadcast through the media, including radio, using emergency systems as the Emergency Alert System which break into regular programming.

Air traffic



Ash cloud from the 2008 eruption of Chaitén volcano stretching across Patagonia from the Pacific to the Atlantic Ocean

Because the aviation industry is especially sensitive to the weather, accurate weather forecasting is essential. Fog or exceptionally low ceilings can prevent many aircraft from landing and taking off. Turbulence and icing are also significant in-flight hazards. Thunderstorms are a problem for all aircraft because of severe turbulence due to their updrafts and outflow boundaries, icing due to the heavy precipitation, as well as large hail, strong winds, and lightning, all of which can cause severe damage to an aircraft in flight. Volcanic ash is also a significant problem for aviation, as aircraft can lose engine power within ash clouds. On a day to day basis airliners are routed to take advantage of the jet stream tailwind to improve fuel efficiency. Aircrews are briefed prior to takeoff on the conditions to expect en route and at their destination. Additionally, airports often change which runway is being used to take advantage of a headwind. This reduces the distance required for takeoff, and eliminates potential crosswinds.

Marine

Commercial and recreational use of waterways can be limited significantly by wind direction and speed, wave periodicity and heights, tides, and precipitation. These factors can each influence the safety of marine transit. Consequently, a variety of codes have been established to efficiently transmit detailed marine weather forecasts to vessel pilots via radio, for example the MAFOR (marine forecast). Typical weather forecasts can be received at sea through the use of RTTY, Navtex and Radiofax.

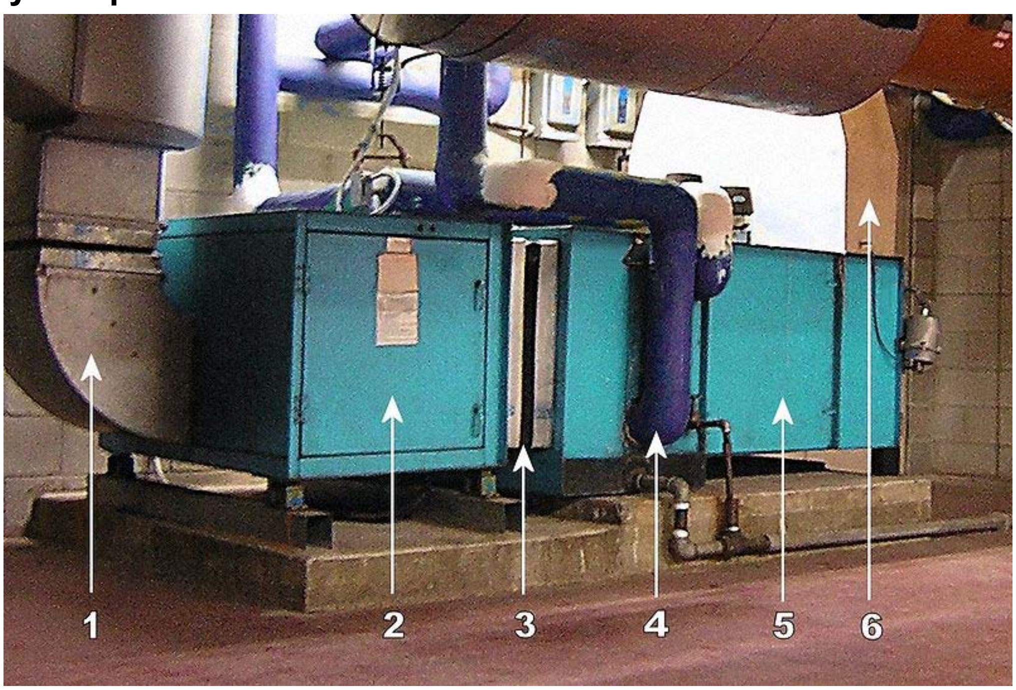
Agriculture

Farmers rely on weather forecasts to decide what work to do on any particular day. For example, drying hay is only feasible in dry weather. Prolonged periods of dryness can ruin cotton, wheat, and corn crops. While corn crops can be ruined by drought, their dried remains can be used as a cattle feed substitute in the form of silage. Frosts and freezes play havoc with crops both during the spring and fall. For example, peach trees in full bloom can have their potential peach crop decimated by a spring freeze. Orange groves can suffer significant damage during frosts and freezes, regardless of their timing.

Forestry

Weather forecasting of wind, precipitations and humidity is essential for preventing and controlling wildfires. Different indices, like the *Forest fire weather index* and the *Haines Index*, have been developed to predict the areas more at risk to experience fire from natural or human causes. Conditions for the development of harmful insects can be predicted by forecasting the evolution of weather, too.

Utility companies



An air handling unit is used for the heating and cooling of air in a central location.

Electricity and gas companies rely on weather forecasts to anticipate demand which can be strongly affected by the weather. They use the quantity termed the degree day to determine how strong of a use there will be for heating (heating degree day) or cooling (cooling degree day). These quantities are based on a daily average temperature of 65 °F (18 °C). Cooler temperatures force heating degree days (one per degree Fahrenheit), while warmer temperatures force cooling degree days. In winter, severe cold weather can cause a surge in demand as people turn up their heating. Similarly, in summer a surge in demand can be linked with the increased use of air conditioning systems in hot weather. By anticipating a surge in demand, utility companies can purchase additional supplies of power or natural gas before the price increases, or in some circumstances, supplies are restricted through the use of brownouts and blackouts.

Private sector

Increasingly, private companies pay for weather forecasts tailored to their needs so that they can increase their profits or avoid large losses. For example, supermarket chains may change the stocks on their shelves in anticipation of different consumer spending habits in different weather conditions. Weather forecasts can be used to invest in the commodity market, such as futures in oranges, corn, soybeans, and oil.

Military applications

Emblem of JTWC Joint Typhoon Warning Center

Similarly to the private sector, military weather forecasters present weather conditions to the war fighter community. Military weather forecasters provide pre-flight and in-flight weather briefs to pilots and provide real time resource protection services for military installations. The United States Navy provides a special service to both themselves and the rest of the federal government by issuing forecasts for tropical cyclone across the Pacific and Indian Oceans through their Joint Typhoon Warning Center.

United States

Within the United States, four branches of the armed forces have independent weather forecasting techniques tailored for their specific needs: Naval forecasters cover the waters and ship weather forecasts; Air Force forecasters cover air operations in both wartime and peacetime operations and provide Army support; United States Coast Guard marine science technicians provide ship forecasts for ice breakers and other various operations within their realm; and Marine forecasters provide support for ground- and air-based United States Marine Corps operations. All four military branches take their initial meteorology training at Keesler Air Force Base. Military and civilian forecasters actively cooperate in analyzing, creating and critiquing weather forecast products.

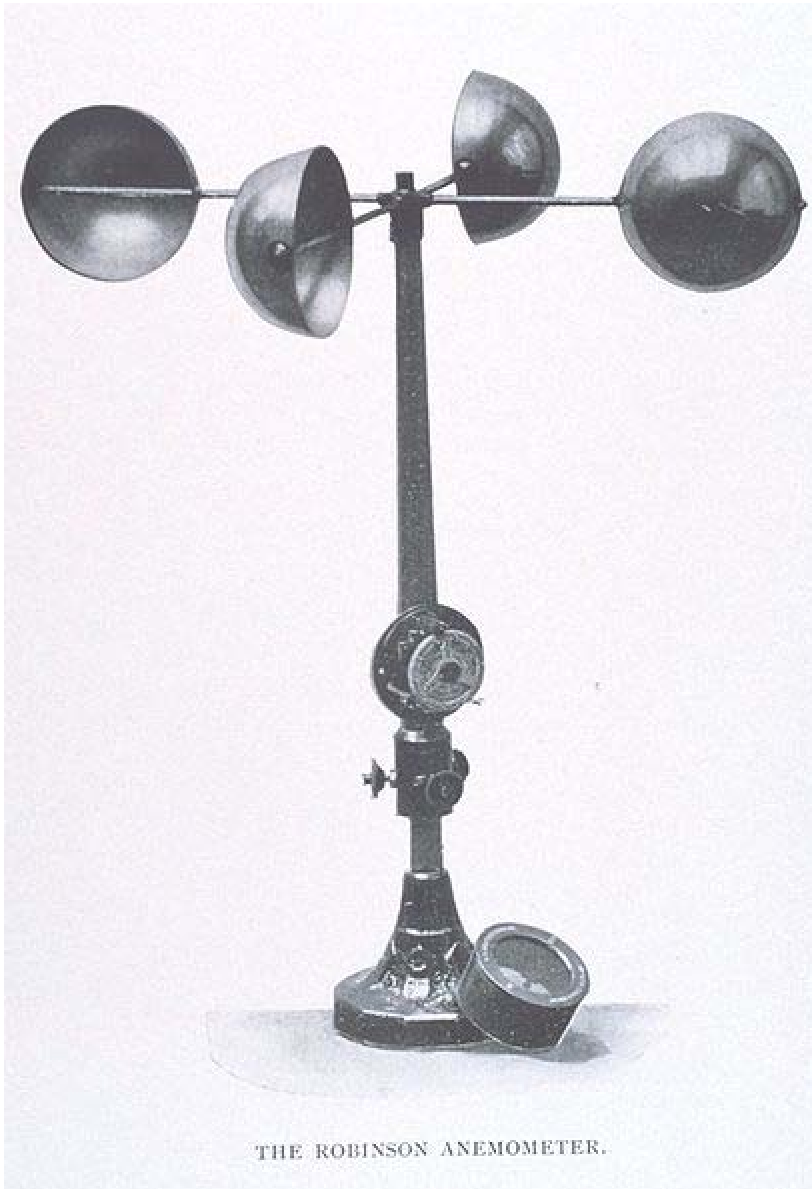
Chapter-6

Meteorological Instrumentation

Meteorological instrumentation is the equipment used to sample the state of the atmosphere at a given time. Each science has its own unique sets of laboratory equipment. However, meteorology is a science which does not use much lab equipment but relies more on field-mode observation equipment. In science, an observation, or *observable*, is an abstract idea that can be measured and for which data can be taken. Rain was one of the first quantities to be measured historically. Two other accurately measured weather-related variables are wind and humidity. Many attempts had been made prior to the 15th century to construct adequate equipment to measure atmospheric variables.

The devices to measure these three sprang up in the mid-15th century and were respectively the rain gauge, the anemometer, and the hygrometer. The 17th century saw the development of the barometer and the Galileo thermometer, while the 18th century saw the development of the thermometer with the Fahrenheit and Celsius scales. The 20th century developed new remote sensing tools, such as weather radars and weather satellites, which provide better sampling both regionally and globally. Remote sensing instruments collect data from remote weather events and subsequently producing weather information. Each remote sensing instruments collects data about the atmosphere from a remote location and, usually, stores the data where the instrument is located.

History of measurement and scales

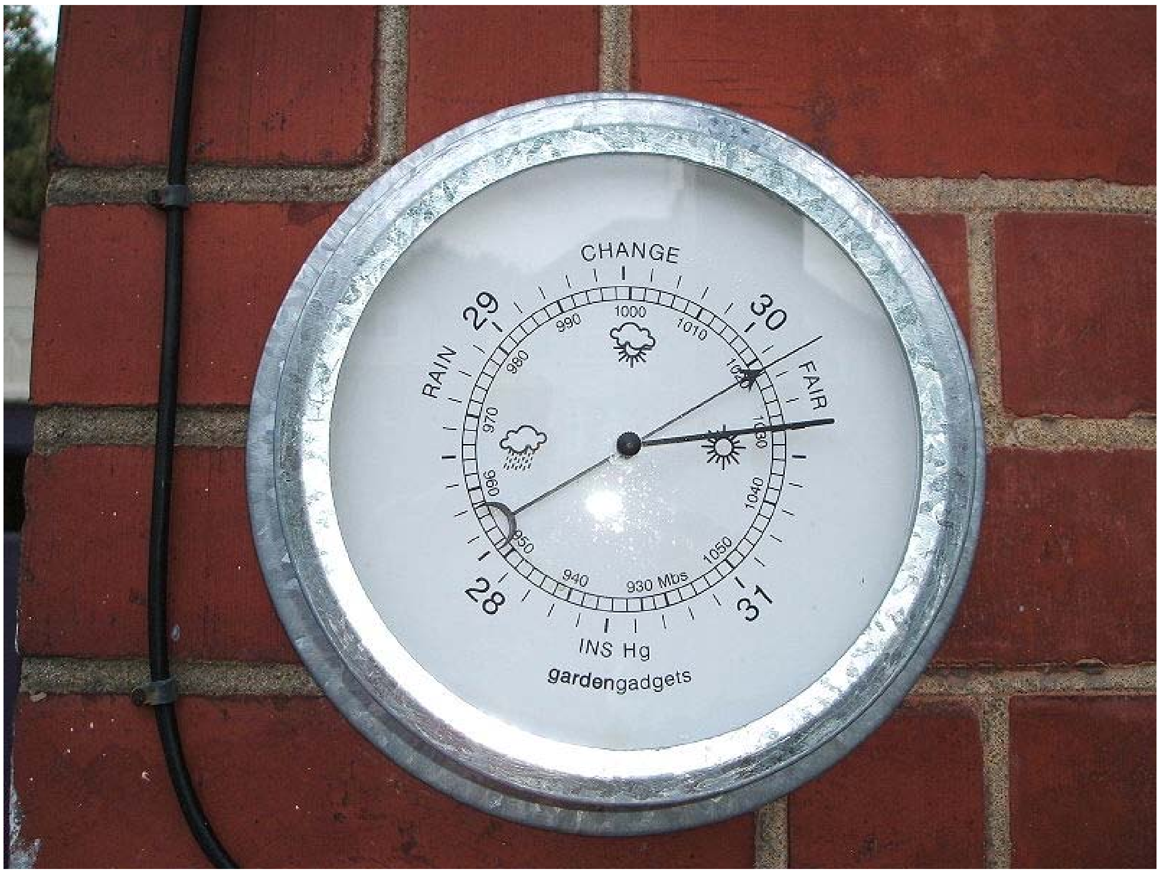


A hemispherical cup anemometer

In 1441, king Sejong's son, Prince Munjong, invented the first standardized rain gauge. These were sent throughout the Joseon Dynasty of Korea as an official tool to assess land taxes based upon a farmer's potential harvest. In 1450, Leone Battista Alberti developed a swinging-plate anemometer, and is known as the first *anemometer*. In 1607, Galileo Galilei constructs a thermoscope. In 1643, Evangelista Torricelli invents the mercury barometer. In 1662, Sir Christopher Wren invented the mechanical, self-emptying, tipping bucket rain gauge. In 1714, Gabriel Fahrenheit creates a reliable scale for measuring temperature with a mercury-type thermometer. In 1742, Anders Celsius, a

Swedish astronomer, proposed the 'centigrade' temperature scale, the predecessor of the current Celsius scale. In 1783, the first hair hygrometer is demonstrated by Horace-Bénédict de Saussure. In 1806, Francis Beaufort introduced his system for classifying wind speeds. The April 1960 launch of the first successful weather satellite, TIROS-1, marked the beginning of the age where weather information became available globally.

Types



Modern aneroid barometer

A thermometer measures air temperature, or the kinetic energy of the molecules within air. A barometer measures atmospheric pressure, or the pressure exerted by the weight of the Earth's atmosphere above a particular location. An anemometer measures the wind speed and the direction the wind is blowing from at the site where it is mounted. A hygrometer measures the relative humidity at a location, which can then be used to compute the dew point. Radiosondes directly measure most of these quantities, except for wind, which is determined by tracking the radiosonde signal with an antenna or theodolite. Supplementing the radiosondes a network of aircraft collection is organized by the World Meteorological Organization, which also use these instruments to report weather conditions at their respective locations. A sounding rocket, sometimes called a research rocket, is an instrument-carrying rocket designed to take measurements and perform scientific experiments during its sub-orbital flight.

A pyranometer is a type of actinometer used to measure broadband solar irradiance on a planar surface and is a sensor that is designed to measure the solar radiation flux density (in watts per metre square) from a field of view of 180 degrees. A ceilometer is a device that uses a laser or other light source to determine the height of a cloud base. Ceilometers can also be used to measure the aerosol concentration within the atmosphere. A ceiling balloon is used by meteorologists to determine the height of the base of clouds above ground level during daylight hours. The principle behind the ceiling balloon is a balloon with a known ascent rate (how fast it climbs) and determining how long the balloon rises until it disappears into the cloud. Ascent rate times ascent time yields the ceiling height. A disdrometer is an instrument used to measure the drop size distribution and velocity of falling hydrometeors. Some disdrometers can distinguish between rain, graupel, and hail. Rain gages are used to measure the precipitation which falls at any point on the Earth's landmass.

Remote sensing, as used in meteorology, is the concept of collecting data from remote weather events and subsequently producing weather information. Each remote sensing instruments collects data about the atmosphere from a remote location and, usually, stores the data where the instrument is located. The common types of remote sensing are Radar, Lidar, and satellites (or photogrammetry). The main uses of radar are to collect information concerning the coverage of precipitation and wind. Satellites are chiefly used to determine cloud cover, as well as wind. SODAR (SOnic Detection And Ranging) is a meteorological instrument also known as a wind profiler which measures the scattering of sound waves by atmospheric turbulence. SODAR systems are used to measure wind speed at various heights above the ground, and the thermodynamic structure of the lower layer of the atmosphere. RADAR and LIDAR are not passive because both use EM radiation to illuminate a specific portion of the atmosphere. Weather satellites along with more general-purpose Earth-observing satellites circling the earth at various altitudes have become an indispensable tool for studying a wide range of phenomena from forest fires to El Niño.

Weather stations

A weather station is a facility with instruments and equipment to make observations of atmospheric conditions in order to provide information to make weather forecasts and to study the weather and climate. The measurements taken include temperature, barometric pressure, humidity, wind speed, wind direction, and precipitation amounts. Wind measurements are taken as free of other obstructions as possible, while temperature and humidity measurements are kept free from direct solar radiation, or insolation. Manual observations are taken at least once daily, while automated observations are taken at least once an hour.

Surface weather observations

Weather station at Mildura Airport, Victoria, Australia.

Surface weather observations are the fundamental data used for safety as well as climatological reasons to forecast weather and issue warnings worldwide. They can be taken manually, by a weather observer, by computer through the use of automated weather stations, or in a hybrid scheme using weather observers to augment the otherwise automated weather station. The ICAO defines the International Standard Atmosphere, which is the model of the standard variation of pressure, temperature, density, and viscosity with altitude in the Earth's atmosphere, and is used to reduce a station pressure to sea level pressure. Airport observations can be transmitted worldwide through the use of the METAR observing code. Personal weather stations taking automated observations can transmit their data to the United States mesonet through the use of the Citizen Weather Observer Program (CWOP), or internationally through the Weather Underground Internet site. A thirty-year average of a location's weather observations is traditionally used to determine the station's climate.

Airports

ASOS sensors, located at Salinas, California

Surface weather observations have traditionally been taken at airports due to safety concerns during takeoffs and landings. The ICAO defines the International Standard Atmosphere (also known as ICAO Standard Atmosphere), which is the model of the standard variation of pressure, temperature, density, and viscosity with altitude in the Earth's atmosphere. This is useful in calibrating instruments and designing aircraft, and is used to reduce a station's pressure to sea level pressure where it can then be used on weather maps.

In the United States, the FAA mandates the taking of weather observations for safety reasons. To help facilitate the purchase of an automated airport weather station, such as ASOS, the FAA allows federal dollars to be used for the installation of certified weather stations at airports. The airport observations are then transmitted worldwide using the METAR observing code. METAR reports typically come from airports or permanent weather observation stations. Reports are generated once an hour; however, if conditions change significantly, they may be updated in special reports called SPECI's.

Data Reported

Surface weather observations can include the following elements:

- The **Station Identifier**, or Location identifier, consists of four characters for METAR observations, with the first representing the region of the world the station lies within. For example, the first letter for areas in and around the Pacific ocean is P, and for Europe is E. The second character may represent the country/state the location lies within. For Hawaii, the first two letters are "PH" while for Great Britain, the first two letters of the station identifie are "EG". Canada and the contiguous United States are an exception, with the first letters C and K representing the regions, respectively. The final two or three letters normally represent the name of the location or airport.

- **Visibility**, measured in meters for most sites worldwide, except in the United States where statute miles are reported.

- **Runway visibility**, measured in meters in many locations worldwide, or feet within the United States.

- **Temperature** is a measure of the kinetic energy of a sample of matter. Temperature is the unique physical property that determines the direction of heat flow between two objects placed in thermal contact. If no heat flow occurs, the two objects have the same temperature; otherwise heat flows from the hotter object to the colder object. Temperature, within meteorology, is measured with thermometers exposed to the air but sheltered from direct solar exposure. In most of the world, the degree Celsius scale is used for most temperature measuring purposes. However, the United States is the last major country in which the degree Fahrenheit temperature scale is used by most lay people, industry, popular meteorology, and government. Despite this, METAR reports from the United States also report the temperature (and dewpoint, see below) in degrees Celsius.

- **Dew Point** is the temperature to which a given parcel of air must be cooled, at constant barometric pressure, for water vapor to condense into water. The condensed water is called dew. The dew point is a saturation point. When the dew point temperature falls below freezing it is called the frost point, as the water vapor no longer creates dew but instead creates frost or hoarfrost by deposition. The dew point is associated with relative humidity. A high relative humidity indicates that the dew point is closer to the current air temperature. If the relative humidity is 100%, the dew point is equal to the current temperature. Given a constant dew point, an increase in temperature will lead to a decrease in relative humidity. At a given barometric pressure, independent of temperature, the dew point determines the specific humidity of the air. The dew point is an important statistic for general aviation pilots, as it is used to calculate the likelihood of carburetor icing and fog. When used with the air temperature, a formula can be used to estimate the height of cumuliform, or convective, clouds.
- **Wind speed and direction** is determined using anemometers located a standard 10 metres (33 ft) above ground level. Average wind speed is measured using a two-minute average in the United States, and a 10 minute average elsewhere. Wind direction is measured using degrees, with north representing 0 or 360 degrees, with values increasing from 0 clockwise from north. Wind gusts are reported when there is variation of the wind speed of more than 10 knots (5.1 m/s) between peaks and lulls during the sampling period.
- **Sea level pressure** is the pressure at sea level or (when measured at a given elevation on land) the station pressure reduced to sea level assuming an isothermal layer at the station temperature. This is the pressure normally given in weather reports on radio, television, and newspapers or on the Internet. When barometers in the home are set to match the local weather reports, they measure pressure reduced to sea level, not the actual local atmospheric pressure. The reduction to sea level means that the *normal range of fluctuations* in pressure is

the same for everyone. The pressures which are considered *high pressure* or *low pressure* do not depend on geographical location. This makes isobars on a weather map meaningful and useful tools.

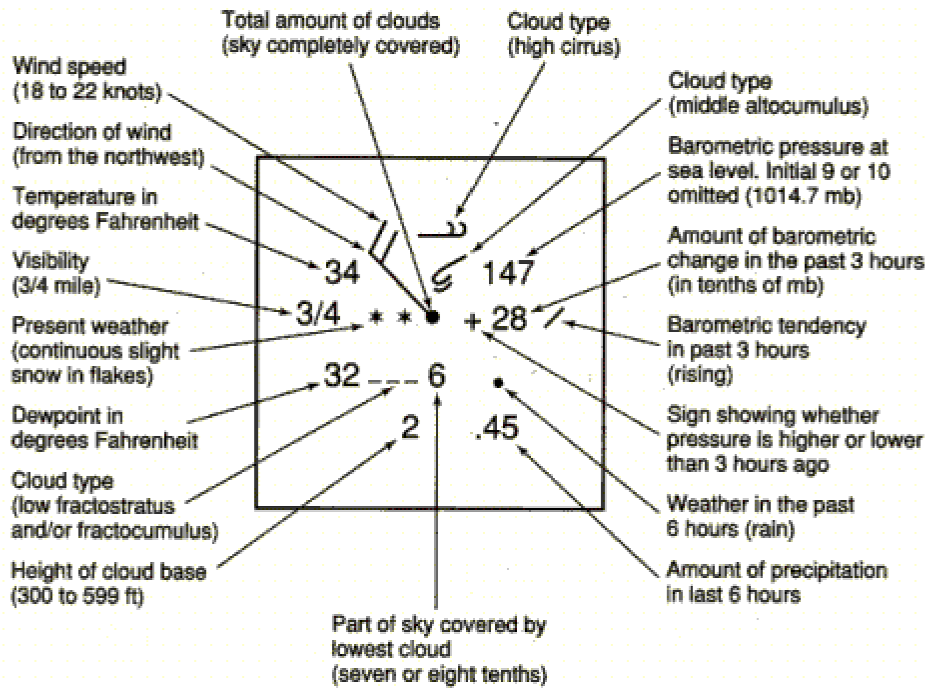
- **Altimeter setting** is a term and quantity used in aviation. The regional or local air pressure at mean sea level is called the altimeter setting, and the pressure which will calibrate the altimeter to show the height above ground at a given airfield.
- **Present weather**, which present restrictions to visibility or presence of thunder or squalls, are reported in observations to indicate to aviation any possible threats during landings and takeoffs from airports. Types included in surface weather observations include precipitation, obscurations, other weather phenomena such as, well-developed dust/sand whirls, squalls, tornadic activity, sandstorms, volcanic ash, and duststorms.
- **Intensity of precipitation** is primarily measured for meteorological concerns. However, it can be of concern to aviation as heavy precipitation can limit visibility. Also, intensity of freezing rain can determine how hazardous it is for pilots to fly nearby certain locations since it can be an in-flight hazard by depositing ice on the wings of aircraft, which can be detrimental to flight.
- **Precipitation amount** over the past 6 or 24 hours is of particular interest to meteorologists in verifying forecast amounts of precipitation and determining station climatologies.
- **Snowfall amount** during the past 6 hours is taken for meteorological and climatological concerns.
- **Snow depth** is measured for meteorological and climatological concerns once a day. However, during periods of snowfall, it is measured each six hours to determine amount of recent snowfall.

Example of a METAR surface weather observation

METAR LBBG 041600Z 12003MPS 310V290 1400 R04/P1500N R22/P1500U +SN BKN022 OVC050 M04/M07 Q1020 NOSIG 9949//91=

Personal weather stations, maintained by citizens rather than government officials, do not use METAR code. Software allows information to be transmitted to various sites, such as Weather Underground globally, or CWOP within the United States, which can then be used by the appropriate meteorological organizations either to diagnose real-time conditions, or be used within weather forecast models.

Use on weather maps

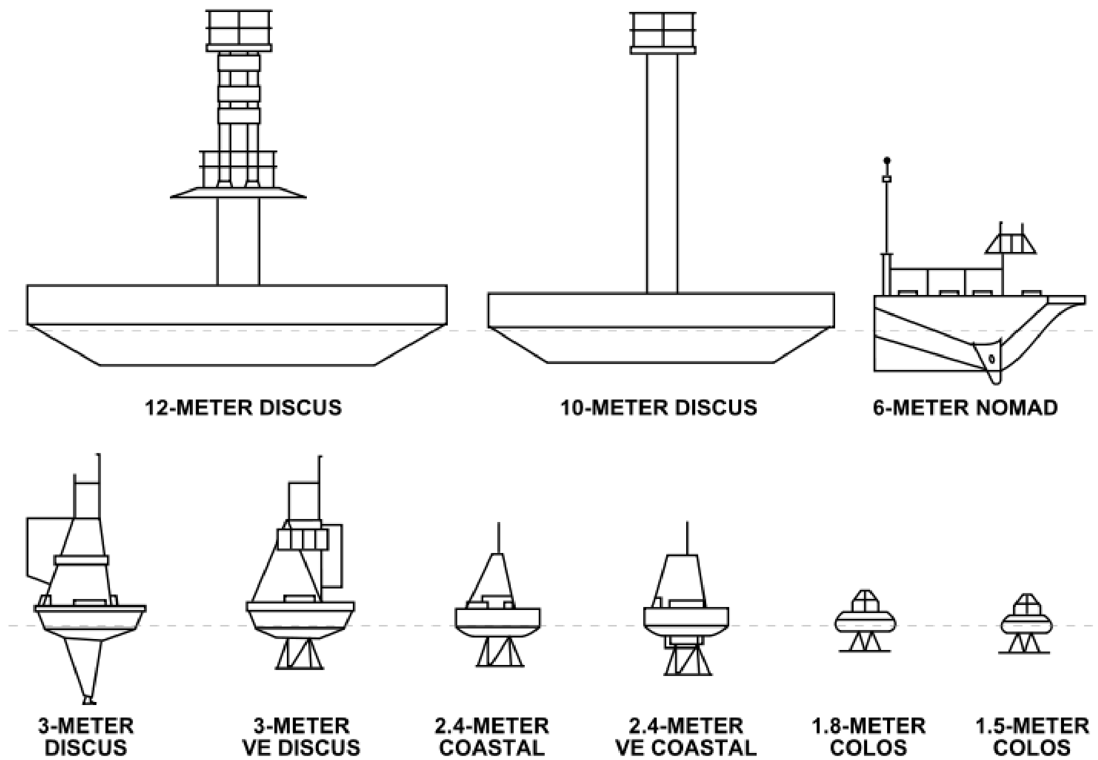


Station model used on surface weather maps

Data collected by land locations coding in METAR are conveyed worldwide via phone lines or wireless technology. Within many nations' meteorological organizations, this data is then plotted onto a weather map using the station model. A station model is a symbolic illustration showing the weather occurring at a given reporting station. Meteorologists created the station model to plot a number of weather elements in a small space on weather maps. Maps filled with dense station-model plots can be difficult to read, but they allow meteorologists, pilots, and mariners to see important weather patterns.

Weather maps are used to display information quickly showing the analysis of various meteorological quantities at various levels of the atmosphere, in this case the surface layer. Maps containing station models aid in the drawing of isotherms, which more readily identifies temperature gradients, and can help in the location of weather fronts. Two-dimensional streamlines based on wind speeds show areas of convergence and divergence in the wind field, which are helpful in determining the location of features within the wind pattern. A popular type of surface weather map is the surface weather analysis, which plots isobars to depict areas of high pressure and low pressure.

Ship and buoy reports



Different shapes and sizes of buoys

For over a century, reports from the world's oceans have been received real-time for safety reasons and to help with general weather forecasting. The reports are coded using the synoptic code, and relayed via radio or satellite to weather organizations worldwide. Buoy reports are automated, and maintained by the country that moored the buoy in that location. Larger moored buoys are used near shore, while smaller drifting buoys are used farther out at sea.

Due to the importance of reports from the surface of the ocean, the voluntary observing ship program, known as VOS, was set up to train crews how to take weather observations while at sea and also to calibrate weather sensors used aboard ships when they arrive in port, such as barometers and thermometers. The beaufort scale is still generally used to determine wind speed from manual observers out at sea. Ships with anemometers have issues with determining wind speeds at higher wind speeds due to blockage of the instruments by increasing high seas.

Use in establishing climate of a location

Climate, (from Ancient Greek *klima*) is commonly defined as the weather averaged over a long period of time. The standard averaging period is 30 years for an individual location, but other periods may be used. Climate includes statistics other than the average, such as the magnitudes of day-to-day or year-to-year variations. The Intergovernmental Panel on Climate Change (IPCC) glossary definition is:

Climate in a narrow sense is usually defined as the "average weather", or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

The main difference between climate and everyday weather is best summarized by the popular phrase "Climate is what you expect, weather is what you get." Over historic time spans there are a number of static variables that determine climate, including: latitude, altitude, proportion of land to water, and proximity to oceans and mountains. Degree of vegetation coverage affects solar heat absorption, water retention, and rainfall on a regional level.

Chapter-7

Spatial Scales in Meteorology

In the study of the atmosphere, meteorology can be divided into distinct areas of emphasis depending on the temporal scope and spatial scope of interest. At one extreme of this scale is climatology. In the timescales of hours to days, meteorology separates into micro-, meso-, and synoptic scale meteorology. Respectively, the geospatial size of each of these three scales relates directly with the appropriate timescale.

Other subclassifications are available based on the need by or by the unique, local or broad effects that are studied within that sub-class.

Microscale

Microscale meteorology is the study of short-lived atmospheric phenomena smaller than mesoscale, about 1 km or less. These two branches of meteorology are sometimes grouped together as "mesoscale and microscale meteorology" (MMM) and together study all phenomena smaller than synoptic scale; that is they study features generally too small to be depicted on a weather map. These include small and generally fleeting cloud "puffs" and other small cloud features. Microscale meteorology controls the most important mixing and dilution processes in the atmosphere. Important topics in microscale meteorlogy include heat transfer and gas exchange between soil, vegetation, and/or surface water and the atmosphere caused by near-ground turbulence. Measuring these transport processes involves use of micrometeorological (or flux) towers. Variables often measured or derived include net radiation, sensible heat flux, latent heat flux, ground heat storage, and fluxes of trace gases important to the atmosphere, biosphere, and hydrosphere.

Mesoscale

Mesoscale meteorology is the study of weather systems smaller than synoptic scale systems but larger than microscale and storm-scale cumulus systems. Horizontal dimensions generally range from around 5 kilometers to several hundred kilometers. Examples of mesoscale weather systems are sea breezes, squall lines, and mesoscale convective complexes.

Vertical velocity often equals or exceeds horizontal velocities in mesoscale meteorological systems due to nonhydrostatic processes such as buoyant acceleration of a rising thermal or acceleration through a narrow mountain pass.

Subclasses

Mesoscale Meteorology is divided into these subclasses (Orlanski, 1975):

- **Meso-gamma** 2-20 km, deals with phenomena like thunderstorm convection, complex terrain flows (at the edge to microscale, also known as storm-scale)

- **Meso-beta** 20-200 km deals with phenomena like sea breezes, lake effect snow storms

- **Meso-alpha** 200-2000 km fronts, deals with phenomena like squall lines, mesoscale convective systems (MCS), tropical cyclones at the edge of synoptic scale

Mesoscale boundaries

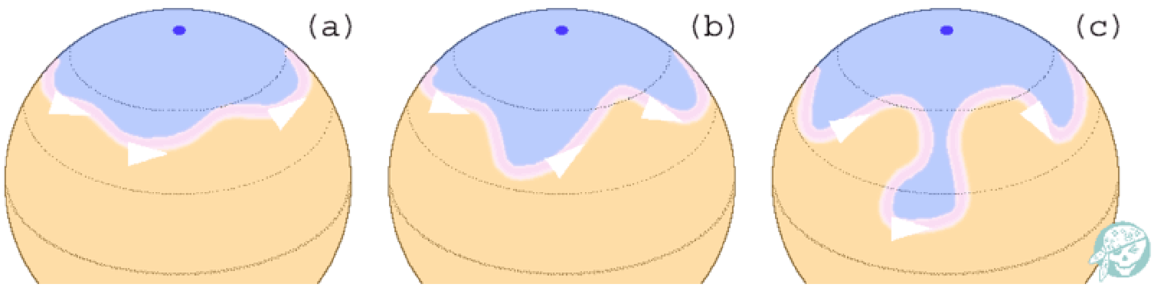
As in synoptic frontal analysis, literature about mesoscale analysis uses cold, warm, and occluded fronts on the mesoscale to help describe phenomena. On weather maps mesoscale fronts are depicted as smaller and with twice as many bumps or spikes as the synoptic variety. In the United States, opposition to the use of the mesoscale versions of fronts on weather analyses, has led to the use of an overarching symbol (a trough symbol) with a label of outflow boundary as the frontal notation.

Synoptic scale

The **synoptic scale** in meteorology (also known as **large scale** or **cyclonic scale**) is a horizontal length scale of the order of 1000 kilometres (about 620 miles) or more. This corresponds to a horizontal scale typical of mid-latitude depressions. Most high and low pressure areas seen on weather maps such as surface weather analyses are synoptic-scale systems, driven by the location of Rossby waves in their respective hemisphere. Low pressure areas and their related frontal zones occur on the leading edge of a trough within the Rossby wave pattern, while surface highs form on the back edge of the trough. Most precipitation areas occur near frontal zones. The word **synoptic** is derived from the Greek word *sunoptikos* meaning *seen together*.

The Navier-Stokes equations applied to atmospheric motion can be simplified by scale analysis in the synoptic scale. It can be shown that main terms in horizontal equations are Coriolis force and pressure gradient terms; therefore, one can use geostrophic approximation. In vertical coordinates the momentum equation simplifies to the hydrostatic equilibrium equation. Extratropical cyclones in particular are driven by large scale waves at upper levels of the troposphere known as rossby waves.

Atmospheric Rossby waves



Meanders of the northern hemisphere's jet stream developing (a, b) and finally detaching a "drop" of cold air (c). Orange: warmer masses of air; pink: jet stream.

Rossby waves in the atmosphere are easy to observe as (usually 4-6) large-scale meanders of the jet stream across the Northern or Southern Hemispheres. When these loops become very pronounced, they detach the masses of cold, or warm, air that become cyclones and anticyclones and are responsible for day-to-day weather patterns at mid-latitudes.

The wave speed is given by

$$c = u - \frac{\beta}{k^2},$$

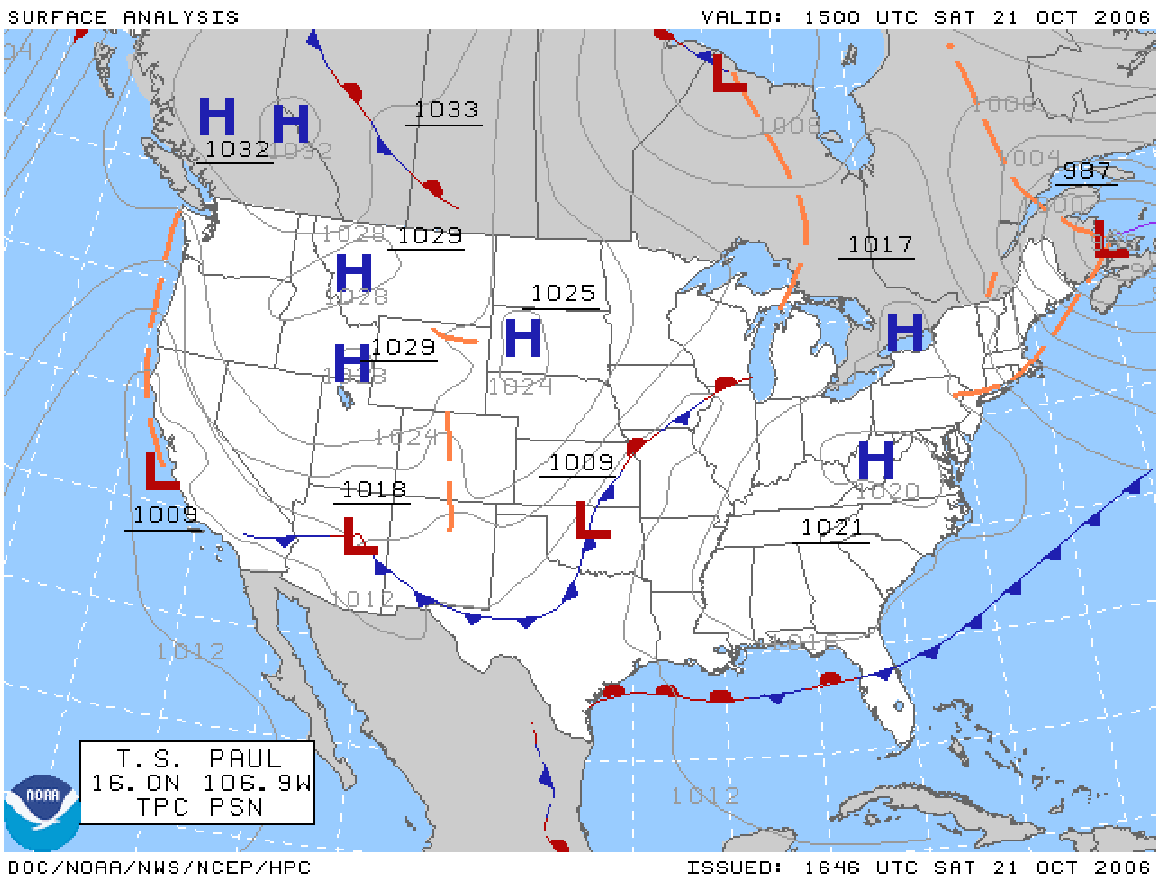
where c is the wave speed, u is the mean westerly flow, β is the Rossby parameter, and k is the total wavenumber.

Furthermore, the Rossby parameter is defined:

$$\beta = \frac{1}{a}\frac{d}{d\phi}(2\omega sin\phi) = \frac{2\omega cos\phi}{a}$$

φ is the latitude, ω is the angular speed of the Earth's rotation, and a is the mean radius of the Earth.

Surface weather analysis



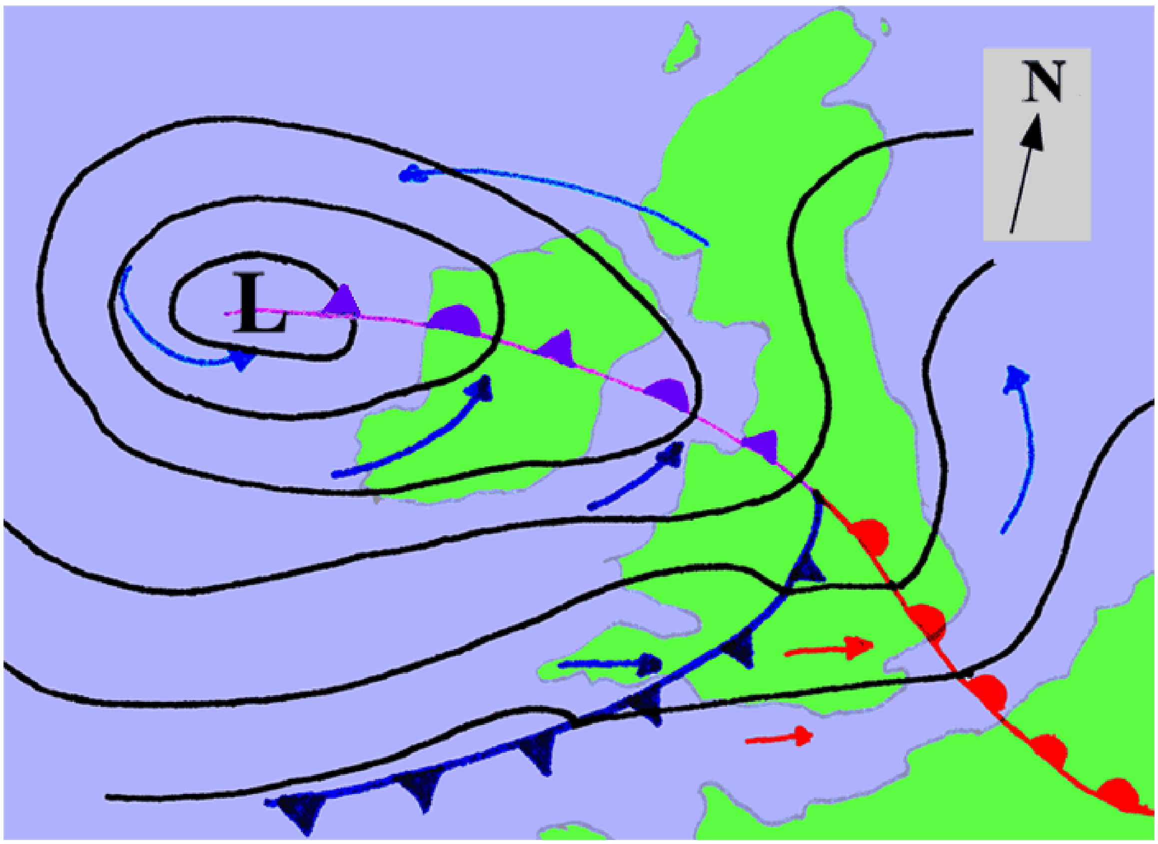
A surface weather analysis for the United States on October 21, 2006.

A surface weather analysis is a special type of weather map that provides a view of weather elements over a geographical area at a specified time based on information from ground-based weather stations. Weather maps are created by plotting or tracing the values of relevant quantities such as sea level pressure, temperature, and cloud cover onto a geographical map to help find synoptic scale features such as weather fronts.

The first weather maps in the 19th century were drawn well after the fact to help devise a theory on storm systems. After the advent of the telegraph, simultaneous surface weather observations became possible for the first time, and beginning in the late 1840s, the Smithsonian Institution became the first organization to draw real-time surface analyses. Use of surface analyses began first in the United States, spreading worldwide during the 1870s. Use of the Norwegian cyclone model for frontal analysis began in the late 1910s across Europe, with its use finally spreading to the United States during World War II.

Surface weather analyses have special symbols which show frontal systems, cloud cover, precipitation, or other important information. For example, an *H* represents high pressure, implying good and fair weather. An *L* represents low pressure, which frequently accompanies precipitation. Various symbols are used not just for frontal zones and other surface boundaries on weather maps, but also to depict the present weather at various locations on the weather map. Areas of precipitation help determine the frontal type and location. Mesoscale systems and boundaries such as tropical cyclones, outflow boundaries and squall lines also are analyzed on surface weather analyses. Isobars are commonly used to place surface boundaries from the horse latitudes poleward, while streamline analyses are used in the tropics.

Extratropical cyclone



A fictitious synoptic chart of an extratropical cyclone affecting the UK and Ireland. The blue arrows between isobars indicate the direction of the wind, while the "L" symbol denotes the centre of the "low". Note the occluded, cold and warm frontal boundaries.

An **extratropical cyclone** is a synoptic scale low pressure weather system that has neither tropical nor polar characteristics, being connected with fronts and horizontal gradients in temperature and dew point otherwise known as "baroclinic zones".

The descriptor "extratropical" refers to the fact that this type of cyclone generally occurs outside of the tropics, in the middle latitudes of the planet. These systems may also be described as "mid-latitude cyclones" due to their area of formation, or "post-tropical cyclones" where extratropical transition has occurred, and are often described as "depressions" or "lows" by weather forecasters and the general public. These are the everyday phenomena which along with anti-cyclones, drive the weather over much of the Earth.

Although extratropical cyclones are almost always classified as baroclinic since they form along zones of temperature and dewpoint gradient within the westerlies, they can sometimes become barotropic late in their life cycle when the temperature distribution around the cyclone becomes fairly uniform with radius. An extratropical cyclone can transform into a subtropical storm, and from there into a tropical cyclone, if it dwells over warm waters and develops central convection, which warms its core.

Surface high pressure systems

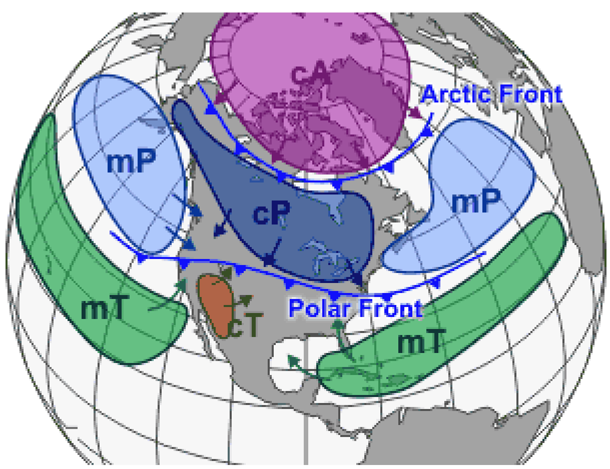
Golden Gate Bridge in fog

High pressure systems are frequently associated with light winds at the surface and subsidence through the lower portion of the troposphere. Subsidence will generally dry out an air mass by adiabatic, or compressional, heating. Thus, high pressure typically brings clear skies. During the day, since no clouds are present to reflect sunlight, there is more incoming shortwave solar radiation and temperatures rise. At night, the absence of clouds means that outgoing longwave radiation (i.e. heat energy from the surface) is not absorbed, giving cooler diurnal low temperatures in all seasons. When surface winds become light, the subsidence produced directly under a high-pressure system can lead to a build up of particulates in urban areas under the ridge, leading to widespread haze. If the low level relative humidity rises towards 100 percent overnight, fog can form.

Strong, vertically shallow high-pressure systems moving from higher latitudes to lower latitudes in the northern hemisphere are associated with continental arctic air masses. The low, sharp inversion can lead to areas of persistent stratocumulus or stratus cloud, colloquially known as anticyclonic gloom. The type of weather brought about by an anticyclone depends on its origin. For example, extensions of the Azores high pressure may bring about anticyclonic gloom during the winter, as they are warmed at the base and will trap moisture as they move over the warmer oceans. High pressures that build to the north and extend southwards will often bring clear weather. This is due to being cooled at the base (as opposed to warmed) which helps prevent clouds from forming.

On weather maps, these areas show converging winds (isotachs), also known as confluence, or converging height lines near or above the level of non-divergence, which is near the 500 hPa pressure surface about midway up through the troposphere. High-pressure systems are alternatively referred to as anticyclones. On weather maps, high-pressure centers are associated with the letter H in English, or A in Spanish, because alta is the Spanish word for high, within the isobar with the highest pressure value. On constant pressure upper level charts, it is located within the highest height line contour.

Weather fronts

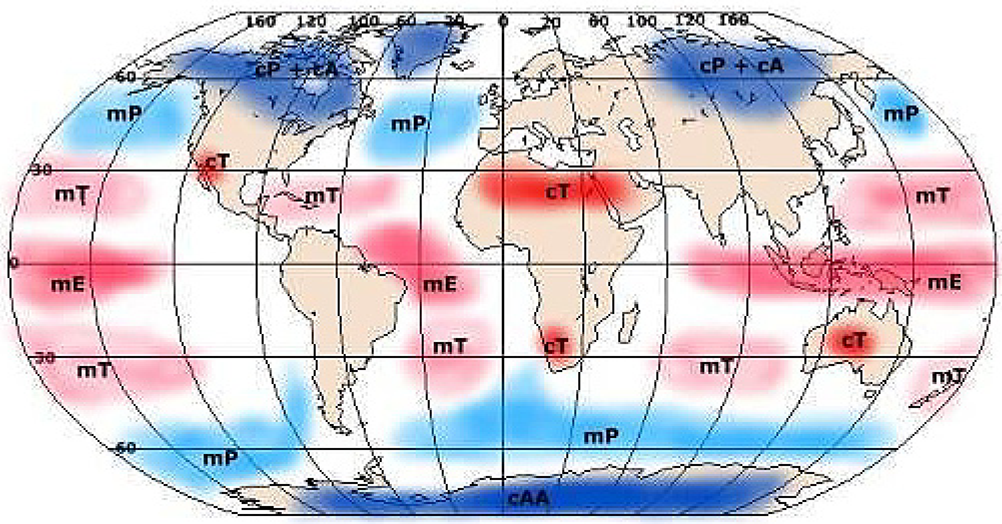


Different air masses tend to be separated by frontal boundaries. The Arctic front separates Arctic from Polar air masses, while the Polar front separates Polar air from warm air masses. (cA is continental arctic; cP is continental polar; mP is maritime polar; cT is continental tropic; and mT is maritime tropic.)

A **weather front** is a boundary separating two masses of air of different densities, and is the principal cause of meteorological phenomena. In surface weather analyses, fronts are depicted using various colored lines and symbols, depending on the type of front. The air masses separated by a front usually differ in temperature and humidity. Cold fronts may feature narrow bands of thunderstorms and severe weather, and may on occasion be preceded by squall lines or dry lines. Warm fronts are usually preceded by stratiform precipitation and fog. The weather usually clears quickly after a front's passage. Some fronts produce no precipitation and little cloudiness, although there is invariably a wind shift.

Cold fronts and occluded fronts generally move from west to east, while warm fronts move poleward. Because of the greater density of air in their wake, cold fronts and cold occlusions move faster than warm fronts and warm occlusions. Mountains and warm bodies of water can slow the movement of fronts. When a front becomes stationary, and the density contrast across the frontal boundary vanishes, the front can degenerate into a line which separates regions of differing wind velocity, known as a shearline. This is most common over the open ocean.

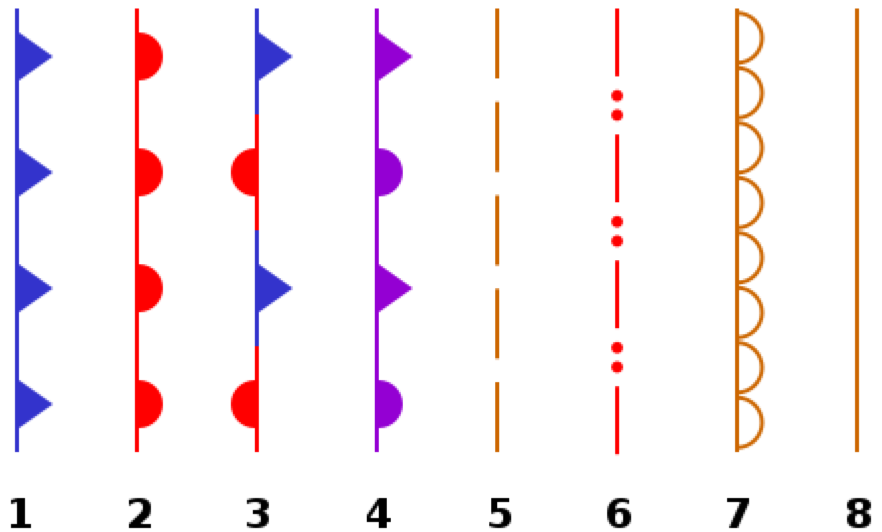
Bergeron classification of air masses



Source regions of global air masses

The Bergeron classification is the most widely accepted form of air mass classification. Air mass classification involves three letters. The first letter describes its moisture properties, with c used for continental air masses (dry) and m for maritime air masses (moist). The second letter describes the thermal characteristic of its source region: T for tropical, P for polar, A for arctic or Antarctic, M for monsoon, E for equatorial, and S for superior air (dry air formed by significant downward motion in the atmosphere). The third letter is used to designate the stability of the atmosphere. If the air mass is colder than the ground below it, it is labeled k. If the air mass is warmer than the ground below it, it is labeled w.

Surface weather analysis



Weather map symbols:
1. cold front;
2. warm front;
3. stationary front;
4. occluded front;
5. surface trough;
6. squall/shear line;
7. dry line;
8. tropical wave

A surface weather analysis is a special type of weather map which provides a view of weather elements over a geographical area at a specified time based on information from ground–based weather stations. Weather maps are created by plotting or tracing the values of relevant quantities such as sea-level pressure, temperature, and cloud cover onto a geographical map to help find synoptic scale features such as weather fronts. Surface weather analyses have special symbols which show frontal systems, cloud cover, precipitation, or other important information. For example, an *H* may represent high pressure, implying fair weather. An *L* on the other hand may represent low pressure, which frequently accompanies precipitation. Various symbols are used not just for frontal zones and other surface boundaries on weather maps, but also to depict the present weather at various locations on the weather map. In addition, areas of precipitation help determine the frontal type and location.

Front types

Cold front

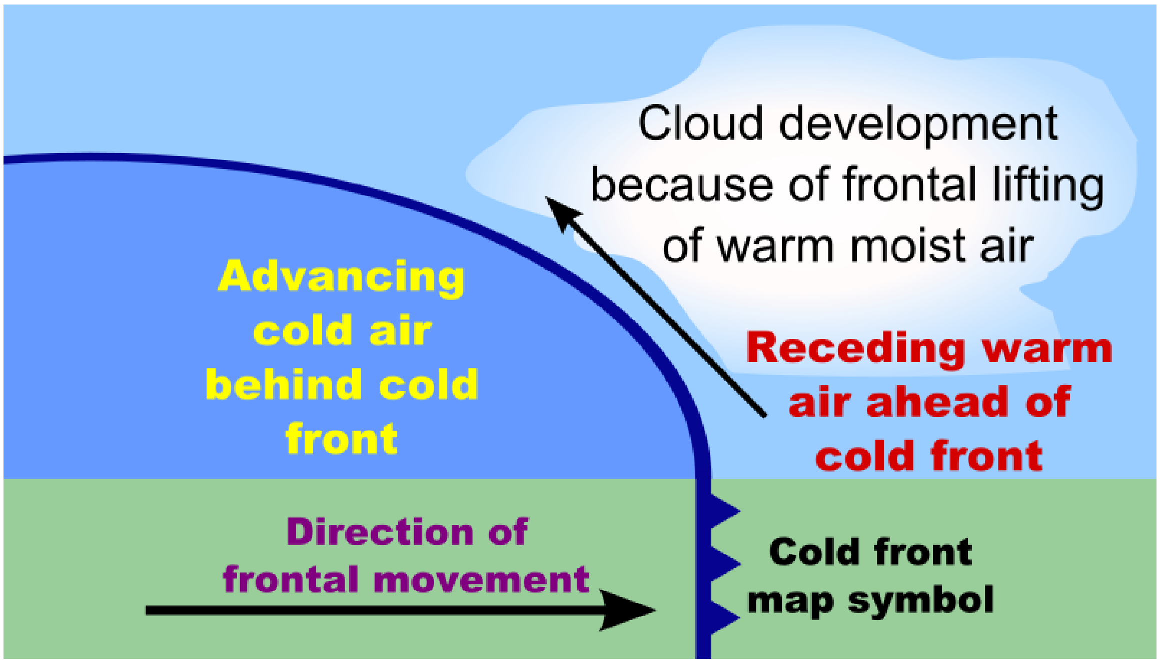


Illustration of a cold front

A cold front is located at the leading edge of the temperature drop off, which in an isotherm analysis shows up as the leading edge of the isotherm gradient, and it normally lies within a sharp surface trough. Cold fronts can move up to twice as fast and produce sharper changes in weather than warm fronts, since cold air is denser than warm air and rapidly replaces the warm air preceding the boundary. On weather maps, the surface position of the cold front is marked with the symbol of a blue line of triangle-shaped pips pointing in the direction of travel, and it is placed at the leading edge of the cooler air mass. Cold fronts come in association with a low pressure area. The concept of colder, dense air "wedging" under the less dense warmer air is often used to depict how air is lifted along a frontal boundary. This lift would then form a narrow line of showers and thunderstorms if enough moisture were present. However, this concept isn't an accurate description of the physical processes; upward motion is not produced because of warm air "ramping up" cold, dense air, rather, frontogenetical circulation is behind the upward forcing.

Warm front

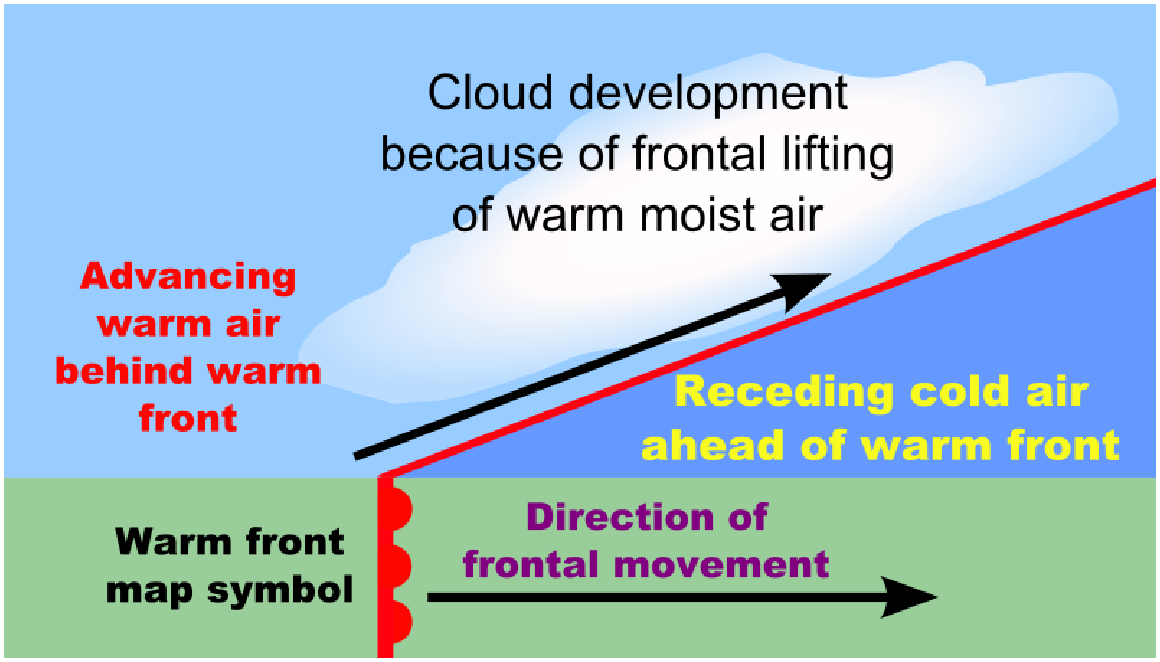
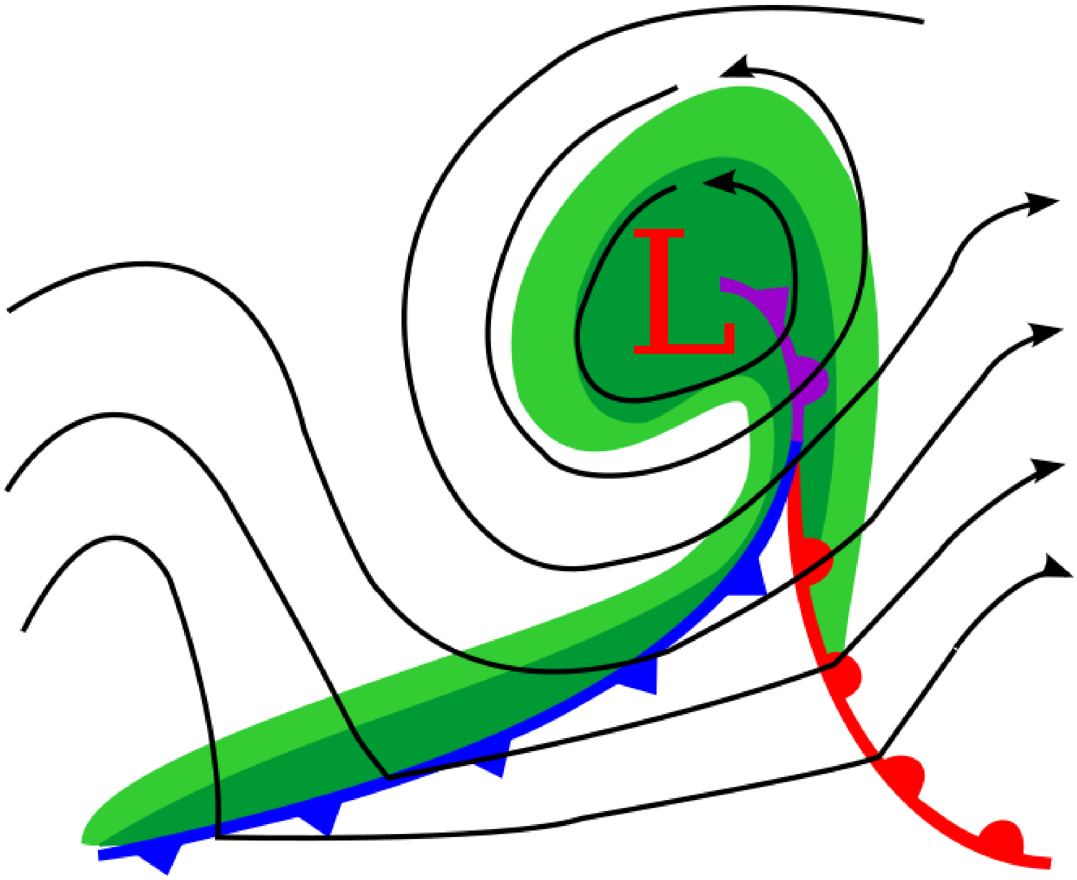


Illustration of a warm front

Warm fronts are at the leading edge of a homogeneous warm air mass, which is located on the equatorward edge of the gradient in isotherms, and lie within broader troughs of low pressure than cold fronts. A warm front moves more slowly than the cold front which usually follows because cold air is denser and harder to remove from the Earth's surface. This also forces temperature differences across warm fronts to be broader in scale. Clouds ahead of the warm front are mostly stratiform, and rainfall gradually increases as the front approaches. Fog can also occur preceding a warm frontal passage. Clearing and warming is usually rapid after frontal passage. If the warm air mass is unstable, thunderstorms may be embedded among the stratiform clouds ahead of the front, and after frontal passage thundershowers may continue. On weather maps, the surface location of a warm front is marked with a red line of semicircles pointing in the direction of travel.

Occluded front



Occluded front depiction

An occluded front is formed when a cold front overtakes a warm front. The cold and warm fronts curve naturally poleward into the point of occlusion, which is also known as the triple point. It lies within a sharp trough, but the air mass behind the boundary can be either warm or cold. In a cold occlusion, the air mass overtaking the warm front is cooler than the cool air ahead of the warm front and plows under both air masses. In a warm occlusion, the air mass overtaking the warm front is warmer than the cold air ahead of the warm front and rides over the colder air mass while lifting the warm air.

A wide variety of weather can be found along an occluded front, with thunderstorms possible, but usually their passage is associated with a drying of the air mass. Occluded fronts are indicated on a weather map by a purple line with alternating half-circles and triangles pointing in direction of travel. Occluded fronts usually form around mature low-pressure areas.

Stationary front and shearline

A stationary front is a non-moving (or stalled) boundary between two air masses, neither of which is strong enough to replace the other. They tend to remain essentially in the same area for extended periods of time, usually moving in waves. There is normally a broad temperature gradient behind the boundary with more widely spaced isotherm packing.

A wide variety of weather can be found along a stationary front, but usually clouds and prolonged precipitation are found there. Stationary fronts either dissipate after several days or devolve into shear lines, but they can transform into a cold or warm front if conditions aloft change. Stationary fronts are marked on weather maps with alternating red half-circles and blue spikes pointing in opposite directions, indicating no significant movement.

When stationary fronts become smaller in scale, degenerating to a narrow zone where wind direction changes significantly over a relatively short distance, they become known as shearlines. A shearline is depicted as a line of red dots and dashes.

Dry line

A similar phenomenon to a weather front is the dry line, which is the boundary between air masses with significant moisture differences. When the westerlies increase on the north side of surface highs, areas of lowered pressure will form downwind of north–south oriented mountain chains, leading to the formation of a lee trough. Near the surface during daylight hours, warm moist air is denser than dry air of greater temperature, and thus the warm moist air wedges under the drier air like a cold front. At higher altitudes, the warm moist air is less dense than the dry air and the boundary slope reverses. In the vicinity of the reversal aloft, severe weather is possible, especially when a triple point is formed with a cold front. A weaker form of the dry line seen more commonly is the lee trough, which displays weaker differences in moisture. When moisture pools along the boundary during the warm season, it can be the focus of diurnal thunderstorms.

The dry line may occur anywhere on earth in regions intermediate between desert areas and warm seas. The southern plains west of the Mississippi River in the United States are a particularly favored location. The dry line normally moves eastward during the day and westward at night. A dry line is depicted on National Weather Service (NWS) surface analyses as an orange line with scallops facing into the moist sector. Dry lines are one of the few surface fronts where the pips indicated do not necessarily reflect the direction of motion.

Squall line

A shelf cloud such as this one can be a sign that a squall is imminent

Organized areas of thunderstorm activity not only reinforce pre-existing frontal zones, but can outrun cold fronts in a pattern where the upper level jet splits apart into two streams, with the resultant Mesoscale Convective System (MCS) forming at the point of the upper level split in the wind pattern running southeast into the warm sector parallel to low-level thickness lines. When the convection is strong and linear or curved, the MCS is called a squall line, with the feature placed at the leading edge of the significant wind shift and pressure rise. Even weaker and less organized areas of thunderstorms lead to locally cooler air and higher pressures, and outflow boundaries exist ahead of this type of activity, which can act as foci for additional thunderstorm activity later in the day.

These features are often depicted in the warm season across the United States on surface analyses and lie within surface troughs. If outflow boundaries or squall lines form over arid regions, a haboob may result. Squall lines are depicted on NWS surface analyses as an alternating pattern of two red dots and a dash labelled SQLN or SQUALL LINE, while outflow boundaries are depicted as troughs with a label of OUTFLOW BNDRY.

Precipitation produced

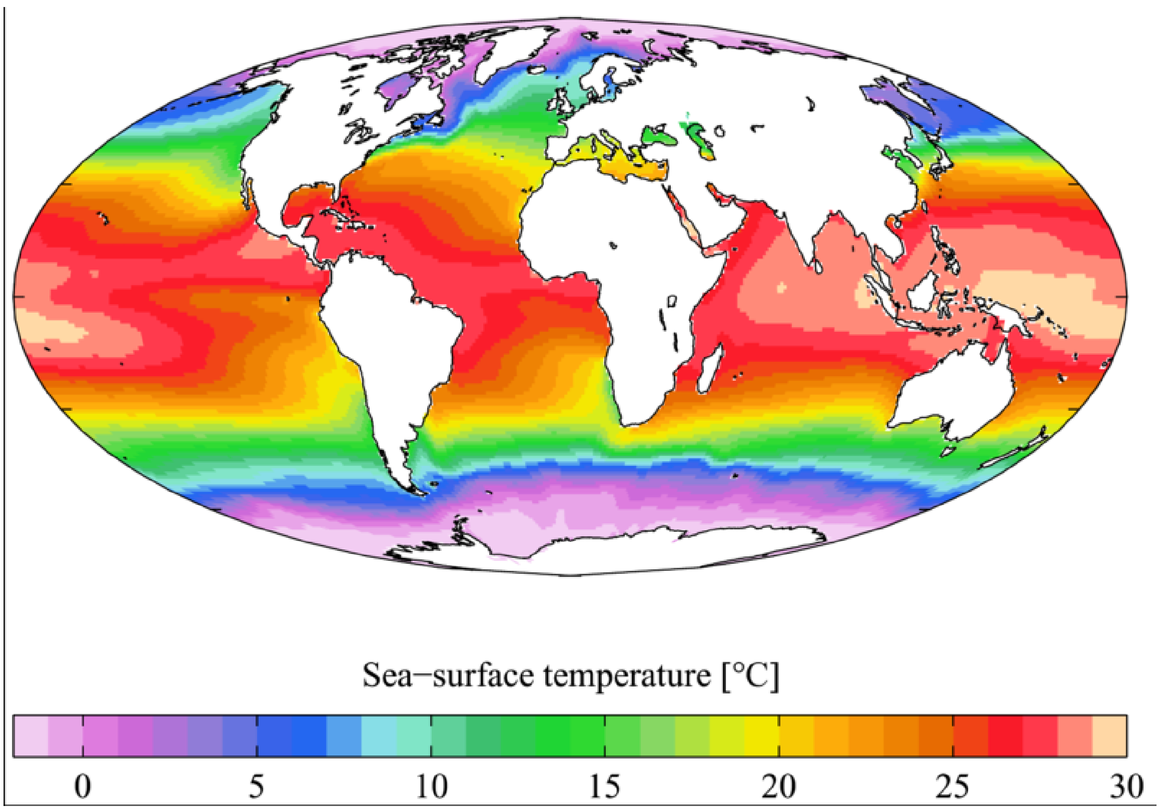
Convective precipitation

Fronts are the principal cause of significant weather. *Convective precipitation* (showers, thundershowers, and related unstable weather) is caused by air being lifted and condensing into clouds by the movement of the cold front or cold occlusion under a mass of warmer, moist air. If the temperature differences of the two air masses involved are large and the turbulence is extreme because of wind shear and the presence of a strong jet stream, "roll clouds" and tornadoes may occur.

In the warm season, lee troughs, breezes, outflow boundaries and occlusions can lead to convection if enough moisture is available. *Orographic precipitation* is precipitation created through the lifting action of air moving over terrain such as mountains and hills, which is most common behind cold fronts that move into mountainous areas. It may sometimes occur in advance of warm fronts moving northward to the east of mountainous terrain. However, precipitation along warm fronts is relatively steady, as in rain or drizzle. Fog, sometimes extensive and dense, often occurs in pre-warm-frontal areas. Although, not all fronts produce precipitation or even clouds because moisture must be present in the air mass which is being lifted.

Movement

Fronts are generally guided by winds aloft, but do not move as quickly. Cold fronts and occluded fronts in the Northern Hemisphere usually travel from the northwest to southeast, while warm fronts move more poleward with time. In the Northern Hemisphere a warm front moves from southwest to northeast. In the Southern Hemisphere, the reverse is true; a cold front usually moves from southwest to northeast, and a warm front moves from northwest to southeast. Movement is largely caused by the pressure gradient force (horizontal differences in atmospheric pressure) and the Coriolis effect, which is caused by Earth's spinning about its axis. Frontal zones can be slowed down by geographic features like mountains and large bodies of warm water.



Annual mean sea surface temperatures.

Global scale

Global scale meteorology is study of weather patterns related to the transport of heat from the tropics to the poles. Also, very large scale oscillations are of importance. Those oscillations have time periods typically longer than a full annual seasonal cycle, such as ENSO, PDO, MJO, etc. Global scale pushes the thresholds of the perception of meteorology into climatology. The traditional definition of climate is pushed in to larger timescales with the further understanding of how the global oscillations cause both climate and weather disturbances in the synoptic and mesoscale timescales.

Numerical Weather Prediction is a main focus in understanding air-sea interaction, tropical meteorology, atmospheric predictability, and tropospheric/stratospheric processes. Currently (2007) Naval Research Laboratory in Monterey produces the atmospheric model called **NOGAPS**, a global scale atmospheric model, this model is run operationally at Fleet Numerical Meteorology and Oceanography Center. There are several other global atmospheric models.