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Summary

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Keywords: Carbon Budgets, Climate Policy, IPCC
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Regional carbon budgets: do they matter for climate policy?

Massimo Tavoni (FEEM and Politecnico di Milano), Detlef van Vuuren (PBL and Utrecht University)

Abstract

Carbon budgets have emerged as a robust metric of warming, but little is known about the usefulness of regional carbon budgets as indicators of policy. This article explores the potential of regional carbon budgets to inform climate policy. Using the large database of scenarios from IPCC AR5 WGIII, we show that regional budgets are important metrics of the long term contribution to climate change and the effort required to mitigate it. However, their value appears to be more limited for informing short term courses of actions, and for predicting the economic consequences of emission reduction policies.

1. Introduction and methods

Carbon budgets are a powerful way to translate the complexities of climate science into an easily understandable, yet remarkably robust, linear relation between cumulative emissions and temperature increase. Since their inception, they have received increasing attention and have been validated in many different contexts (Zickfeld et al. 2009; Allen et al. 2009; Meinshausen et al. 2009; Matthews et al. 2009), most notably in the latest assessment report of the IPCC (Edenhofer et al. 2014). The relationship emerges, among others, as CO_2 dominates in the long-term the total greenhouse gas forcing. The relationship derived in the IPCC report on the basis of climate model calculations of the Representative Concentration Pathways (D. van Vuuren et al. 2011) indicate that in order to likely remain below the 2^oC target – currently discussed in international negotiations - the carbon budget is around 1000 $GtCO_2$ or lower (Friedlingstein et al. 2014).

The proportionality between the sum of CO2 emissions and temperature lends itself to a natural method for disaggregation across scales and time: the global temperature increase can be retrieved by summing up the regional temperature contributions obtained by direct multiplication of the regional carbon budgets. So far, most of the literature related regional contributions to global targets has focused on specific annual targets or emissions pathways either using burden sharing rules or assuming a global cost-effective response (leading to the same marginal price in all regions). Examples of such approaches include (M. den Elzen and Höhne 2008; Ciscar et al. 2013; Jacoby et al. 2009; Kober, van der Zwaan, and Rösler 2013; Miketa and Schrattenholzer 2006). An useful overview of these approaches is provided by (Hof, den Elzen, and Van Vuuren 2009). While similar approaches can also be used for carbon budgets, only few studies have done so yet (e.g. Anderson, Bows, and Mander 2008; BOTZEN, GOWDY, and BERGH 2008; Tavoni et al. 2014).

In this article we explore the potential and limitations of regional budgets to inform climate policy. We use the large ensemble of scenarios generated by integrated assessment models (IAMs) for the WGIII of the 5th assessment of the IPCC. The database, which is publicly available[1], contains several hundred scenarios, spanning a wide range of climate categories, policy and technology implementations. Scenarios have been generated by multiple IAMs, often in the context of multi model comparison projects. A great deal of information, including CO_2 and non-CO_2 emission pathways, energy system and economic indicators, is

[1] At https://secure.iiasa.ac.at/web-apps/ene/AR5DB/dsd?Action=htmlpage&page=about

contained in the data base. Most of the climate policy scenarios have focused on long term forcing targets, though some model ensembles have directly implemented budgets as policies (E. Kriegler et al. 2014).

In our calculations here, we have only included results from IAMs which can generate long term, i.e.meaning up to 2100, CO_2 emissions profiles. We focus on the results of 4 (of the 5) IPCC regions, namely OECD, ASIA, Latin and Central America (LAM) and Middle East and Africa (MAF)[2]. We consider all scenarios, including both 'first best' (e.g. full cooperation on mitigation, full technology availability) as well as 'second best' (e.g. delayed/fragmented participation in mitigation, technology restrictions) ones.

2. Regional carbon budgets

We begin by exploring the outcomes of IAMs in terms of regional budgets. We first focus on the results for no climate policy or business as usual scenarios. We subsequently report on regional budget for policies aimed at achieving climate stabilization at some predetermined levels.

2.1. No climate policy scenarios

As policies will not be formulated at the global level, one of the most natural extensions of the global carbon budget concept is to compute cumulative CO2 emissions at the regional level. The proportionality of the budget-warming relations can thus be used to calculate the regional contributions to climate change, an appealing policy indicator.

Figure 1 reports the CO2 budget for the four representative regions of interest. The figure is consistent with the idea that in the absence of climate policies, fossil fuels are sufficiently abundant and cost competitive to lead to continued emissions. Figure 1 shows that –according to the scenarios included in the IPCC WG3 DB- the magnitude of these carbon budgets would be significant.

The carbon budget of Asia has a median value of exceeding 2500 $GtCO_2$. This budget alone would be more than double the global allowable budget compatible with 2^oC, represented by the colored areas in the chart. Indeed, Asia alone would add more CO2 to the atmosphere in the remaining of this century than all the CO2 added since pre-industrial times globally. This is of course a result of the sheer size –population and economic wise- of the continent. However, large contributions are also expected from the other regions. Most notably, the OECD countries, which have already contributed disproportionately to historical CO2 emissions, would still contribute in excess of 1000 GtCO2, if no specific policy to reduce emissions were to be implemented. The variations across models, and also within the same model but for different scenarios, are reflected in the large ranges reported in Figure 1. However, with the exception of LAM, all other regions show budgets which by themselves exhaust the total admissible 2C budget[3].

[2] The fifth region used in the AR5 WGIII is REF (Reforming economies, or economies in transition, which roughly correspond to Former Soviet Union). The regions is not included here to simplify our figures. The results are less interesting than for some of the other regions.

[3] It should be remarked, however, that the BAU scenarios in the IPCC DB are not meant to span the full ranges of possible futures, and thus represent only a subset of potential outcomes of no policy cases. The new shared socio economic pathways, which are being released at the time of this writing, will provide additional alternatives, further enlarging the space of BAU outcomes.

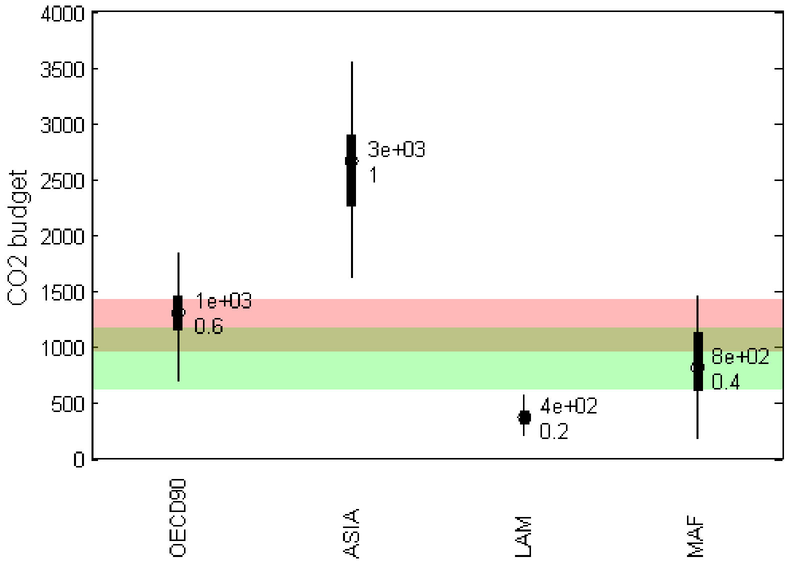

Figure 1. Boxplot of regional CO2 budgets for four representative regions (OECD,ASIA, LAM, MAF) for Business as usual (BAU) scenarios. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to 1.5 the interquartile range. The green and red shades indicate the temperature carbon budgets from IPCC WGIII consistent with 66% and 50% chances of keeping temperature below 2C respectively. The numbers represent the median carbon budgets (in GtCO2) and temperature increase over 2010 corresponding to an average TCRE of 0.48C/1000GtCO2.

It is natural to translate the regional carbon budgets into equilibrium temperature contributions. Due to the linearity of their relation, global warming can be simply recovered by summing the regional warming contributions. The temperature increase associated with the median budgets, and using a central TCRE estimate of 0.48C/1000GtCO2, is also reported in Figure 1. With this parametrization, OECD90 and Asia together would add about 2C (to the current warming of 0.7C), and another half degree would come from LAM and MAF. Of course, this is the warming generated by CO2, on top of which one should add the warming of nonCO2 radiative forcing.

2.2. Climate stabilization scenarios

When a climate stabilization policy is in place is useful to derive regional carbon budgets The allocation of emissions, and thus the consequent budget, will depend on the policy formulation at the regional level, e.g to the targets countries would agree upon in an international agreement. In policy settings aimed at achieving global targets at the minimum global costs, climate policies are implemented either though a uniform carbon tax, or via a cap and trade system with a single price on carbon and trade of CO2 permits across regions. In such a setting, regional carbon budgets are determined by the regional mitigation potentials (in such a way to equalize marginal abatement costs): allowances above or below these optimal values would then be traded (e.g either sold or bought respectively). This has important economic consequences, as we'll see in the next sections, but (at least in the ideal model world) does not matter for carbon budgets: once a single carbon price is in place, regional budgets are univocally determined, irrespective of emission allowances. Emission allowances determine who pays for mitigation, and thus equity and efficiency can be dealt with separately[4]. Without the use of flexible instruments, it also possible to establish regional carbon budgets but potentially leading to much higher overall costs.

Figure 2 reports the regional CO2 budgets for two classes of climate stabilization targets of different stringency, of 430-530 ppm-eq and 530-650 ppm eq respectively. For each region, the three bars show the budgets till 2030, 2050, and 2100. Focusing first on the 2100 budgets (rightmost bars for each region), the chart shows that under climate objectives consistent with the 2°C target, no region would have a budget higher than few hundreds GtCO2. Compared to the much larger BAU budgets of Figure 1, these imply that very significant mitigation efforts are needed in all regions in order to attain the target. Figure 2 also highlights important regional differences: the LAM and MAF regions have significant lower budgets than the OECD and ASIA regions, even compared to the baseline. The larger relative reduction is a result of different mitigation opportunities across regions. Integrated assessment models foresee large biological mitigation potential in tropical regions such as LAM and MAF, through forest management and bioenergy practices (Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, et al., n.d.).

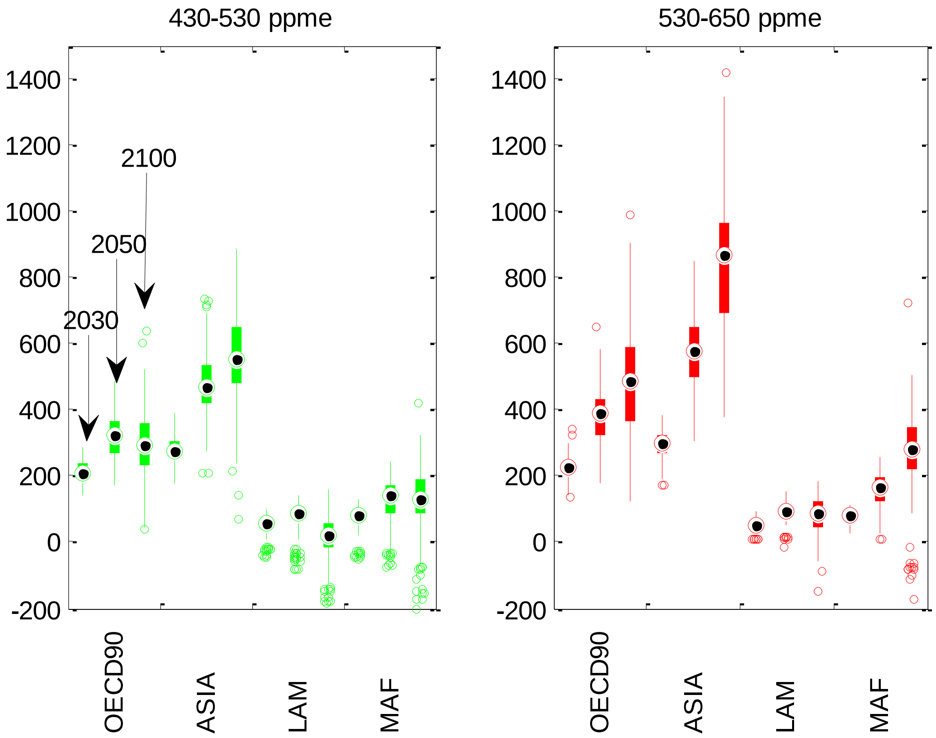

Figure 2. Boxplot of regional CO2 budgets (in GtCO2) for two ranges of climate stabilization targets (430-530 and 530-650 ppm). For each region, the three boxplots show the budgets from 2010 to 2030, 2050 and 2100 respectively. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to 1.5 times the interquartile range, and outliers are plotted individually.

[4] This requires perfect markets with no transaction costs and no income effects, an assumption often violated in reality. IAMs make it nonetheless for sake of simplicity.

A less stringent climate target of 530-650 ppm CO_2-e (closer to 3^oC warming) leads to higher regional budgets. The increase of 100 ppm translates in roughly 200 additional GtCO2 of budget for each of the four analyzed regions.

Although the budgets convey important information about regional climate policy, they lack the temporal dynamics which is more relevant for policy. Figure 2 provides the additional information of the distribution of the budgets over three policy relevant periods: 2010-2030, 2010-2050, and the already discussed 2010-2100. Several insights emerge: the 2050 budget appears to be very close to the 2100 one, especially for the most stringent climate category. In some regions (e.g. LAM), the 2050 budget can be even higher than the 2100 one. The reason is that cumulative CO_2 emissions in the second part of the century in most stringent scenarios are very low or even net negative. When moving to the less stringent target of 530-650 ppm CO_2-e budgets are spread more even over time, thanks to the larger overall budgets. Budgets keep growing over time, though at a reduced rate, but not in all regions. Once again LAM shows a particularly striking patters, with no emission growth post 2050.

The issue of negative emissions deserves further scrutiny. IAMs feature mitigation technologies which can absorb CO2 from the atmosphere, and resort to these when confronted with stringent targets, or even with lenient climate targets but with delayed mitigation action in the next few decades or with limited conventional technology availability. Carbon dioxide removal is thus a key mitigation option under certain conditions, and most IAMs implement it mostly in terms of biological removal coupled with carbon capture and storage (ie. BECCS)(Tavoni and Socolow 2013; Azar et al. 2010; D. P. van Vuuren et al. 2013; Elmar Kriegler et al. 2013; Edmonds et al. 2013). The feasibility of large scale negative emissions programmes is hard to assess at the moment, and will require significant technological progress to become viable (Fuss et al. 2014; Smith and Torn 2013).

Figure 3 reports the 'negative carbon budgets' at the regional level. They are the cumulative sum (in absolute values) over the entire century of CO2 emissions, when these are negative. Negative carbon budgets explain the patterns observed in Figure 2, with limited or even negative growth of emissions post 2050. The chart points to significant quantities of net negative emissions, especially in some regions and for the most stringent climate objective. The median negative emission budget in LAM for the 430-530 target is in the order of 75 GtCO2. Globally, these add to several hundred GtCO2 of net negative emissions. It should be remarked that since IAMs generally assume that some residual emissions will remain positive throughout the century in specific sectors or for certain activities, the negative budgets are smaller than the total use of carbon dioxide removal (CDR). Some of the the global IAMs show cumulative carbon dioxide removal of up to 1000 GtCO2 (Tavoni and Socolow 2013).

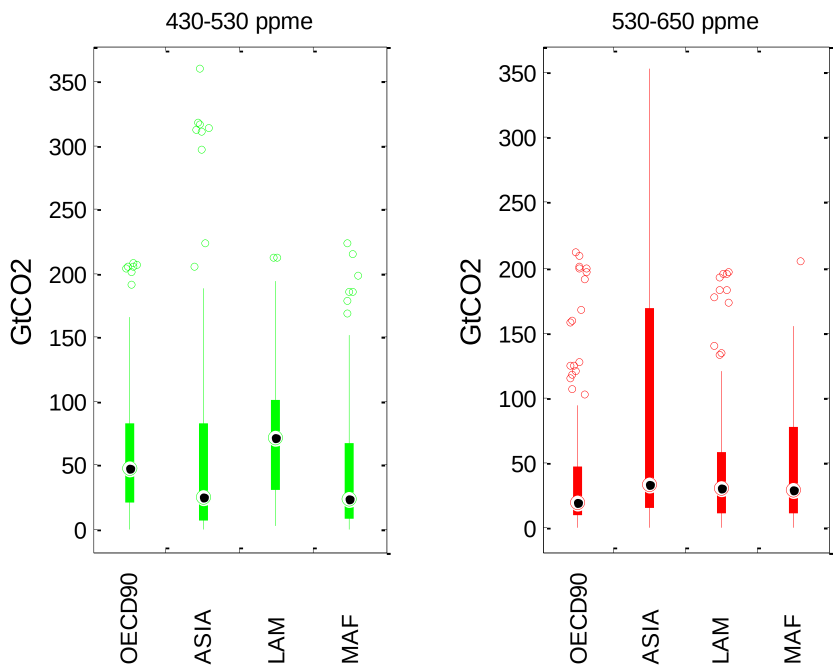

Figure 3. 'Negative CO2' budgets. Total cumulative emissions during the period of net negative emissions. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to 1.5 times the interquartile range, and outliers are plotted individually.

The charts shows a great deal of uncertainty over the amount of negative CO2 budgets. This is the outcome of two processes. First, negative emissions are very sensitive to the policy setting. They play a fundamental role in scenarios with delayed global participation, fragmented regional action, and limited availability of conventional mitigation options such as renewables and nuclear power. At the same time, they require specific technologies. In models, IAMs represent negative emission technologies in the form of such as CCS: given the uncertainty around CCS several scenarios in the IPCC DB explored cases without it. Secondly, different IAMs make importantly different assumptions about the technical and economic potential of CDR, and their repercussions on land use.

The overall picture suggests that large negative CO2 budgets are an important –albeit uncertain- component of the mitigation strategy foreseen by IAMs. This has direct repercussions on the interpretation of carbon budgets for policy purposes: a carbon budget of 1000 GtCO2 which embeds either 500 or 0 GtCO2 of negative CO2 budget is identical in terms of the cumulative emissoins, but entails completely different consequences in terms of temporal allocation of emission reductions, transformation of the energy sector, land use change, etc.

Finally, we look at the distinction between carbon budgets and emission allowances. In those policy settings which permit trading of CO2, significant quantities of CO2 might be exchanged between countries. The magnitude and direction of trade will be determined by the allocation of emission allowances and the regional carbon budgets representing the cost-optimal allocation. The allocations can be set at any level, e.g. incorporating different assumptions about equity. A common allocation scheme is based on the equity principle of equalizing per capita emissions across countries, but many others exist (M. den Elzen and Höhne 2008; M. G. J. Elzen et al. 2012). Although the mitigation strategy –in terms of energy and land use sector transformation- is solely determined by the regional carbon budgets, the economic consequences are not. It is indeed the scope of carbon trading to distinguish who will mitigate from who will pay.

The traded CO2 budgets are shown in Figure 4. The chart shows large ranges, due to the different choices of allocation schemes across scenarios. Across scenarios, LAM and MAF tend to be net sellers of permits, and the OECD a net buyer. ASIA is in between. The magnitude of the traded budgets is significant, with LAM selling cumulatively over the century on average 100 GtCO2, and OECD buying as much as 200 GtCO2 in the less stringent climate targets, where more trading can be observed. Economic revenues will be determined by the carbon price at which permits are exchanged, which will depend positively on the stringency of the climate target. Previous research has indicated that the trade flows would be sufficient to finance large portions of clean energy investments in developing regions, but that the institutional requirements for managing such large markets would be very significant (Wara 2007; Tavoni et al. 2014). This analysis suggests that carbon budgets might not be good indicators of the economic effort needed to achieve climate mitigation policies, in the presence of large international carbon markets.

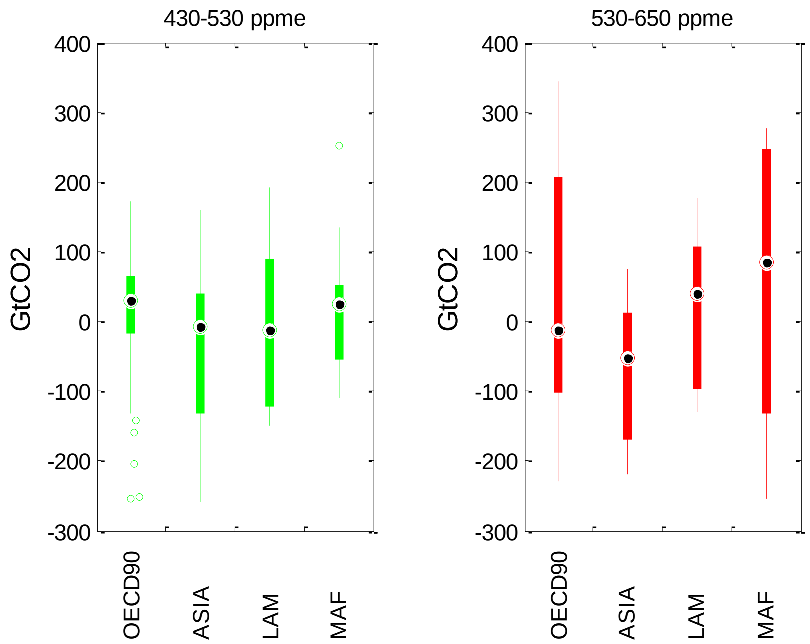

Figure 4 Boxplot of regional traded CO2 budgets (positive=buying, negative=selling) for four representative regions (OECD,ASIA, LAM, MAF) (see Figure 3 for further explanation)

3. Are carbon budgets a good indicator of policy?

In the previous section we have shown that carbon budgets are useful indicators for determining both the regional contribution to climate change in no policy (BAU) scenarios, and the regional stringency of mitigation compatible with given global climate stabilization objectives. In this section, we take a closer look at the correlation between carbon budget and policy effort.

3.1. Correlation with mitigation effort

As indicator of policy effort, we first look at the relative reduction in emissions with respect to BAU. The ratio (mitigation effort) is one of the most important drivers of energy and carbon intensities, carbon prices and mitigation costs. Figure 5 show the relation between carbon budgets and cumulative mitigation, both expressed until 2100. The chart shows a strong correlation between these two indicators. Across our four regions of interest, cumulative mitigation is almost linearly negatively related to budgets.

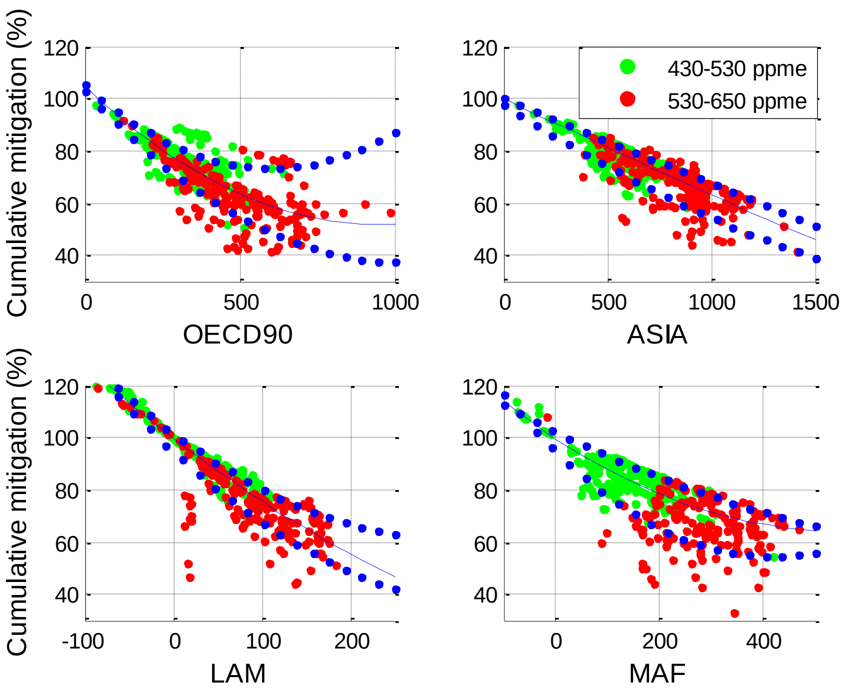

Figure 5. Relation between regional CO2 budgets and cumulative mitigation (till 2100, relative to BAU), for two groups of climate categories (430-530 and 530-650 ppm eq). Each dot is a scenario. Budgets below 0 and cumulative mitigation above 100% are possible due to negative emissions. The blue lines shows the quantile regressions, at 10, 50 and 90 percentiles.

As expected the lower the budget, the higher the cumulative emission reduction with respect to a scenario without climate policy. In accordance with what shown in the previous sections, the LAM and MAF regions can accommodate net negative budgets, which require cumulative mitigation efforts which exceed 100%.

The strong relation between budgets and cumulative mitigation is not an obvious one, given that mitigation is measured against emissions in a counterfactual scenario (BAU), which can vary significantly across countries (Blanford, Rose, and Tavoni 2012). Nonetheless, the two concepts are related, and they both extend throughout the entire century. However, as shown in Figure S1, the relation remains strong even if we were to focus (both for mitigation and budgets) only on the first half of the century.

However, cumulative mitigation with respect to BAU is not frequently used for designing short to medium term climate policies. This is because it does not provide clearly defined targets in specific periods of time, and also because of the arbitrariness of counterfactual BAU scenarios, which are subject to a great deal of uncertainty. A more common, though less precise, metric of effort is simply the mitigation in a determined year, with respect to some given level, e.g. today's emissions. In the past, for example, the 2°C has been associated with a global emissions reduction target of around 50-80% by 2050 over today ({IPCC} 2007). And the major economies in 2009 pledged a reduction in the range of 80-95% using the same metric –also based on the IPCC, 2007 report.

Figure 6 shows the relation between century scale carbon budgets and CO2 mitigation in 2050 with respect to 2010. Clearly, a relation between carbon budget and mitigation effort, defined in this way, is observable. However, it is considerably weakened with respect to what shown in Figure 5. This is particularly true for the regions which have the smallest budgets, and therefore achieve the more stringent mitigation, LAM and MAF. In these regions carbon budgets do not accurately predict mitigation for a specific year (2050) and with respect a given reference (today).

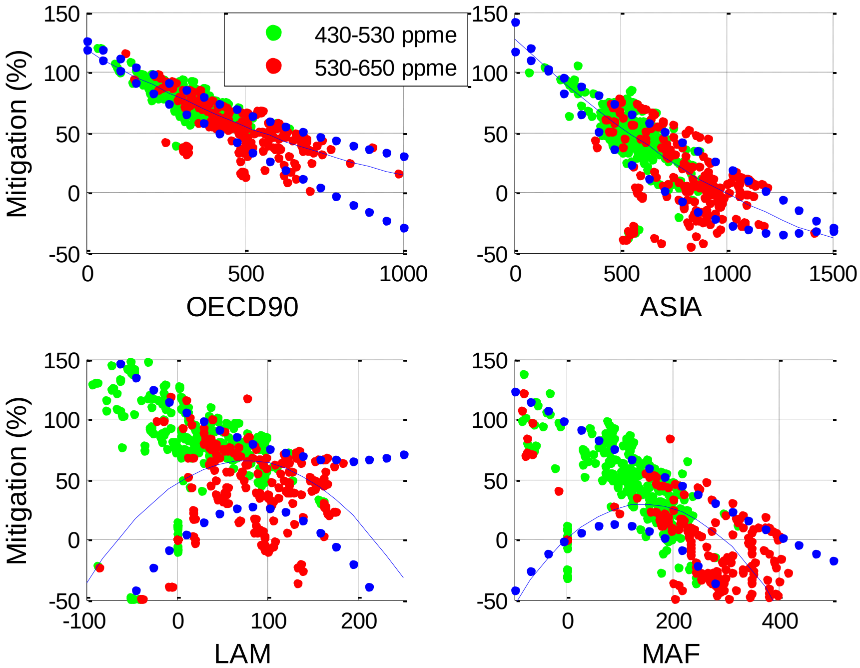

Figure 6 Relation between regional CO2 budgets (till 2100) and mitigation (in 2050, relative to 2010), for two groups of climate categories (430-530 and 530-650 ppm eq). Each dot is one scenario. The blue lines shows the quantile regressions, at 10, 50 and 90 percentiles.

The mitigation targets discussed in climate policy often refer to a basket of greenhouse gases. The Kyoto gases –aggregated using 100 year GWP- are commonly used. This induces another degree of freedom. Indeed, as shown in Figure S2, the relation between budgets and mitigation is further worsened when we consider the latter in terms of all Kyoto gases, and not just CO2.

We finally focus on the correlation between carbon budgets and the timing of mitigation effort. The years in which emissions either reach negative values or attain the maximum are useful focal points for climate policy. In the first case, this indicates by when during this century, if ever, the entire energy and land use system is expected to reach overall carbon neutrality. The second provides an indication of the time by when emissions will have to begin to decline, which is an important turning point for those economies where emissions are growing particularly rapidly.

Figure 7 shows a relatively clear and strong correlation between carbon budgets and the year by when CO2 emissions are predicted to become negative (for those scenarios which do predict globally net negative emissions). Scenarios with low or negative carbon budgets are consistent with emissions turning negative shortly after mid century.

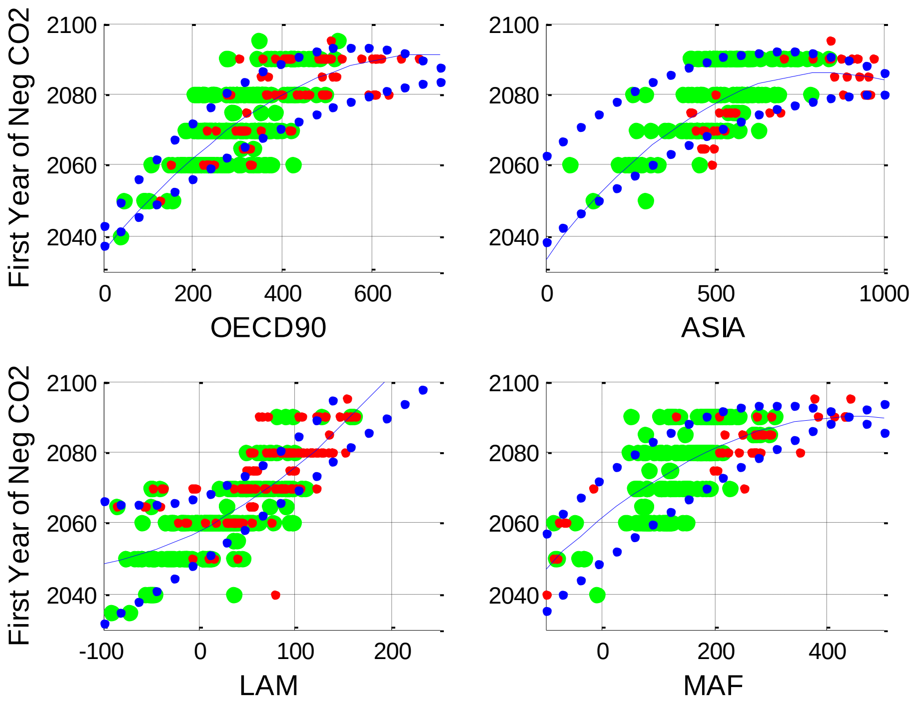

Figure 7. Relation between regional CO2 budgets and first year of net negative CO2 emissions, for two groups of climate categories (430-530 and 530-650 ppm eq). The blue lines shows the quantile regressions, at 10, 50 and 90 percentiles. The green markers are bigger for improved clarity.

As for the year of emission peaking, Figure 8 confirms some correlation with budgets, but only for the fast growing economies of ASIA (and also of MAF). Climate policies consistent with 2^{o}C (430-530 ppm-eq) suggest a peaking of CO2 emissions in ASIA which would not exceed 2030, and median century scale budgets of about 500 GtCO2. Thus, the commitment recently made by China to have emissions peak by 2030 would likely need to be strengthened and most importantly matched by other large Asian economies, a level of effort which probably exceeds what will be issued in terms of national commitments in the next future.

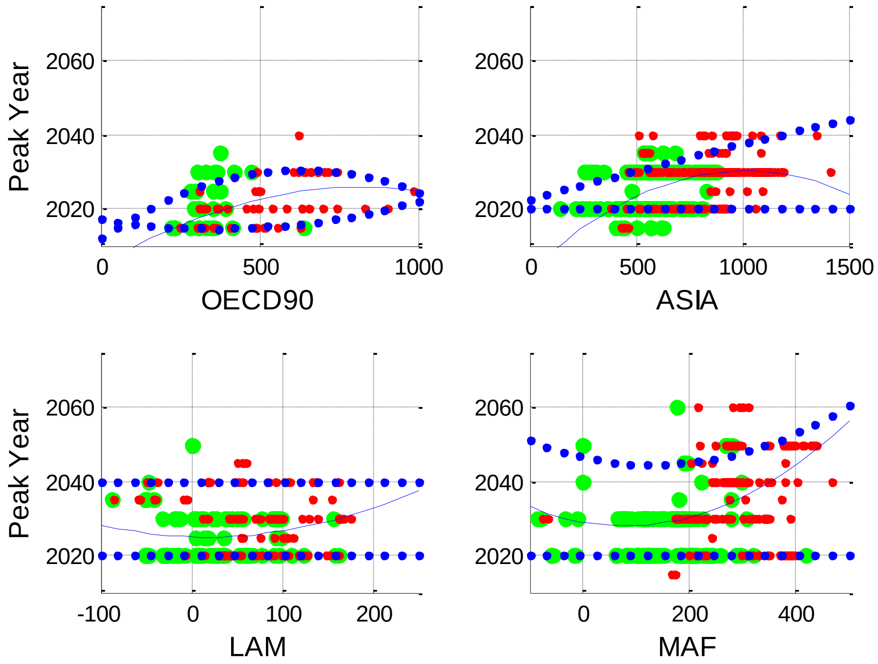

Figure 8 **Relation between regional CO2 budgets and year of peaking of CO2 emissions, for two groups of climate categories (430-530 and 530-650 ppm eq). The blue lines shows the quantile regressions, at 10, 50 and 90 percentiles. The green markers are bigger for improved clarity.**

Summing up, this section has shown that carbon budgets correlated well with measures of mitigation efforts which focus on the long term (e.g. cumulative mitigation, time of zero emissions), but significantly less so with the ones more frequently used for short and medium term policy making more short term ones (e.g. mitigation by mid-century, year of peaking emissions).

3.2. Correlation with economic mitigation costs

Finally, we examine the relation between carbon budgets and economic indicators of mitigation policies. Political feasibility of legislating climate policies is heavily dependent on the economic repercussions which such policies will exert. Although the global costs of climate stabilization policies are often found to be relatively modest by IAMs, the regional variations can be much larger (Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, et al., n.d.). Since policymakers care about national and regional impacts on economic activities, it is important to examine the relation between carbon budgets and economic policy costs[5]. It should be noted, however, that the costs presented here should be used with care. They are based on scenarios in regional mitigation is based on marginal costs (see previous section), so not assuming any prior allocation or pledges based on equity considerations.

[5] It should be remarked that different models express mitigation costs in different metrics. Top down economic IAMs use GDP or consumption losses. Bottom up IAM express costs in terms of area under the marginal abatement cost curve, or in terms of additional energy system costs. Here we combine all metrics, with preference to GDP loss for those models which report more than one metric.

Figure 9 shows large regional variation in costs, with developing economies showing relatively higher costs than OECD, as suggested in the literature (Stern, Pezzey, and Lambie 2012; Tavoni et al. 2014). The figure shows that there is a correlation between budgets and economic costs, but with vary large uncertainty ranges, especially in developing economies. This result can be ascribed to various factors. First, the differences in costs are again one level up in term of uncertainty than the mitigation effort discussed in the previous paragraph. Models make very different assumptions on the costs development of different technologies and the implications of using more expensive technologies for the economy as a whole. Second, if policies are not 'first best', costs will depend on the policy structure. However, even when plotting the same chart focusing only on first best policies, a similar relation is observed. Third, mitigation costs are discounted using a given net present value, which puts more value on immediate rather than deferred costs. However, even when looking at different discount rates things do not change much. Finally, an additional key factor for mitigation costs is the carbon intensity of the economy in the BAU, as well as terms of trade effects for fossil exporting countries (Stern, Pezzey, and Lambie 2012; Tavoni et al. 2014). This information is not accounted for by the carbon budgets and therefore it is not surprising to find that budgets that there is considerable uncertainty between carbon budgets and mitigation costs.

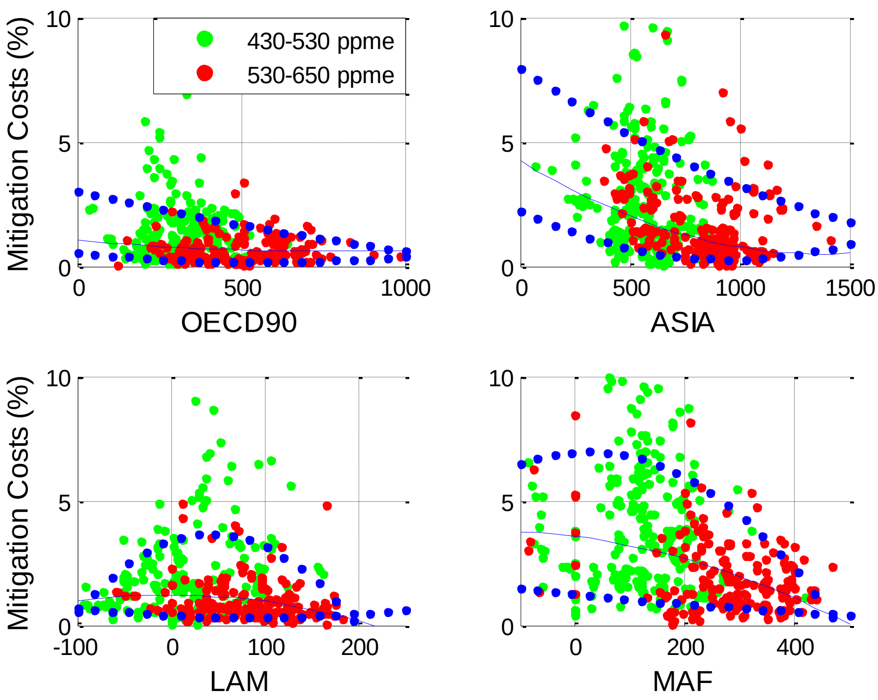

Figure 9. Relation between regional emission budgets and mitigation costs (NPV at 5% discounting), for two groups of climate categories (430-530 and 530-650 ppm eq). The blue lines shows the quantile regressions, at 10, 50 and 90 percentiles.

Figure S3 shows that a somewhat stronger relation can be established between carbon budgets and the marginal costs of mitigation, e.g. carbon prices (actualized in net present values). But even in this case, the unexplained variation remains large, testifying to the fact that carbon budgets alone fail to predict accurately the economic consequences of climate policies.

4. Conclusions and recommendations

This paper has assessed the validity and usefulness of regional carbon budgets for climate policy. The regional focus of the paper is motivated by the policy relevance and importance of regional policy indicators, such as in the context of the ongoing UFCCC negotiations. Defining the right metrics of comparability of effort is a key step to evaluate countries climate change mitigation effort (Joseph E. Aldy and Pizer 2014). In order to do so, we have resorted to the largest scenarios ensembles database currently available, the one prepared for the IPCC WGIII 5th assessment report.

Our results suggest an important but confined role for carbon budgets in climate policy. Thanks to the linearity between budgets and temperature increase, regional carbon budgets are particularly useful for predicting the regional contribution to global warming for BAU scenarios. Similarly for the global carbon budgets, the main limitation is the missing warming contribution of the non-CO2 forcing, which is expected to be substantial. Budgets are also good predictors of mitigation effort, but mostly when this is measured in the long term. The correlation is weaker for shorter term, imperfect, and yet more widely used metrics such as emissions reductions in a given year or time of peaking or of negative emissions. Finally, budgets are relatively poor predictors of the economic costs of mitigation. However, it is difficult to devise single indicators which forecast well mitigation costs, so this criticism applies as well to most other indicators.

Making progress on international climate policy requires comprehensive effort by all the major emitters. In this sense, developing and testing a variety of indicators of effort is an important area where research can fruitfully contribute to policy. Carbon budgets provide an important step in this direction. More research is needed to validate and increase the confidence of the regional measures, as well as in expanding the analysis from large regional aggregates described in this paper to the country level. We leave these unanswered questions for future research.

Acknowledgements

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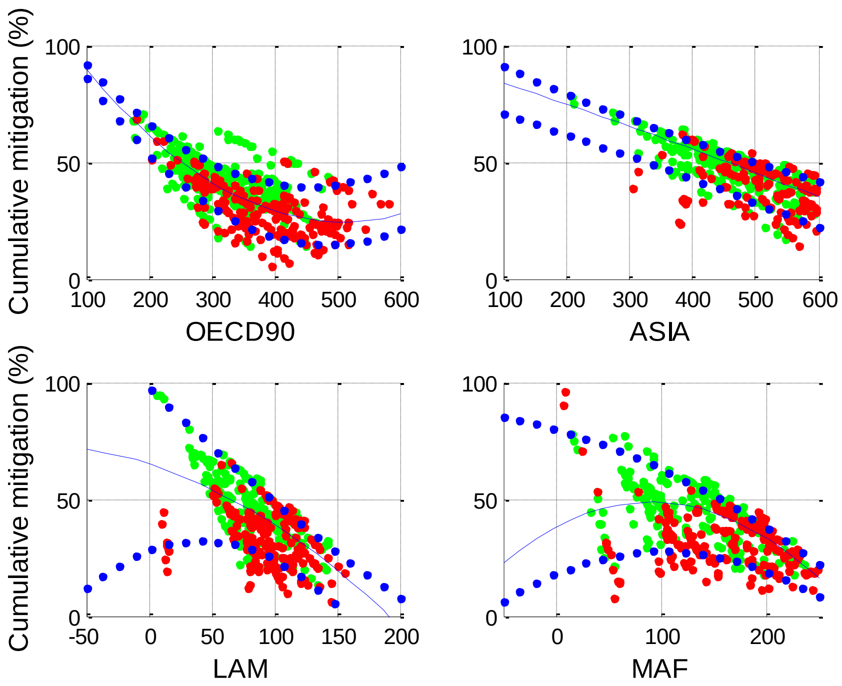

Figure S1: Same as Figure 5 but with carbon budgets and cumulative mitigation to 2050.

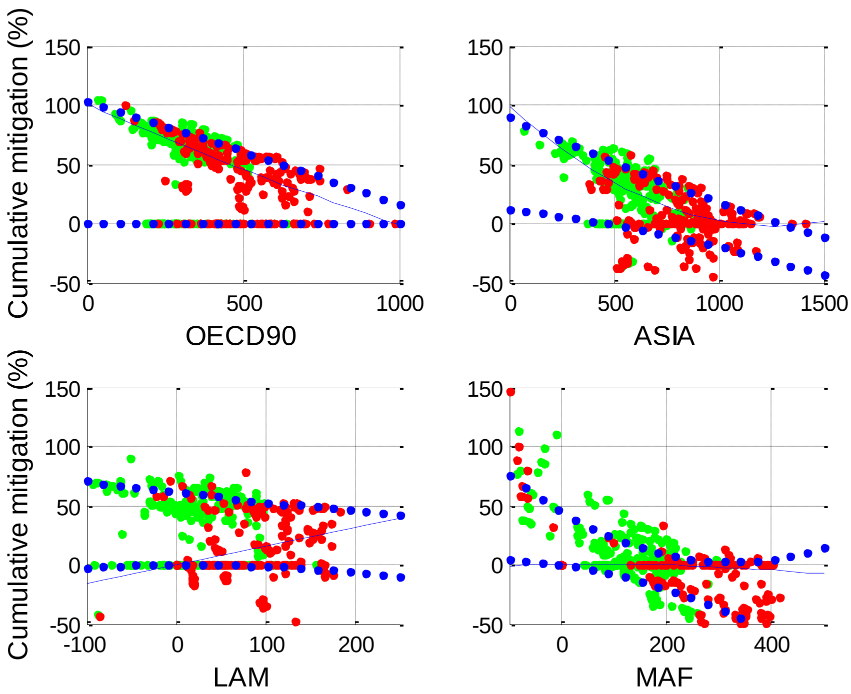

Figure S2: same as Figure 6**, but for mitigation is for all Kyoto gases (budgets are still in CO2)**

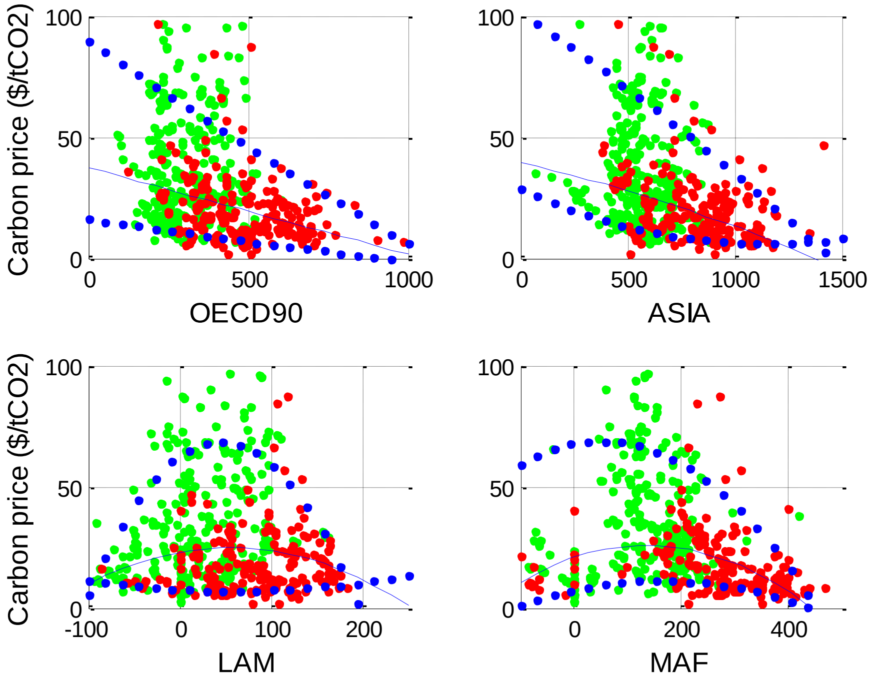

Figure S3: Relation between regional emission budgets and carbon prices (NPV at 5% discounting), for two groups of climate categories (430-530 and 530-650 ppm eq). The blue lines shows the quantile regressions, at 10, 50 and 90 percentiles.

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