Real World Globes - Jovian Jets: Investigating Jet Streams and Atmospheric Dynamics on Jupiter

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Purpose:
- To investigate and understand the banded structure of Jupiter's upper atmosphere
- To be able to identify the locations and names of different belts and zones on Jupiter
- To understand the main differences between belts and zones (their appearance, locations, and properties).
- To investigate the directions in which jet streams blow on Jupiter.
- To understand how jet stream counter-directional shear creates cyclonic and anticyclonic circulation in Jupiter's upper atmosphere.

Target Audience:
- High school students

Materials:
- Jupiter Globe™
- Clear 18" hemisphere
- Dry-erase markers, eraser

Related Lesson Activities:
- Investigating the Coriolis Effect - Globe Activity
- Investigating Jet Streams and Planetary (Rossby) Waves - Globe Activity

Introduction:

Jupiter is the 5th planet from the Sun in our solar system. Named "Iuppiter" after the chief Roman God, it is the largest planet in the solar system both by volume and by mass. In fact, more than 1,300 Earths could fit inside of it! It is also the fastest rotating planet (completing one rotation every 10 hours). In addition to its 67 known moons, Jupiter has a faint ring system, as well as one of the strongest magnetic fields in the solar system (14 times stronger than Earth's). Jupiter is also classified as a gas giant - a planet that is composed mainly of hydrogen and helium. These are the same primary elements that compose stars and, because of this, gas giants are sometimes called "failed stars" because they do not have the critical mass needed to ignite nuclear fusion in their cores. Other gas giants in our solar system include Saturn, Uranus, and Neptune.

One of the most interesting features of Jupiter is its uniquely beautiful cloud banding patterns and massive storms, some of which can engulf the entire Earth! First visible to Italian astronomer Galileo Galilei, Jupiter's alternating banded pattern is a striking feature of this planet, in addition to its Great Red Spot - a storm that has been raging in Jupiter's southern hemisphere for at least 400 years. The primary objective of this activity is to familiarize the student with the characteristics of Jupiter's upper atmosphere, and the underlying physical and meteorological principles governing its dynamic nature.

Figure 1: The unique banding pattern of Jupiter is readily apparent through observations using powerful telescopes. In this image, Jupiter's Great Red Spot can be clearly seen. (Courtesy of Wikipedia).

Composition of Jupiter:

Jupiter's composition is extremely interesting to planetary scientists. While not much is known about the interior of Jupiter from direct experiments, models of Jovian atmospheric conditions have been recreated here on Earth and studied by chemists and physicists. Data from these experiments can be used to infer the possible composition of Jupiter's interior (see figure 2 for a description). For this activity, we will be focusing on the dynamics of the upper 100 km of Jupiter's atmosphere - the clouds.

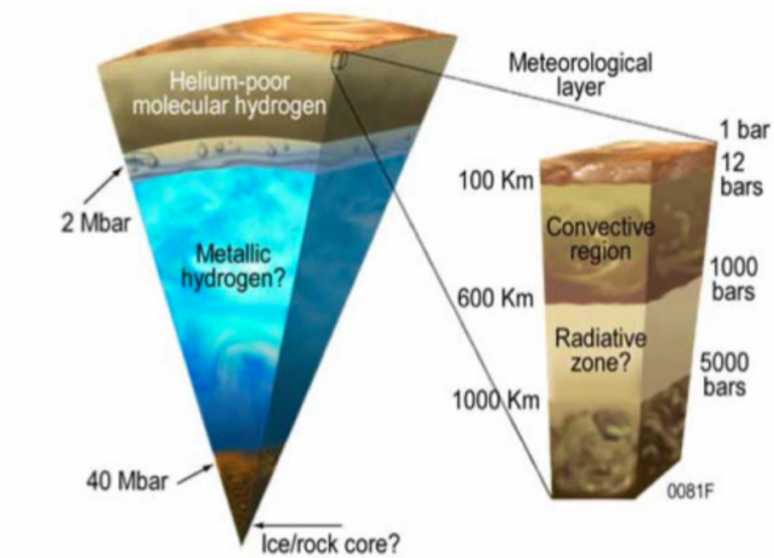

Figure 2: A cross-sectional view of Jupiter. The top of the wedge represents the surface of Jupiter. The bottom of the wedge represents Jupiter's ice/rock core. Only the top 100 km of Jupiter consists of swirling, fast-moving clouds. Beneath these clouds lies a deep layer of molecular hydrogen (H_2) which, under increasing temperature and pressure, becomes a liquid. Deeper still, hydrogen is compressed into an electrically-conductive material known as metallic hydrogen. The majority of Jupiter's mass comes from this metallic hydrogen layer. (Courtesy of SpaceFlight Insider).

Cloud Dynamics:

The upper 1000 km of Jupiter's atmosphere is known as the **meteorological layer**. This is where **convection**, **radiation** (outward movement of heat from the planet's interior), and **upper-level wind patterns** (such as **jet streams**) occur. In this activity, we will be focusing on the convective region and upper-level cloud top region (top 600 km) of Jupiter's atmosphere. It is in these regions where the familiar cloud bands are found.

Jet streams on Jupiter are found at the boundaries between zones and belts, and are produced by the Coriolis effect as a result of Jupiter's rotation (see **Coriolis Effect Globe Activity**). In Jupiter's northern hemisphere, at the cloud tops where "air" is flowing northward as it transitions from a zone to a belt, there is a rightward (eastward) deflection due to the action of the Coriolis force on this air. Similarly, at the cloud tops where "air" is flowing southward as it transitions from a zone to a belt, there is a rightward (westward) deflection. In Jupiter's southern hemisphere the deflections are reversed, and always occur in a leftward direction. The dynamics between the zone-belt transitions and the associated jet streams and their directions can be found in figure 3.

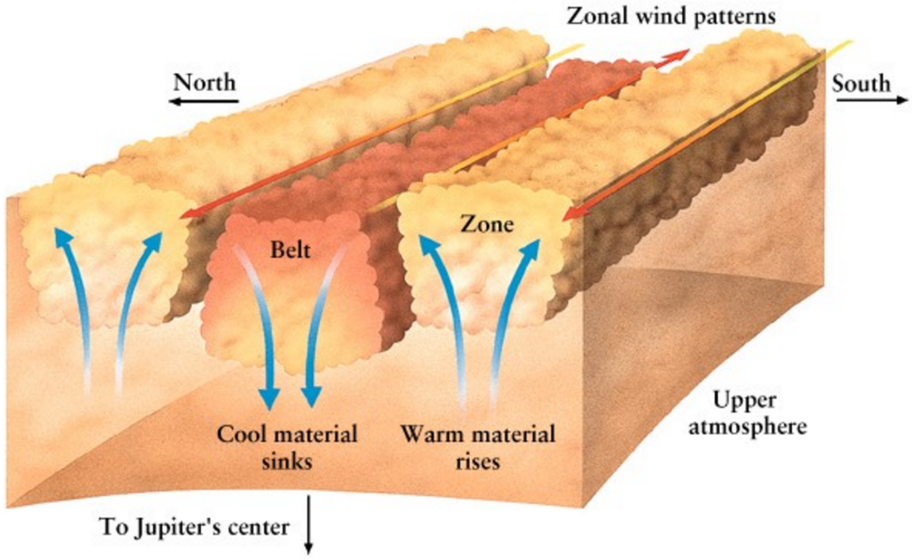

Figure 3: Light-colored bands of clouds in Jupiter's upper atmosphere are called **zones**, and are found higher in the atmosphere. They represent the upwelling of warm material from deeper within the planet. As the material expands and cools adiabatically, it becomes denser and begins to sink (downwelling), forming darker-colored clouds called **belts**. These form the **convective cells** of Jupiter. Jet streams can be found at the boundaries between zones and belts. (Courtesy of Cosmic Pursuits).

Cyclonic and Anticyclonic Vortices:

As a result of the Coriolis force acting to produce counterflowing jet streams at the boundaries between zones and belts, an interesting planetary circulation pattern emerges. Due to directional **wind shear** (changing direction of winds that varies with latitude), in Jupiter's northern hemisphere, counterclockwise-rotating vortices are formed (**cyclonic vortices**) in belts. In zones, clockwise-rotating (**anticyclonic vortices**) are formed. The situation is reversed in the southern hemisphere: clockwise-rotating cyclonic vortices are formed in belts, and counterclockwise-rotating anticyclonic vortices are formed in zones. This is illustrated in figure 4.

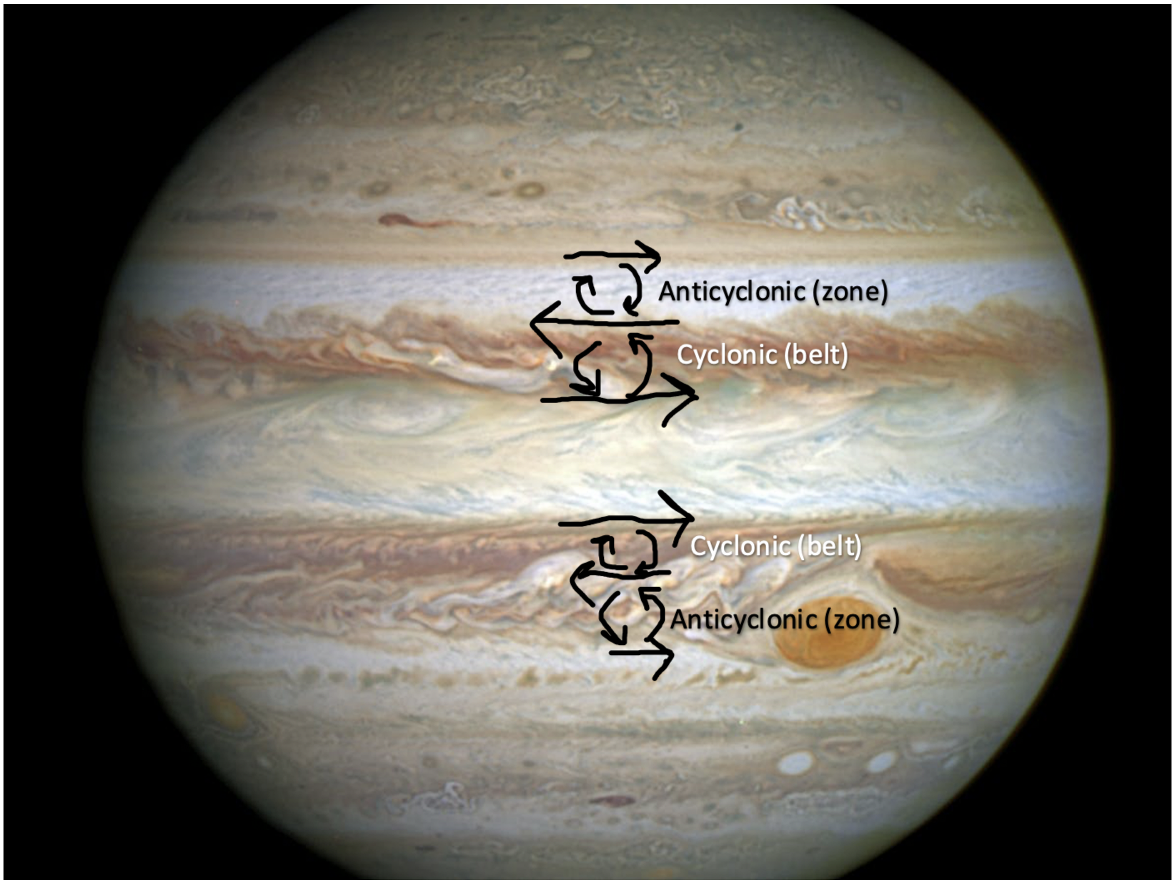

Figure 4: Counterflowing jet streams at the boundaries between belts and zones produce wind shear, which leads to the formation of vortices. As a general rule: belts contain cyclones, whereas zones contain anticyclones. The exception to this is the equatorial zone (EZ) - the thick white zone along the equator where winds are always prograde (in the same direction as Jupiter's rotation, to the east). The direction of rotation of cyclones and anticyclones is opposite between the northern and southern hemispheres. (Photo courtesy of NASA, ESA, and A. Simon - Goddard Space Flight Center).

Naming Jupiter's Belts and Zones:

The many belts and zones of Jupiter are named according to a specific convention, which is illustrated in figure 5. They are designated by their hemisphere (north or south), latitude (equatorial, tropical, temperate), and type of cloud band (zone or belt). Using this naming convention, planetary scientists are able to communicate about specific regions of Jupiter. Note that because of the ever-evolving nature of Jupiter's upper atmosphere, some bands may disappear, only to reappear at a different time.

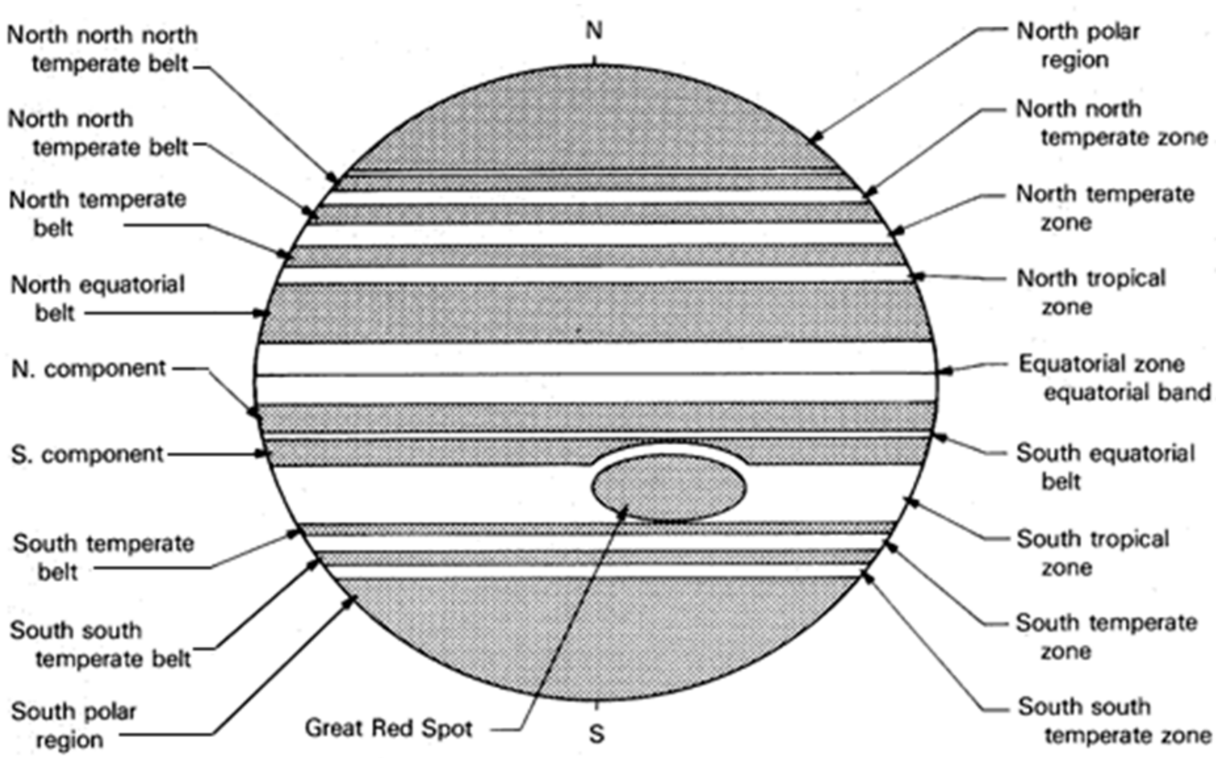

Figure 5: Naming convention of Jupiter's belts (left side of the figure) and zones (right side of the figure). (Courtesy of Cosmic Pursuits).

Activity 1 - Locating and Labeling Jupiter's Cloud Bands:

Using the 18" Jupiter globe, clear plastic hemispheric shells, a dry-erase marker, and figure 5 to help guide you, label each of the belts and zones. You may wish to use abbreviations so that you take up less space on your globe (e.g. STropZ - south tropical zone). FIgure 6 shows commonly-used abbreviations.

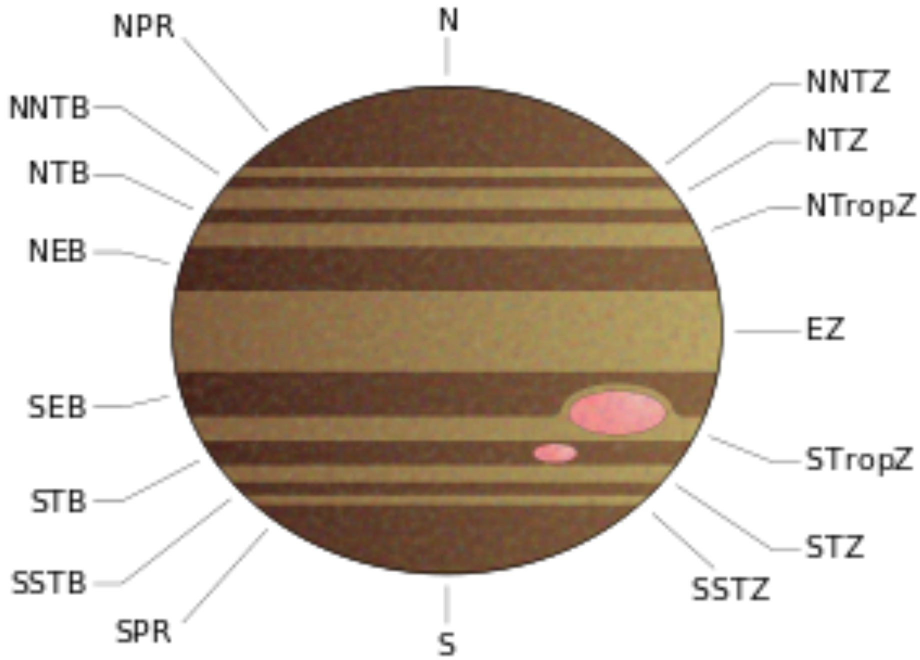

Figure 6: Commonly-used abbreviations for belts and zones of Jupiter. (Courtesy of Wikipedia).

Activity 2 - Locating and Labeling Jupiter's Jet Streams:

Using figure 4 as a pattern guide, draw arrows to denote the direction of the jet streams. Use longer arrows to denote faster-moving winds. Use figure 7 to help you determine the direction and relative wind speeds found in each jet.

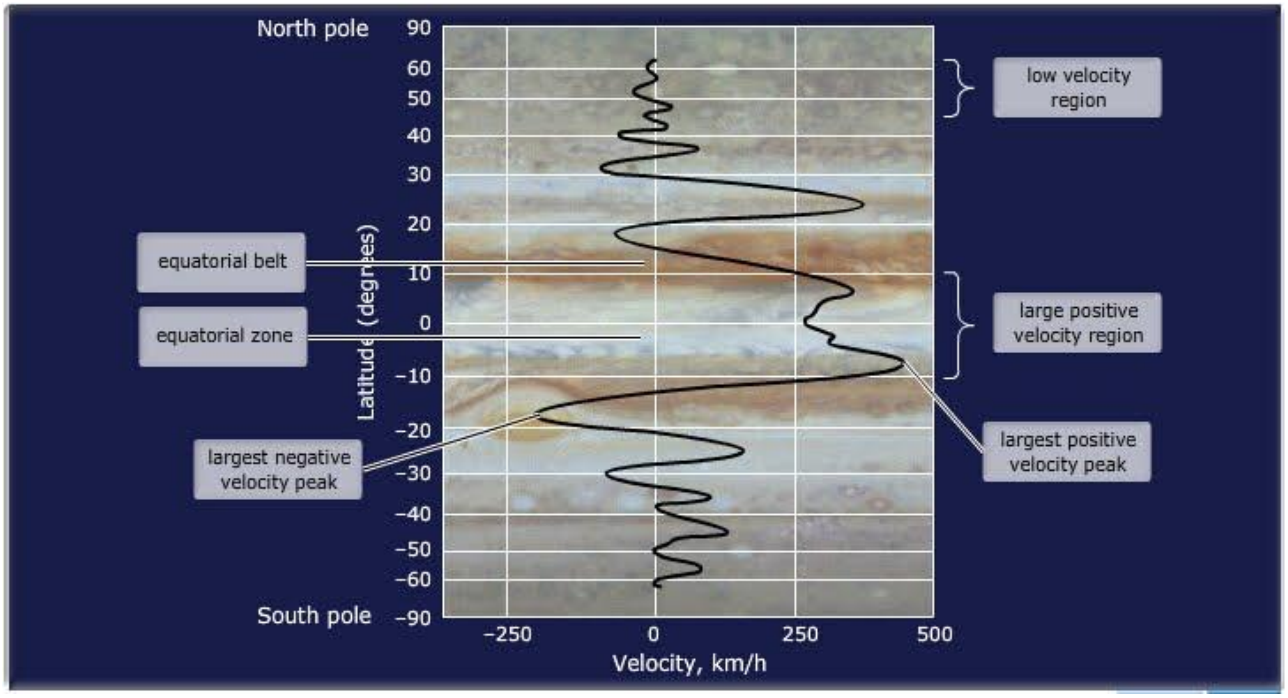

Figure 7: Jet stream locations at different latitudes. The black line traces out directions, and wind speed velocities. At latitudes where the black line is to the left of the "0 velocity" mark, winds are moving toward the west (retrograde). Where the black line is to the right of the "0 velocity" mark, winds are moving toward the east (prograde). The further the black line is from the "0 velocity" mark, the faster the winds at that latitude. (Figure adapted from Luca Bombelli, The University of Mississippi).

Activity 3 - Locating Cyclones and Anticyclones:

Using figure 4 as a pattern guide, draw vortices at each belt and zone on the globe. Remember that vortices are cyclonic in belts, and anticyclonic in zones (except for the equatorial zone, EZ).

As an added challenge, you can use the wind direction and velocity data in figure 7 to determine how wind shear in the EZ might produce vortices in this region. Draw what these vortices might look like on the globe.

Follow-Up Questions:

1. Watch this video (link below) showing a time-lapse animation of how cloud bands move and vortices rotate on Jupiter. Compare the direction of rotation of the vortices you drew on your globe with those you saw in the video. Do they match up?

   https://en.wikipedia.org/wiki/Atmosphere_of_Jupiter#/media/File:PIA02863_-_Jupiter_surface_motion_animation.gif

2. Jupiter's Great Red Spot is located in the south tropical zone (STropZ). Given only this information, is this massive storm cyclonic or anticyclonic in nature?

3. Given your answer to question #2, and the fact that the Great Red Spot is located in Jupiter's southern hemisphere, which direction (clockwise or counterclockwise) is this storm rotating?

4. It is known that cyclonic systems have low atmospheric pressure at their centers, and anticyclonic systems have high atmospheric pressure at their centers. Given your answer to question #2, does the Great Red Spot have a central high or low pressure?

5. It is also known that cyclonic systems have converging winds (winds tend to spiral inward toward the central low pressure region) and, conversely, anticyclonic systems have diverging winds (winds tend to spiral outward away from the central high pressure region). Given your deductive reasoning knowledge so far about the Great Red Spot (from questions 2 - 4), would winds be converging or diverging in the Great Red Spot?

6. An infrared image of the Great Red Spot taken by the ground-based Very Large Telescope shows that this storm is actually colder than its surroundings (see figure 8). Using your answer from question #5, and your knowledge about the adiabatic cooling of air parcels as they rise and expand in the atmosphere, explain why it makes sense that the Great Red Spot would be a "cold storm."

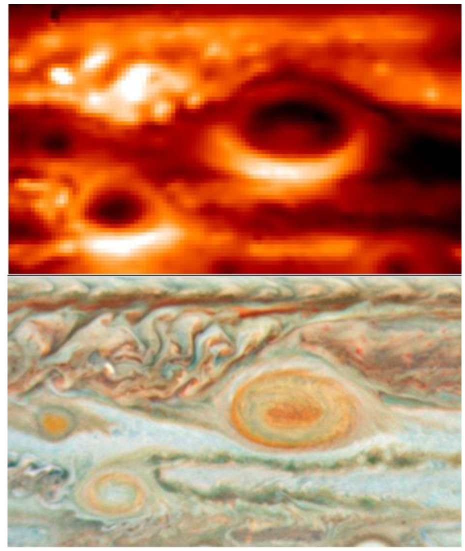

Figure 8: Infrared image of the Great Red Spot (upper image) shows that the Great Red Spot is colder than its surroundings, as evidenced by the darkened color. Brighter regions denote hotter temperatures. (Courtesy of NASA/JPL/ESO).

California's Next Generation Science Standards (NGSS) for K–12
Alternative Discipline Specific Course
Grade Six – Earth and Space Sciences

Students who demonstrate understanding can:

MS-ESS1-1. Develop and use a model of the Earth-sun-moon system to describe the cyclic patterns of lunar phases, eclipses of the sun and moon, and seasons. [Clarification Statement: Examples of models can be physical, graphical, or conceptual.]

MS-ESS1-2. Develop and use a model to describe the role of gravity in the motions within galaxies and the solar system. [Clarification Statement: Emphasis for the model is on gravity as the force that holds together the solar system and Milky Way galaxy and controls orbital motions within them. Examples of models can be physical (such as the analogy of distance along a football field or computer visualizations of elliptical orbits) or conceptual (such as mathematical proportions relative to the size of familiar objects such as their school or state).] [Assessment Boundary: Assessment does not include Kepler's Laws of orbital motion or the apparent retrograde motion of the planets as viewed from Earth.]

MS-ESS1-3. Analyze and interpret data to determine scale properties of objects in the solar system. [Clarification Statement: Emphasis is on the analysis of data from Earth-based instruments, space-based telescopes, and spacecraft to determine similarities and differences among solar system objects. Examples of scale properties include the sizes of an object's layers (such as crust and atmosphere), surface features (such as volcanoes), and orbital radius. Examples of data include statistical information, drawings and photographs, and models.] [Assessment Boundary: Assessment does not include recalling facts about properties of the planets and other solar system bodies.]

MS-ESS1-4. Construct a scientific explanation based on evidence from rock strata for how the geologic time scale is used to organize Earth's 4.6-billion-year-old history. [Clarification Statement: Emphasis is on how analyses of rock formations and the fossils they contain are used to establish relative ages of major events in Earth's history. Examples of Earth's major events could range from being very recent (such as the last Ice Age or the earliest fossils of homo sapiens) to very old (such as the formation of Earth or the earliest evidence of life). Examples can include the formation of mountain chains and ocean basins, the evolution or extinction of particular living organisms, or significant volcanic eruptions.] [Assessment Boundary: Assessment does not include recalling the names of specific periods or epochs and events within them.]

The performance expectations above were developed using the following elements from the NRC document *A Framework for K–12 Science Education*:

*The performance expectations marked with an asterisk integrate traditional science content with engineering through a Practice or Disciplinary Core Idea.
**California clarification statements, marked with double asterisks, were incorporated by the California Science Expert Review Panel
***Multiple DCIs show supplemental DCIs with three asterisks at the end of the DCI description. These are core ideas from other science disciplines that are important to understanding the DCI.
The section entitled "Disciplinary Core Ideas" is reproduced verbatim from *A Framework for K–12 Science Education: Practices, Cross-Cutting Concepts, and Core Ideas*.

California's Next Generation Science Standards (NGSS) for K–12
Alternative Discipline Specific Course
Grade Six – Earth and Space Sciences

Science and Engineering Practices

Developing and Using Models
Modeling in 6–8 builds on K–5 experiences and progresses to developing, using, and revising models to describe, test, and predict more abstract phenomena and design systems.

- Develop and use a model to describe phenomena. (MS-ESS1-1),(MS-ESS1-2)

Analyzing and Interpreting Data
Analyzing data in 6–8 builds on K–5 experiences and progresses to extending quantitative analysis to investigations, distinguishing between correlation and causation, and basic statistical techniques of data and error analysis.

- Analyze and interpret data to determine similarities and differences in findings. (MS-ESS1-3)

Constructing Explanations and Designing Solutions
Constructing explanations and designing solutions in 6–8 builds on K–5 experiences and progresses to include constructing explanations and designing solutions supported by multiple sources of evidence

Disciplinary Core Ideas

ESS1.A: The Universe and Its Stars

- Patterns of the apparent motion of the sun, the moon, and stars in the sky can be observed, described, predicted, and explained with models. (MS-ESS1-1)
- Earth and its solar system are part of the Milky Way galaxy, which is one of many galaxies in the universe. (MS-ESS1-2)
  ****Supplemental DCI PS2.B*

ESS1.B: Earth and the Solar System

- The solar system consists of the sun and a collection of objects, including planets, their moons, and asteroids that are held in orbit around the sun by its gravitational pull on them. (MS-ESS1-2),(MS-ESS1-3) ****Supplemental DCI PS2.B*
- This model of the solar system can explain eclipses of the sun and the moon. Earth's spin axis is fixed in direction over the short-term but tilted relative to its orbit around the sun. The seasons are a result of that tilt and are caused by the differential intensity of

Crosscutting Concepts

Patterns

- Patterns can be used to identify cause-and-effect relationships. (MS-ESS1-1)

Scale, Proportion, and Quantity

- Time, space, and energy phenomena can be observed at various scales using models to study systems that are too large or too small. (MS-ESS1-3),(MS-ESS1-4)

Systems and System Models

- Models can be used to represent systems and their interactions–such as inputs, processes and outputs–and energy, matter, and information flows within systems. (MS-ESS1-2)

Connections to Engineering, Technology, and Applications of Science

Interdependence of Science, Engineering, and Technology

- Engineering advances have led to important discoveries in virtually every field of science and scientific discoveries

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MS-ESS2 Earth's Systems

MS-ESS2 Earth's Systems
Students who demonstrate understanding can: **MS-ESS2-4. Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.** [Clarification Statement: Emphasis is on the ways water changes its state as it moves through the multiple pathways of the hydrologic cycle. Examples of models can be conceptual or physical.] [Assessment Boundary: A quantitative understanding of the latent heats of vaporization and fusion is not assessed.] **MS-ESS2-5. Collect data to provide evidence for how the motions and complex interactions of air masses results in changes in weather conditions.** [Clarification Statement: Emphasis is on how air masses flow from regions of high pressure to low pressure, causing weather (defined by temperature, pressure, humidity, precipitation, and wind) at a fixed location to change over time, and how sudden changes in weather can result when different air masses collide. Emphasis is on how weather can be predicted within probabilistic ranges. Examples of data can be provided to students (such as weather maps, diagrams, and visualizations) or obtained through laboratory experiments (such as with condensation).] [Assessment Boundary: Assessment does not include recalling the names of cloud types or weather symbols used on weather maps or the reported diagrams from weather stations.] **MS-ESS2-6. Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.** [Clarification Statement: Emphasis is on how patterns vary by latitude, altitude, and geographic land distribution. Emphasis of atmospheric circulation is on the sunlight-driven latitudinal banding, the Coriolis effect, and resulting prevailing winds; emphasis of ocean circulation is on the transfer of heat by the global ocean convection cycle, which is constrained by the Coriolis effect and the outlines of continents. Examples of models can be diagrams, maps and globes, or digital representations.] [Assessment Boundary: Assessment does not include the dynamics of the Coriolis effect.]
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Science and Engineering Practices

Developing and Using Models

Modeling in 6–8 builds on K–5 experiences and progresses to developing, using, and revising models to describe, test, and predict more abstract phenomena and design systems.

- Develop and use a model to describe phenomena. (MS-ESS2-6)
- Develop a model to describe unobservable mechanisms. (MS-ESS2-4)

Planning and Carrying Out Investigations

Planning and carrying out investigations in 6–8 builds on K–5 experiences and progresses to include investigations that use multiple variables and provide evidence to support explanations or solutions.

- Collect data to produce data to serve as the basis for evidence to answer scientific questions or test design solutions under a range of conditions. (MS-ESS2-5)

Disciplinary Core Ideas

ESS2.C: The Roles of Water in Earth's Surface Processes

- Water continually cycles among land, ocean, and atmosphere via transpiration, evaporation, condensation and crystallization, and precipitation, as well as downhill flows on land. (MS-ESS2-4)
  ****Supplemental DCI PS1.A*
- The complex patterns of the changes and the movement of water in the atmosphere, determined by winds, landforms, and ocean temperatures and currents, are major determinants of local weather patterns. (MS-ESS2-5)
- Global movements of water and its changes in form are propelled by sunlight and gravity. (MS-ESS2-4)
- Variations in density due to variations in temperature and salinity drive a global pattern of interconnected ocean currents. (MS-ESS2-6)
  ****Supplemental DCI PS3.B, PS4.B*

ESS2.D: Weather and Climate

- Weather and climate are influenced by interactions involving sunlight, the ocean, the atmosphere, ice, landforms, and living things

Crosscutting Concepts

Cause and Effect

- Cause and effect relationships may be used to predict phenomena in natural or designed systems. (MS-ESS2-5)

Systems and System Models

- Models can be used to represent systems and their interactions—such as inputs, processes and outputs—and energy, matter, and information flows within systems. (MS-ESS2-6)

Energy and Matter

- Within a natural or designed system, the transfer of energy drives the motion and/or cycling of matter. (MS-ESS2-4)

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