Controls on global peat fires and consequences for the carbon cycle

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Abstract

The global peat carbon pool exceeds that of global vegetation and is similar to the current atmospheric carbon pool. Because fire is increasingly appreciated as a threat to peatlands and their carbon stocks, here we review the controls on and effects of peat fires across biomes. Peat fires are dominated by smouldering combustion, which ignites more easily than flaming combustion and persists in wet conditions. In undisturbed peatlands, most of the peat C stock typically is protected from smouldering, and resistance to fire has increased peat carbon storage in boreal and tropical regions over long time scales. However, drying as a result of climate change and anthropogenic activity lowers the peatland water table and increases the frequency and extent of peat fires. The combustion of deep peat affects older soil carbon that has not been part of the active carbon cycle for centuries to millennia, and will dictate the importance of peat fire emissions to the carbon cycle and feedbacks to the climate.

Peatlands are ecosystems that accumulate thick organic soil layers because of a long-term imbalance in which plant production exceeds decomposition throughout the entire organic soil column (Figure 1). Peatlands cover only about 2-3% of the Earth's land surface, but store around 25% of the world's soil carbon (C)[1]. They are most abundant at northern high latitudes (Figure 2A), where they cover approximately 4,000,000 km^2 of land[1] and store an estimated 500 - 600 Gt (Gt = 10^{15}) C. Tropical peatlands store an additional ~100 Gt C across 400,000 km^2, primarily in Southeast Asia[1,2]. Hence the global peat C pool exceeds that of global vegetation (~560 Gt C) and may be of similar magnitude to the atmospheric C pool (~850 Gt C)[3].

Peat is defined as an organic soil composed of partially decayed plant remains with less than 20-35% mineral content. Slow decomposition rates created by anaerobic conditions are viewed as a necessary condition for peatland development[4]. Plant remains are deposited into the upper peat layer, which often is located above the mean water table for at least part of the year, and undergoes aerobic decomposition. Remaining organic matter is buried and transferred to the saturated peat layer below the water table where decomposition is minimal. Thus, water table depth is a key regulator of peatland decomposition and peat accumulation rates. If warming or disturbance lowers the water table in peatlands, removal of anaerobic constraints on decomposition will stimulate loss of peat carbon to the atmosphere[5]. A lower water table also will stimulate the loss of peat carbon via combustion during wildfires[2,6], which we discuss in more detail in the sections below.

Peatland vulnerability to burning

Due to high moisture contents, the bulk of peat soils in pristine peatlands are naturally protected from burning, which facilitates the accumulation of peat over centuries to millennia in both boreal and tropical settings[7,8]. In contrast, while a shallow peat layer accumulates in many well-drained boreal forests, these soil organic layers are typically consumed during wildfires, resulting in negligible soil C accumulation across multiple fire cycles[9].

As with all wildland fires, peatlands burn when an ignition event occurs in the presence of fuel and the right conditions to support combustion. In low biomass systems, such as grasslands, fuel load availability and continuity controls fire spread. However, in high biomass systems such as peatlands, fires are controlled by heat transfer[10] and water content[11]. Peat fires generally are dominated by smouldering combustion[12], a flameless form of combustion that occurs more readily than flaming combustion[10]. Smouldering fires can persist under low temperatures, high moisture content and low oxygen concentrations[13] and as a result can burn for long periods (e.g. weeks, months) despite rain events or changes in fire weather[12]. While fast moving flaming fires can travel over 10 km h^{-1}, the rate of spread of smouldering can be as slow as 0.5 m per week[14]. Smouldering and flaming combustion during wildfires often are coupled. For example, smoldering peat can provide a pathway to a flaming fire even if the heat sources (embers or lightning) are too weak to ignite a flame directly.

In general, the peat C stock is protected from deep smouldering because of hydrologic self-regulation in peatlands[15,16]. The high porosity and storativity (storage coefficient) of surface peat layers minimizes water table variability and helps peatlands to maintain conditions too wet to sustain smouldering. If surface peat does dry and become flammable, wet dense organic layers found deeper in the peat profile typically serve as a fire barrier. However, when natural or anthropogenic disturbances interfere with hydrologic self-regulation and allow further drying, deep peat becomes vulnerable to more frequent or more severe burning.

Across some boreal regions, particularly continental North America, mean annual burn area has more than doubled in the past several decades, associated at least in part with regional warming[17,18]. Even during severe fire years, burning in undisturbed boreal peatlands typically is limited to the upper 10-20 cm of peat[19,20]. Forestry, agriculture, peat harvesting, and road construction in boreal regions all lead to peatland drainage, which can greatly exacerbate the burning of peat. Experimental drainage of a Canadian fen increased fire emissions nine-fold, resulting in release of more than 450 years' worth of peat accumulation during a single fire[6].

In the tropics, abundant and regular rainfall combined with a humid understory microclimate ensures that water inputs usually exceed evapotranspiration losses from peatlands, maintaining high peat moisture[21]. As a result, tropical swamps in their natural state are fire resistant owing to moist microclimate and low-flammability soils. Prior to large-scale settlement and agricultural conversion of peatlands, only occasional fires were detected on peatlands in Southeast Asia, even during drought spells, and with a sufficient time between fires to allow recovery of forest cover[22]. Human activities in the tropics, including plantation development, agriculture, and logging, have made peatlands more vulnerable to burning[23]. For example, disturbed peatlands in Southeast Asia are fire-prone owing to the high amount of dry, flammable materials and the lower humidity that results from a reduced tree canopy. Additionally, increased human access and activities increase the number of accidental or intentional fire ignitions. As a result, drained tropical peats tend to burn extensively. Fires consumed peat up to depths of 50 cm during the ENSO events of 1997/98 and 2006[24,25]. Drainage and logging in tropical peatlands also has shortened fire frequencies, and repeated burning has further reduced the peatland carbon stock[26].

Fire and ecological feedbacks

Due to fire resistance, fire has not played a significant historic role in the ecology of tropical peatlands. In contrast, wildfire plays an important role in the functioning of undisturbed boreal peatlands. Fire in boreal peatlands initiates plant successional change, increases soil temperatures, and increases nutrient availability similarly to burning in other ecosystems[27,28]. Heterogeneous patterns in the combustion of peat promote biodiversity by supporting the establishment of more species-rich pioneer plant communities[27]. Spatial variation in combustion also influences the undulating hummocks and hollows that characterize the ground surface of most northern peatlands. In part because of the water use strategies of *Sphagnum* (peat mosses), hummock peat has greater water holding capacity and burns less extensively than peat in hollows, which reinforces these microtopographic features[28,29].

Deeper burning of peat resulting from water table drawdown has consequences for post-fire ecosystem function and succession in both boreal and tropical regions. Although energy release from flaming fires is more intense than smouldering, active flaming produces high temperatures at the ground surface for only a brief period of time, with minimal heating of even shallow soil layers[31]. The longer duration of smouldering transfers more heat to surrounding soils and plants than active flaming. As a result, smouldering fires transfer heat deeper into the soil, and can lead to extensive fuel consumption that can be two orders of magnitude larger than that in flaming fires[12]. Increased smouldering of deeper peat as a result of water table drawdown will increase damage to heat-sensitive plant roots and microorganisms such as ectomycorrhizae and bacteria[32,33]. These altered fire effects are likely to be more long-lived in disturbed peatlands. Post-fire succession can cause disturbed boreal and tropical peatlands to shift from nonflammable to more flammable fuel types, increasing fire risk[26]. These post-fire shifts also are indicative of a loss of hydrological regulation in these systems, which likely cause a diminishment of peat accumulation even in the absence of repeated fires.

Carbon emissions from peatland burning

Due to the accumulation of peat and their role as a persistent global sink of atmospheric CO_2 throughout the Holocene, peatlands have had a net cooling effect on the Earth's climate[34]. This is despite the fact that these systems also serve as a source of methane[34], which is produced by microbes under anaerobic conditions. However, increased soil C losses from disturbed peatlands may have significant climate impacts in the future[35]. From an atmospheric viewpoint, fires in undisturbed peatlands are most likely to be CO_2 neutral because the combustion of surface peat influences carbon that is cycling rapidly (i.e., combusted carbon is quickly re-sequestered by recovering vegetation). This type of burning results in a near zero effect on atmospheric carbon over time scales of decades to centuries[36]. However, the combustion of deep peat has the potential to affect older soil carbon that has not been part of the active carbon cycle for centuries to millennia. If increases in fire frequency or burn severity lead to deeper burning in peatlands, these fires will no longer be carbon neutral, at least on time scales of centuries to millennia.

Perhaps as a harbinger of future emissions, widespread and deep burning peat fires in Indonesia in 1997 and 1998 released approximately 0.95 Gt of carbon[24,37], equivalent to ~ 15 % of global fossil fuel emissions at that time. Peat fire emissions also have indirect climate impacts. Smoke produced by peat smouldering leads to regional haze and reduced light levels, which suppresses plant CO_2 uptake[39]. Smoke from peat fires could have more widespread influences, such as on marine ecosystems[40]. Smouldering is known to produce larger emissions of CO and CH_4, volatile organic compounds, polyaromatic hydrocarbons, and particulate matter than flaming combustion. For example, tropical peat fires emit as much as three to six times more particulate matter than grassland, forest, or plantation fires per unit carbon combusted[8]. An understanding of the contribution of aerosols from biomass burning to radiative forcing in general is limited[3], and the lack of attention to aerosols from peat fires creates a striking knowledge gap with respect to future global climate change[41]. The quantity of peat fire-derived emissions and the amounts emitted under different flaming and smouldering phases is poorly understood[12] and represent important areas of future research.

At regional to global scales, estimates of fire C emissions usually are derived from coarse-scale models, typically at spatial resolutions of 0.50° or 0.25° (Figure 2), that have not been specifically designed to estimate peatland fire emissions. Peatlands themselves are difficult to map[42], and as a result there are few remote sensing products that allow for spatially explicit assessments of peatland abundance or the effects of wildfire on peatland carbon dynamics. Smouldering fires also are inherently difficult to detect with spatial data such as thermal anomaly maps, which often are used in wildfire detection[43]. For these reasons, estimates of fire carbon emissions depend on rough indications of fire frequencies (Figure 2) and cannot resolve the high spatial variability typically associated with peatland fire dynamics. Despite these uncertainties, it is clear that peat fires have the potential to contribute significantly to global emissions of greenhouse gases.

Current and future risks of peat fires

This review has highlighted a number of important areas in which tropical and boreal peatlands differ in fire vulnerability. Low latitude peatlands, like those of Indonesia, Malaysia, Peru, Brazil, and the Caribbean region, are juxtaposed with densely populated urban areas. In these regions, drainage due to anthropogenic activities and increased frequency of human-caused ignitions has converted many peatlands from fire-resistant to fire-prone systems. In contrast, drier soils and increased lightning ignitions as a result of a warming climate are the most important factors increasing the likelihood of northern high latitude peat fires. The role of expanding human populations in this region is not well understood. Independent of these anthropogenic factors, it seems likely that future climate will increase the vulnerability of peatlands to fire at a global scale. In virtually all areas where peatlands are abundant, relative humidity is expected to decrease during the burning season (Figure 2C), which may increase the likelihood of peat fires.

Our synthesis of the current state of knowledge on peatland ecosystem carbon fluxes indicates that losses via fire can exceed those due to enhanced decomposition in disturbed boreal and tropical peatlands (Figure 1). Climatic or anthropogenic drying of peatlands enhances microbial decomposition of organic soils and stimulates fire activity. While drying in some boreal peatlands will stimulate tree growth and enhance total vegetation C uptake, reduced moss productivity combined with a more frequent and severe fire regime will diminish peat accumulation and long-term C storage. In the tropics, anthropogenic drainage and deforestation reduces the vegetation carbon sink and shifts vegetation towards more flammable fuels. Drying in peatlands also increases the depth of belowground fuel combustion, releasing carbon that has been stored in soils for centuries to millennia to the atmosphere, thus creating a positive feedback to the climate system (Figure 1). These conclusions are limited by the current state of research, but clearly point to the importance of fire to future peatland carbon balance.

The past decade of geoscience research has greatly improved our understanding of the controls on peat fires, their effects on ecosystems, and feedbacks to climate. Increases in peat fires also have landscape and health consequences that extend beyond the geosciences. Because smouldering peat fires are difficult to suppress, land managers will require new tools to respond to extreme fire danger situations in areas where peatlands are prone to burning. Peat fire emissions cause diminished air quality[44], resulting in respiratory disease and human mortality[45-47]. In some cases, fire can cause a long-term change in the environment, e.g. the thawing of the underlying frozen ground in permafrost peatlands, the initiation of extensive peat erosion in upland temperate peatlands[48] or replacement of biodiverse forested peatlands in SE Asia by species-poor herbaceous communities[26]. If these changes enhance peat drying and lead to the accumulation of flammable fuels, they will increase fire frequencies and lead to even more severe burning of peat. Alternatively, if vegetation regrowth decreases insolation and wind penetrance, increases in local humidity could reduce peatland fire risk. Similarly, a reduction in woody fuels in favor of sparse, discontinuous vegetation could limit the spread of wildland fires in peatlands. Due to these uncertainties, there is a need for studies that address the ecology of peat fires, and the role of peat fires in long-term Earth System processes.

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Acknowledgements

We thank A. D. McGuire and M. Flannigan for comments on previous versions of this manuscript. We also thank our numerous colleagues working in boreal and tropical regions for their efforts and progress on the subject of peat fires. MRT is supported by NSERC and NASA grants, GvdW is supported by European Research Council grant 280061.

Author Contributions

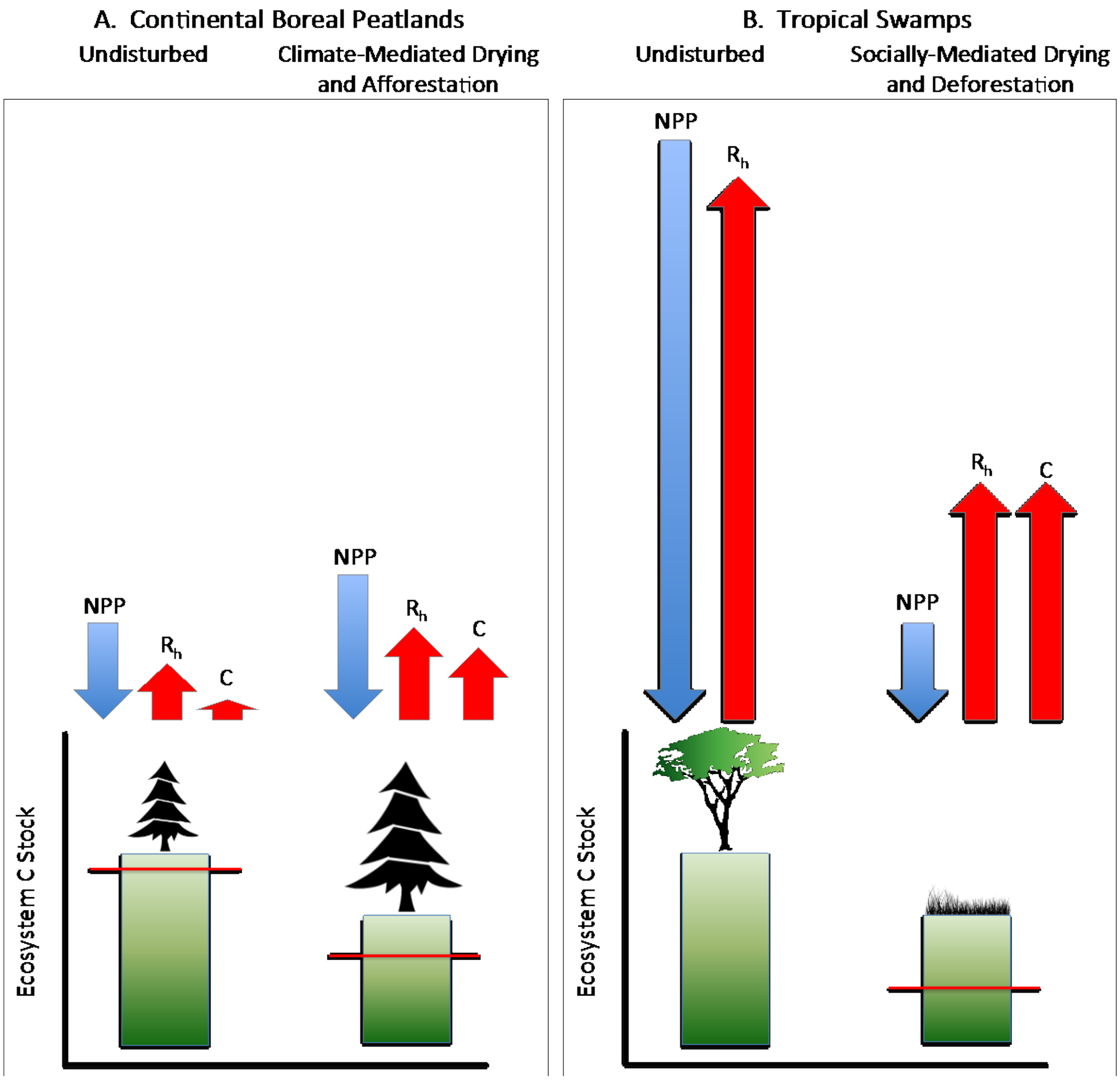
M.R.T. led this synthesis and all authors contributed to writing and ideas presented.

There are no competing financial interests.

Figure Legends

Figure 1. Drying and fires increase peat carbon loss to the atmosphere. Changes in ecosystem carbon stocks in response to fire and drying scenarios in (A) North American continental boreal peatlands, and (B) SE Asian swamps. Ecosystem carbon balance is the difference between net CO_2 uptake by plants (NPP) and CO_2 loss to the atmosphere through decomposition (Rh) and combustion (C). In undisturbed peatlands, peat accumulates because the vegetation carbon sink exceeds soil carbon losses throughout the entire peat column. Drying associated with climate warming or human activities can influence peatland carbon balance by altering plant carbon uptake or losses such as decomposition (Rh) and combustion (C). Changes in the amount of belowground fuels with drying or drainage is denoted by the red line. Arrows depict the direction of carbon transfer, with the length of the arrows indicating the magnitude of changes in flux over a 100-year period relative to the undisturbed state. Cooling effects on climate are shown by blue arrows; warming effects by red arrows.

Figure 2. Fire and climate dynamics in peatlands. (A) Global peatland abundance based on multiple data sources[49], (B) average fire return intervals based on satellite derived burned area[50] in 0.25 × 0.25° grid cells coinciding with the peatland abundance data, and (C) average change in relative humidity in the peatland grid cells based on the multi-model mean CMIP5 climate projections (http://cmip-pcmdi.llnl.gov/cmip5/) in 2081-2100 compared to 1991-2010. In all panels, insets show an enlargement of SE Asia for visual purposes.


A. Continental Boreal Peatlands
Undisturbed
Climate-Mediated Drying and Afforestation
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B. Tropical Swamps
Undisturbed
Socially-Mediated Drying and Deforestation
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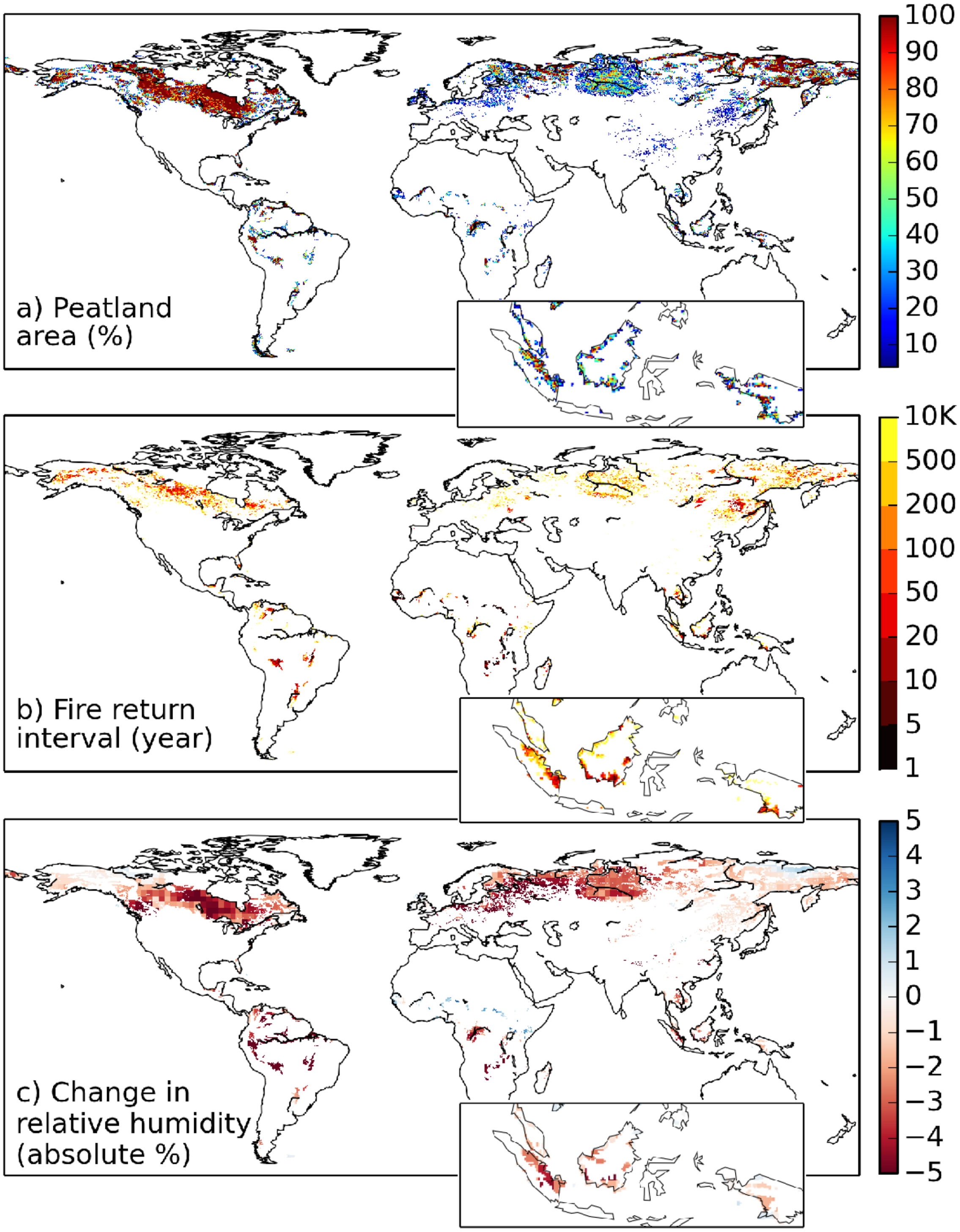
Ecosystem C Stock


a) Peatland area (%)
100
90
80
70
60
50
40
30
20
10
b) Fire return interval (year)
10K
500
200
100
50
20
10
5
1
c) Change in relative humidity (absolute %)
5
4
3
2
1
0
−1
−2
−3
−4
−5

404