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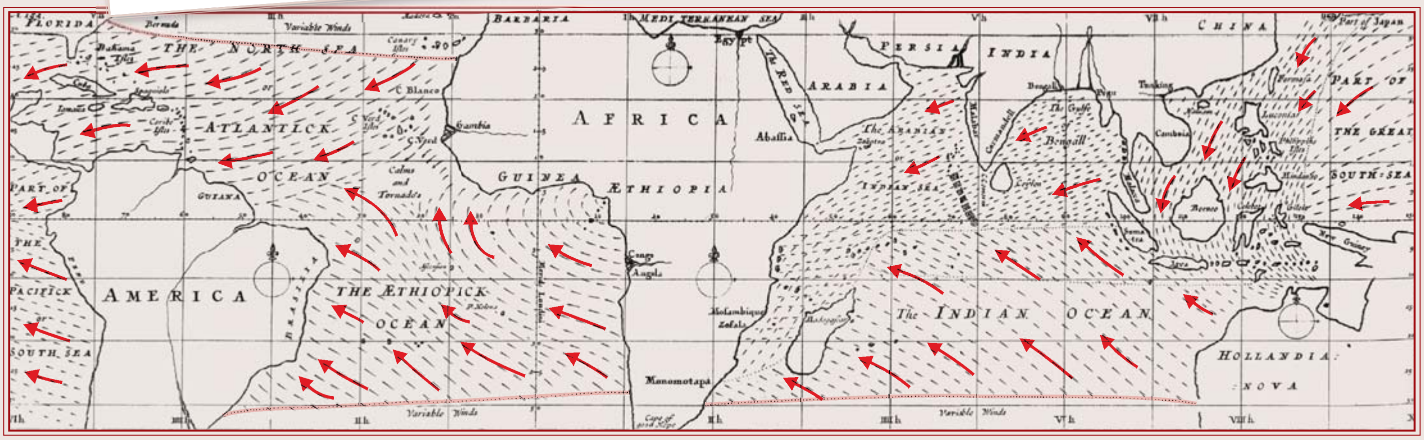

The belt emerges as a fundamental climatic feature of atmospheric circulation patterns on a rotating and differentially heated planet. But locating its edges and discerning anthropogenic influences remain difficult research problems.

"What's the good of Mercator's North Poles and Equators,
Tropics, Zones, and Meridian Lines?"
So the Bellman would cry: and the crew would reply
"They are merely conventional signs!"

—Lewis Carroll, "The Hunting of the Snark"



Astronomer, geoscientist, mathematician, and meteorologist Edmond Halley is probably best known for his remarkable prediction, some 50 years in advance, of the appearance of a comet on Christmas Day 1758. Halley's Comet last appeared in 1986, and its return approximately every 76 years continues to fascinate us.

Another remarkable scientific contribution by Halley, also with enduring relevance, resulted from his visit at age 20 to the South Atlantic island of Saint Helena to map the stars of the Southern Hemisphere. Although his voyage aboard an East India Company ship was not, by a long shot, the first crossing of the tropical ocean, Halley published the first map of surface winds over the tropics and a large portion of the globe from his and others' observations.[1] Figure 1 shows the scientist in his early thirties, the period of his life when he produced and analyzed the map (shown above).

A key feature of Halley's map, from both navigational and geophysical perspectives, is the easterly trade winds—the relatively steady tropical and subtropical winds blowing from the east and toward the equator. Those winds stand in contrast to the more variable winds blowing generally from the west ("westerlies") at higher latitudes, mentioned but not drawn on the map. Bounding the region of easterly trade winds are zones of calm air near 30° latitude in the Northern and Southern Hemispheres. Most of the world's deserts reside in those subtropical zones, where slowly subsiding warm and dry air suppresses the formation of clouds and storms.

Halley's depiction of the tropical belt—the region of easterlies in Earth's tropics and subtropics—is in remarkable agreement with our current understanding of average conditions, but the atmosphere

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is highly variable day to day, month to month, and season to season. Furthermore, recent studies have uncovered strong observational evidence that the tropical belt has been expanding toward the poles over the past 35 years—and doing so at a rate that is difficult to reconcile with prevailing theory. The shifting of the dry zones associated with the belt can have dramatic local consequences for climate, ecosystems, water resources, economies, and agriculture.

In this article we describe how the tropical belt emerges from the delicate balances among different aspects of Earth's climate system. Simple theories exist only for parts of how it emerges, and a unique and cogent notion of what constitutes the width of the tropical belt remains elusive. But researchers are forming conceptual pictures that may lead to a more complete understanding of this centuries-old problem.

Early views of wind patterns

The prime driver of the atmosphere's global air currents, known as the general circulation, is the Sun's differential heating of Earth's surface. Because our planet is approximately spherical, regions near the equator are, on average, warmed more than higher-latitude regions. Tropical and subtropical regions exhibit an energy surplus, because the energy gain due to incoming solar radiation exceeds the energy loss due to emitted terrestrial radiation, and the opposite conditions hold in midlatitudes and polar regions.

The general circulation acts as a giant heat engine: It transfers heat from low to high latitudes by exchanging fluid between relatively warm and cold regions. That simple construct is complicated by Earth's counterclockwise, eastward rotation around its axis. Because of its opposing direction, air within the easterly trade winds lags behind Earth's rotation and gains angular momentum through surface friction. Conversely, air within the midlatitude westerlies loses angular momentum to Earth. To balance the difference, angular momentum must be transported from low to high latitudes.

Halley invoked the global heat imbalance (but not angular momentum) as driving atmospheric circulation, particularly the trade winds. He recognized the tendency of air to rise near the equator, where it is relatively warm, flow toward the poles in the upper atmosphere, sink in colder regions, and flow back toward the equator near the surface. That air circulation along meridians, known as meridional overturning, explains the equatorward, but not the westward, component of the trade winds. Halley wrongly hypothesized that the apparent westward movement of the Sun pulls the air behind it. Despite his own doubts about that strange part of his theory, it survived many decades, possibly due to his eminence in astronomy and in the Royal Society.[2]

The hypothesis lasted until 1735, when a much less eminent investigator, lawyer and amateur meteorologist George Hadley, argued that air appears to be deflected toward the west because it flows equatorward from latitudes of reduced eastward velocity.[3] He envisioned hemispheric overturning circulation cells that extend from the equator to the poles. We now know that angular momentum conservation on our fast-rotating planet confines the circulation cells, known as Hadley cells, to the tropics and subtropics.[4] Nevertheless, Hadley impressively concluded that the westward trade winds inside the tropics must be compensated by eastward surface winds elsewhere. Otherwise, the atmosphere would change the rotation rate of the planet through surface friction.

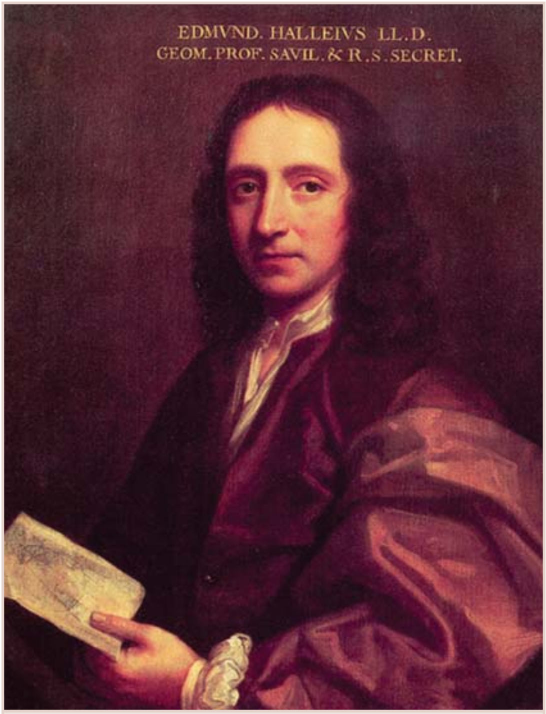
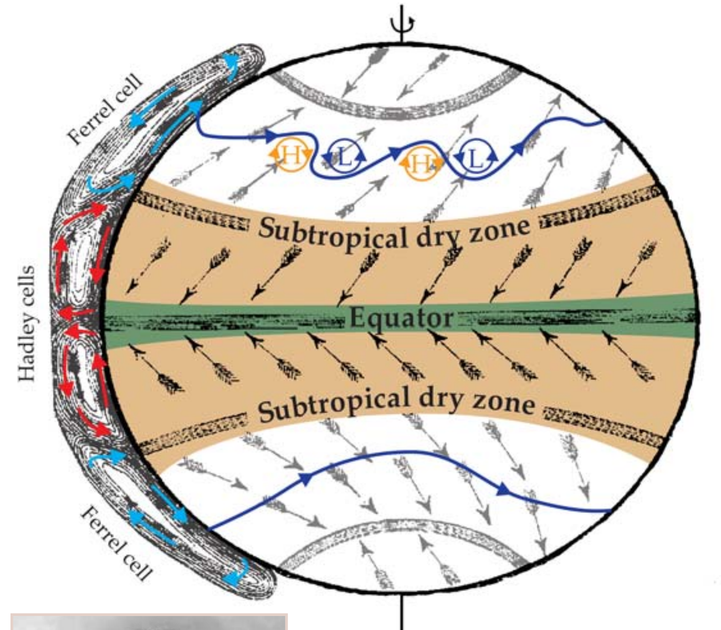


Figure 1. Edmond Halley (1656–1742) published his map,[1] shown on page 38, and analysis of Earth's surface winds in 1686. (Portrait by Thomas Murray, circa 1687.)

Modern explanations of the westward deflection of trade winds toward the equator invoke the Coriolis effect, which arises due to the rotating reference frame. Gaspard-Gustave Coriolis introduced his apparent force in 1835 while studying rotating machinery. Twenty years later the self-taught American schoolteacher William Ferrel, unaware of Coriolis's work, introduced the concept to atmospheric science in the obscure *Nashville Journal of Medicine and Surgery*.[5] In 1858 Ferrel, writing in the *Astronomical Journal*, stated, "If a body is moving in any direction, there is a force, arising from the earth's rotation, which always deflects it to the right in the northern hemisphere, and to the left in the southern."

Ferrel concluded that the eastward surface winds in midlatitudes result from that deflection acting on poleward flow. He postulated that Halley's and Hadley's circulation cells are confined to the tropics and hypothesized another cell circulating in the opposite sense at midlatitudes. Air in that cell, now known as a Ferrel cell, moves upward near 60° latitude, equatorward at upper levels, downward in the subtropics, and poleward near the surface, as shown in figure 2.



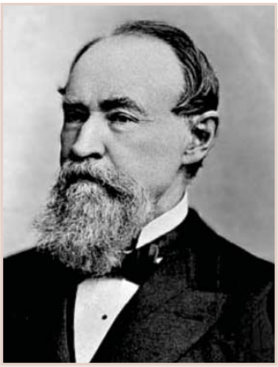


Figure 2. William Ferrel (1817–91) and his schematic depiction (as arrows and closed loops) of Earth's surface wind directions and circulation cells. The cells in the tropics (red) are now named after lawyer and amateur meteorologist George Hadley, and those at midlatitudes (blue) are named after Ferrel. Green and tan shading mark approximate regions of precipitation surplus and deficit, respectively. At midlatitudes, above and below the north and south borders of the subtropical dry zones, generally eastward air currents often curl up into high- and low-pressure areas (H and L). In the tropics and subtropics more energy is gained due to incoming solar radiation than is lost due to emitted terrestrial radiation, and the atmosphere gains angular momentum from Earth. The opposite conditions hold in higher latitudes, and heat and momentum move from low to high latitudes. (Adapted from W. Ferrel, *Nashville J. Medic. Surgery* **11**, 287, 1856.)

We now understand that the two Ferrel cells—one circling the globe in each hemisphere—are of secondary importance for heat transport across latitudes. Weather systems made up of turbulent eddies dominate heat transport outside the tropics and primarily drive the Ferrel cells. Nonetheless, as we'll see, the basic concept of overturning cells informs contemporary notions of what constitutes the edge of the tropical belt.

Climatic consequences

The tropical circulation patterns envisioned by Halley, Hadley, and Ferrel are axially symmetric along circles of constant latitude. Similar considerations generally hold for the water cycle (see the article by Bjorn Stevens and Sandrine Bony, PHYSICS TODAY, June 2013, page 29), notwithstanding regional monsoon rains. Converging trade winds from north and south of the equator form the so-called intertropical convergence zone (ITCZ) in which moist air from the warm tropical oceans is forced upward to produce some of the most abundant precipitation on the planet. High-reaching tropical thunderstorms in the ITCZ account for most of that upward transport.

The warm ocean surface also evaporates profusely over much of the tropics and subtropics. Regional climate is therefore determined mainly by the balance of precipitation and evaporation, as shown in figure 3. If defined as the region of westward trade winds, the tropical belt includes large portions of dry subtropical climate as well as wet regions filled with tropical rainforests.

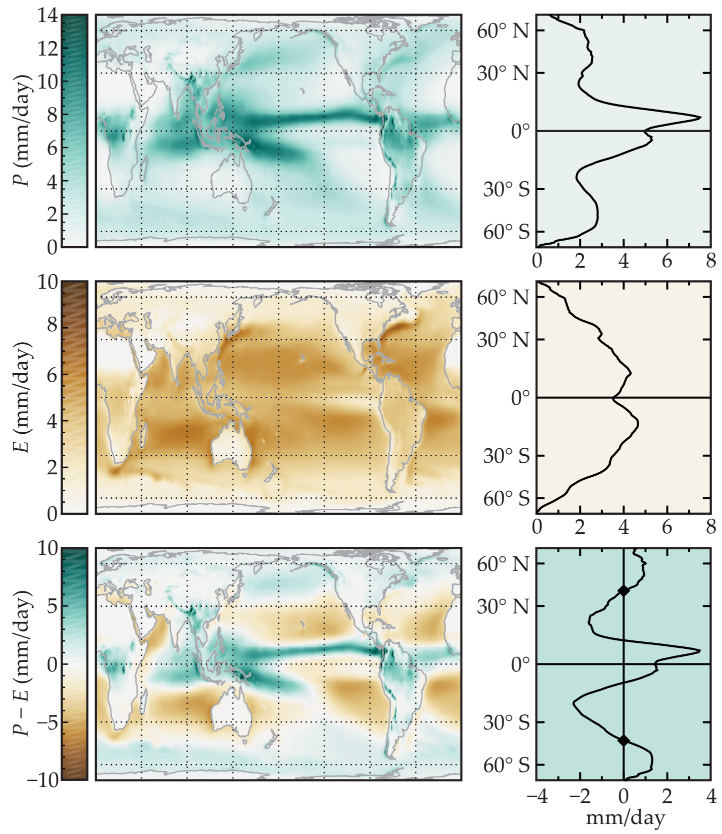
Whereas precipitation, evaporation, and the trade winds represent surface manifestations of the tropical belt, the Hadley cells extend some 15 km upward through almost 90% of the atmosphere by mass. The lower atmosphere consists of a dome of warm air within the region of the westward trade winds, with strong temperature gradients across the edges of the tropical belt near 30° N and 30° S. As the temperature drops with altitude throughout the troposphere, the winds strengthen and form eastward subtropical jets near the tropopause—the interface region between the troposphere and the stratosphere. Temperature generally increases with height in the stratosphere. (See figure 4.)

As mentioned earlier, the Hadley cells are usually conceptualized as axially symmetric flows, driven by the differential heating across latitudes.[4] That simplification becomes problematic when applied to the Ferrel cells, which are mainly driven by axially asymmetric eddies. Nevertheless, the real Hadley cells are not purely symmetric either. A prominent east–west overturning circulation exists over the Pacific Ocean, and seasonal monsoons that occur because of temperature differences over land and sea in parts of Asia, Africa, Australia, and the Americas can locally reverse the trade winds.

In the idealized axially symmetric case, a ring of air heated along the equator near Earth's surface rises and moves poleward toward colder latitudes. To conserve angular momentum during that motion, the air must also flow eastward, in the same direction as the planet's rotation. Assuming no flow in the upper troposphere at the equator, the speed of the angular-momentum-conserving eastward wind would be about 30 m/s at 15° latitude. At 30° latitude, it would reach an unstably fast flow of 130 m/s. To appreciate that theoretical result, keep in mind that the subtropical jets (marked "J" in figure 4a) average only 30 m/s. A simple angular-momentum-conserving model therefore cannot explain the extent of the poleward outflow from the equator. Its physics pertains instead to a Hadley cell confined to low latitudes.

The Hadley cells also transport heat from the equator to higher latitudes. In equilibrium, their extent is limited by the constraint that the warming they cause at higher latitudes must balance the cooling at low latitudes. In the axially symmetric angular-momentum-conserving model, that happens near 20° latitude, substantially equatorward of the observed edges of the Hadley cells. It is the action of higher-latitude turbulent eddies whose energy is dissipated by the strong winds near the subtropical

Figure 3. Average precipitation (*P*), evaporation (*E*), and the difference between them are mapped on the left for the years 1981–2010. The values are replotted as latitude averages on the right. Subtropical deserts and tropical rainforests are sustained by water deficit and water surplus, respectively. Edges of the tropical belt can be located where precipitation and evaporation balance each other (diamonds in lower right plot).



jets that both slows the cells' circulation and shifts them poleward.[6] Hence the observed latitudinal extent of the Hadley cells comes from the combined action of the near-angular-momentum-conserving, low-latitude overturning circulation and the higher-latitude eddies.

Locating the belt's edges

The extent of the tropical belt can be defined and measured in several ways. The focus in this article is on climate-related metrics used to identify its latitudinal edges, but the term "tropics"—from the Greek for "turning"—is astronomical in origin and refers to the latitudes of Cancer (23.4° N) and Capricorn (23.4° S), the most poleward latitudes at which the Sun appears directly overhead during the year. Subtropical climates extend farther north and south of the Tropics of Cancer and Capricorn; for example, the Sahara desert extends over latitudes of approximately 16–34° N.

Because the Hadley cell is a circulation system, several metrics of its extent relate directly to air-flow patterns. Consider just the east–west surface winds. Assuming that their magnitude varies little over the globe, then equal areas should be covered by the westward and eastward winds, and the belt of trade winds should cover about half the globe, extending to about 30° latitude in each hemisphere. That is roughly the case: The latitudes where the surface wind reverses direction, marked in figure 4a, are at 31° N and 32° S.

A more sophisticated circulation-based metric, shown in figure 4b, involves the mass transport along meridians. Because the Hadley and Ferrel cells circulate air in opposite directions, the edge of each Hadley cell can be defined conveniently as the latitude where the circulation changes from clockwise to counterclockwise.

A third metric considers where each Hadley cell flows away from the equator. Those outflows occur near the tropopause. The tropopause is much higher over the tropical regions than over extratropical regions (see figure 4a), so the edges of the tropical belt can be located at the latitudes of an abrupt change in tropopause height, at about 34° N

Reanalyses: Important but imperfect sources of climate information

For centuries, scientists have relied on maps of atmospheric observations from ships, weather stations, balloons, and satellites to understand weather and climate. Hand-drawn maps, such as Halley's on page 38, have now largely been replaced by meteorological analyses, which are spatially and temporally complete representations of atmospheric conditions such as temperature and wind speeds and direction. The analyses combine the forecasts from numerical weather prediction (NWP) models with available observations, a process called data assimilation.[18]

Advancements in NWP science and computing technologies over the past several decades have led to improvements in the NWP models and data-assimilation methods. But the mere introduction of new, improved models and methods can change the analyses, which undermines their incorporation in climate studies that address long-term changes. Reanalyses address that problem by using a fixed NWP model and assimilation methodology for the entire period of study. Yet changes in, say, measurement schedules, instrument sensitivities, or new technologies also have the potential to create abrupt changes in the reanalyses. The resulting discontinuities in the data and trends complicate the detection of actual climate change.

Despite the deficiencies, researchers rely on reanalyses for some meteorological variables—for instance, the vertical component of wind speed—not directly measured, including some that are used to locate the edge latitudes of the tropical belt. In this article, figures 3, 4, and 5 are constructed from contemporary reanalysis data sets.

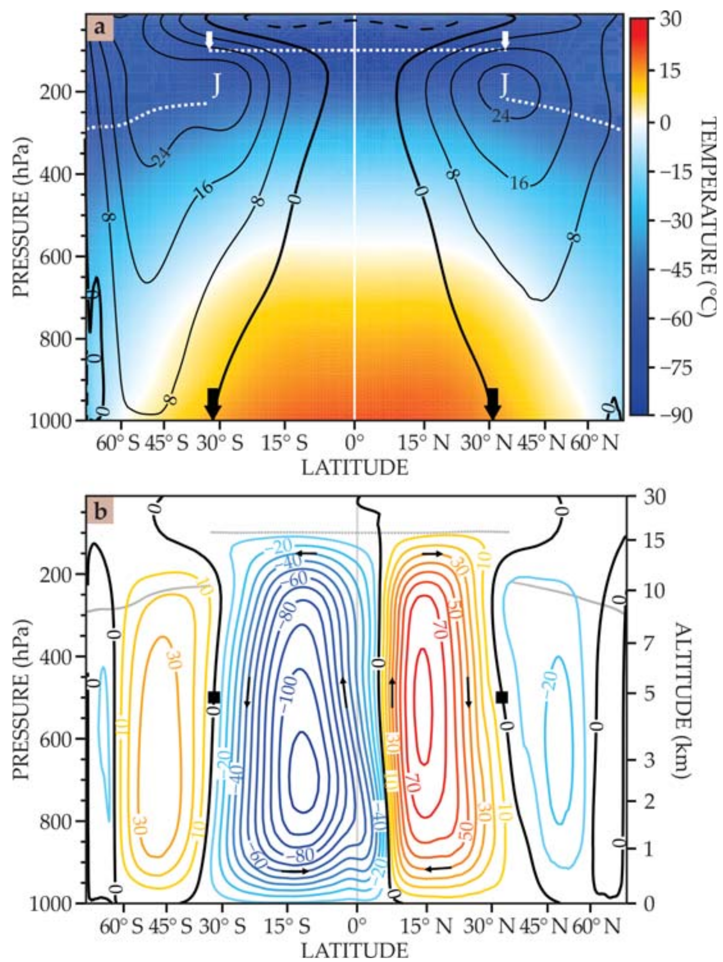


Figure 4. The tropical belt's edges can be located from the distributions of atmospheric temperature and winds. **(a)** In this plot of data averaged over 30 years (1981–2010), a dome of warm air at the equator cools with increasing latitude and decreasing atmospheric pressure (or equivalently, increasing altitude). Black lines mark contours of constant eastward wind speed in units of meters per second. Inside much of the dome, the winds flow westward. At the zero contour, they calm and, with increasing latitude or altitude, reverse direction. The tropopause, the boundary between the troposphere and the stratosphere, is marked by the white dotted line. The edges of the tropical belt may variously be defined as being at the jet-stream cores marked "J," at the transition from westward to eastward surface winds marked by black arrows, or where the tropopause abruptly changes altitude (white arrows). **(b)** The mass stream function plotted here measures the rate of mass transport along meridians between a given altitude and the top of Earth's atmosphere as a function of latitude. Contours of equal mass transport are in units of 10^9 kg/s, with clockwise circulation shown in red and counterclockwise circulation in blue; black lines mark transitions between the circulation patterns. Black squares mark the edges of the subtropical stream function at 500 hPa, halfway through the vertical extent of the Hadley cell.

and 33° S. In those regions, the Hadley cell outflow feeds the subtropical jets, so the position of maximum flow within the jets, known as the jet cores, is yet another measure of tropical belt edges.

Other metrics also exist but involve aspects of tropical climate not directly related to circulation. For example, the thermal IR radiation that Earth emits to space reaches a maximum in the subtropics thanks to the lack of clouds, low humidity, and high surface temperatures there. Alternatively, one can turn to the precipitation–evaporation difference (figure 3), whose outer boundaries of the water-deficit region define the belt's edges at 39° N and 41° S. Finally, the amount of ozone in the atmosphere can also be used to mark edges, because less of it resides in the tropics than outside of it.

Only a few metrics—those based on thermal IR, the tropopause, and ozone among them—can be directly derived from observations. Some metrics, such as those based on wind circulation, cannot be adequately measured and have to be derived from so-called reanalyses, described in the box on page 41. Those recently developed, observationally constrained representations of the atmosphere are a boon to weather and climate studies, although their value for studies of long-term climate change is limited.

The scarcity of purely observational estimates of the tropical-belt width makes it difficult to understand its past variability. Although the mass-transport approach to measuring the transition from Hadley cell to Ferrel cell offers a clean conceptual interpretation, it relies on model and reanalysis variables that are not well constrained by observations. On the other hand, the metrics that are better constrained by observations may not offer a simple interpretation. For example, the tropopause structure, which depends on fairly reliable temperature observations, is in part influenced by the stratospheric circulation, well above the tropospheric Hadley cell.

Recent expansion

A change in the latitudinal extent of the tropical belt can lead to substantial changes in local climate near its edges. The surface temperature gradient across latitudes is large near those edges, typically 1 K per degree latitude. So a shift of just 5° latitude in the tropical belt edge would lead to a local temperature change of about 5 K. Warming of that magnitude exceeds both the roughly 1-K average increase observed globally for the past century and the expected warming through the end of the 21st century.[7]

Likewise, a shift in the pattern of evaporation and precipitation shown in figure 3 can dramatically change the local hydrological balance in the vicinity of the belt edges. Formerly humid areas may turn arid and vice versa. The changes would have major consequences for water availability for urban settlements, farming, ranching and herding, hydropower, and forestry. Natural ecosystems, including parklands, nature reserves, fisheries, and marine and estuarine ecosystems, are also sensitive to hydrological changes. Furthermore, an expansion of the tropical belt could lead to a poleward spread of vector-borne infectious diseases, such as malaria, dengue fever, and cholera.

A change in the latitudinal extent of the Hadley cells is likely to move the location of the subtropical jet streams and thus shift the boundary of the Ferrel cells, with likely shifts in midlatitude storm tracks. Consequent water-cycle changes could strain human and natural systems in those areas too.

Several recent studies offer evidence of a poleward expansion of the tropical belt.[8,9] Estimated rates of that expansion since the beginning of the satellite era in 1979 range from barely detectable (around 0.2° latitude per decade) to quite rapid (around 2° latitude per decade). That range spans an order of magnitude, though the expansion rate is sensitive to the metric used to measure it.[10] Figure 5, taken from the most recent Intergovernmental Panel on Climate Change report,[7] summarizes the past 33-year movement of the northern and southern edges of the tropical belt. Some metrics, such as the mass transport along meridians, reveal a wide spread among different data sets and large year-to-year variability compared with the general trend. Much of that variability is due to natural climate fluctuations. For example, strong El Niño events and suspended aerosols in the stratosphere after large volcanic eruptions can narrow the tropical belt, while strong La Niña events widen it.[11]

Climate-model estimates of the expansion rate in the late 20th century are generally smaller—at the low end of the observationally based estimates.[12] That may indicate insufficiencies in the models' ability to simulate important characteristics of the climate system. Alternatively, the discrepancy between models and reanalyses may be due to insufficiencies with the reanalyses.[13]

According to climate-model studies, a fraction of the small expansion is attributable to increased atmospheric greenhouse gases. However, although the basic thermodynamic effects of greenhouse-gas-induced climate change are simple—changes to the energy budget of the system produce changes in temperature—the response of the general circulation is much more complicated. That's because the general circulation is shaped by the detailed nonlinear balance among the various components of the climate system, including ocean circulation; clouds; sea ice; and the transports of heat, angular momentum, and moisture. Yet it is the atmospheric circulation changes that may be most important to society, insofar as their shifts may have more dramatic consequences on the water cycle than global mean temperature changes.[14]

Researchers attribute a more significant expansion of the southern hemispheric part of the tropical belt to stratospheric ozone loss—particularly the springtime Antarctic ozone hole—and the stratospheric cooling that has occurred around the South Pole over the past three decades.[15] (See the article by Anne Douglass, Paul Newman, and Susan Solomon, PHYSICS TODAY, July 2014, page 42.) Those changes in the stratosphere are related to the southern middle- and high-latitude jet stream and its variability (see the article by John Wallace and David Thompson, PHYSICS TODAY, February 2002, page 28). But the mechanism connecting the stratosphere to the subtropical jet and the edge of the tropical belt is not well understood.

Other mechanisms might also contribute to the widening. Increased levels of black-carbon aerosols and ozone in the troposphere, both byproducts of combustion, may be key to the northern expansion of the tropical belt.[16] However, consensus about that and other possible causes has not yet been reached.

Predicting the future

The planetary-scale circulation cells are driven primarily by the temperature contrast between low and high latitudes. Changes to the latitudinal temperature distribution will therefore undoubtedly affect the strength and shape of the circulations. Based on simple thermodynamic arguments, the tropical upper troposphere—the region at altitudes between roughly 10–15 km and pressures between 300–150 hPa—is expected to warm more than other parts of the atmosphere. And simple conceptual models predict a wider Hadley cell thanks to the increased pole-to-equator temperature differences.

Given the ambiguities about past trends in the

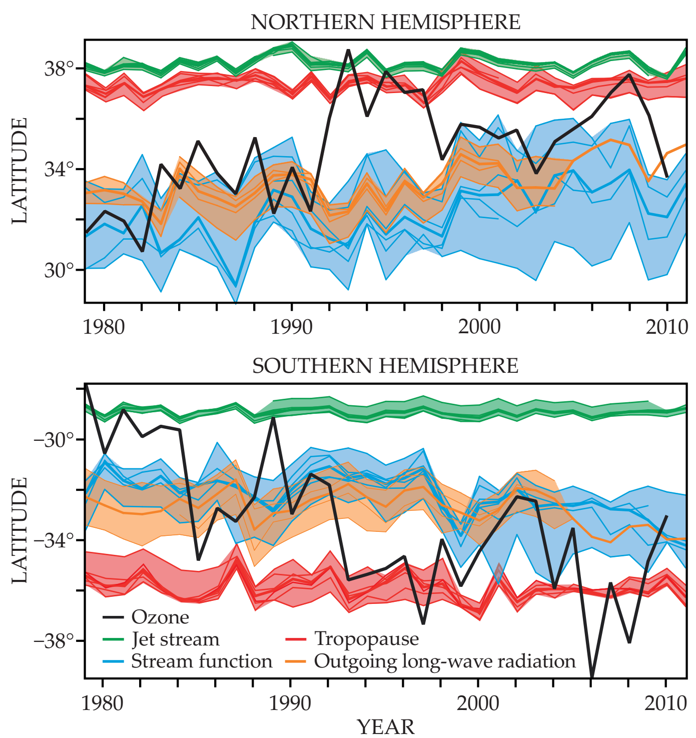


Figure 5. Changes in the edge locations of the Northern and Southern Hemispheres, 1979–2012. The plots include five annually averaged metrics that independently measure the edges of the tropical belt. They are based on reanalyses (see the box on page 41) of the tropopause (red), stream function (blue; see figure 4), and jet stream (green), and on satellite measurements of ozone (black) and thermal IR radiation (orange). Where multiple estimates of a particular metric are available, they are shown as light solid lines, surrounded by shading that indicates their range; a heavy line indicates their median. (Adapted from figure 2.40 of ref. 7.)

width of the tropical belt and what has caused them, it's difficult to project future trends with much confidence. A continued expansion is possible—in particular, the part linked to increased greenhouse gas concentrations. On the other hand, a projected recovery of the ozone layer over the Antarctic by the second half of the 21st century is likely to prompt a contraction, particularly in southern summer.[17] Moreover, natural climate variability can strongly influence the width of the tropical belt, and the extent to which it has done so during the past few decades is incompletely understood. Climate variability and its effect on atmospheric circulation will certainly also influence future trends and may well mask the effects of human-induced climate change. No doubt researchers will seek to reveal the myriad causes and consequences of the changes.

To put it in Halley's words:

> 'Tis likewise very hard to conceive why the limits of the Trade Wind should be fixt, about the thirtieth degree of Latitude all round the Globe; and that they should so seldome transgress or fall short of those bounds; as also that in the *Indian* Sea, only the Northern Part should be subject to the changeable *Monsoons*, and in the Southern there be a constant S. E. [South Easterly]
>
> These are particulars that merit to be considered more at Large, and furnish a sufficient Subject for a just Volume; which will be a very commendable Task for such, who being used to Philosophick Contemplation, shall have leasure to apply their serious thoughts about it. (reference 1, page 168)

By the time Halley's Comet reappears in 2061, his map of the trade winds may have to be revised.

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