Essay 5

Expansion of the Tropics – Evidence and implications

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Expansion of the Tropics

Dr Joanne Isaac & Professor Steve Turton.

There is accumulating evidence that the tropical zone is expanding poleward in both hemispheres, and that the subtropics are also expanding into regions which have previously enjoyed a more Mediterranean climate. This essay is a follow-up to an initial report by the same authors conducted in 2009; there has been considerable further work in this field since 2009 and so we include up-to-date research, investigate how thinking has changed, or not, and whether predictions from five years ago still hold true.

A poleward expansion of the tropical and subtropical zones is likely have significant consequences for a number of the issues raised in the State of the Tropics Report (2014), including the peoples of the Tropics, and for ecosystems and biodiversity.

For example, The State of the Tropics report highlights that the resources required to sustain larger populations and economic growth are putting significant pressures on the natural environment in tropical regions. An expansion of tropical regions will only increase these demands further, and may also cause a shift in ecosystems as some regions will become drier, and others may see more frequent heavy rain events.

The Report also highlights the fact that almost half the human population of the Tropics is vulnerable to water stress – a shift in climatic zones, and potentially drying in regions currently neighbouring the subtropics could increase the number of people who are at risk.

Furthermore, the State of the Tropics report finds that despite improvements in health and nutrition over the past 50 years, the Tropics still bears a 'disproportionate share of the global burden of many communicable and preventable diseases.' An expansion of the tropical zone could increase the prevalence of many diseases, particularly vector-borne diseases, as more areas become climatically suitable for insect vectors.

Introduction

Climate change is unequivocally one of the most important threats facing humanity and the environment (Williams et al. 2008; IPCC 2014). Documented changes already include warming of the atmosphere and ocean, melting of snow and land and sea ice, rise in sea levels and increases in concentrations of greenhouse gases (GHGs) to unprecedented levels (IPCC 2014). While some of the earliest signs of climate change included the warming of temperate regions and the melting of ice in the Arctic, a suite of studies have demonstrated significant impacts in tropical regions which are likely to be disproportionately affected (eg refs of some of the 'suite of studies'). The most recent IPCC Working Group II Report (2013) states that, with high-confidence 'relative to natural internal variability, near-term increases in seasonal mean and annual mean temperatures are expected to be larger in the Tropics and subtropics than in mid-latitudes'.

Additionally, long-term meteorological measurements indicate that climate-driven changes may be responsible for the expansion of the earth's tropical zone (reviewed by Seidel et al. 2008, IPCC 2013, Lucas et al. 2014).

The tropical zone is commonly defined as the portion of the Earth's surface that lies between the Tropic of Cancer at 23.5º north latitude and the Tropic of Capricorn at 23.5º south. The origin of this Cartesian definition lies in astronomy, as these lines mark the northern and southern-most points on the Earth where the sun reaches its zenith at solar noon during the boreal (June 21) and austral (December 21) summer solstices.

However, the definition of the Tropics varies among scientific disciplines, and climatologists use different indicators to define the boundaries of the Tropics, commonly based on surface temperature and precipitation patterns (Seidel et al. 2007). Another, easily tracked characteristic of the Tropics lies high above the Earth, at the boundary between the troposphere, the lowest layer of the earth's atmosphere where weather systems form, and the stable stratosphere above it. This boundary is known as the tropopause and is at its highest over the Tropics where it can reach 18 km in altitude, while over the poles it occurs at around 8 km. Thus, the height of the tropopause is another feature used by climatologists to define tropical regions. In general, climatologists and meteorologists estimate the boundaries of the Tropics extend further from the equator than the traditional Cartesian definition, to around 30º latitude north and south of the equator. This latitude roughly separates the generally slow moving tropical and subtropical air masses from the highly mobile air masses that typify the weather and climate of the mid-to-high latitudes.

The tropical zone is straddled by the less well-defined subtropical zone, the climatic region found adjacent to the Tropics, usually between 20 and 35 degrees latitude in both hemispheres, but occasionally found at slightly higher latitudes.

Tropical regions are characterised by a warm to hot climate, with comparatively smaller seasonal changes in day-to-day temperatures compared to other regions. Another important feature of the Tropics is the prevalence of rain in the moist inner regions near the equator – the 'deep Tropics' - which distinguishes tropical regions from the much drier conditions of the subtropics, where the world's major desert regions are located (Seidel et al. 2007). Seasonality of rainfall in the Tropics increases with distance from the equator.

How much has the tropical zone expanded?

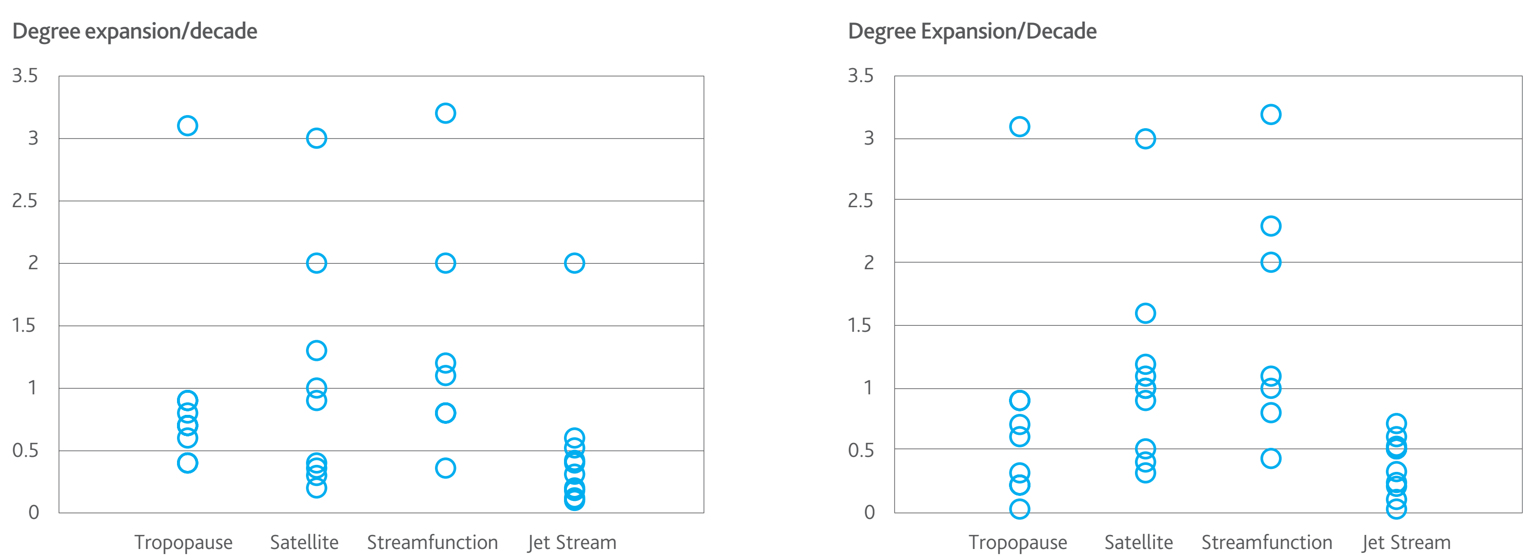
In 2009, we reviewed a number of, then current, studies employing varying methodologies to measure the expansion of the tropical zone. For example, Hudson et al (2006) used long term satellite measurements of ozone concentration and estimated that the area of the northern hemisphere occupied by the Tropics had expanded by approximately 1º latitude per decade in the period 1979-2003 – a total widening of 2.5º. Fu et al. (2006), over the same time period, used satellite temperature observations from 1979-2005 and estimated a slightly lower widening of 2º latitude across both hemispheres, while Seidel and Randal (2007) - using data from weather balloons and climate models - estimated a significantly larger increase of between 5 to 8º in the same period.

Since our initial review, there have been a number of new studies that have estimated the total widening of the tropical zone, recently reviewed by Lucas et al. (2014). There are now at least 32 different estimates of the degree of expansion of the tropical zone - across different time periods (Figure E5.1). An updated mean of the estimates is slightly lower than in 2009, at around 0.5 – 1.0º per decade (summarised in Lucas et al. 2014). However, considerable variation is evident among the estimates, possibly in part due to the different methodologies that have been employed in the studies and the number of years comprising the data.

A thorough critique of these methodologies can be found in Lucas et al. (2014); however we will briefly review the four main ways researchers have estimated the degree of widening of the tropical zone:

- Tropopause methods: this method uses the tropopause height frequency to estimate widening of the Tropics both vertically and horizontally. This method is sensitive to the choice of the tropical tropopause threshold and the definition of the tropical edge. Studies using this method generally estimate a horizontal widening of less than 1º latitude per decade, although there is some variation.
- Satellite methods: Various metrics, such as outgoing long-wave radiation from satellite-based platforms have also been used to investigate expansion. Differences between data sets are large using these methods, and estimates also often differ between the hemispheres – with greater widening seen in the southern hemisphere. Lucas et al. (2014) identify this method as likely to be most problematic.
- Stream-function methods: This metric is the edge of the Hadley Circulation (described below) derived from calculation of the (isobaric) mass stream-function. It generally gives a lower estimate of expansion, averaging less than 0.8º latitude widening per decade in both hemispheres, and shows seasonal differences.
- Jet Stream Methods: this method uses the change in the position of the various jet streams to estimate tropical expansion. Estimates using this method average the lowest of all the different methodologies, around 0.2º latitude per decade.

Figure E5.1 **Figure 1: Summary of studies which have provided an estimate of the degree of expansion of the tropical zone for a) the southern hemisphere, and b) the northern hemisphere (data collated from Lucas et al. 2014)**



Source: Lorem Ipsum

Thus, while evidence has continued to accumulate for the widening of the tropical zone, the estimates now suggest a lower degree of expansion than was reported in our 2009 review. In their recent review, which used all known published estimates, Lucas et al. (2014) found an average trend of 0.5 – 1.0º in latitude expansion per decade, translating to 1.25 – 2.5º per 25 years, or 138 – 277 km. This is much reduced from the estimate of 222 to 533 km per 25 years taken from studies we reviewed in 2009.

In 2006, Fu et al. (2006) also suggested a stronger longitudinal trend for an expansion of the tropical zone in the southern hemisphere, compared to the northern hemisphere. A number of more recent studies have also found a similar trend (i.e.: Lu et al 2009, Birner 2010, Davis and Rosenlof 2012), however this seems more common in studies utilising the troposphere method. Other studies have found the opposite, with the Northern Hemisphere having greater expansion (i.e.: Zhou et al 2011, Hu et al 2011, Hu and Fu 2007) – this seems to be most common in satellite-based studies. Theoretically, one would expect great expansion in the northern hemisphere due to its land dominance compared with the moderating influence of the Southern Ocean in the southern hemisphere. Currently any potential asymmetry in expansion between the north and southern hemispheres is still unclear and may be a methodological artifact.

In addition to observations of the poleward expansion of the tropical zone, studies also suggest that the height of the Tropics, as measured by the height of the tropical tropopause, has also increased by some tens of metres over the past few decades (Seidel and Randal 2007; Zhou et al. 2001; Santer et al. 2003). Taking all estimates into account, Seidel et al. (2008) proposes that the overall three-dimensional growth of the tropical zone over the 25 years prior to 2008 was around 5%.

However, measuring tropopause height is controversial, sensitive to methodology and also varies across seasons (Lucas et al. 2014). For example, a 2010 study by Birner found that using statistics of tropopause height to distinguish between Tropics and extratropics (areas outside the tropical zone) in studies was problematic, and that widening trends were particularly sensitive to changes in the tropopause height threshold.

Additionally, a number of studies have identified shifts and changes in intensity in tropical circulation systems and climatic phenomenon. The primary driver of the climate in the Tropics and sub-tropics is the Hadley Circulation (HC) system, which can be most simply explained as a large-scale overturning of the atmosphere in the tropical zone, driven by latitudinal heating gradients (Webster 2004). The HC system drives the trade winds - and the point at which the trade winds of the northern and southern hemisphere converge and rise is known as the intertropical convergence zone (ITCZ). The ITCZ is a high-precipitation band of thunderstorms and results in the high rainfall patterns typical of the tropical equatorial zone. Following the loss of water vapour over the equatorial Tropics, the descending air dries out and moves further north and south towards higher latitudes. As this dry air begins to sink back toward Earth's surface over the subtropics, it warms, driving evaporation. This is the mechanism leading to the dry conditions experienced in many subtropical regions.

In 2006, Hu and Fu found a poleward expansion of the HC of between 2.0 to 4.5º in each hemisphere since 1979, concluding that this implied a poleward shift of the tropical and subtropical zones. In a more recent analysis, Hu et al. (2011) find a smaller, but still significant expansion of the HC from 1979 -2009 of around 1.23º in latitude in both hemispheres, based on a number of different methods. Similarly, extensive re-analysis by Nguyen et al. (2013) showed an expansion of the HC in both hemispheres of around 1.6º latitude per decade. However they found that this expansion was seasonal and most pronounced and statistically significant during summer and autumn. Choi et al. (2014) recently found a significant poleward shift of the southern edge of the HC, during the austral summer (November-March), from the South Atlantic Ocean eastward to Australia. This is estimated to be equivalent to around 0.22º per decade from 1980 – 2012.

Sachs et al. (2009) indicated that the ITCZ had also moved poleward and was now located more than 500km farther away from the equator than previously; equivalent to a shift of around 4.5º in latitude. The authors estimate the ITCZ is moving poleward in the northern hemisphere at a rate of approximately 1.4 km per year (Sachs et al. 2009). A more recent analysis confirms that the ITCZ is extremely sensitive to high- and low-climate forcings (factors that influence climate – such as energy from the sun, volcanic eruptions, etc), and depending upon cooling or warming conditions, can migrate ± 7º in latitude from its usual position over the Atlantic Ocean (Arbuszewski et al. 2013). Thus, these estimates of the latitudinal expansion of the HC and ITCZ generally fit with studies which demonstrating an expansion of the tropical zone, but can be subject to methodological and temporal/seasonal variability.

Shifts in other climatic phenomenon have also been reported for the same period. For example, a number of studies show a longitudinal, westward extension of around 10º in the Western Pacific subtropical high (WPSH) over 30 years (Ho et al. 2004; Wu et al. 2005). This is significant, as the WPSH is the predominant driver of climate and precipitation patterns across Asia. Hu and Fu (2006) suggest that other changes in more regional circulation patterns, such as the WPSH, may also be contributing to the general expansion of the tropical zone.

Mechanisms behind a tropical expansion

In addition to a general lack of consensus regarding the magnitude of shift, there has also been considerable speculation regarding the proximate and ultimate mechanisms resulting in the widening of the tropical zone (Lucas et al. 2014).
In our initial review, research suggested a role for climate change in the expansion of the tropical zone, and associated changes in climatic events and circulations systems. At that time, the IPCC

in their Fourth Assessment Report (2007) stated that increases in greenhouse gases and associated changes in climate could lead to a variety of changes in atmospheric and climatic phenomenon, including warming of the troposphere, cooling of the stratosphere, rise of the tropopause and a weakening of tropical circulation patterns – all of which may contribute to an expansion of the tropical zone. Hu and Fu (2006) further suggested that an increase in sea surface temperatures (SST) in the Tropics, associated with climate change, could result in an increase in the height of the tropopause and a wider HC.

Since then, numerous studies confirm that the tropopause is indeed warming (reviewed by Thorne et al. 2010), with the majority also suggesting a strong human influence (i.e.: Santer et al. 2013). As a result, the Fifth Assessment Report of the IPCC (IPCC 2013), is much clearer, and certain, on the warming of the troposphere, stating 'It is virtually certain that globally the troposphere has warmed since the mid-20th century. More complete observations allow greater confidence in estimates of tropospheric temperature changes in the extra-tropical Northern Hemisphere than elsewhere. There is medium confidence in the rate of warming and its vertical structure in the Northern Hemisphere extra-tropical troposphere and low confidence elsewhere.'

Anthropogenic factors are thought to influence the troposphere and other climate systems in a variety of ways, and many recent studies have focused on the role of GHG emissions (particularly CO_2), ozone depletion and aerosols in climate forcing and tropical expansion.

In 2009, Lu et al. used the height of the tropopause to characterise the tropical zone, and demonstrated that the observed widening of the Tropics can only be accurately replicated by an atmospheric general circulation model that includes direct radiative effects related to human GHG emissions and stratospheric ozone depletion.

More recent studies have attempted to clarify the relative role of GHGs and ozone depletion. A warming of the troposphere raises the height of the tropopause, as does a cooling of the stratosphere (the layer of the earth's atmosphere above the troposphere – approximately 50 km above the earth's surface). An initial report by Santer et al. (2003) provides support for warming of the troposphere and cooling of the lower stratosphere over the last four decades of the 20th century, and indicates that both of these changes in atmospheric temperature have contributed to an overall increase in tropopause height.

Essentially it is thought that the radiative forcing (the difference between energy from sunlight received by the Earth and energy radiated back to space) of GHGs cause upper trophospheric heating, and potentially stratospheric cooling, resulting in a poleward shift in the mid-latitude jetstream and an expansion of the HC (e.g.: Previdi and Polvani 2014). Evidence suggests that stratospheric ozone is being destroyed by a group of manufactured chemicals which contain chlorine and/or bromine. These ozone-depleting substances (ODS) are safe in the lower atmosphere, but float up into the stratosphere where they are broken apart by the intense ultraviolet light, releasing chlorine and bromine (IPCC 2013).

The contribution of aerosols in the expansion of the tropical zone has gained much attention in recent years, and of primary interest has been black carbon (BC); BC is formed by the incomplete combustion of fossil fuels and can cause global warming by absorbing heat in the atmosphere. It is also thought to reduce the ability to reflect sunlight, or albedo, when deposited on snow and ice. Aerosol forcing of the climate may be significant (Lucas et al. 2014), and may occur when heating associated with absorbing aerosols changes relative humidity and impacts the lifetime of clouds.

However, the relative contribution of GHGs, ozone depletion and BC aerosols in the expansion of the tropical zone and associated climatic forcings is still unclear, with studies finding conflicting results. In a recent analysis, Santer et al. (2013) find that warming of the troposphere is mainly driven by anthropogenic GHG emissions, while cooling of

New Britain.
Image:Michael Johnson.

the lower stratosphere is primarily attributable to human-caused stratospheric ozone depletion. Similarly, Lu et al. (2009) found the widening trend in the tropical zone could be attributed entirely to direct radiative forcing, in particular related to greenhouse gases and stratospheric ozone depletion, while Hu et al (2013) found that widening and poleward shift of HC are caused by anthropogenic forcings and particularly increasing GHGs.

Other studies implicate BC, with Rostatyn and Lohmann (2002) finding that the indirect aerosol effect has been found to potentially drive the observed southerly shift in the ITCZ, and BC has been implicated in a northward displacement of the ITCZ and a strengthening of the HC in the Northern Hemisphere (Wang 2007).

In a recent study published in *Nature* (Allen et al. 2012), BC and tropospheric ozone were found, in models, to better explain the observed expansion of the tropical zone in the Northern Hemisphere than were GHGs. The authors note that atmospheric heating in the mid-latitudes from BC and tropospheric ozone has generated a poleward shift of the tropospheric jets.

The role of increasing sea surface temperature (SST), due to climate change, remains unclear, with studies giving conflicting results. For example, Lu et al. (2009) conclude that SST forcing causes no significant change in the width of the Tropics, and even a contraction in some seasons. However, Allen et al. (2014) state that tropical expansion and contraction are influenced by sea surface temperature variability, which is associated with both the Pacific Decadal Oscillation (a long-lived El Niño-like pattern of Pacific climate variability) and anthropogenic aerosols.

Studies have also identified that natural events and natural variation can impact on the expansion of the tropical zone. Volcanic eruptions, which inject sulfur dioxide into the atmosphere, typically result in cooling on the earth's surface and in the lower atmosphere. They thus have the opposite effect of BC aerosols and absorb radiation – warming the lower stratosphere, and cooling and lowering the tropopause, and potentially thus contraction of the tropical zone (Santer et al. 2003; 2014). The IPCC (2013) stated that several small volcanic eruptions have contributed to radiative cooling from 2008-2011.

In summary, there is still no clear consensus on a single primary forcing mechanism behind the observed expansion of the tropical zone (Lucas et al. 2014). To date, studies and modeling indicate that several interacting factors are likely involved, including anthropogenic GHGs, black carbon and warming sea surface temperature. Volcanic eruptions may contribute to temporarily reverse expansion, and cause contraction.

The implications of an expansion of the tropical zone

The Tropics currently occupy approximately forty percent of the Earths land surface and are home to almost half of the world's human population, and account for more than 80% of the Earths terrestrial biodiversity (e.g. Rosenzweig 1995; State of the Tropics 2014). The majority of the world's endemic plants and animals are also found in the Tropics, where they are commonly adapted to the specific climatic conditions found there. Thus, the implications of a poleward expansion of the tropical and subtropical zones are immense and the effects could result in a variety of social, economic and environmental implications (Seidel et al. 2008), which will be discussed in the following sections.

Drought, drying and shifts in climatic zones
In our initial review, we highlighted a number of predicted scenarios from researchers investigating the observed expansion of the tropical zone. At that point in time (2009), the most important predicted consequence was the poleward extension of the subtropical dry zone - bringing drought conditions to regions which currently have a temperate climate with predicable winter rainfall (Seidel et al. 2008). Fu et al (2006) also demonstrated a robust pattern of warming in the mid-latitudinal region, from around 15 to 45º latitude in both hemispheres, indicative of a poleward shift which was predicted to lead to mid-latitude tropospheric warming and contribute to an increased frequency of droughts in both hemispheres (Fu et al. 2006; Seidel et al. 2008). Of particular concern under these predictions were regions bordering the subtropics which currently experience a temperate 'Mediterranean' climate, including heavily populated regions of southern Australia, southern Africa, the southern Europe-Mediterranean-Middle East region, the south-western United States, northern Mexico, and southern South America – all of which were predicted to experience severe drying (Seager et al. 2007; Seidel et al. 2008).

In 2009, the fingerprint of a poleward march of the subtropics into temperate regions was already becoming evident; climate models from the IPCC (2007) were predicting droughts for regions of the Mediterranean and the south-west of the US, while Seager et al. (2007) similarly forecast that southwestern North America would see an imminent shift to a more arid climate. The south-western state of California was, at that time, already in the grip of a multi-year drought (California Department of Water Resources 2008) and significant drying had been observed in the south-west of Western Australia over the previous 50 years, although other Mediterranean climates in Australia (e.g. South Australia) had experienced less significant declines (Bureau of Meteorology, Australia 2009).

More recent studies indicate that some of predictions may indeed be becoming a new reality. Shin et al. (2012) investigated the expansion of areas of dry climate, comprising steppe and desert climates, in relation to the observed intensification of the HC. They find some evidence of an expansion of these climatic zones from 1950 – 2000, concomitant with an enhanced intensity of the HC was enhanced, particularly during the boreal winter (Novermber – March) and conclude an observational linkage that connects desertification with intensification of Hadley Circulation. Polovina et al (2011) further project that the area of the subtropical region will expand by 30% by 2100.

There are also indications of an increase in drought conditions in areas bordering the subtropics. For example, in 2011, the USA state of Texas experienced its worst single-year drought in history, during a drought period beginning in 2010, and currently still continuing (e.g: Seager et al. 2014) – this drought has also affected the neighbouring state of New Mexico to the west. Severe drought conditions are also continuing to impact the state of California (Aghakouchak et al. 2014).

In south-western Western Australia, low rainfall persists and some regions recently experienced the lowest precipitation conditions on record (BOM 2014). Post et al. (2014) also confirm an ongoing expansion of the HC, of 0.5° latitude per decade, leading to a reduction in winter rainfall and run off in southern Australia. Cai et al. (2012) confirm that a poleward shift of the sub-tropical dry-zone explains most of the decline in rainfall in southeastern Australia during April-May. Increasing droughts have been noted also in the Mediterranean Basin (Hoerling et al. 2012), South America (Morales et al. 2012) and China (Ye 2013).

However, how much of this drying can be attributed to the expansion of the subtropical zone remains unclear. Cai et al. (2012) examined the role of tropical expansion on the drying trend apparent in some southern hemisphere regions during austral autumn (March-May). They found rainfall reduction coincided with a poleward expansion of the tropical and subtropical dry zones by around 2°–3° latitude in the same season. However, while their results show that a poleward shift of autumn rainfall may explain most of the southeastern Australia rainfall decline, it explains only a small portion of the southern Africa rainfall trend and none of autumn drying over southern Chile.

Eastman and Warren (2013) investigated changes in global cloud cover, and find a small decline of 0.4% per decade. However, the trend is primarily attributed to declining clouds in the middle latitudes – particularly across South America and Australia, which both showed continent-wide decreases in total cloud cover. They link cloud changes to the observed poleward shift of the jet streams in both hemispheres. Similarly, Polade et al. (2014) investigated the future increase in dry days in subtropical regions, concluding that many regions could see up to 30 more dry days per year by the end of this century, and that over most of the subtropics, the change in number of dry days dominates the annual changes in precipitation

A decline in visibility, due to an increase in conditions leading to smog, has also been associated with the intensification and westward extension of the WPSH in eastern China. A decline of 1.4 km of visibility per decade has been estimated, equivalent to 34% over 37 years, linked to more days with stable, hot and humid weather (Qu et al. 2013).

Recent studies also implicate some of the pollutants associated with tropical widening, such as the indirect aerosol effect and black carbon, as drivers of drought. For example, the indirect aerosol effect has been associated with a southward shift in the ITCZ, potentially associated with past Sahelian drought (a climate zone between the African savanna grasslands to the south and the Sahara desert to the north, across West and Central Africa; Rotstayn and Lohmann 2002). Changes in cloud type associated with the Indian monsoon are also consistent with the suggestion that BC could be affecting monsoonal precipitation and causing drought in northern India (Eastman and Warren 2013), while Turner and Annamalai (2012) found that BC could intensify the Asian summer monsoon.

If the dry subtropics belt expands into regions more used to a temperate, wet winter season, there will be consequences for water resources, natural ecosystems and agriculture, with cascading social and health implications (Fu et al. 2006; Seidel et al. 2008). In many tropical regions, more than 90% of the population works in agriculture and, since water dictates tropical agriculture, variability of climate may be responsible for economic weakness in such areas (Balek 1983). The State of the Tropics report (2014) notes that current water use patterns are considered unsustainable in many tropical regions; agriculture accounts for 81% of water withdrawals in the Tropics compared with 69% globally. Historical records show that higher growing season temperatures have dramatic impacts on agricultural productivity, farm incomes, and hence food security (Battisti and Naylor 2009). Thus, increasing drought could lead to large scale human migrations as people search for jobs, which may lead to overcrowding, violence, disease outbreaks and pressure on local resources in neighbouring areas (Matthew 2008). Droughts and global food crises have recently been implicated as a causal factor of riots and violence in a number of regions, including South Africa (Bar-Yam et al. 2013). Studies already demonstrate that climate change related drought in developing countries can result in the loss of human lives to hunger, malnutrition and diseases, the emergence of environmental refugees, and the collapse of national economies (Batterbury and Warren, 2001; Mortimore and Adams, 2001). For example, the Sahal region, which borders the southern edge of the Sahara desert in Africa, has seen a decline in per capita food production following drought, exposing many people to food insecurity and income poverty (Battersby and Warren, 2001).

However, while many regions are predicted to become hotter and drier, some may experience more rain. For example, studies suggested a poleward expansion of the ICTZ may also bring increased precipitation to areas at a greater distance from the equator, while areas close to the equator may receive less rainfall (Sachs et al. 2009) and also that wetter, higher-latitude regions may become wetter still and experience extreme rainfall events (Seager et al. 2007). In 2009, severe flooding affected the normally arid northeastern region of Brazil apparently due to an anomaly in the path of the ITCZ, while Southern Brazil was gripped by drought – events potentially related to the poleward movement of the ITCZ in the northeast and the expansion of the dry subtropics to the south.

Furthermore, due to the apparently simultaneous shift of other climatic events, such as the WPSH, some regions, particularly parts of Asia, actually appear to experience a cooling effect, rather

Bali.
Image: Andy Holt.

than the more widespread warming (Gong and Ho 2002, Hu et al. 2003, Fu et al. 2006). There is some evidence that the severe polar vortex affecting the north east USA - following drought in California - was influenced by GHG emissions and poleward shifts in other climatic phenomena (Wang et al. 2014).

Shifts in tropical cyclone tracks and activity
In 2009, a number of climate scientists were predicting a poleward shift in the paths of extra-tropical and tropical cyclones over the next 100 years (Yin 2005; IPCC 2007; Walsh and Kafney 1999). However, others were arguing that increased vertical wind shear and upper tropospheric warming might negate some effects (e.g.: Vecchi and Soden 2007). Extra-tropical storms, also known as mid-latitude cyclones, occur within the mid-latitudinal band from around 30º to 60º latitude in both hemispheres and studies have documented a poleward shift in the mean latitude of extra-tropical cyclones, by about 2º, over the past 60 years (McCabe et al. 2001; Fyfe 2003).

More recent studies add observational support for a change in storm tracks; for example Bender et al. (2012) find a poleward shift in extra-tropical storm tracks between 1983-2008, while Solman and Orlanski (2013) find an enhancement of the frontal activity shifted to higher latitudes in the northern hemisphere. Similarly, ozone depletion has been associated with a poleward shift in cyclone frequency over the Southern Ocean, but with minimal influence on intensity and lifetime (Grise et al. 2014). Significantly, a very recent study shows a poleward shift in the area of maximum intensity in cyclones in both the Northern and Southern hemispheres, of 53 and 62 km per decade respectively; equivalent to a shift of around 2.5º in latitude per 25 years (Kossin et al. 2014). Shifts in the behavior and tracks of cyclones in Australia have also been noted with tropical cyclone activity is currently at its lowest in Queensland and Western Australia for many centuries (Haig et al. 2014). However, Haig et al. (2014) caution that while there will be fewer cyclones, cyclones that do hit will be of higher intensity.

The shifts in tropical storm tracks have been related to enhanced warming in the tropical upper troposphere and increased tropopause height (Yin 2005); there is also some evidence that the degree of shift is likely to be greater in the mid-latitudes of the southern hemisphere (IPCC 2007; Yin 2005). Predictions were for greater cyclonic activity at higher latitudes in both the tropical and mid-latitude bands (IPCC 2007), increasing flood risk in regions not prepared for extreme precipitation events.

A change in the activity and tracks of tropical cyclones has been noted in some regions. For example, tropical cyclone Gonu tracked unusually far to the northwest into the Gulf of Oman in 2007, hitting landfall in Oman and Iran, a region with no known records of having been hit by a cyclone (WMO 2008). Similarly, in Asia there has been a significant westward shift in typhoon (cyclone) tracks over the past 40 years, resulting in greater storm activity in subtropical East Asia but a decline in typhoons over the South China Sea. 2004 saw a record number of storms hit Japan, while South China faced drought due to a lack of land falling typhoons, and the authors suggest this shift is related to the westward movement of the WPSH (Wu et al. 2005).

More recent studies highlight further changes in cyclone activity; black carbon and other aerosols have been implicated in causing intensification of cyclones in the Arabian Sea region, with significant impacts expected for human health (Evan et al. 2011). In Taiwan, cyclone frequency has almost doubled since 2000, consistent with a northward shift of the typhoon track over the western North Pacific-East Asian region, and an increase of typhoon frequency over the Taiwan-East China Sea; the authors associate these changes with the weakening of the Western North Pacific subtropical high (Tu et al. 2009). Finally, Murakami (2013) finds a decline in typhoon frequency over western Japan and the Korean peninsula, but an increase over eastern Japan, related to the southward shift of the subtropical jet stream.

The economic costs of increasing extreme weather events such as drought, extreme heat waves, flooding and destructive winds, could be considerable. Since the 1950s, the global costs of extreme weather events have risen by around six orders of magnitude, with much of the increase occurring since the late 1980s (UNEP 2005). The total cost of extreme weather events in the USA, in 2011, was estimated to be over US$53 billion, not including health care (NRDC 2011). Extreme weather events resulting in destruction of crops could also be considered a global food security issue (Brown and Funk 2008).

Impacts on biodiversity

Biodiversity is greater in the Tropics across most taxonomic groups, with an equivalently higher proportion of threatened species. For those plants and animals for which there are adequate data, loss of biodiversity is greater in the Tropics compared to the rest of the world (State of the Tropics 2014). The Tropics contains more biodiversity 'hotspots' (Myers 2000) and more endemic species than any other region. In 2009, there was accumulating evidence that many animal and plant species were moving poleward in an attempt to track their preferred climatic conditions (e.g. Parmesan and Yohe 2003) and since then documented range shifts have been reported in many species from many different taxa, including those in the Tropics (e.g.: Chen et al. 2011, Vanderwal et al. 2013).

In 2003, Parmesan and Yohe (2003) estimated that species around the globe had moved 6.1 km per decade towards the poles. Converting this to a 25 year average, in line estimates of the expansion of the Tropics in earlier sections, this means that most species were predicted to move only around 15 km, or 0.13 º in latitude – implying that the poleward movement of most plants and animals would lag behind the movement of climatic zones by at least 207 km, or 1.87º latitude based on the most conservative estimates at that time – which could potentially lead to species loss and extinction in the Tropics.

A more recent meta-analysis (Chen et al. 2011) found that - on average - species have moved at 16.9 km per decade, equivalent to 42.24 km or 0.38º latitude in 25 years – more than twice as fast as the estimate from Parmesan and Yohe (2003) in their seminal paper. Combined with the revised lower average estimates of the poleward shift of the tropical zone (see previous section), the lag between species and climate zones is now estimated to be at least 0.87º latitude or 96 km. While this indicates that plants and animals are shifting their range quicker than was previously thought, it still means they are lagging almost 100 km behind potential physical shifts in climate (and, as a result, vegetation) zones. However, the response of species to climate change is likely to be far more complex, and VanDerWal et al. (2013), using 60 years of Australian climatic data and changes in climatic niche space in 464 Australian birds, show that shifts in climatic niche space occur rapidly, and in multiple directions – not just poleward, as has been previously suggested. They suggest multi-directional shifts are related to both changes in temperature and precipitation patterns, and estimate that, if measured only in terms of poleward shifts, the fingerprint of climate change will be underestimated by an average of 26% in temperate regions of the continent, and 95% in tropical regions (VanDerWal et al. 2013).

Potential expansion of pests and disease

A further implication of the potential expansion of the tropical zone is the expansion of associated diseases and pests. Of particular concern has been the potential for an extension in the geographical range of vector-borne diseases such as malaria, dengue fever and Lyme's disease, as temperatures and precipitation patterns become more suitable for disease vectors including mosquitoes and ticks (Githeko et al. 2000; Kovats et al. 2001). In 2010 the Tropics region represented 96% of cases and 99% of deaths from malaria, and approximately 72% of dengue infections occur in the Tropics (State of the Tropics 2014), thus any expansion in the range of these diseases will have significant impacts. Githeko et al. (2000) propose that the greatest impact on transmission rates will occur at the extremes of the range at which transmission now occurs, suggesting an increase in occurrence in the subtropical regions bordering the tropical zone. Patz et al. (1998) modeled the potential spread of dengue carrying mosquitoes and conclude that endemic potential could increase by up to 47% in regions already at risk, and that incidence may increase first in those regions which currently border endemic zones in either latitude or altitude. The greatest increase in the annual epidemic potential of dengue was forecast to occur in subtropical regions, including the southern United States, China and Northern Africa in the northern hemisphere, and South America, southern Africa, and most of Australia in the southern hemisphere.

In 2009, the evidence supporting actual changes in disease transmission rates and geographic range was limited, particularly in the case of malaria (e.g.: Hay et al 2002; Reiter 2005). At that time, many models were predicting an increase in occurrence and the range of disease vectors with increasing temperatures. However, since mosquitoes and ticks can desiccate easily and die under dry conditions (WHO 2003), regions predicted to become more arid as a result of tropical expansion may in fact be less at risk. Despite this, there was some evidence accumulating for an increase in the occurrence of tick-borne disease and dengue fever outside of the normal range - tick-borne encephalitis in Sweden had shown an increase in recent years and had been linked to milder temperatures (Lindgren and Gustafson 2001). Gatewood et al. (2009) also proposed that milder temperatures will result in more virulent strains of Lyme disease in North America while the World Health Organization recorded the extension of dengue fever into 15 new locations, including Hawaii, Nepal and Bhutan, in the period from 2000-2008.

More recent peer-reviewed studies reveal a stronger indication that disease vectors may be expanding their geographical range. For example, Lambrechts et al. (2010) state that the mosquito Aedes albopictus has dramatically expanded its geographic range over the past three decades, with implications for a variety of arthropod-borne viruses that it can carry, including dengue fever. There has also been a reemergence of dengue fever in Florida, since 2009 (Radke et al. 2012). There are also a number of studies which show an increase in range for tick species which carry Lyme disease. For example, the primary tick vector of Lyme disease in North America, *Ixodes scapularis*, has expanded its range northward from the USA to colonise new regions in southern Canada; the authors state that this expansion is likely related to climatic warming (Leighton et al. 2012). Milder, shorter winters are also favouring the northern expansion of the white-footed mouse in Quebec, which is an important reservoir host for *Borrelia burgdorferi*, the pathogen responsible for Lyme disease (Roy-Dufresne et al. 2013). A similar picture has been found in Europe, where the range of the tick vector *Ixodes ricinus* is predicted to spread across northern Scandinavia, due to climate warming, and eventually encompass most of Sweden, Norway and Finland (Jaenson and Lindgren 2010).

Tonnag et al. (2010) have predicted a redistribution of malaria vectors in Africa based on climate change scenarios, with shifts in species boundaries expected southward and eastward. A recent study also provides evidence for an increase in the altitude of malaria distribution during warmer years in the highlands of Ethiopia and Columbia, implying that warming conditions could result in an increase of malaria in densely population highland regions of Africa and South America (Siraj et al. 2014).

Dengue hemorrhagic fever kills up to 12,000 people a year, mainly children, and the annual economic cost in the Americas and Asia of dengue fever is around US$1.8 billion (Suaya et al. 2009). Githeko et al. (2000) propose that human settlement patterns in different regions will influence disease trends and that health risks will differ between countries that have developed health infrastructures and those that do not.

Conclusions and summary

In 2009, we found there was accumulating evidence for the expansion of the tropical zone in both hemispheres. At that time, the Tropics were estimated to be expanding by between 222 to 533 km per 25 years, taken from studies we reviewed. In the five years since that report, evidence has continued to amass pointing to a tropical expansion, and more robust methodologies have been developed and critiqued. An estimate from more than 30 studies now puts the rate of tropical expansion somewhere between 1.25 – 2.5º, or 138 – 277 km, per 25 years. Thus more recent studies tend to agree on a lower, but nonetheless significant, rate of expansion. However there is still disparity among estimates, most likely due to different methodologies used in estimates. In our earlier report, the drivers of the tropical expansion were very unclear, but recent research has identified that the primary drivers are likely to be greenhouse gases, black carbon, aerosols and other man-made pollutants, though this is expected to be an area of research that sees further developments in the near future.

The implications of a poleward tropical expansion are significant; subtropical arid, conditions may be seen in regions at higher latitudes which have historically enjoyed a more temperate climate, with implications for management of water resources and agricultural systems. However, some regions which currently border the equatorial zone may experience an increase in extreme rainfall, which could result in flooding, the displacement of communities and increased incidence of disease.

The poleward expansion of the Tropics appears to be linked to a concomitant expansion in the tracks of tropical cyclones, potentially bringing cyclonic activity to regions which have previously not experienced such weather events. Changes to the tracks and activity of cyclones, and other extreme weather events, will impact on human health, biodiversity and the economy. The burden of vector-borne diseases on health and the economy of the Tropics may also increase as more regions become climatically suitable for insect vectors.

The Tropics are the most biodiverse region on earth, with more endemic species and more biodiversity 'hotspots' than anywhere else. However research suggests that although many species are tracking climate changes, species in the Tropics may be lagging behind the rate of tropical expansion – meaning some species may not be able to sufficiently track their preferred environment and climate and may potentially risk extinction.

Steenbok, Kalahari.
Image: Frank Vassen.

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