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Abstract. In this article we use temperature and precipitation for the current period and outputs from a Global Climate Model to analyze projected future climate compared to the current conditions of the World's Protected Areas. We stratified the Global Land Cover 2000 into major latitudinal bands and broad landcover extents including forest, woodland/grassland, managed/bare, and water, and projections were generated using the HadCM3 model and two different scenarios, the A1FI and B1. Based on these landcover types, we combined precipitation and temperature outputs for 2050 versus the current conditions with the landcover data and extracted areas of change, those projected to experience greater than one standard deviation above the mean change in either precipitation or temperature, and areas of no-change to assess how different landcover types may be impacted. We also compared the projected range in annual mean monthly amounts of precipitation and temperature for the Protected Areas in each latitudinal band. Results reveal that of the Protected Areas in the more than 200 countries surveyed, over 50% are projected to experience greater than 20% change and almost 38% are projected to experience greater than 50% change by 2050. The range in annual mean monthly temperature for Protected Areas included similar projected changes in range under both the A1FI and B1 scenarios for Protected Areas in the mid- & high-northern latitudes exhibit, whereas Protected Areas in the temperate north, tropics, and mid- & high-southern latitudes exhibit less of an increase in mean monthly temperature under the B1 vs. the A1FI scenario. Annual mean monthly precipitation results were more varied over the range of broad landcover extents. The conclusion presents a discussion of the conservation strategies that may be relevant for Protected Areas in different regions.

INTRODUCTION

Climate change has been observed at global, regional, and local scales (IPCC 2000, 2007a; Fitzpatrick et al. 2008) and is projected to impact precipitation and temperature patterns to varying degrees in different parts of the world (Root et al. 2005; Williams et al. 2007). Differences in both the seasonal distribution and annual total accumulations of precipitation, or mean monthly temperature patterns and variation may impact the local-regional environment, and the welfare of both humans and biodiversity within that environment.

For example, shifts in precipitation may affect species ranges and distributions in tropical forests (Engelbrecht et al. 2007). As well, changes in hydrological processes may impact the frequency and severity of flooding in some of the most vulnerable areas of the world (Bradshaw 2007) and alter soil moisture, in turn affecting crop productivity and, potentially, global food availability (Wang 2005). Further, changes in the annual accumulation of precipitation in parts of the world may eliminate certain types of forests, in turn causing localized species extinctions (Enquist 2002).

Changes in temperature could yield similarly disruptive impacts such as increased droughts as a result of higher temperatures (Sheffield and Wood 2008), or altered tree fruiting patterns and other phenologies, with cascading impacts on frugivore populations. Root et al. (2005), for example, analyzed temperature data and the spring phenological traits of 130 species and observed a shift towards an earlier spring onset date for such traits. And Rull and Vegas-Vilarubbia (2006) suggest that differences in temperature in the Guyana Highlands may manifest in the extinction of species adapted to high elevations as their habitats disappear. Similarly, species that currently inhabit lowland forests may be forced to shift to higher elevations to access the same temperature environments (Pimm 2008).

According to the IPCC's Fourth Assessment Report, Global Climate Models (GCMs) "are used to make projections of possible future changes over time scales of many decades" (Randall 2007). GCM outputs have been widely used to analyze the potential impacts of changes in precipitation, temperature, and cloud cover patterns based on different emissions forcings, and while the outputs are often model dependent, generally have a coarse spatial resolution, and are subject to much uncertainty (Barnett 1999; Berliner 2003; Raisanen 2007), they can be paramterized to model a suite of potential emissions trajectories. A range of possible trajectories are addressed through the emissions scenarios considered in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (IPCC 2000). These scenarios, following four main storylines which are divided into four scenario families (A1, A2, B1, and B2), address a range of potential developments in population dynamics, economic progress, and technological advances. However, because much uncertainty exists regarding the potential future trajectories of emissions, all scenarios are considered equally probable (IPCC 2000; Meehl 2007).

Researchers have applied GCM outputs to assess potential climate impacts in a variety of areas and, increasingly, to evaluate potential impacts on biodiversity. For example, Beaumont and Hughes (2002) used outputs from multiple scenarios to analyze the potential distributions of selected endemic Australian butterflies. Enquist (2002) used the Holdridge life zones and nine climate scenarios to analyze the effects of climate change on vegetation in Costa Rica. And Higgins (2007) used HadCM3 outputs to investigate species richness in E. Brazil and the Guinea Shield.

In this study we examined the projected impacts of climate change on PAs using GCM outputs from the HadCM3 model in monthly precipitation and temperature for 2050 vs. the current conditions. The HadCM3 model is produced by the UK Meteorological Office (UKMO) (Gordon et al. 2000). We analyzed outputs for two IPCC scenarios, one business-as-usual scenario and the other a progressive 'global solutions' scenario. Projections were analyzed based on landcover type and latitude to assess how PAs in different landcover types may be impacted. We selected the global PA network for several reasons. Firstly, while PAs account for 11.5% of global land under current climate conditions (Rodrigues 2004), their boundaries assume a static condition and, as a result of projected future changes in the climate, the areas within these boundaries may experience very different climatic conditions (Dudley 2003; Willis et al. 2008). Therefore, global scale analyses are necessary to identify the range of changes that may occur in different areas with respect to PAs. Secondly, while multiple climate change-related studies have been performed using PAs at the regional/national scale, the literature for the global scale is more limited. And, thirdly, global scale analyses inform PA planners and managers, and assist with the appropriate targeting of scarce conservation resources by identifying potentially vulnerable areas.

DATA SOURCES GLOBAL LANDCOVER

We selected landcover types based on the Global Landcover 2000 (GLC2000) dataset (GLC2000 2003). The GLC2000 classifies 22 global landcover types at a spatial resolution of 1km including: ten tree cover classes, four shrubby and herbaceous, four cultivated and bare, and three water, snow, and artificial surface classes. We generated four broad landcover types by grouping and reclassing 20 of the GLC2000 classes into forest (classes 1-8, 10), woodland/grassland (classes 9, 11-15), managed/bare (classes 16-19), and water (class 20). Classes 21 and 22 were omitted from the analysis. These four broad landcover types were stratified among six latitudinal bands including areas North of +70 degrees (high-northern latitudes), areas between 50 – 70 degrees North (mid-northern latitudes), areas between 23.5 – 50 degrees North (temperate North), areas between 23.5d N - 23.5d S (tropics), areas between 23.5d S - 50d S (mid-southern latitudes), and areas South of 50degrees S (high-southern latitudes).

CLIMATE DATA

We used monthly precipitation and temperature data generated by the Tyndall Data Centre and hosted by the Climate Research Unit (CRU) of the University of East Anglia (UEA) (Mitchell et al. 2004). The Tyndall Data Centre regridded projected climate data from selected GCMs to a spatial resolution of 0.5 degrees. GCM outputs were selected by the Tyndall Data Centre based on their being ‘the only GCMs for which any SRES simulations had been performed and deposited with the IPCC Data Distribution Centre (DDC) at the time of scenario construction’ (Mitchell et al. 2004). For this study, these data represented some of the only data available at a relatively fine spatial resolution. We selected climate outputs from HadCM3 because this model, and earlier versions, has been widely used (Beaumont and Hughes 2002; Battin et al. 2007; Midgley et al. 2002; Scott et al. 2004; Thuiller 2004; Mika et al. 2008). We used HadCM3 precipitation and temperature outputs for two emissions scenarios from different scenario families, the fossil-fuel intensive A1FI (business-as-usual) scenario from the business-as-usual family and the ‘resource-efficient technologies’ B1 (global solutions) scenario from the innovative and global solutions family (IPCC 2000). The A1FI scenario emphasizes economic growth based on fossil-fuel intensive technologies and is characterized by a mid-century peak in human population and high cumulative emissions. Conversely, the B1 scenario focuses on innovation & global solutions. The scenario incorporates economic growth but with a focus on service and information using clean/resource-efficient technologies. A mid-century peak in population is also a characteristic, but emissions decline fastest in this scenario.

PROTECTED AREA DATA

We used the 2005 version of the World Database of Protected Areas (WDPA) (WDPA 2005). The WDPA is compiled annually by UNEP-WCMC and the IUCN World Commission on Protected Areas (IUCN-WCPA). The data are produced, largely, to aid in conservation related analyses, and represent the most comprehensive global dataset of marine and terrestrial PAs available. However, there are some limitations to the data. Some countries provide incomplete, or no, reporting of their PAs to the Commission resulting in data gaps for certain areas. Further, inaccuracies occur as a result of geographic or attribute inconsistencies. For example, various data sources may be used for the boundary delineation or attribute information of a PA resulting in differing polygon extents or attribute information for the same PA. In addition, misspelling of PA names can result in multiple entries for the same PA. Finally, complex PAs, such as those containing both a terrestrial and marine component, could not be accommodated by the 2005 version (WDPA 2005) .

Following Rodrigues et al. (2004) and others, we used all records for class I-IV PAs in the WDPA except (a) point records without geographic location (zero latitude and longitude), (b) records that did not seem to correspond to an established PA, (c) point records for which no area data were available, and (d) records corresponding to areas smaller than 100 hectares (ha). This 100-ha threshold is well below most estimates of the minimum area needed to support intact communities of vertebrate species (Gurd et al., 2001), and so it serves to exclude PAs that are likely to be largely irrelevant for the conservation of the analyzed vertebrate species (although they may play other important conservation roles). Excluding PAs smaller than 100 ha, and those for which no area was known, eliminated 54% of the PA records (mostly in Europe) but made little change in the overall area protected (only reducing it from 11.5% of the terrestrial surface to 10.9%).

METHODOLOGY

We calculated annual mean monthly temperature and precipitation for the two scenarios and for two temporal periods. Following Beaumont and Hughes (2002) and others, we selected 2050 and a control period (averaged from 1961 – 90) (Mitchell et al., 2004). We selected 2050 to capture a mid-century snapshot of potential climate conditions for the world’s PA network using the outputs of one widely used GCM. Based on the annual mean monthly calculations, we generated difference grids

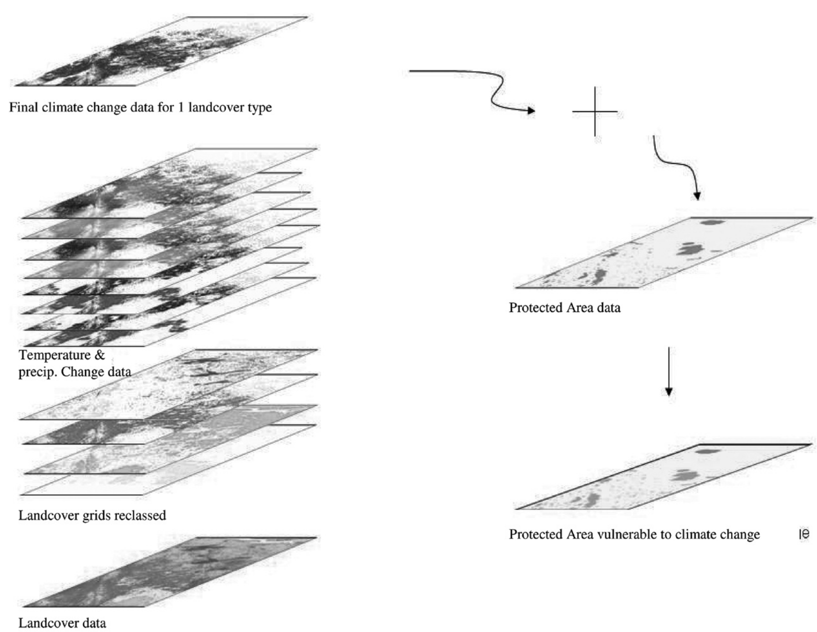

Figure 1. Processing methodology for one sample region.

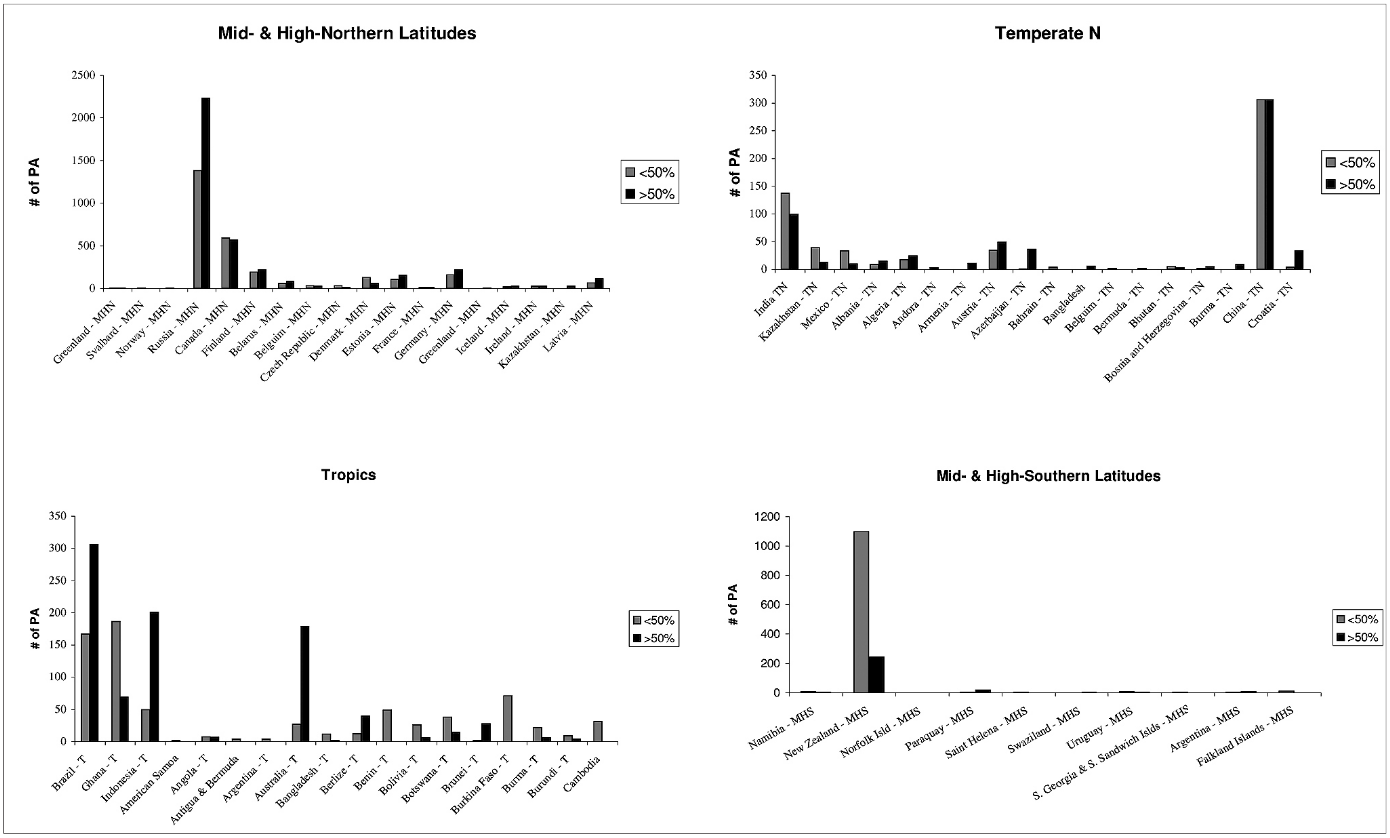

Figure 2. PAs projected to experience >50% compared to PAs projected to experience <50% climate change for selected

for each precipitation and temperature climate variable; this yielded four difference grids, two for the A1FI and B1 temperature variables and two for the A1FI and B1 precipitation variables.

To analyze the PAs by landcover type, the difference grids were combined with the landcover grids, created above, generating ninety-six combined climate variable-landcover grids. We extracted areas of change +/- one standard deviation above the mean projected change for each of the four land cover types within each latitudinal band yielding ninety-six standard deviation change grids. We then identified areas of agreement, where both scenario outputs projected +/- one standard deviation above the mean change, by combining the four standard deviation grids per land cover type per latitudinal band. Areas where two or more climate variables exhibit agreement were recoded as change and all other areas recoded to no-change. These final twenty-four grids, one per landcover type per latitude, represent those areas within each land cover type where there is agreement among at least two climate variables of projected climate change. Within one latitudinal band, eight possible values exist representing areas of no-change and change for the four landcover types. We overlaid the global PA data layer on the change/no-change grids and ran a series of tabulate areas to calculate the amount of change/no-change per landcover type per Protected Area. We then calculated the total area of change and no-change per Protected Area. Figure 1 illustrates the processing methodology for one sample region.

To investigate the projected change in amounts of annual mean monthly precipitation and temperature under the two scenarios, we also analyzed the difference grids, created above, for each precipitation and temperature climate variable individually. We intersected the global PA data layer with each difference grid and extracted the mean change in annual monthly temperature and precipitation for each PA within each broad landcover extent.

RESULTS

Figure 2 highlights the change/no-change outputs, based on the +/- one standard deviation above the mean projected analysis, for selected countries. Countries with a high number of PAs projected to experience >50% climate change in their areal extent include Russia, Brazil, Australia, and Indonesia. These countries contain large numbers of PAs located in the mid- & high-northern latitudes and tropical extents. Countries containing a high number of no-change PAs include New Zealand, Benin, Burkina Faso, and Ghana, located in the mid- & high-southern latitudes, and tropical extents. While the WDPA data includes inconsistencies in reporting amongst countries, these results illustrate the percent of PA vulnerability in selected countries. Further, as most PAs are designated by national or local authorities, illustrating the results by country may serve to motivate countries to address biases and shortfalls in coverage.

Intersection of the temperature and precipitation change difference grids with the global Protected Areas layer revealed an overall contraction in the range of temperature change throughout the majority of the broad landcover extents for PA locations under the global solutions scenario vs. business-as-usual scenario. Conversely, the patterns of potential change in precipitation for PAs under both scenarios are similar, with a general increase in projected precipitation for the majority of PAs (57%), consistent with expected precipitation change (Berliner 2003). However, precipitation is inherently difficult to model using GCMs (Wang 2005).

Because of the low number of PAs available for the high-northern and high-southern latitudes these PAs have been combined with their respective neighbors, mid-northern latitudes and mid-southern latitudes. The results were analyzed within each broad landcover extent (1) by comparing the projected change in annual mean monthly precipitation vs. temperature for each PA for the two scenarios (A1FI and B1) (Figure 3), (2) by comparing A1FI vs. B1 temperature change and precipitation change for each PA (Figure 4), and (3) by identifying the total percentage of PAs in each temperature and precipitation strata per broad landcover extent (Table 1).

PAs in the high- and mid-northern latitudes are projected to experience an increase in mean temperature, in agreement with expected increased warming in all areas especially poleward in the Northern hemisphere (IPCC 2007b), with over 55% of PAs projected to experience a mean increase of >= 3dC under both scenarios. The majority of PA locations in this area, over 98% under both scenarios, are projected to experience a +/- 30mm change in annual mean monthly precipitation. For PAs in the mid- and high-northern latitudes, as increased warming of >=3dC is projected to affect the majority of PA locations and similar precipitation patterns are projected under both scenarios, conservation strategies and management practices that focus on adaptation may be more appropriate than those based on mitigation.

Temperature increases are also projected for PAs in the Temperate North under both scenarios. However, under the gobal solutions scenario, less than 25% of PAs are projected to experience an increase of >=3dC compared to almost 75% under the business-as-usual scenario. The annual mean monthly precipitation projections for PA locations in this area exhibit similar patterns under both scenarios. This again may be attributable to the inherent limitations associated with precipitation projections. However, conservation strategies that focus on mitigation may serve to reduce the impacts of climate change on PAs in this region.

Over 80% of PA locations in the tropics are projected to experience >=2dC increase in temperature, with almost 18% projected to experience >=3dC increase, under the A1FI scenario. Conversely, under the global solutions scenario, <20% of PAs are projected to experience >=2dC increase in temperature and <2% projected to experience >=3dC. The majority of PA locations in the tropics, over 70%, are projected to experience similar change in precipitation under both scenarios. However, based on the very different temperature change projections under the two scenarios, conservation

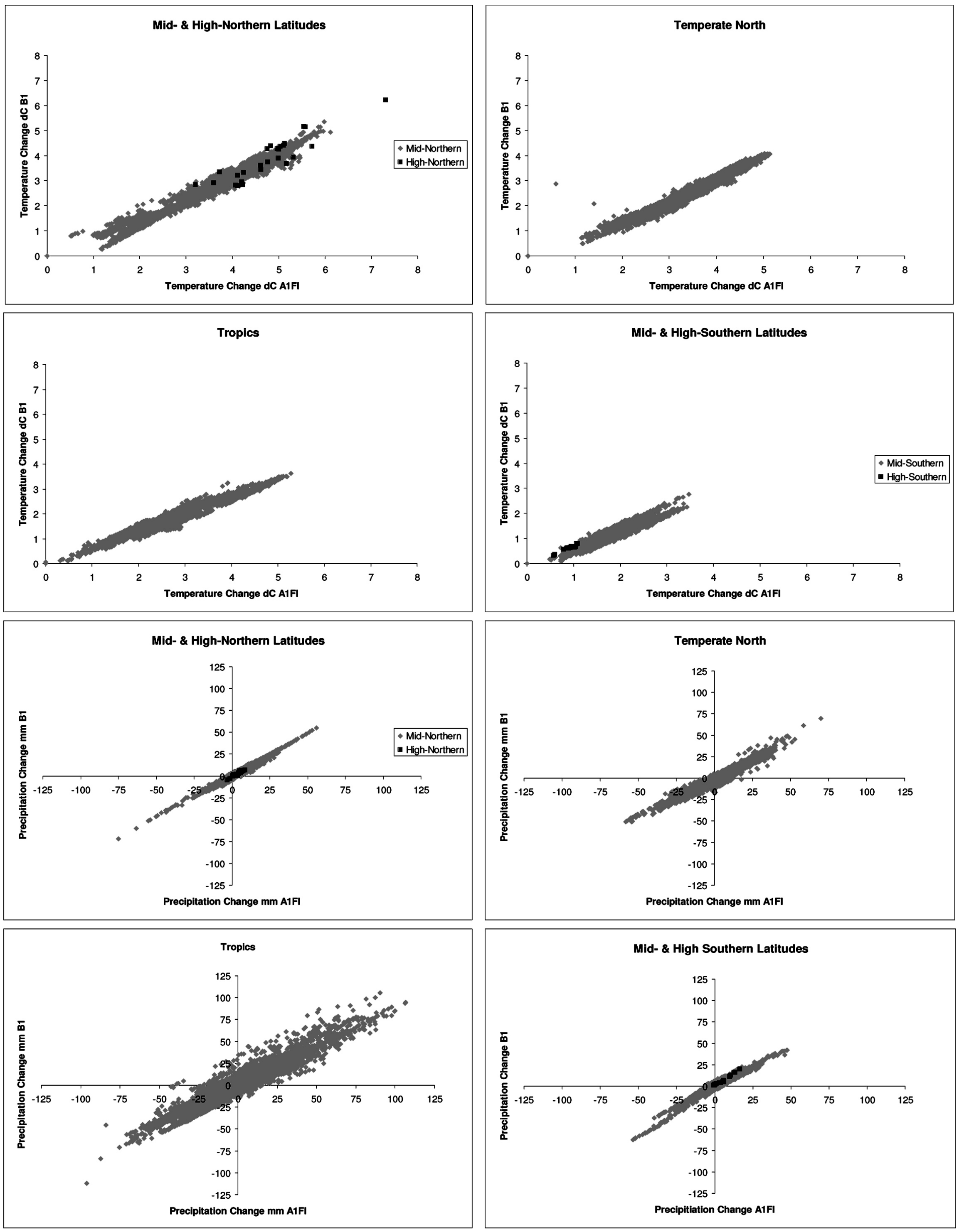

Figure 3.
Temperature and Precipitation Correlations for A1FI and B1.

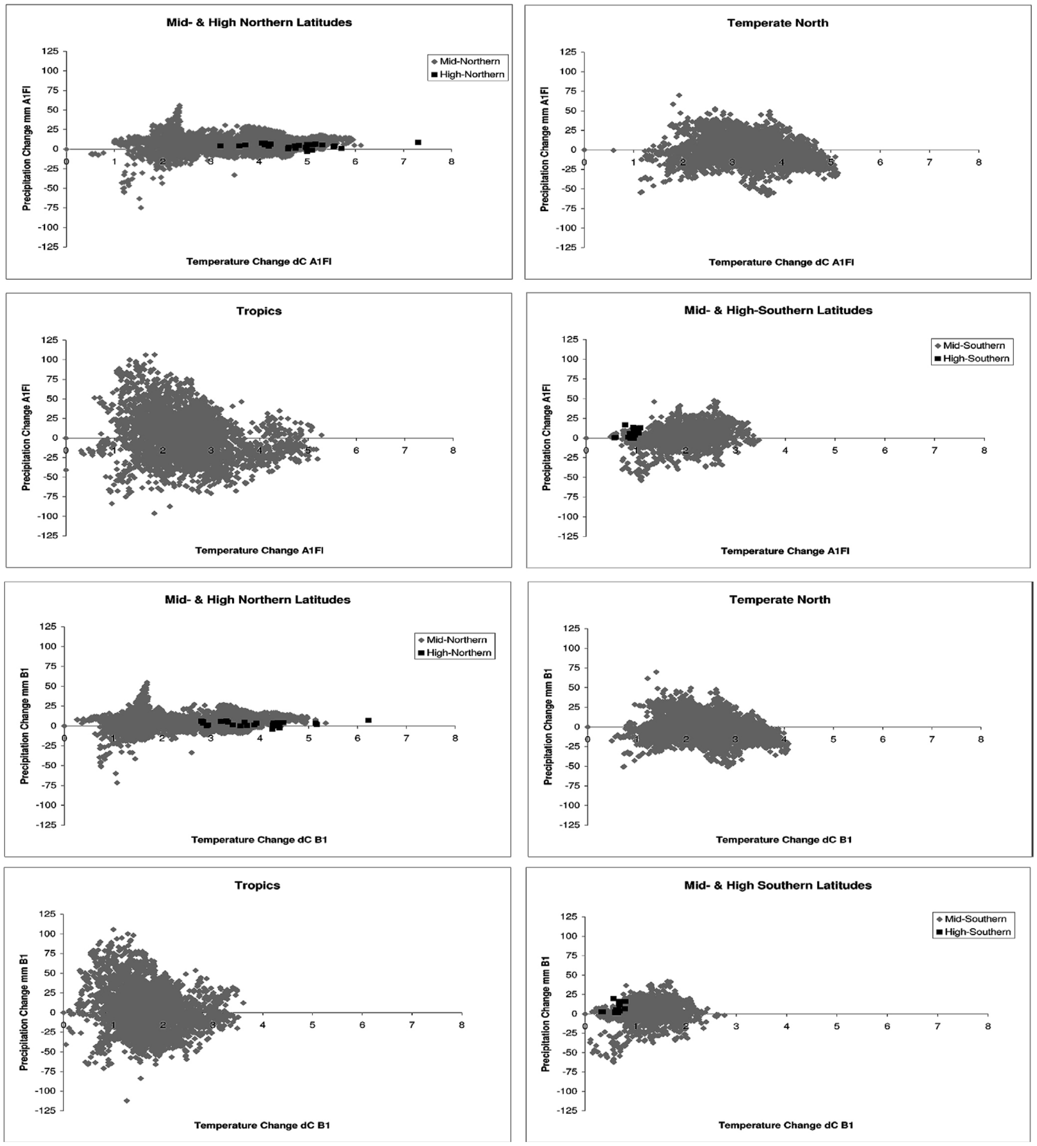

Figure 4.bTemperature vs. Precipitation change per PA.

approaches that incorporate mitigation strategies may again serve to reduce the impacts of climate change that may affect PA locations in the tropics.

The PAs of the mid- and high-southern latitudes also exhibit differences in projected temperature under the two scenarios. Almost 40% of PAs in this region are projected to experience >2 ºC increase in annual mean monthly temperature under the business-as-usual scenario compared to <4% of PAs under the global solutions scenario. Projected precipitation change for this region is similar, with 95% of PA locations projected to experience +/-30mm change under both scenarios. Again, conservation strategies that emphasize mitigation may prove useful in this region.

DISCUSSION AND CONCLUSIONS

Several limitations must be recognized with respect to this study. First, the nature of parameterizing GCMs and associated emissions scenario runs, necessitates assumptions and generalizations about the climate, thus requiring the interpretation of outputs considers the limitations of such models (Smith et al. 1997; IPCC 2000; Berliner 2003; Wang 2005). Second, the resolution of the climate data, while relatively fine compared to raw GCM outputs, remain coarse for the spatial extents of this analysis; the PAs used in this study range in size from a few km2 to over 900,000km2. Third, the 2005 version of the WDPA that was available for this study has a number of limitations including inaccurate, or missing, PA boundaries and/or attribute information, and inconsistency in PA coverage reporting for individual countries; these factors may have impacted the results in some areas. Finally, the network of global PAs falls short of encompassing the magnitude of current conditions and therefore represents a biased sample of both current climate conditions (Pyke et al. 2005) and biodiversity and ecological systems (Andelman and Willig 2003).

However, these limitations being considered, this analysis still provides broad observations regarding how the Protected Area system within different countries and broad landcover extents may be impacted by changes in selected climate variables. Further, it provides a starting point for considering how conservation strategies and management approaches for adaptation to, or mitigation of, the impacts of climate change on PAs in different areas may be implemented. While repeated analyses are planned using an updated version of the WDPA and downscaled climate outputs from multiple GCMs, this analysis provides one possible, though preliminary, outlook using two very different emissions scenarios.

Given the broad range of Protected Areas projected to be impacted by climate change, the results of this study underline the importance of mitigation vs. adaptation to secure biodiversity, both within and outside of PAs for future generations. In particular, although mitigation policies will impact global emissions, mitigation may be particularly beneficial for PAs in the temperate north, tropics, and mid- & high-southern latitudes. PA locations in these regions suggest large differences in mean monthly temperature under the global solutions than the business-as-usual scenario. In contrast, our results suggest that mitigation alone may be insufficient for PAs in mid- and high-latitudes, because projected temperature changes under both the A1FI and B1 scenarios are similar. Additional analyses are needed to understand how projected changes in precipitation, which are much more variable, and more difficult to model (Raisanen 2007), are likely to impact PAs and the biodiversity they contain.

Habitat loss is likely to compound the impacts of climate change, by isolating PAs and curtailing opportunities for species migration in response to climate change. Based on the findings of the Millennium Ecosystem Assessment, many of the same regions that will be impacted by climate change will also be heavily impacted by deforestation. Therefore, setting aside additional PAs in these regions, particularly forested areas, together with forest restoration, may be beneficial, not only for mitigation, but for adaptation as well.

Table 1. Total % of PAs per mean monthly temperature and precipitation band per broad landcover extent

SCENARIO			BIOME			TEMPERATURE CHANGE ºC			PRECIPITATION TEMPERATURE CHANGE ºC CHANGE MM		
		0-1	1-2	2-3	3+	<-60	-60--30	-30-0	0-30	30-60	>60
Business-as-usual	High-Northern Latitudes	0	0	0	100	0	0	7	93	0	0
A1FI	Mid-Northern Latitudes	2	7	22	69	0	0	26	73	1	0
	Temperate North	1	3	22	74	0	2	54	42	2	0
	Tropics	2	18	67	14	1	12	35	38	11	3
	Mid-Southern Latitudes	3	57	39	1	0	3	48	48	2	0
	High-Southern Latitudes	75	25	0	0	0	0	8	92	0	0
Global solutions	High-Northern Latitudes	0	0	22	78	0	0	11	89	0	0
B1	Mid-Northern Latitudes	5	23	16	56	0	0	24	75	1	0
	Temperate North	2	22	51	25	0	1	57	40	1	0
	Tropics	7	74	18	2	0	10	37	40	10	2
	Mid-Southern Latitudes	23	73	4	0	0	3	44	51	2	0
	High-Southern Latitudes	100	0	0	0	0	0	0	100	0	0

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