Guide to the Science of Climate Change in the 21st Century

Chapter 7
Global Circulation of the Atmosphere

David H. Manz
PhD., P. Eng., AOE, FCAE
2024

Eco-print, “Atmosphere”, Nora Manz 2020

Table of Contents

List of Figures

Figure 7.9 Effect of the omega block under the area of high pressure from https://www.rmets.org/metmatters/what-heat-dome.

Figure 7.10 Mean total precipitable water from satellite microwave scans showing bands of significant precipitable water from https://www.remss.com/measurements/atmospheric-water-vapor/ and https://images.remss.com/cdr/climate_data_record_browse.html.

Figure 7.11 Atmospheric river flowing across Western United States https://www.noaa.gov/stories/what-are-atmospheric-rivers.

Figure 7.12 Atmospheric river flowing across Western United States https://www.climatecentral.org/news/global-warming-atmospheric-rivers-18645.

Figure 7.13 Atmospheric river flow across the Western United States October 25, 2021 as reported by the Washington Post https://www.washingtonpost.com/weather/2021/10/25/atmospheric-river-record-rain-california/?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20211026&utm_medium=email&utm_source=Revue%20Daily.

Figure 7.14 Atmospheric river flow across Western Canada November 2021 as reported by the weather network https://www.theweathernetwork.com/ca/news/article/over-100-mm-of-rain-en-route-to-b-c-with-latest-atmospheric-river.

Figure 7.15 Rainfall accumulation resulting from atmospheric river impacting southwest British Columbia as reported by the weather network https://www.theweathernetwork.com/ca/news/article/over-100-mm-of-rain-en-route-to-b-c-with-latest-atmospheric-river.

Figure 7.16 Classification of atmospheric rivers. See paper by Ralph et al 2019 https://journals.ametsoc.org/view/journals/bams/100/2/bams-d-18-0023.1.xml .

Figure 7.17 Ozone hole over Antarctica shown in blue.

7.0 Global Circulation of the Atmosphere

7.1 Introduction

Global circulation of Earth's air mass, the atmosphere, together with ocean currents, are responsible for the movement and redistribution of solar energy received by the Earth that is not immediately reflected or absorbed and emitted back into space. It is responsible for the mixing of air masses, the movement of water evaporated from the surface of the oceans and the land surfaces and the manner with which it is precipitated back to the Earth's surface. Global circulation of the atmosphere together with topographic and local photosynthesizing effects determine weather and climate. As well, it is responsible for the mixing, storage and redistribution of greenhouse gases, airborne particulate matter and pollution that enters the atmosphere. Global circulation of the atmosphere ultimately determines the climate and quality of the air mass over of all regions of the Earth's surface.

7.2 Characteristics of the atmosphere

Global circulation of the atmosphere is a result of the convective and advective energy transfer between earth's surface and the atmosphere, particularly the troposphere. The troposphere is the layer of the atmosphere next to the surface of the Earth (See Figure 7.1). Most of the mixing of the atmosphere and weather occurs in the troposphere. The temperature of the atmosphere steadily decreases with elevation. The layer of air above the troposphere is the stratosphere. The temperature of air in the stratosphere starts to increase with elevation. The troposphere and the stratosphere are separated by a comparatively thin layer of atmosphere known as the tropopause. The thickness of the troposphere is greatest at the equator gradually thinning out to the poles.

7.3 Early perception of global circulation of the atmosphere

An early perception of global circulation is illustrated in Figure 7.2 where the circulation in the northern and southern hemispheres did not cross the equator; that is, there was very little if any mixing of the respective air masses. This view of atmospheric circulation has changed dramatically since the mid twentieth century with increased information on the characteristics of the various air masses within the atmosphere and has evolved to the more complex and accurate view as illustrated in Figure 7.3. An important take-away from Figure 7.3 is that air masses, everywhere on the planet, affect each other and intermingle.

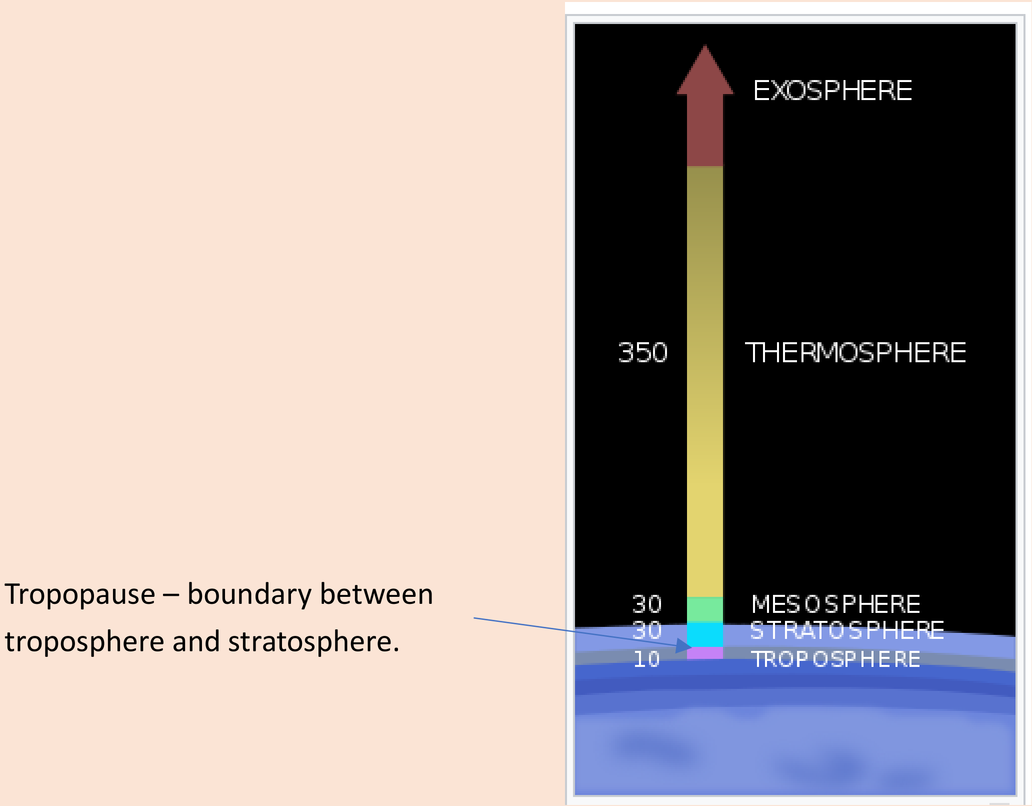


Figure 7.1 Schematic showing different layers of the atmosphere (not to scale).

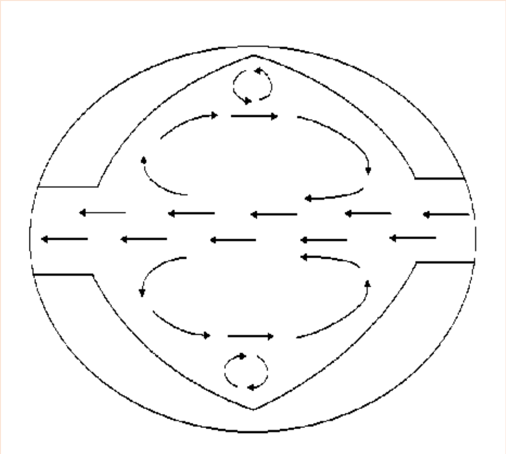


Figure 7.2 Early perception of global circulation of the atmosphere.

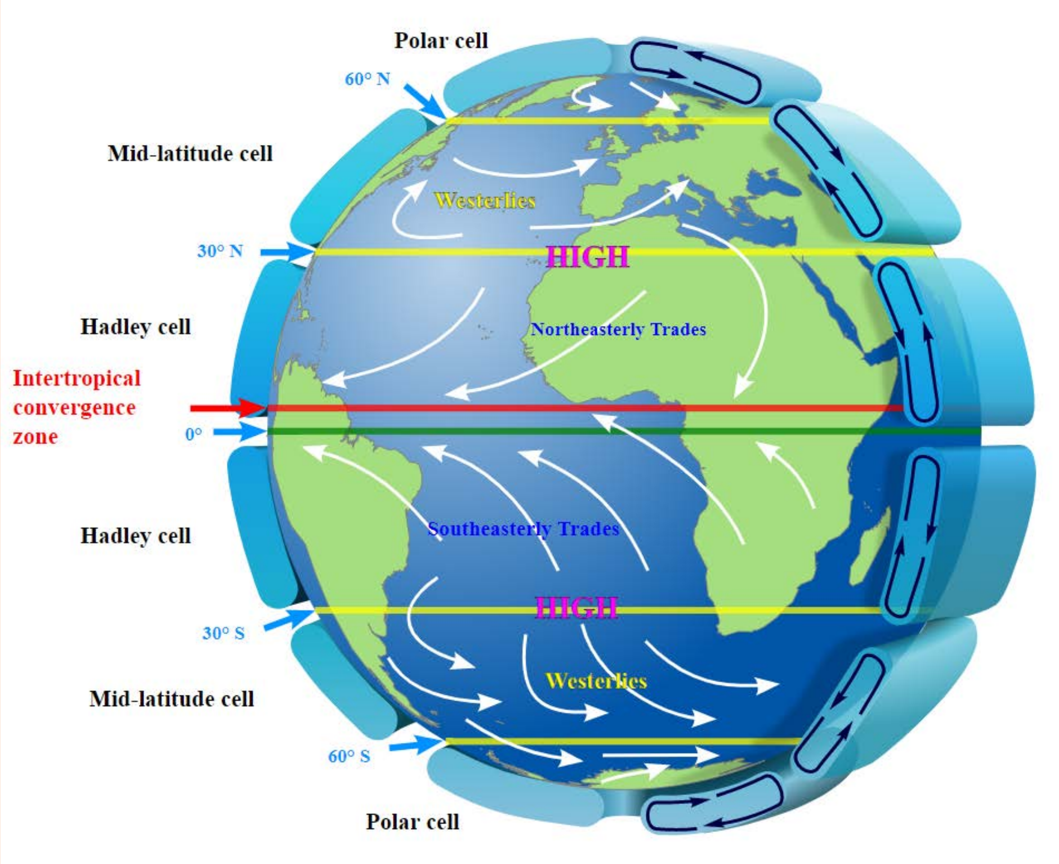
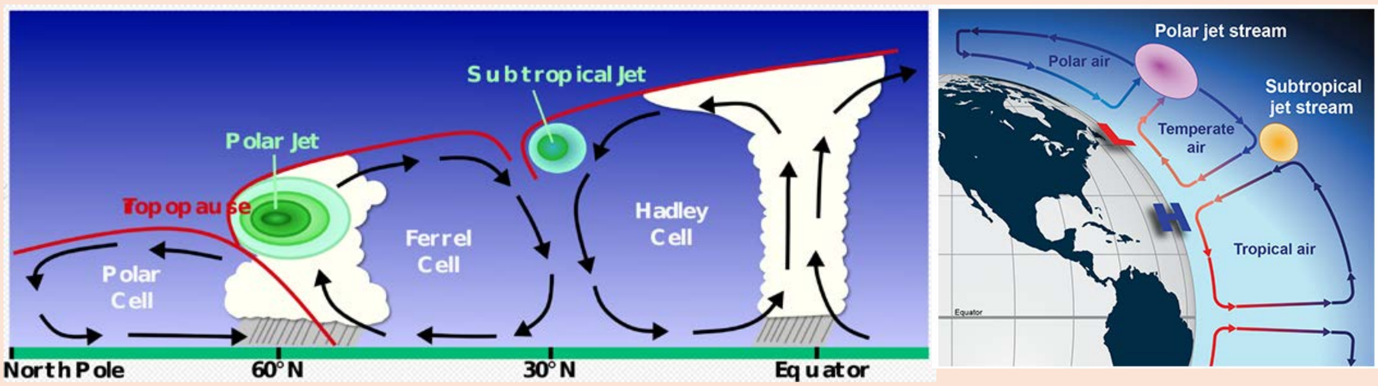


Figure 7.3 Actual global circulation of the atmosphere.

7.4 Actual global circulation of the atmosphere

There are three major circulations of the atmosphere north and south of the equator known as the Hadley cell, Mid-latitude or Ferrel cell and the Polar cell. Figure 7.3 and Figure 7.4 (a) and (b) illustrate the interaction between these cells. Warm air rises at the equator, falls at 30° and rises at 60°. The tropopause shown as the red line in Figure 7.4 (a) is the interface between the troposphere and the stratosphere. The atmosphere in the Hadley cell is the warmest so the thickness of the troposphere in the Hadley cells are the greatest and the atmosphere in the Polar cell is the coldest and the thickness of the troposphere in the Polar cells is the least.

As shown in Figure 7.3 the cells are actually very wide and contain all or parts of weather systems carried by the Westerlies or the Northeastern and Southeastern Trades. The weather systems themselves can be very large in diameter and overlap or move through cells. In this way air masses in both northern and southern hemispheres are well mixed both latitudinally and longitudinally.



(a) (b)

Figure 7.4 (a) and (b) Cross section of the subtropical and polar jet streams by latitude**.**

Also shown in Figure 7.4 (a) and (b) are the jet streams. Jet streams are fast flowing, narrow, meandering air currents that occur at the interface of the Hadley cell and the Ferrel cell and at the interface of the Polar cell and the Hadley cell. The jets are known as the subtropical jet and polar jet respectively. The jet streams circle the Earth from west to east in an irregular pattern known as Rossby waves, as shown in Figure 7.5. The jet streams are driven by the circulation and difference in temperature of the air in the adjacent cells. Jet streams are also responsible for moving/ guiding weather systems and associated air masses around the planet.

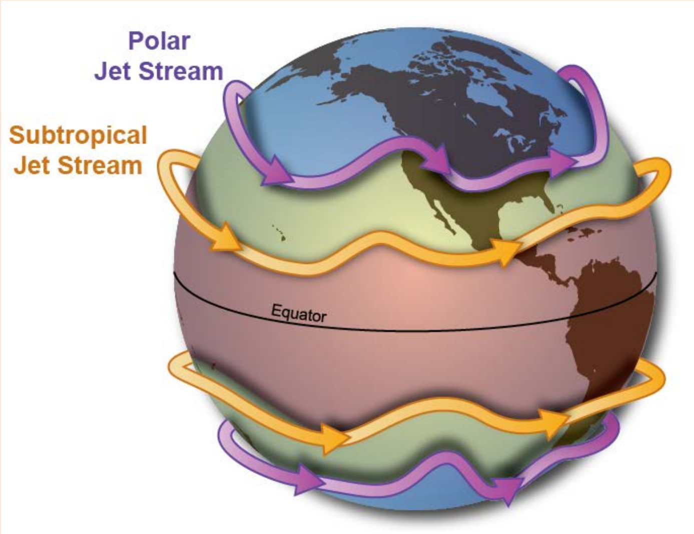


Figure 7.5 General configuration of the subtropical and polar jet streams by latitude.

The National Oceanic and Atmospheric Administration provides a detailed description of a jet stream, how it behaves and its influence on weather, https://scijinks.gov/jet-stream/. They explain the science behind the polar vortex in the web site, https://www.noaa.gov/multimedia/infographic/science-behind-polar-vortex-you-might-want-to-put-on-sweater and the web site, https://www.climate.gov/news-features/understanding-climate/understanding-arctic-polar-vortex.

The Met Office has produced two videos that help understand the jet stream and how it affects weather, https://www.youtube.com/watch?v=Lg91eowtfbw and https://www.youtube.com/watch?v=5wCq2Y9CB6Y

The World Economic Forum has published a paper in August 2022 explaining the current European heat waves and how is influenced by the formation of a double jet stream, https://www.weforum.org/agenda/2022/08/jet-stream-winds-fuelling-heatwaves/ . A paper published in the journal, Nature Communications 04 July 2022 titled, 'Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia', https://www.nature.com/articles/s41467-022-31432-y , explain how double jet streams can contribute to the development of heat waves over Europe. See Section 7.7 for how a double jet stream contributes to the formation of a heat dome.

Warming of air masses in the polar cell (Arctic) have the effect of weaking the polar jet stream. Cooling them (Antarctic ozone depletion) has an opposite effect.

Warming of air masses in the equatorial zone, Hadley cells, have the effect of strengthening the subtropical jet stream assuming the mid latitude zone, Ferrel cells, are not affected to a similar degree.

7.5 Omega blocking, Rex bocking and heat domes

7.5.1 Omega blocking

The National Oceanic and Atmospheric Administration (NOAA) describes Omega blocking (See Figure 7.6.) as follows:
'Omega blocks get their name because the upper air pattern looks like the Greek letter omega (Ω). Omega blocks are a combination of two cutoff lows with one blocking high sandwiched between them.
Because of their size, Omega blocks are often quite persistent and can lead to flooding and drought conditions, depending upon the location under the pattern. Cooler temperatures and precipitation accompany the lows, while warm and clear conditions prevail under the high.'

Also see the explanation provided by the Weather Network at https://www.theweathernetwork.com/en/news/science/explainers/what-is-omega-block-rex-block-upper-level-jet-stream-weather-pattern .

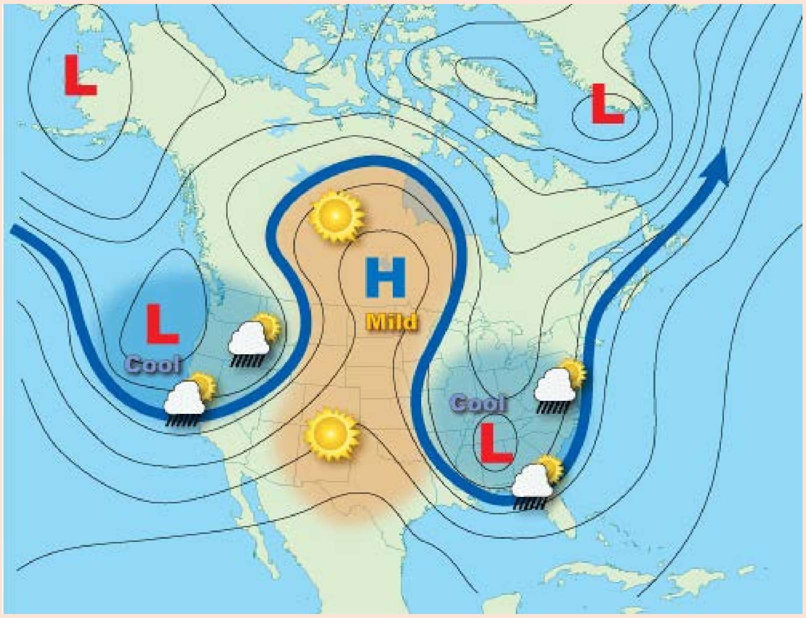


Figure 7.6 Example of jet stream forming 'Omega blocking' over North America. https://www.noaa.gov/jetstream/upper-air-charts/basic-wave-patterns

7.5.2 Rex blocking

The National Oceanic and Atmospheric Administration (NOAA) describes Rex blocking (See Figure 7.7.) as follows:

'Rex blocks are characterized by a high-pressure system located pole-ward of a low-pressure system. The Rex block will remain nearly stationary until one of the height centers changes intensity, unbalancing the high-over-low pattern.

Unsettled, stormy weather is usually found near the low pressure, while dry conditions are typical with the high-pressure. Strong, particularly persistent Rex blocks can cause flooding near the low-pressure part of the block and short-term drought under the high-pressure part.'

Also see the explanation provided by the Weather Network at https://www.theweathernetwork.com/en/news/science/explainers/what-is-omega-block-rex-block-upper-level-jet-stream-weather-pattern .

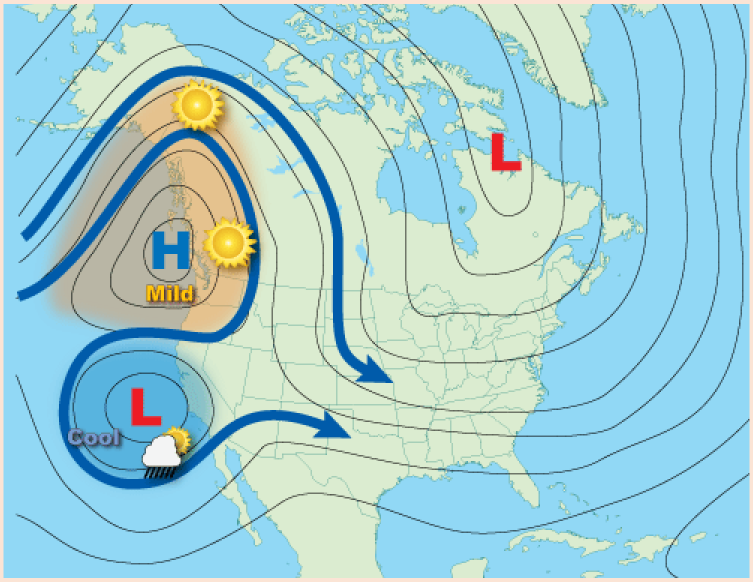
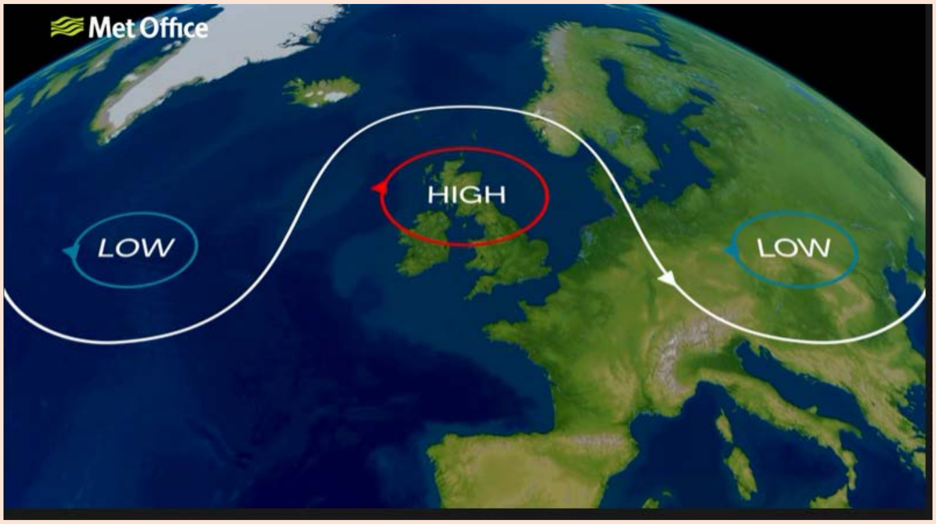


Figure 7.7 Example of jet stream forming 'Rex blocking' over west coast of North America. https://www.noaa.gov/jetstream/upper-air-charts/basic-wave-patterns

7.5.3 Heat domes

Heat domes often result in extremely high temperatures over affected areas. The Royal Meteorological Society, RMS, provides a very good description of what it is, how it is formed and what the consequences might be, https://www.rmets.org/metmatters/what-heat-dome. The following explanation which uses experiences in Europe, is extracted from their web page.

"The position and strength of the jet stream can lead to blocking situations, such as an omega block where high pressure ends up sandwiched between two low pressure systems, forming a shape like the Greek letter omega Ω ". (See Figures 7.8 (a) and (b).)



(a)

(b)

Figure 7.8 (a) and 7.8 (b) High pressure system in red blocked by two low pressure systems from https://www.rmets.org/metmatters/what-heat-dome.

"The high pressure stops weather fronts moving through, so they either skirt round the edges of the high or grind to a halt. Your position under the omega block will determine the weather you get. Under the high the weather is usually dry and settled, whereas low pressure brings wet and windy conditions. Weather blocks can persist for days, weeks or even months."

The effect of omega block is a heat dome as illustrated in Figure 7.9. The RMS describes the situation: "The problem with a stubborn area of high pressure is that already warm or hot air trapped under the high will become hotter and hotter, creating a heat dome. Hot air will rise into the atmosphere, but high-pressure acts as a lid and causes the air to subside or sink. As the air sinks it warms by compression and the heat builds. The ground also warms, losing moisture and making it easier to heat even more.
Until the pressure pattern changes, the high will continue to exacerbate the hot conditions, bringing a risk of wildfires, drought and heat-health issues."

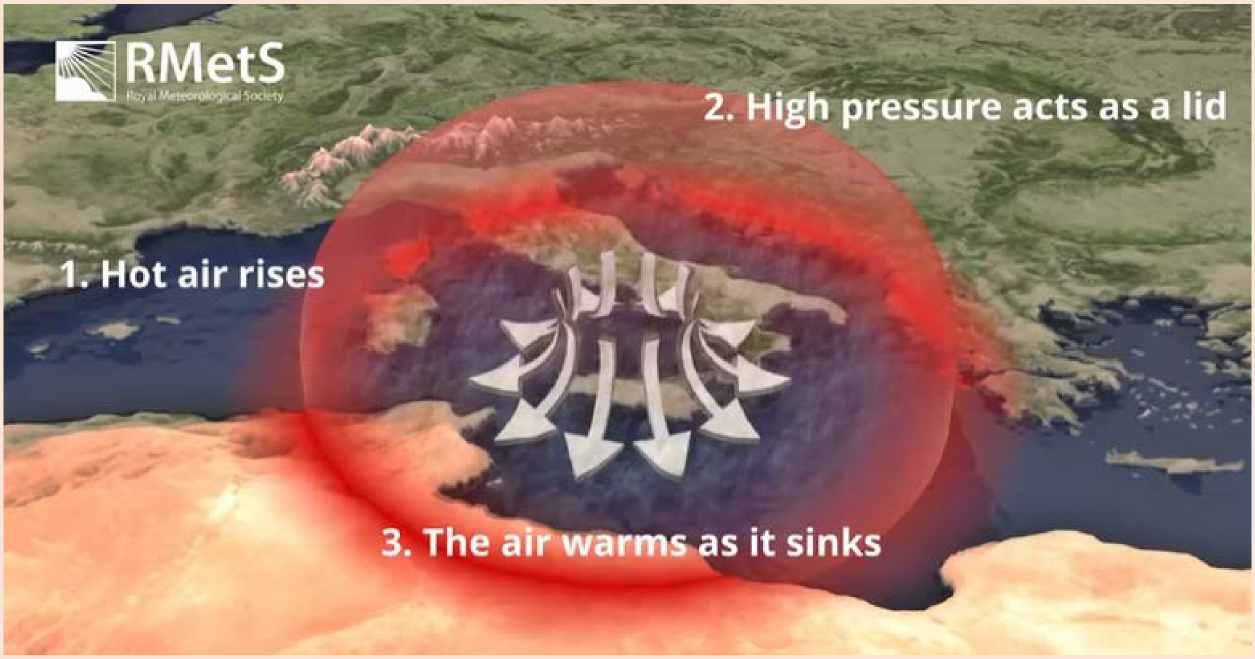


Figure 7.9 Effect of the omega block under the area of high pressure from https://www.rmets.org/metmatters/what-heat-dome.

7.6 Atmospheric rivers

The absolute amount of water vapour in a column of atmosphere from the surface of the Earth to the tropopause (i.e., the troposphere) is measured in terms of the depth of liquid water equivalent measured in millimeters also called the integrated water depth or total precipitable water, TPW, (https://en.wikipedia.org/wiki/Atmospheric_river and https://www.remss.com/measurements/atmospheric-water-vapor/). TPW does not include water contained in clouds. Two centimeters or more of water in the column is considered significant and is used as the criteria for defining an atmospheric river (discussed later). As the references describe, satellites are able to measure and map the TPW in the atmosphere (over oceans only – not land surfaces) using microwave scans and able to produce maps of atmospheric rivers as shown in Figure 7.10.   There are numerous methods in various stages of use and development which endeavour to measure TPW over land and to measure how the water vapour concentration in the atmosphere varies with elevation. The ability to distinguish between clouds and water vapour, to identify the elevation in the atmosphere where the clouds occur and to characterize the manner (velocity and direction) the different layers of atmosphere (and therefore the clouds) are moving. (Clouds are important elements of the energy budget because of their thermodynamic properties and ability to reflect, absorb and emit radiation.)

Liquid water content or LWC (https://www.remss.com/measurements/cloud-liquid-water-content/) is a term used to measure the liquid (not frozen) mass of water in clouds.

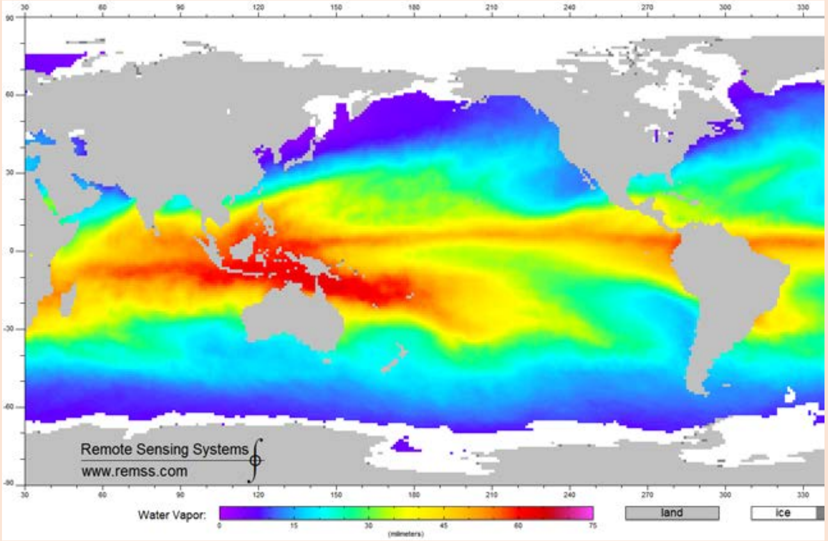


Figure 7.10 Mean total precipitable water from satellite microwave scans showing bands of significant precipitable water from https://www.remss.com/measurements/atmospheric-water-vapor/ and https://images.remss.com/cdr/climate_data_record_browse.html.

Atmospheric river or AR is a term used to describe a region of the atmosphere, as viewed by a satellite, where a narrow band or corridor (or filament) of atmosphere containing significant amounts of water vapor is moving. The atmospheric river may be several thousand kilometers long and a few hundred kilometers wide carrying as much water as the Amazon River. Figure 7.10 shows an image of total precipitable water across the subtropical latitudes of the Indian, Pacific and Atlantic Oceans. Cyclones, weak or strong, may move this moisture north or south to the midlatitudes where it may result in precipitation events resulting from orographic cooling of the air mass or interaction with other cooler air masses https://www.noaa.gov/stories/what-are-atmospheric-rivers.   This is shown in Figures 7.11, 7.12 and 7.13. There are other meteorologic phenomena that will result in the formation of atmospheric rivers such as described by Dacre, et al. 2015 https://journals.ametsoc.org/view/journals/bams/96/8/bams-d-14-00031.1.xml . which occurs in the North Atlantic where cyclones (warm air) evaporating water below it continuously moves it against a cold front resulting in local precipitation along the length of the cold front as the cyclone migrates northward.   A good description of atmospheric rivers and how they are characterized may be found in a paper by Ralph, F. M. et al. in the Journal of the American Meteorological Society 01 Feb 2019 https://journals.ametsoc.org/view/journals/bams/100/2/bams-d-18-0023.1.xml.

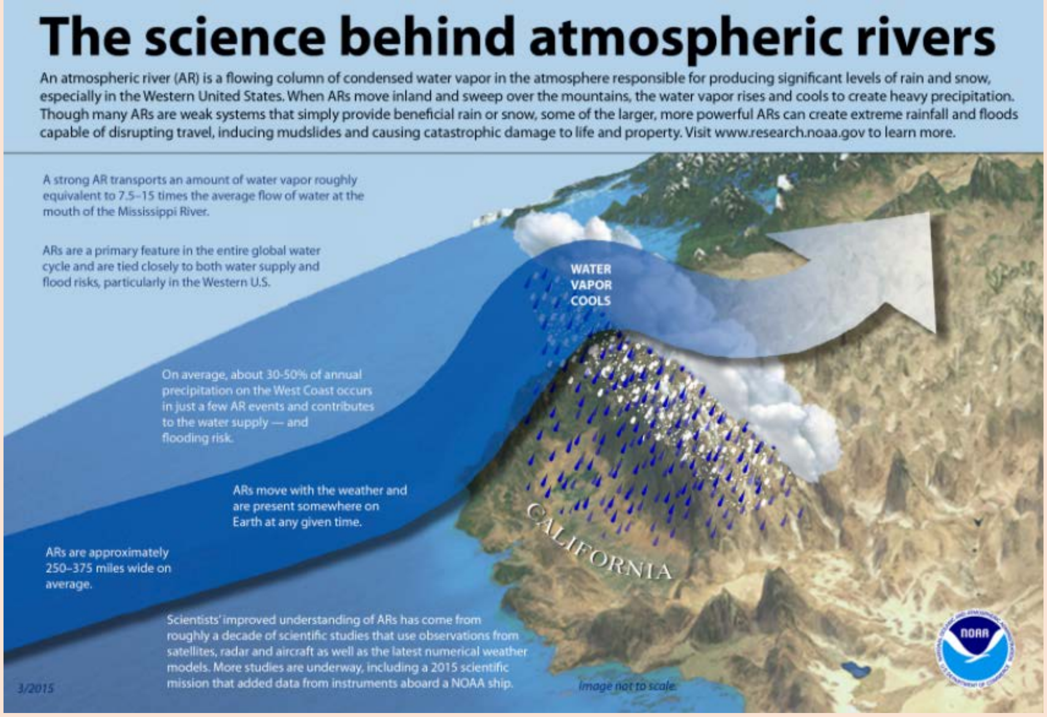


Figure 7.11 Atmospheric river flowing across Western United States https://www.noaa.gov/stories/what-are-atmospheric-rivers.

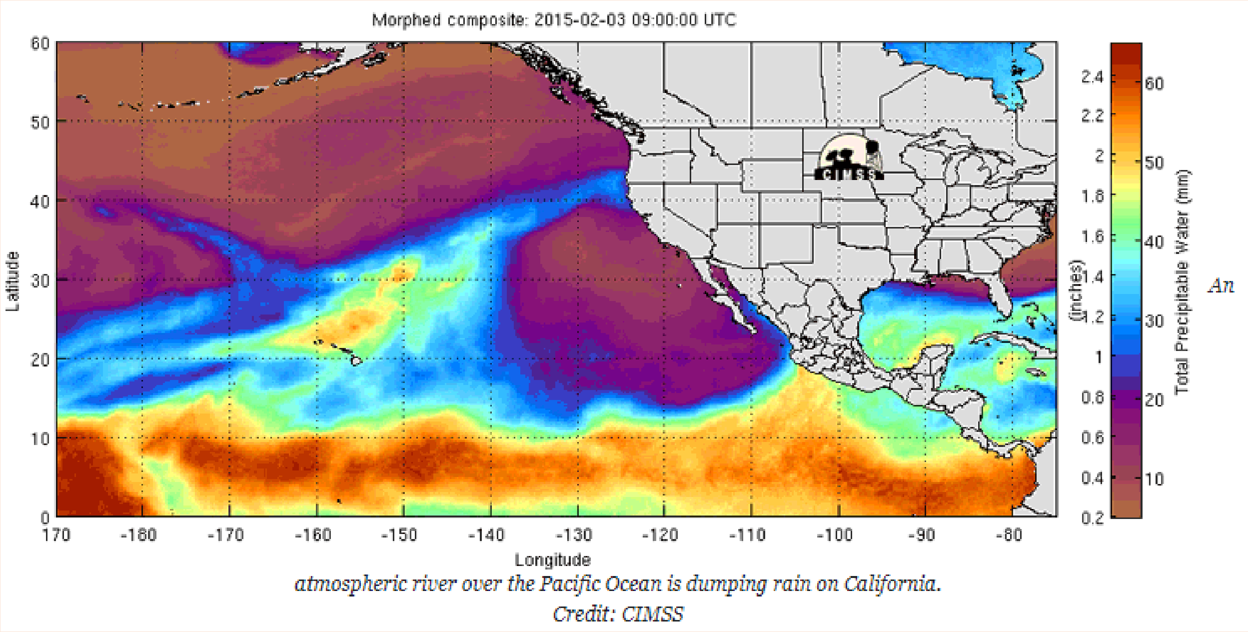


Figure 7.12 Atmospheric river flowing across Western United States
https://www.climatecentral.org/news/global-warming-atmospheric-rivers-18645.

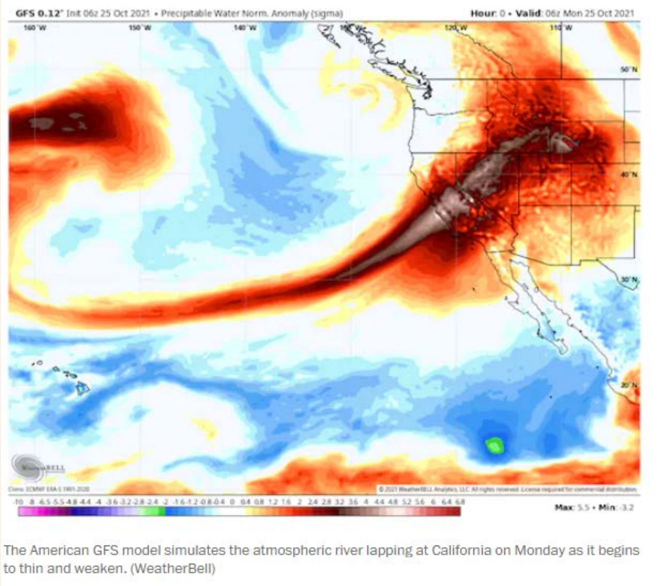


Figure 7.13 Atmospheric river flow across the Western United States October 25, 2021 as reported by the Washington Post
https://www.washingtonpost.com/weather/2021/10/25/atmospheric-river-record-rain-california/?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20211026&utm_medium=email&utm_source=Revue%20Daily

Figure 7.14 shows a satellite image of an atmospheric river known as the ‘Pineapple Express’ for its origin in the Pacific Ocean near Hawaii. This particular atmospheric river resulted in significant and damaging precipitation in southwest British Columbia as shown in Figure 7.15. The atmospheric river was classified as strong based on the classification by Ralph et al 2019 and shown in Figure 7.16 provided by the Weather Network courtesy of the University of California.

Figure 7.14 Atmospheric river flow across Western Canada November 2021 as reported by the weather network https://www.theweathernetwork.com/ca/news/article/over-100-mm-of-rain-en-route-to-b-c-with-latest-atmospheric-river.

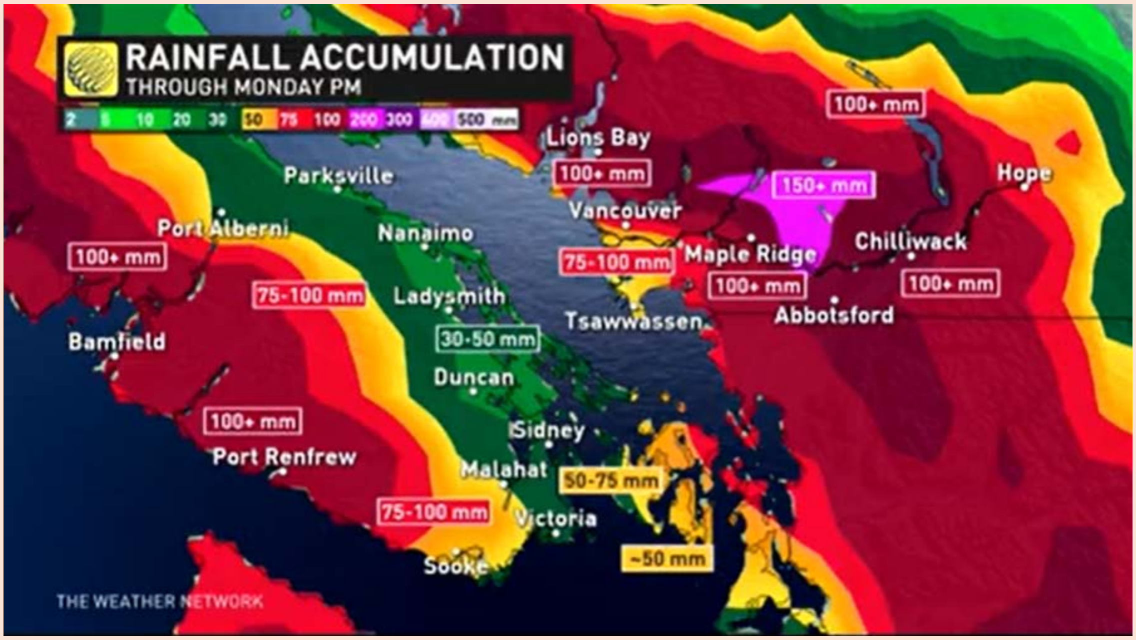


Figure 7.15 Rainfall accumulation resulting from atmospheric river impacting southwest British Columbia as reported by the weather network https://www.theweathernetwork.com/ca/news/article/over-100-mm-of-rain-en-route-to-b-c-with-latest-atmospheric-river.

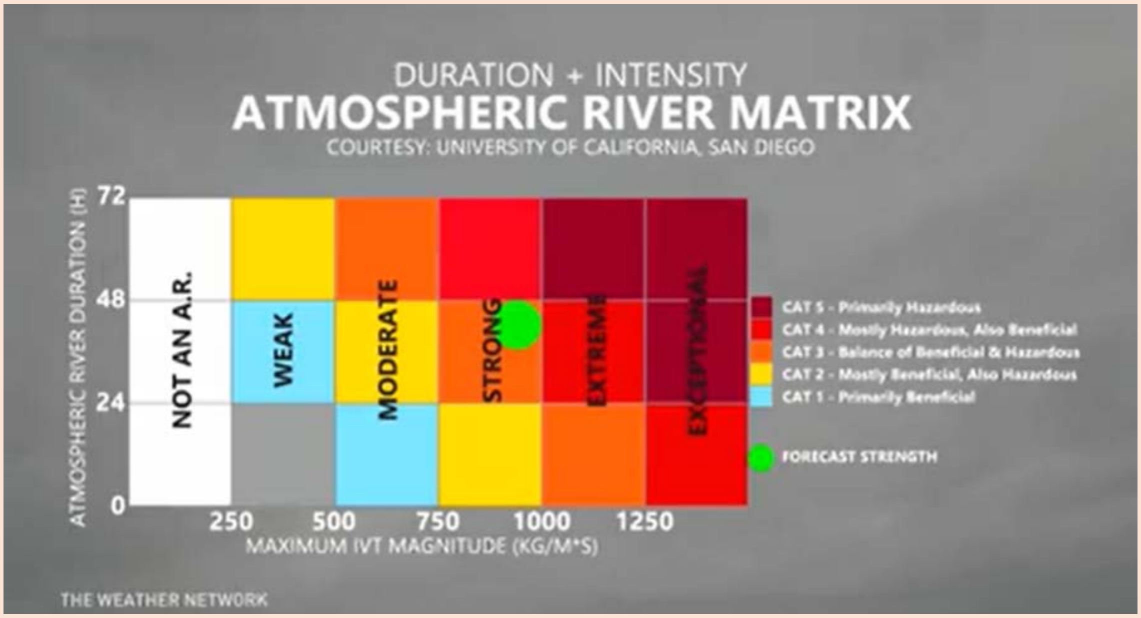


Figure 7.16 Classification of atmospheric rivers. See paper by Ralph et al 2019 https://journals.ametsoc.org/view/journals/bams/100/2/bams-d-18-0023.1.xml .

The significance of atmospheric rivers to the Pacific Northwest is highlighted in a recent Bloomberg report, https://www.bloomberg.com/news/articles/2021-10-19/river-from-the-sky-to-bring-california-fire-season-closer-to-end?cmpid=BBD102021_GREENDAILY&utm_medium=email&utm_source=newsletter&utm_term=211020&utm_campaign=greendaily.

7.7 Ozone and the ozone hole

Regarding ozone: Ozone in the stratosphere absorbs ultraviolet light preventing it from reaching the Earth's surface and harming living organisms. Ozone forms in the atmosphere and is circulated upward into the stratosphere. While ozone is a strong greenhouse gas the quantity is so small as to have an insignificant effect on global warming.

Ozone in the stratosphere can be depleted as a result of reaction with ozone depleting chemicals such as compounds with chlorine and/ or fluorine attached to carbon, known as chlorofluorocarbons or CFCs. The Montreal Protocol, which was finalized in 1987, is a global agreement to protect the stratospheric ozone layer by phasing out the production and use of ozone depleting substances (including CFCs). The effect is most pronounced over Antarctica where the ozone may be completely depleted forming what is known as the ozone hole as shown in Figure 7.17.

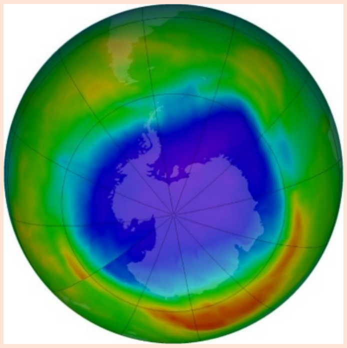


Figure 7.17 Ozone hole over Antarctica shown in blue https://climate.nasa.gov/faq/15/is-the-ozone-hole-causing-climate-change/#:~:text=What%20scientists%20have%20uncovered%20recently,over%20the%20Southern%20Hemisphere%20colder.

Without the ozone the stratosphere over Antarctica cools resulting in faster winds near the pole. The impacts extend to the equator affecting tropical circulation and rainfall at lower latitudes.

The ozone hole does not cause global warming but does affect atmospheric circulation.

7.8 Information support

Key web sites:

1. Global atmospheric circulations. https://courses.lumenlearning.com/geophysical/chapter/global-atmospheric-circulations/

2. Weather systems and patterns. https://www.noaa.gov/education/resource-collections/weather-atmosphere/weather-systems-patterns

3. Global circulation patterns. https://www.metoffice.gov.uk/weather/learn-about/weather/atmosphere/global-circulation-patterns

4. Atmospheric circulation. https://www.globalsecurity.org/military/library/policy/navy/nrtc/14312_ch3.pdf

5. Jet stream. https://en.wikipedia.org/wiki/Jet_stream

6. The jet streams. https://www.weather.gov/jetstream/jet

7. What is a jet stream? NOAA, https://scijinks.gov/jet-stream/

8. Polar vortex. NOAA, https://scijinks.gov/jet-stream/

9. Science behind the polar vortex. NOAA, https://www.noaa.gov/multimedia/infographic/science-behind-polar-vortex-you-might-want-to-put-on-sweater

10. Understanding the Arctic polar vortex, NOAA, https://www.climate.gov/news-features/understanding-climate/understanding-arctic-polar-vortex

11. Videos on description of jet and how it affects weather, Met Office, https://www.youtube.com/watch?v=Lg91eowtfbw and https://www.youtube.com/watch?v=5wCq2Y9CB6Y

12. Jet streams and heatwaves: what's the link? World Economic Forum Aug 8, 2022. https://www.weforum.org/agenda/2022/08/jet-stream-winds-fuelling-heatwaves/

13. Double jet streams – heatwaves over Europe 2022, https://www.rmets.org/metmatters/what-heat-dome

14. Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia., in journal Nature Communications 04 July 2022. https://www.nature.com/articles/s41467-022-31432-y

15. Ozone hole and climate change. https://climate.nasa.gov/faq/15/is-the-ozone-hole-causing-climate-change/#:~:text=What%20scientists%20have%20uncovered%20recently,over%20the%20Southern%20Hemisphere%20colder.

16. Montreal Protocol 1988. https://www.mcgill.ca/iasl/files/iasl/montreal1988.pdf.

17. Atmospheric rivers Wikipedia. https://en.wikipedia.org/wiki/Atmospheric_river.

18. Atmospheric water vapor, Remote Sensing Systems. https://www.remss.com/measurements/atmospheric-water-vapor/ and https://images.remss.com/cdr/climate_data_record_browse.html.

19. Cloud liquid water content, Remote Sensing Systems. https://www.remss.com/measurements/cloud-liquid-water-content/.

20. Atmospheric river NOAA. https://www.noaa.gov/stories/what-are-atmospheric-rivers.

21. Atmospheric river Climate Central. https://www.climatecentral.org/news/global-warming-atmospheric-rivers-18645.

22. How do atmospheric rivers form? By Dacre, H. F., et al. 2015 Journal of the American Meteorological Society. https://journals.ametsoc.org/view/journals/bams/96/8/bams-d-14-00031.1.xml.

23. Atmospheric rivers. West Coast Rain, Bloomberg Report, 2021. https://www.bloomberg.com/news/articles/2021-10-19/river-from-the-sky-to-bring-california-fire-season-closer-to-end?cmpid=BBD102021_GREENDAILY&utm_medium=email&utm_source=newsletter&utm_term=211020&utm_campaign=greendaily.

24. Atmospheric River flow across the Western United States October 25, 2021 as reported by the Washington Post https://www.washingtonpost.com/weather/2021/10/25/atmospheric-river-record-rain-

california/?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20211026&utm_medium=email&utm_source=Revue%20Daily

25. A scale to characterize the strength and impacts of atmospheric rivers by Ralph, F. M. et al. in the Journal of the American Meteorological Society 01 Feb 2019. https://journals.ametsoc.org/view/journals/bams/100/2/bams-d-18-0023.1.xml.

26. Atmospheric river impacting southwest British Columbia, November 2021 as presented by the Weather Network,

27. https://www.theweathernetwork.com/ca/news/article/over-100-mm-of-rain-en-route-to-b-c-with-latest-atmospheric-river.

28. Examples of omega and Rex blocking over North America. https://www.noaa.gov/jetstream/upper-air-charts/basic-wave-patterns

29. Also see the explanation provided by the Weather Network at https://www.theweathernetwork.com/en/news/science/explainers/what-is-omega-block-rex-block-upper-level-jet-stream-weather-pattern .

30. Heat dome description, Royal Meteorological Society, https://www.rmets.org/metmatters/what-heat-dome.