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A climate change index: Where climate change may be most prominent in the 21st century

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[1] A Climate Change Index (CCI) is developed that is composed of annual and seasonal temperature and precipitation indicators. These indicators are aggregated to a single index that is a measure for the strength of future climate change relative to today's natural variability. The CCI does not represent climate impacts. Its aim is to comply with the increasing need of policy makers to gain a quick overview of complex scientific findings by means of summarized information. The index is calculated on the basis of three GCM simulations of the 21st century under the IPCC emission scenarios A2 and B2. The results indicate that the strongest climate changes by the end of the 21st century, relative to today's natural variability, will occur in the tropics and in high latitudes (especially in the northern hemisphere). The CCI is also calculated on a country basis, allowing for comparison with social and economic country indicators. **Citation:** Baettig, M. B., M. Wild, and D. M. Imboden (2007), A climate change index: Where climate change may be most prominent in the 21st century, *Geophys. Res. Lett.*, *34*, L01705, doi:10.1029/2006GL028159.

1. Introduction

[2] It is widely recognized that policy makers need reliable and well-synthesized information about climate change and its impacts in order not to get lost in too much detail [*Organisation for Economic Cooperation and Development (OECD)*, 2002]. One possibility to meet these needs is by indicators and aggregated indices that help to gain a quick overview of scientific facts. In the field of climate change numerous specific indicators exist, but there are only few composite indices. This is astonishing considering that climate change is a strongly debated issue in international politics with thousands of policy-makers involved. Interviews by the authors with 57 country delegates at the UN Climate Change Conference 2005 in Montreal show that a majority judge an aggregate measure for climate change as helpful.

[3] The aim of this paper is to present an aggregated Climate Change Index (CCI) that summarizes different climatic information into a single number, a possible measure for projected climate change. For political use, it is aggregated on a country level allowing for comparison with social and economic indicators that are only available on a country level. The CCI is composed of different temperature and precipitation indicators. We focus on climate change indicators and not on climate impact indicators as the former are closer to model data, depend on less assumptions and are less complex to communicate. Indicator calculations are based on multi model ensemble scenarios of the 21st century. The validity of the index is discussed in the light of existing scientific findings.

2. Method

[4] The goal of this study was to develop an index that is a measure for projected climate change. A main challenge was to identify those indicators that best represent climate change. Traditionally, global mean temperature is the standard indicator for climate change [*Intergovernmental Panel on Climate Change (IPCC)*, 2001]. However, it is generally accepted that changes in precipitation patterns and extreme events may have stronger impacts on the environmental and societal systems [e.g., *Allen and Ingram*, 2002; *Hegerl et al.*, 2004; *IPCC*, 2001]. Thus, four indicator groups were selected that together are able to describe important facets of climate change: changes in annual temperature, changes in annual precipitation, changes in extreme temperature events, and changes in extreme precipitation events, including droughts.

[5] Indicator calculations are based on gridded global monthly surface air temperature and precipitation data. In a first application we calculated the CCI with data from three Global Climate Models (GCM), namely ECHAM5 [*Roeckner et al.*, 2003], HadCM3 [*Gordon et al.*, 2000], and CGCM2 [*Flato et al.*, 2000]. Each data set consists of a control run (1961–1990) and two greenhouse runs (2071–2100), based on the IPCC SRES scenarios A2 and B2 (approx. 860 and 620 ppmv CO2 concentration in 2100). Each indicator is a multi model ensemble mean of these data. The different model grids were interpolated to the coarsest grid size of the CGCM2 model (3.75°*3.75°). Calculations were conducted globally at each grid point.

2.1. Calculated Climate Indicators

[6] In the following, the four indicator groups are described (see Table 1). All indicators are calculated according to the same principle, i.e. to identify the "1 in 20 years" most extreme event of the reference period and to calculate the occurrence of such an event within the scenario period. This method is based on the assumption that climate change and climate impacts manifest themselves through an increased occurrence of extreme events over a longer time period [*Barnett et al.*, 2005]. To calculate the indicators, a cumulative density function was fitted to the data of the control period and into those of the scenario period. The quantile corresponding to the 95th (and 5th) percentile was determined using the control period distribution function,

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Table 1. Overview of the Indicator Groups and Individual Indicators That Are Aggregated to the Climate Change Index

Indicator Group / *Individual Indicator*	Applied Concept
Change in annual temperature *1. Additional hottest years*	additional occurrence of the "1 in 20 years" hottest year of the control period
Change in annual precipitation *2. Additional driest years* *3. Additional wettest years*	additional occurrence of the "1 in 20 years" driest and wettest year of the control period
Change in extreme temperature events *4. Additional extremely warm JJA* *5. Additional extremely warm DJF*	additional occurrence of the "1 in 20 years" hottest JJA and DJF of the control period
Change in extreme precipitation events *6. Additional extremely dry JJA* *7. Additional extremely wet JJA* *8. Additional extremely dry DJF* *9. Additional extremely wet DJF*	additional occurrence of the "1 in 20 years" driest JJA/DJF and wettest JJA/DJF of the control period

then the probability of this quantile was calculated under the scenario period. In the following, this procedure is called "1 in 20 years" principle. As the analyzed time period consists of only 30 data points, for reasons of accuracy, we did not calculate events less frequent than "1 in 20 years".

[7] Within the first indicator group "change in annual temperature", only one indicator was calculated: the additional occurrence of the hottest year of the control period, $I_{HOTyear}$. For the probability calculation, temperature data were assumed to be normally distributed. Indicator values are between 0 and 19 and express additional extreme hot years within 20 years.

[8] In the second indicator group "change in annual precipitation", two indicators were computed: the future additional occurrence of the driest and wettest years of the reference period, $I_{DRYyear}$ and $I_{WETyear}$. Only values indicating an increased probability of occurrence were taken into account. Precipitation data were assumed to be gamma distributed. For the fit of the gamma cumulative density function, the maximum likelihood estimates (MLE) were used.

[9] The third and fourth indicator group describe changes of seasonal extreme events such as heat waves, droughts, and extremely wet periods that may cause floods. These seasonal changes may have strong impacts on crucial sectors such as agriculture, water, energy, and health. Investigated seasons were boreal summer (JJA) and winter (DJF).

[10] In the group "change in extreme temperature events", the additional occurrence of the "1 in 20 years" hottest JJA and DJF was calculated, I_{HOTjja} and I_{HOTdjf}. In the category "extreme precipitation events", four indicators were computed: the additional number of driest and wettest JJA, I_{DRYjja} and I_{WETjja}, as well as driest and wettest DJF, I_{DRYdjf} and I_{WETdjf}.

2.2. Aggregation of Selected Climate Indicators

[11] Since all indicators represent the number of additional events in the scenario period and thus lie between 0 and 19, normalization of the scale was not necessary. For the aggregation, each indicator group was assigned a total weight of one. Within the groups, weights were equally distributed among the indicators.

[12] The Climate Change Index was calculated as the weighted mean of the indicators. It can thus assume values between 0 and 19. The square brackets in the following formula illustrate the indicator groups:

$$CCI = \Big(I_{HOTyear} + [I_{DRY} + I_{WET}]_{year} + [0.5 I_{HOTjja} + 0.5 I_{HOTdjf}] + \big[0.5(I_{DRY} + I_{WET})_{jja} + 0.5(I_{DRY} + I_{WET})_{djf}\big] \Big) \Big/ 4$$

The CCI on a country basis is the mean of all grid values over the surface area of each country. In order to get a finer resolution along country borders, each grid cell was divided into 16 subcells.

3. Results and Discussion

3.1. Individual Climate Indicators

[13] Figure 1 shows the multi-model ensemble mean of the nine indicators over land describing temperature and precipitation changes.

[14] Annual mean temperature is predicted to change strongly. The hottest year in 20 years of the reference period will be the norm for the majority of all regions over land (Figure 1a). The lowest calculated value corresponds to 12 additional hottest years.

[15] In this study, we also calculated additional coldest years. However, only a very small area in the North Atlantic Ocean shows a future increase of coldest years. As over land no such effect was found, we did not include this indicator in the CCI.

[16] Extreme seasonal temperature events also show a strong increase (Figures 1c and 1d): hot seasons that occurred once in 20 years in the reference period will occur 5.5 to 19 additional times in boreal summers and 2.4 to 19 additional times in boreal winters. Extremely warm DJF are expected most frequently in tropical regions and high latitudes. Extremely warm JJA are predicted to become the standard in most regions. For Europe, these results are in agreement with those by *Scherrer et al.* [2005] who used indicators depending on natural variability as well. Their results also show strongest temperature changes in summer.

[17] In contrast to temperature, changes in precipitation are less pronounced. Additional 1 in 20 wettest and driest years, respectively, are summarized in Figure 1b. Positive values indicate more wet events, negative values denote more dry events. On global average, the climate is predicted to become wetter. The strongest changes are projected in the tropics, subtropics and high latitudes. Projections show a general drying in the tropics and subtropics but an increase in rainfall for Central Africa. In high latitudes, rainfall will also notably increase.

[18] Results for the extreme dry seasons indicators predict a drying in Central America, the Amazon, the Mediterranean, Southern Africa and Australia (Figures 1e and 1f). Up to 9 additional extremely dry seasons will occur. The expected change is slightly stronger in boreal summers than in boreal winters.

[19] Additional extremely wet JJA and DJF are projected to occur mainly in Alaska, Greenland, Northern Europe, Northern Asia, Central Africa, Tibet, and Antarctica (Figures 1g and 1h). There will be up to 11 additional extremely wet seasons. In accordance with *Tebaldi et al.*

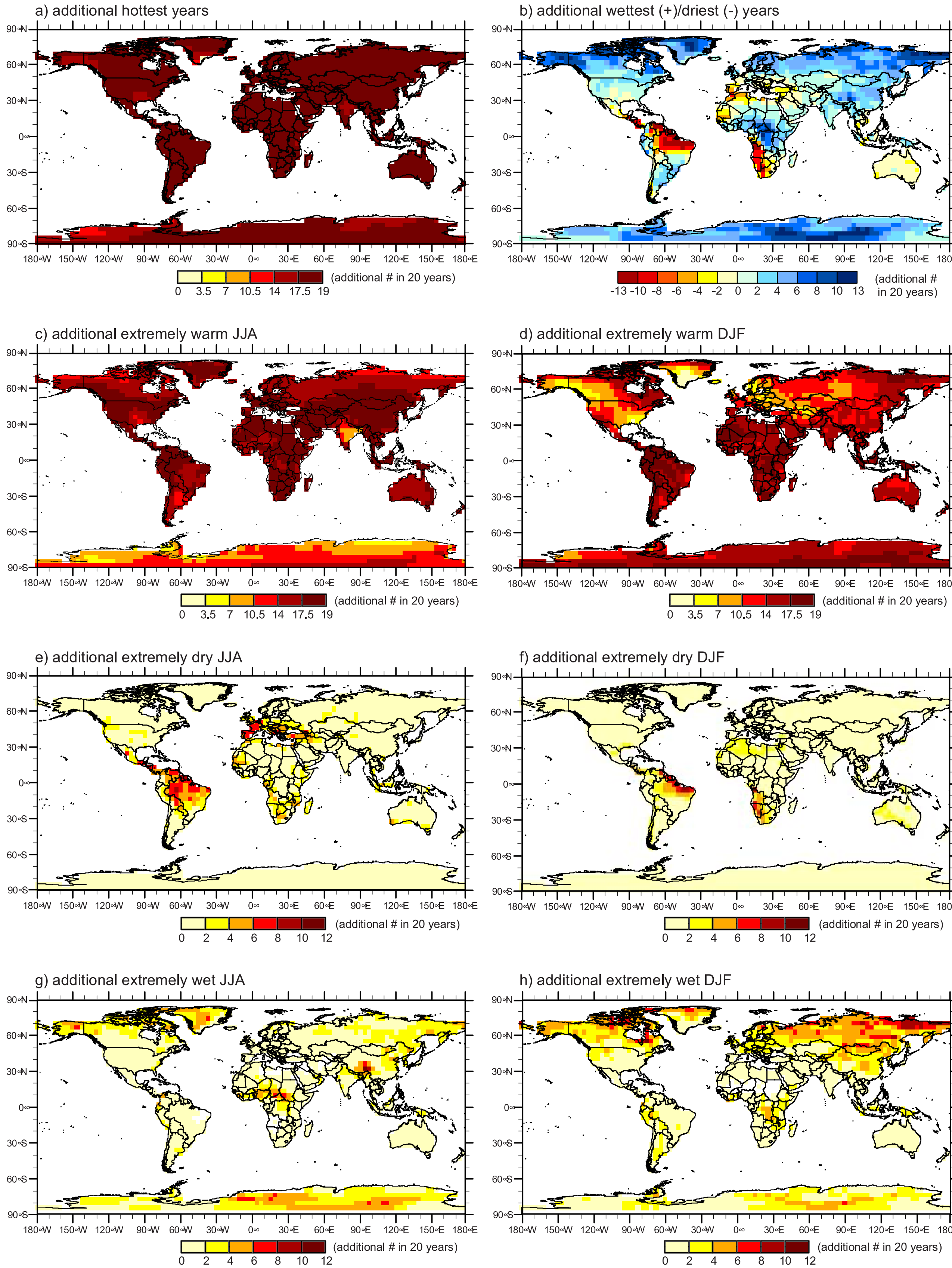

Figure 1. Individual CCI-indicators. Each indicator is a multi model ensemble mean of the two IPCC SRES scenarios A2 and B2. Changes refer to the control period 1961–1990 and the scenario period 2071–2100.

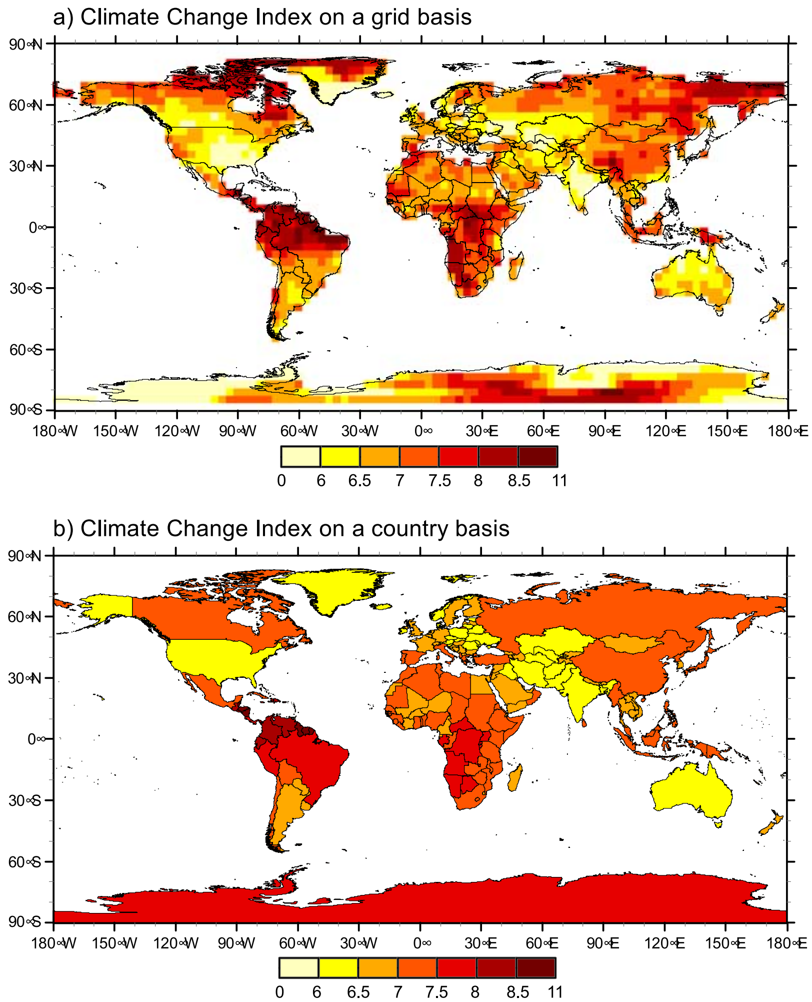

Figure 2. The aggregated CCI in two versions: (a) on a grid basis and (b) on a country basis. The country value is the mean of all grid values over the surface area of each country.

[2004], additional extremely wet DJF will increase more than additional wet JJA.

[20] *Giorgi and Bi* [2005] analyzed regional precipitation and temperature changes for different 20-year periods in the 21st century. They used a different GCM ensemble and other indicators. A qualitative comparison shows that their results for rainfall changes are in agreement with our findings, except for the Amazon where Giorgi and Bi found only a small precipitation change, and in Central Asia and Southern South America where they found a decrease in precipitation.

3.2. Aggregated Climate Change Index

[21] In Figure 2 we present the aggregated Climate Change Index. Figure 2a shows the CCI on a grid basis. The values are between 3.8 and 10.7 additional strong climate events, with most lying between 5 and 9. The CCI indicates that climate will change most strongly relative to today's natural variability in the high latitudes and the tropics. The effect in the high latitudes has been reported by many others [e.g., *IPCC*, 2001]. In the CCI, this effect results mainly from an increase in extremely wet years and seasons, but also from an increase in annual temperatures. The high CCI-values in the tropics are caused by precipitation changes but also seasonal temperature events. Although several authors have reported strong tropical precipitation changes [e.g. *Hegerl et al.*, 2004; *IPCC*, 2001], this effect has not attracted much attention until today. Concerning strong temperature changes, it has to be noted that in the tropics the hot temperature indicator responds more strongly to absolute changes in mean than elsewhere, because natural temperature variability is much smaller in the tropics than in higher latitudes [e.g., *Räisänen*, 2002].

[22] In a recent study *Giorgi* [2006] presented a similar approach to calculate regional climate change hot-spots. He uses an index to compare climate change between different regions that, in contrast to our approach, is not relative to the natural variability. The Mediterranean and Northeastern Europe are identified as the most prominent hot-spots. In our study, these regions have an average CCI-value. According to both studies, climate will change strongly in high latitudes. The pronounced tropical changes predicted by the CCI are not identified by Giorgi, except for Central America. These differences may be explained by the above mentioned differences in indicators as well as by differences in GCM selection, analyzed time periods, weighting factors, and the level of aggregation.

[23] Figure 2b shows the average CCI for each country. The spatial aggregation of the data allows to compare the CCI with socio-economic country indicators. The Human Development Index (HDI) which is calculated on a country basis by the United Nations Development Programme is an index that is frequently used as a first approximation for vulnerability of countries towards climate change. Most African and some South East Asian countries have a low HDI and are therefore less capable to protect against and adapt to climate change. According to the CCI, climate is expected to change more strongly relative to today's natural variability in these more vulnerable countries than in many countries with a high HDI and thus lower vulnerability, such as the United States, European states and Australia. This general observation is supported by the correlation between the HDI and the CCI which is -0.25.

3.3. Robustness of the Climate Change Index

[24] Zonal means of the CCI for all three GCMs were calculated, both over land and ocean, and over land only. The patterns over land and ocean are similar for all three models, except in polar regions where differences occur. Zonal means over land are less similar between the models but more consistent in high latitudes. In both calculations strongest changes are visible in the tropics and the northern hemisphere polar region, while changes for the southern polar region are less pronounced. The similarity between the GCMs may be an indication for the robustness of the CCI.

[25] The CCI was also tested by applying different normalization methods and weighting factors to the selected indicators. The main features of the results did not change, which confirms the robustness of the index. CCI calculations with the individual IPCC SRES scenarios A2 and B2 also resulted in the same general picture.

[26] We also tested other indicators, most extensively relative mean change indicators. They relate absolute mean changes to the standard deviation. We calculated the standardized change in mean temperature and the Standardized Precipitation Index (SPI) [*McKee et al.*, 1993]. A correlation analysis showed that the Spearman rank-order correlation between the standardized change in mean temperature and the $I_{HOTyear}$ is 0.82, the correlation between the SPI and the indicator of Figure 1b ($I_{WETyear} - I_{DRYyear}$) is 0.99. This result shows that "1 in 20 years" indicators, applied to annual events, also stand for relative mean change, which is not obvious at first glance.

[27] To estimate the uncertainty of the "1 in 20 years" principle, a bootstrap analysis was conducted. On average, for precipitation indicators, the 95% confidence interval is $+3.1/-2.1$ additional "1 in 20 years" dry events, and $+3.7/-3.6$ additional "1 in 20 years" wet events. For temperature indicators, the average 95% confidence interval is $+0.3/-0.4$ additional "1 in 20 years" hot events.

3.4. Limitations and Further Development

[28] Even though aggregated indices hold a high potential to convey simple messages and are appreciated by their users, they are discussed controversially [e.g., *Freudenberg*, 2003; *OECD*, 2002]. They are often criticized for not being transparent enough and thus potentially causing wrong interpretations. We address this weakness with a transparent communication of all steps and assumptions and by interpreting the index and comparing it with existing scientific findings.

[29] The inclusion of additional indicators describing storms or sea level rise, indicators that are based on daily data, and indicators that describe a relevant decrease of extreme events such as extreme cold events, could be part of a further development of the CCI. Also, the CCI could further be improved by including other seasons and especially by enlarging the multi-model ensemble.

4. Summary and Conclusion

[30] In this paper, we present a method to calculate a Climate Change Index (CCI). The CCI is a measure for how strongly future climate will change relative to today's natural variability. It is the average of nine individual temperature and precipitation indicators. Each of these can assume values between 0 and 19 that represent the additional future occurrence of the respective "1 in 20 years" extreme event today.

[31] The aim of the CCI is to provide a simple and comprehensive concept for policy-makers. It has to be noted that climate impacts – which might easily be confused with changes in the strength of climate change – are not the subject of the index.

[32] The presented CCI shows strongest expected climate change in the tropics and in high latitudes, especially in the northern hemisphere.

[33] For policy makers the CCI is calculated on a country basis, facilitating comparison with socio-economic country indicators. A correlation with the Human Development Index suggests that in many less developed – and thus more sensitive and less adaptable – countries climate is expected to change more strongly than in more developed countries.

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References

Allen, M. R., and W. J. Ingram (2002), Constraints on future changes in climate and the hydrologic cycle, *Nature*, *419*, 224–232.
Barnett, T., et al. (2005), Detecting and attributing external influences on the climate system: A review of recent advances, *J. Clim.*, *18*, 1291–1314.
Flato, G. M., et al. (2000), The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate, *Clim. Dyn.*, *16*, 451–467.
Freudenberg, M. (2003), Composite indicators of country performance: A critical assessment, *Pap. DSTI/DOC* (*2003*)*16*, 34 pp., Organ. for Econo. Coop. and Dev., Paris.
Giorgi, F. (2006), Climate change hot-spots, *Geophys. Res. Lett.*, *33*, L08707, doi:10.1029/2006GL025734.
Giorgi, F., and X. Bi (2005), Updated regional precipitation and temperature changes for the 21st century from ensembles of recent AOGCM simulations, *Geophys. Res. Lett.*, *32*, L21715, doi:10.1029/2005GL024288.
Gordon, C., et al. (2000), The simulation of SST, sea ice extents, and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Clim. Dyn.*, *16*, 147–168.
Hegerl, G. C., et al. (2004), Detectability of anthropogenic changes in annual temperature and precipitation extremes, *J. Clim.*, *17*, 3683–3700.
Intergovernmental Panel on Climate Change (IPCC) (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, New York.

McKee, T. B., et al. (1993), The relationship of drought frequency and duration to time scales, paper presented at 8th Conference on Applied Climatology, Am. Meteorol. Soc., Anaheim, Calif., 17–22 Jan.

Organisation for Economic Cooperation and Development (OECD) (2002), Aggregated environmental indices—Review of aggregation methodologies in use, *Rep. ENV/EPOC/SE* (*2001*)*2/FINAL*, 43 pp., Working Group on Environ. Inf. and Outlooks, Paris.

Räisänen, J. (2002), CO_2–Induced changes in interannual temperature and precipitation variability in 19 CMIP2 experiments, *J. Clim.*, *15*, 2395–2411.

Roeckner, E., et al. (2003), The atmospheric general circulation model ECHAM5—Part I: Model description, *Rep. 349*, 127 pp., Max Planck Inst. for Meteorol., Hamburg, Germany.

Scherrer, S. C., C. Appenzeller, M. A. Liniger, and C. Schär (2005), European temperature distribution changes in observations and climate change scenarios, *Geophys. Res. Lett.*, *32*, L19705, doi:10.1029/2005GL024108.

Tebaldi, C., L. O. Mearns, D. Nychka, and R. L. Smith (2004), Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations, *Geophys. Res. Lett.*, *31*, L24213, doi:10.1029/2004GL021276.

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