

Widening of the tropical belt in a changing climate

Some of the earliest unequivocal signs of climate change have been the warming of the air and ocean, thawing of land and melting of ice in the Arctic. But recent studies are showing that the tropics are also changing. Several lines of evidence show that over the past few decades the tropical belt has expanded. This expansion has potentially important implications for subtropical societies and may lead to profound changes in the global climate system. Most importantly, poleward movement of large-scale atmospheric circulation systems, such as jet streams and storm tracks, could result in shifts in precipitation patterns affecting natural ecosystems, agriculture, and water resources. The implications of the expansion for stratospheric circulation and the distribution of ozone in the atmosphere are as yet poorly understood. The observed recent rate of expansion is greater than climate model projections of expansion over the twenty-first century, which suggests that there is still much to be learned about this aspect of global climate change.

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A fundamental feature of the Earth's climate is the distinction between the tropical and extratropical regimes. However, the boundaries of the tropics are not uniquely defined and vary among scientific disciplines. In astronomy and cartography, the edges of the tropical belt are the Tropics of Cancer and Capricorn, at latitudes of ~23.5 degrees north and south, where the sun is directly overhead at solstice. They are determined by the tilt of the Earth's axis of rotation relative to the planet's orbital plane, and their location varies slowly, predictably and very slightly — by about 2.5 degrees latitude over 40,000 years. In climatology, on the other hand, there are several indicators of the boundaries of the tropics, and they do not all necessarily yield the same location. Moreover, their positions vary by much larger amounts and much more rapidly and unpredictably than the astronomically defined tropics.

Climatologists and geographers have traditionally defined the tropics using classification systems, notably that of Köppen¹, based on surface temperature and precipitation patterns. Tropical temperatures are warm, and, except for the major monsoon regions, both seasonal and day-to-day changes are small compared with extratropical climates. Another important feature of the tropics is the prevalence of rain in the moist inner tropical regions near the equator, as distinct from the dry conditions in subtropical regions.

This precipitation pattern is largely determined by large-scale atmospheric wind patterns, known as the Hadley circulation, which

manifests itself in several ways throughout the atmosphere, as depicted in Fig. 1. The ascending branch of the Hadley circulation, in equatorial regions, carries moisture into the air, promoting rainfall, whereas the descending branches, at the edges of the tropical belt, are notably drier. Within the Hadley circulation cell, atmospheric mass in the lower atmosphere moves towards the equator, whereas outside the cell it moves toward the poles. The latitude at which the net north–south flow is zero can be considered the poleward extent of the Hadley cell and therefore can be used to estimate the width of this tropical circulation. Within the tropical belt, surface winds generally blow from east to west, whereas in midlatitudes they blow from west to east and intensify upward from the surface to form the jet streams.

Two jets streams are identifiable in each hemisphere, although they are not always well separated. The subtropical jet, located at the poleward boundaries of the Hadley cell, is the more permanent feature, but the polar front (or eddy-driven) jet, at higher latitudes, is intimately connected with the former through dynamical processes^{2,3}. Thus the distance separating the two subtropical jets on both sides of the equator is another measure of the boundaries of the tropics, and variations in that distance may be linked to aspects of the polar front jets.

Within the stratosphere, a major atmospheric flow pattern is the Brewer–Dobson overturning circulation, which consists of large-scale upward motion in the tropics and descending motion at higher latitudes. This circulation system carries stratospheric ozone from the tropics poleward, resulting in higher ozone concentrations in the extratropics, allowing for an ozone-based demarcation of the width of the tropics. The tropopause, which separates the troposphere below from the stratosphere above, is higher over the tropics than elsewhere, and it, too, can serve to identify a distinctly tropical region.

Thus from various perspectives, climate scientists find clear distinguishing features of the tropics that can be used to estimate the width of this climatic zone. Several recent studies suggest that

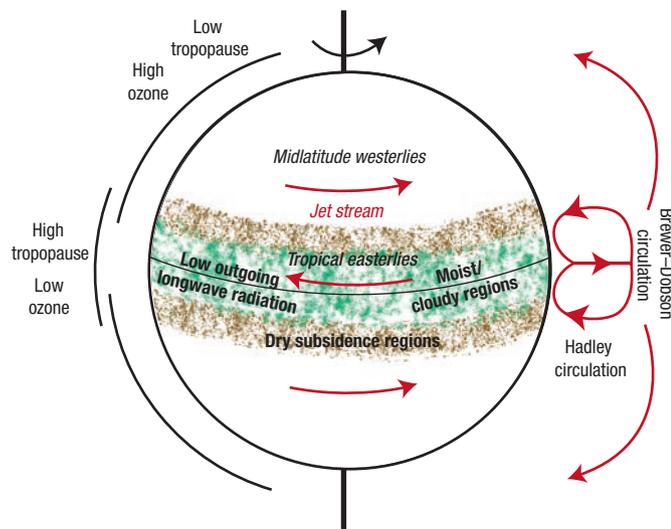


Figure 1 What climatological features distinguish the tropics? Some of the atmospheric structure, circulation, and hydrological features shown in this schematic diagram of the Earth have moved poleward in recent decades, indicating a widening of the tropical belt and the Hadley circulation.

the tropics have been expanding over the past few decades and that this widening may continue into the future in association with anthropogenic climate change. Such an expansion of the tropical belt could have broad scientific implications and societal impacts.

EFFECTS OF GLOBAL WARMING ON THE WIDTH OF THE TROPICAL BELT

According to the most recent assessment of the Intergovernmental Panel on Climate Change⁴, increases in greenhouse gases and other human-induced climate forcings would lead to warming of the troposphere (the lower atmosphere), cooling of the stratosphere, rise of the tropopause, weakening of tropical circulation patterns, poleward migration of midlatitude storm tracks, an increase in tropical precipitation, and other climatic changes. Many of these have already been seen in observations covering the last few decades or more⁵. Taken together, it is not obvious how these changes might relate to variations in the width of the tropical belt, and it is only recently that this question has received much attention.

As summarized in Box 1, several recent studies found that in climate model simulations the jet streams and the associated wind and precipitation patterns tend to move poleward under global warming. As the jet streams are indicators of the poleward limits of the tropics, this implies that the tropics will expand as the Earth warms. Based on these studies, it appears that climate forcings over the twenty-first century would be expected to lead to an expansion of the tropics by as much as 2 degrees latitude.

WIDENING OF THE TROPICAL BELT SINCE 1979

Remarkably, the tropics appear to have already expanded — during only the last few decades of the twentieth century — by at least the same margin as models predict for this century. Several recent studies, using independent datasets, show robust trends in different measures of the width of the tropical belt. Based on five different types of measurement, they find a widening of several degrees latitude since 1979.

Hudson *et al.*⁶ analysed satellite observations of atmospheric ozone concentrations, focusing on the well-known distinction

Box 1 Climate model projections of expansion of the tropics

Climate models are widely used to simulate the effects of natural and anthropogenic perturbations on climate. Although most attention has been paid to projected changes in temperature, precipitation, the cryosphere, and sea level, several recent studies have also investigated how the atmospheric circulation is altered under a changing climate. Some of these indicate that the tropical belt expands under global warming.

Listed here are some climate model studies with results consistent with a widening of the tropics:

- Southern Hemisphere jet stream moves poleward under global warming²⁶.
- Stratospheric cooling intensifies the stratospheric polar vortex and induces a poleward shift of tropospheric jets^{27,28}.
- Midlatitude storm tracks shift poleward under global warming, particularly in the Southern Hemisphere^{29,30}.
- Stratospheric cooling leads to a lifting of the tropopause, which causes poleward movement of tropospheric jet streams^{17,18}.
- Specific anomalies in sea surface temperatures lead to a poleward shift of the zonal mean atmospheric circulation^{15,16}.
- During the twenty-first century, global warming will shift the boundaries of the Hadley circulation and subtropical dry zone poleward, and it will decrease precipitation and soil moisture in the subtropics^{14,22}.

Under the most extreme warming scenario (the A2 scenario⁴), the model projected mean change is about two degrees latitude over the course of the twenty-first century, with a wide range of predictions from individual models. Surprisingly, this widening is smaller than the expansion that observations indicate has already taken place during the past 25 years (See Fig. 2).

Analysis of predicted twenty-first century changes suggests that the decadal time-scale variability of the width of the tropical belt alone is probably not large enough to explain the trends observed over the past quarter century. In a sample of 40 100-year projections by 16 climate models, under the A2 scenario, widening over 25-year periods has a mean value of 0.5 degrees latitude, exceeds 2 degrees in only 3% of the cases, and never exceeds 2.75 degrees (C. M. Johanson, personal communication). Similar inconsistency has been noted between observed and model-projected trends in a related feature of the climate system, Northern Hemisphere sea-level pressure patterns³¹. However, those predictions are from models that do not represent stratospheric processes and interactions between the stratosphere and troposphere well, which may play an important role in the observed recent changes. Reducing uncertainties associated with these trend estimates will require not only more refined observations and better models, but also a more complete understanding of the processes responsible for the simulated and observed expansion and its drivers. Ultimately, this will improve predictions of future climate change.

between the tropical regions, where total column ozone concentration is relatively low, and extratropical regions, where it is higher. In an effort to distinguish chemical and meteorological effects on ozone trends, they demonstrated that 1979–2003 trends in total column ozone in the Northern Hemisphere are partly due to trends in the relative area of the tropics, midlatitudes and polar regions, as defined meteorologically. As shown in Fig. 2, their analysis indicates that the area of the Northern Hemisphere occupied by the tropical region, as defined by ozone values, grew during the 25-year period at a rate of 1 degree latitude per decade (or a net widening of about 2.5 degrees in the Northern Hemisphere part of the tropics).

From analysis of a completely independent set of satellite-based microwave observations of atmospheric temperature, Fu *et al.*⁷ inferred tropical-belt widening for the period 1979–2005. Noting that stratospheric cooling and tropospheric warming trends are stronger in the 15–45 degree latitude belts of both hemispheres, they invoked dynamical and thermodynamical arguments to suggest that, unless compensated by surface pressure changes, the shape of tropospheric pressure surfaces would change in such a way as to shift the jet streams of both hemispheres poleward. They estimate a net widening of the tropical belt of about 2 degrees latitude, which is about half of the ozone-based estimate made by Hudson *et al.*⁶ for the Northern Hemisphere alone.

A third approach, by Seidel and Randel⁸ used tropopause height changes in the subtropics to estimate changes in the width of the tropics. Radiosonde (weather balloon) and reanalysis (observations assimilated into, and analysed by, an atmospheric model) data both show that the height of the tropopause has a bimodal distribution in subtropical latitudes, but not within the tropics or the high latitudes. Defining the tropics as the region of frequent high (> 15 km) tropopause, they report an expansion of 5 to 8 degrees latitude during 1979–2005, with the Southern Hemisphere showing a more longitudinally consistent trend than the Northern Hemisphere. Reichler and Held (presented at the American Meteorological Society Conference on Climate Variability and Change, 2005) found consistent results in other aspects of the tropopause.

Using two other types of observations, Hu and Fu⁹ also found a widening of the tropical Hadley circulation system, and estimate its magnitude as 2 to 4.5 degrees latitude during 1979–2005. They used atmospheric reanalysis data to locate the latitude of zero net wind flowing in a north–south direction. They also used satellite observations of outgoing longwave (infrared) radiation emitted by the Earth (which is strongly dependent on cloud cover and atmospheric water vapour) to find the dry subsidence regions at the edges of the Hadley cells. Both methods showed robust evidence of tropical belt expansion.

In addition to this poleward expansion of the tropical belt, its height, as measured by the height of the tropical tropopause, has also increased, by some tens of metres over the past few decades^{10–12}. The overall three-dimensional growth of the atmospheric volume of the tropical belt is roughly 5%.

OUTSTANDING RESEARCH QUESTIONS

These findings are intriguing and raise a number of questions for further research. As summarized above, there are differences among the various observational estimates of widening trends which have not been examined. These differences might be due to a decoupling of the physical processes involving different measures of the width of the tropics, or they may be reconcilable in terms of observational uncertainty. Regional and seasonal characteristics of the widening have not been explored in any detail. The observed widening appears to have occurred faster than climate models predict in their projections of anthropogenic climate change. What does this tell us about the ability of models to simulate the processes responsible for the observed changes? To explain this difference

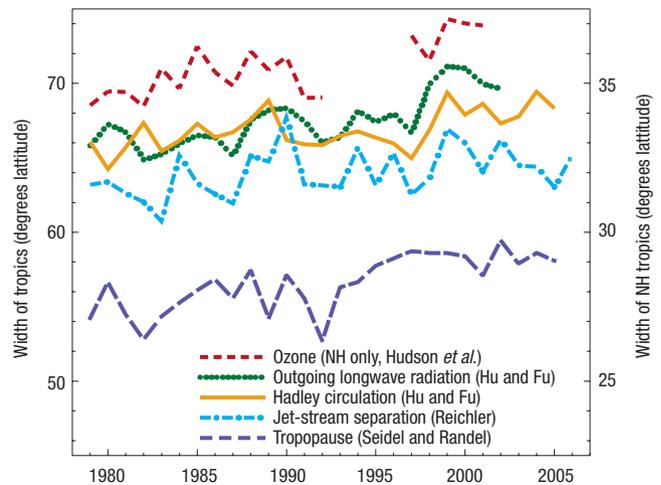


Figure 2 Changes in several estimates of the width of the tropical belt since 1979. These include: the width of the Hadley circulation, based on both outgoing longwave radiation and horizontal winds streamfunction⁹; the separation of the Northern and Southern Hemisphere subtropical jet-stream cores; the width of the region of frequent high tropopause levels⁸; and the width of the region with tropical column ozone levels (Northern Hemisphere only, right axis, ref. 6). Although each shows an increase since 1979, the rates vary from 2.0 to 4.8 degrees latitude per 25 years, with an even larger range when considering the entire spread of trend estimates in each individual study.

will require a more nuanced understanding of the nature of the widening and its causes.

There are other indicators, some as yet unexamined, of the width of the tropical belt. For example, other aspects of the hydrologic cycle (in addition to clouds) may be helpful in delineating the tropical belt and finding evidence of changes in its width. These include atmospheric water vapour, which may have a sharp gradient at the edge of the tropics¹³, precipitation, and the location of the ‘zero-crossing’ of precipitation minus evaporation fields¹⁴. Aspects of the tropospheric wind field could be examined in more detail, including the boundary between the tropical easterlies and midlatitude westerlies, the position of the axis of the subtropical jet streams, and the location of maximum surface westerlies. Stratospheric circulation (the Brewer–Dobson circulation) may show evidence of changes in the tropics and may give indications of linkages between stratospheric, tropospheric and tropopause changes. Aspects of changes in atmospheric radiation fields might be usefully explored to determine whether the expansion is related to changes in atmospheric composition.

Indeed, considerable uncertainty surrounds the mechanisms causing the observed widening of the tropics and, specifically, of the Hadley circulation. Some possibilities include: internal low-frequency climate variability; stratospheric ozone depletion; warming of sea surface temperatures¹⁵; a change in the vertical temperature structure of the troposphere^{14,16}; and an overall increase in tropopause height^{10,17–19}. Other potential, still unexplored, mechanisms include changes in the El Niño Southern Oscillation system²⁰, stratospheric climate changes, and changes in the characteristics of extratropical weather systems and ocean currents and how they redistribute heat and moisture from the tropics into the higher latitudes²¹.

WORLDWIDE IMPLICATIONS

The edges of the tropical belt are the outer boundaries of the subtropical dry zones (Fig. 1) and their poleward shift could lead

to fundamental shifts in ecosystems and in human settlements. Shifts in precipitation patterns²² would have obvious implications for agriculture and water resources and could present serious hardships in marginal areas. Of particular concern are the semi-arid regions poleward of the subtropical dry belts, including the Mediterranean, the southwestern United States and northern Mexico, southern Australia, southern Africa, and parts of South America. A poleward expansion of the tropics is likely to bring even drier conditions to these heavily populated regions, but may bring increased moisture to other areas. Widening of the tropics would also probably be associated with poleward movement of major extratropical climate zones due to changes in the position of jet streams, storm tracks, mean position of high and low pressure systems, and associated precipitation regimes. An increase in the width of the tropics could bring an increase in the area affected by tropical storms, or could change climatological tropical cyclone development regions and tracks.

Widening of the tropics may also lead to changes in the distribution of climatically important trace gases in the stratosphere. The Brewer–Dobson circulation moves air upwards from the troposphere into the stratosphere in the tropics. If the area over which this upwelling occurs increases, transport of water vapour into the stratosphere might be enhanced. This could lead to an enhanced greenhouse effect, including tropospheric warming and stratospheric cooling²³, and reduced ozone²⁴.

More far-reaching changes in the climate system include the oceans and biosphere. Because atmospheric winds and air-sea exchanges drive the ocean currents, changes in the Hadley circulation may induce changes in the ocean circulation. These may have important feedbacks on tropospheric climate, marine ecosystems (including fisheries) and biogeochemical cycles, which have been hypothesized to lead to irreversible climate change²⁵.

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