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Evaluation of the absolute regional temperature potential

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Abstract

The Absolute Regional Temperature Potential (ARTP) is one of the few climate metrics that provides estimates of impacts at a sub-global scale. The ARTP gives the time-dependent temperature response in four latitude bands (90–28° S, 28° S–28° N, 28–60° N and 60–90° N) as a function of the regional forcing imposed in those bands. It is based on a large set of simulations performed with a single atmosphere-ocean climate model. Here I evaluate ARTP estimates of regional temperature responses due to historic aerosol forcing in three independent climate models and show that the ARTP metric provides results in good accord with the actual responses in those models. Nearly all ARTP estimates fall within ±20 % of the actual responses, and in particular for the tropics and the Northern Hemisphere mid-latitudes this range appears to be roughly consistent with the 95 % confidence interval. Land areas within these two bands respond 41 ± 6 % and 19 ± 28 % more than the latitude band as a whole. The ARTP, presented here in a slightly revised form, thus appears to provide a relatively robust estimate for the responses of large-scale latitude bands and land areas within those bands to inhomogeneous radiative forcing.

1 Introduction

The ARTP is a simple metric to provide estimates of regional (latitude band) temperature responses to radiative forcings taking into account the latitude bands at which the forcings are imposed. It was developed in Shindell and Faluvegi (2010) based on simulations examining the response to localized radiative forcing (RF) in a full coupled atmosphere-ocean climate model (Shindell and Faluvegi, 2009). The RTP does not provide temperature change estimates at the small spatial scales required for many impact assessments, but does provide addition insight into the spatial pattern of temperature response to inhomogeneous forcings beyond that available from traditional global metrics. Very few metrics have attempted to examine sub-global scales thus far.

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The Specific Forcing Pulse (Bond et al., 2011) examined the dependence of regional radiative forcing on the location of emissions. Those results require a matrix such as the RTP coefficients to connect forcing to temperature response, however. As such, the ARTP provides a valuable, and thus far unique, tool with which to derive estimates of regional temperature response to forcing calculated from a range of models extending from full composition models to multiplication of emissions changes by specific forcing pulses.

The previous work presented a matrix of RTP coefficients derived from the GISS climate model and described the RTP methodology. While the uncertainties were characterized for that model (Shindell and Faluvegi, 2009), that provides no information as to how consistent the regional forcing/response relationships are across models. Here I present an evaluation of the robustness of the ARTP estimates when applied to independent climate models. I also document minor corrections and improvements to the methodology and a small extension to the ARTP method to allow estimates of land-area temperature changes.

2 ARTP definition

The ARTP was developed as an analogue of the absolute global temperature potential (AGTP), which provides an estimate of the global mean temperature response to a given global mean radiative forcing as a function of time (Shine et al., 2005). The ARTP has been developed for four latitude bands: the Southern Hemisphere extratropics (90–28° S; SHext), the tropics (28° S–28° N), the Northern Hemisphere mid-latitudes (28–60° N; NHml) and the Arctic (60–90° N). It is essentially the time integral of forcing times the surface temperature impulse response function. The surface temperature change in area a between time 0 and time t is given by:

$$\mathrm{ARTP_a}(t) = dT_\mathrm{a}(t) = \int_0^t (k_{\mathrm{SHext,a}} \cdot F_{\mathrm{SHext}}(t') + k_{\mathrm{Tropics,a}} \cdot F_{\mathrm{Tropics}}(t') + k_{\mathrm{NHml,a}} \cdot F_{\mathrm{NHml}}(t') + k_{\mathrm{Arctic,a}} F_{\mathrm{Arctic}}(t')) \cdot f(t-t')\mathrm{d}t'$$

where F_area is the radiative forcing in the particular area and $k_{x,y}$ is the dimensionless coefficient relating temperature response in area y to forcing in area x (Table 1). The first term in the integral represents the RF weighted by the ratios of regional to global sensitivities while the second term, $f(t)$, is an impulse response function describing the inertial response of global mean surface temperature in K per W m^{-2}. The latter can be defined as:

$$f(t) = 0.541/8.4\exp(-t/8.4) + 0.368/409.5\exp(-t/409.5)$$

where t is the time in years and the two exponentials represent the relatively rapid response of the land and upper ocean and the slower response of the deep ocean as reported for simulations with the Hadley Centre climate model (Boucher and Reddy, 2008), but with absolute responses scaled by 0.857 to match the transient climate sensitivity of the GISS model. The sum of the first coefficients in each term, 0.541 and 0.369, gives the approximate equilibrium climate sensitivity assumed in the limit of long times (0.91 C per W m^{-2}; corresponding to 3.4 C for a doubling of CO_2). The approximate equilibrium response, or the transient response at a particular point in time, in any model (or for any chosen climate sensitivity) is simply the regionally weighted RF (the first term above) multiplied by the climate sensitivity (equilibrium or transient, as appropriate):

$$\mathrm{ARTP_a} = dT_\mathrm{a} = (k_{\mathrm{SHext,a}} \cdot F_{\mathrm{SHext}} + k_{\mathrm{Tropics,a}} \cdot F_{\mathrm{Tropics}} + k_{\mathrm{NHml,a}} \cdot F_{\mathrm{NHml}} + k_{\mathrm{Arctic,a}} \cdot F_{\mathrm{Arctic}}) \cdot (\text{Global-mean sensitivity})$$

The ARTP can be related to emissions by calculating the regional forcings per unit emission, though for short-lived compounds this will depend on the location and timing

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of emissions (Berntsen et al., 2005; Bond et al., 2011; Naik et al., 2007). As with the global metric, the ARTP can be normalized by dividing by the ARTP for a 1 kg emission pulse of CO_2 (which is the same as AGTP as CO_2 forcing is quasi-uniform). Since impulse response functions have been given in terms of response to global mean forcing, the ARTP must weight the impact of forcing in different locations on the response region relative to the impact of global mean forcing on that region. I therefore give the regional response coefficients required for the ARTP calculation based on responses in the GISS model relative to the same model's global sensitivity in Table 1. Compared with Shindell and Faluvegi (2010), this representation normalizes by the global sensitivity rather than the local temperature response to global forcing ($k_{\mathrm{Global,a}}$). This is a better representation of the regional responses, as the $k_{\mathrm{Global,a}}$ values incorrectly removed the regional inhomogeneity in sensitivity seen even for a globally uniform forcing.

Presenting the RTP coefficients in this manner also makes their physical meaning clearer. The global column (Table 1) represents the regional climate sensitivity relative to the global mean. For example, the Arctic response to a globally uniform forcing is 158 % of the global mean response, while the SHext response is only 75 % of the global mean. The regional responses to regional forcings show how much the forcing in each band affects the local area relative to the impact of globally uniform forcing. Hence for a given band, these values indicate how much the local and remote forcings contribute to the climate sensitivity of that band. For example, in the Arctic, roughly half the 158 % Arctic relative sensitivity comes from local Arctic forcing. At Northern Hemisphere mid-latitudes, both tropical and NHml forcing both contribute about 50 % of the response to globally uniform forcing, while the Southern Hemisphere extratropical and Arctic forcings add another 10–15 % to bring the total NHml sensitivity to a value somewhat above 100 % of the global mean sensitivity. Note that the global column values come from separate simulations (of the response to doubled CO_2) from the regional ones and are presented solely to examine non-linearity. Comparing the response to global forcing with the sum of the responses to forcings in the four bands indicates that the

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SHext responses show substantial non-linearity, approximately a factor of two, while the other three regions are fairly linear (8–24 % difference).

Regional responses to different agents were typically statistically indistinguishable for sulfate, black carbon (BC) and ozone. Hence I present here the results using sulfate, as this was the largest forcing and hence has the smallest uncertainty. The only large deviations from the sulfate responses are seen in the Arctic response to Arctic ozone, which is 0.23, and the Arctic response to Arctic BC, which is −0.17 (though the latter includes only the direct RF and neglects the BC albedo forcing, so is an incomplete measures of Arctic BC's impacts). In cases where ozone and BC forcing diagnostics are available, those coefficients could be used. There is minimal difference between the values presented here for sulfate and the averages presented in Shindell and Faluvegi (2010) for the average of sulfate and idealized CO_2 forcings. I switch to sulfate-only results only as many are uncomfortable with the use of results from idealized CO_2 perturbation experiments (though they were intended to be illustrative only).

3 Evaluation of multiple climate models

A previous study examined the spatial patterns of radiative forcing and climate response in four coupled atmosphere-ocean climate models driven by historical changes in aerosols (Shindell et al., 2010). Results are analyzed here from those same simulations, using mixed-layer oceans in the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) (Ming and Ramaswamy, 2009) and University of Tokyo, National Institute for Environmental Studies and Frontier Research Center for Global Change (MIROC/SPRINTARS) (Takemura et al., 2006) models, and with full dynamic oceans in the Institute Pierre Simon Laplace (IPSL) (Dufresne et al., 2005; Hourdin et al., 2006) and NASA Goddard Institute for Space Studies (GISS) (Hansen et al., 2007) models. All models included both direct and indirect aerosol effects (total net RF due to all species, direct plus indirect, is used here), though the IPSL simulations included reflective aerosols only. The regional forcings and responses from the IPSL, GFDL and

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SPRINTARS models can be examined to evaluate the robustness of the GISS-based RTP coefficients. Model simulations were either equilibrium (GFDL and SPRINTARS), or results are total linear trends from transient simulations (IPSL and GISS), so there is no time-dependence. In the analysis, I thus use the time-invariant version of the temperature response equation presented above. The global mean sensitivities (global mean temperature change divided by global mean RF) are used for ARTP calculations for each model: 0.90 K per W m^{-2} for GFDL, 0.89 K per W m^{-2} for IPSL, and 1.10 K per W m^{-2} for SPRINTARS. These values are similar to the 0.86 K per W m^{-2} that is the long-term response embodied in the time-dependent impulse response function based on the GISS sensitivity (or the 1.06 K per W m^{-2} for the original Hadley Centre model) in the time-varying ARTP.

Comparison of the ARTP results with the actual responses in the three independent models shows that they are in general in very good agreement with the actual responses seen in those models' climate simulations (Fig. 1). The overall correlation of the regional values from the three models is $r^2 = 0.75$, and nearly all points lie within 20 % of the RTP estimates. Thus the RTP coefficients derived with the GISS model seem fairly robust, and their use captures most of the regional variations in the three independent climate models. Use of the matrix described in Shindell and Faluvegi (2010) gives an r^2 correlation of 0.71, so is nearly the same. The GISS model results from a historical all-aerosol forcing simulation are shown as well, though these are of course not an independent test as they are from the same model used to derive the ARTP results. However, they do indicate that the RTP coefficients derived from idealized simulations provide a good estimate of the actual response to realistic temporally and spatially varying forcing.

Two points stand out as different in Fig. 1, with the ARTP calculations substantially underestimating the actual response in the SHext for GFDL and in the Arctic for SPRINTARS. The latter could result from either a larger polar amplification in SPRINTARS than in the other models or from a weaker impact of BC in the Arctic than the use of the sulfate-based ARTP coefficients implicitly assumes. For the SHext case, as

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discussed previously there is a large non-linearity in the SHext responses so that the sum of responses to forcing in each region is only about half the response to global mean forcing. Thus the underestimate in the GFDL model may reflect the weak response in this region in the GISS localized forcing experiments, although the SHext RTP estimates agree well with the actual response for the IPSL and SPRINTARS models. Note that both points with large biases occur in areas with comparatively little forcing and in mixed-layer ocean models. Thus these biases could well reflect the lack of dynamic ocean responses that affect these areas. Analysis of additional dynamic ocean-atmosphere models would help clarify the robustness of the Arctic and SHext responses. As the ARTP results for the tropics and NHml are all within ±20 % of the actual responses, it seems appropriate to consider 20 % to be the approximate 95 % confidence interval. For the Arctic and SHext cases, 20 % seems to be more representative of the 1-sigma confidence interval (∼ 66 %).

4 Extension of ARTP to land area response

I have also examined the ratio of temperature change over land areas within a band to the temperature change of the band as a whole. Land areas are known to response more rapidly to forcing (Meehl et al., 2007), so these ratios would be expected to generally be greater than one for the temperature response induced by historic aerosol changes (especially in the transient simulations). The multi-model analysis allows precise quantification of this ratio and determination of its robustness. I find that tropical land areas respond 41 ± 6 % more than the entire tropics, and NHml land areas change 19 ± 28 % more than the NHml band as a whole (where uncertainties are 2 standard deviations across the four models). The full ranges across the four models are 39–45 % and 9–39 %, respectively. Enhancement for land areas in the Arctic and the SHext are not consistent in sign across models. Thus in the tropics and NHml, where the ratio is relatively robust across the models (despite their differing configurations), multiplication of the ARTP temperature estimates by these ratios can provide a useful projection of

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land area temperatures while adding uncertainty that is small (tropics) or comparable (NHml) to that from the ARTP methodology itself.

5 Discussion and conclusion

This paper presents a revised ARTP metric for estimating the regional temperature response to inhomogeneous forcing. Evaluation of the ARTP applied to forcing in three independent climate models shows that the metric generally provides a good estimate of latitude band temperature responses, with a particularly narrow uncertainty range of ~ 20 % (95 % confidence) in the tropics and the NH mid-latitudes. In those regions, ARTP estimates of land area responses can be estimated by multiplying the ARTP by 1.41 and 1.19, respectively, with corresponding uncertainties of 20 % and 34 %. Hence the ARTP appears to provide a useful metric for evaluation of large-area temperature responses.

There is of course also uncertainty in the climate response function. In the time-varying ARTP, depending on the rate of ocean heat uptake and the complexity of the processes (e.g. carbon cycling) included in the temperature response calculation, the impulse response function can vary substantially (Gillett and Matthews, 2010; Sarofim, 2012). Though such uncertainty does not affect the ARTP evaluation presented here, as those calculations used the actual modeled global mean sensitivity rather than an impulse response function, such uncertainty needs to be included in temperature estimates based on the ARTP (or other metrics). In the time-invariant version, the uncertainty in the temperature response at a point in time (e.g. equilibrium) could be characterized by including uncertainty in global mean climate sensitivity.

While the ARTP metric extends beyond the information provided by global mean metrics, there is clearly a large gap remaining between the spatial scales of information available from the ARTP and that needed for impact assessment. Further work is clearly needed to see how much more regional information can be provided by regional climate metrics, including investigation of impacts beyond temperature. The conclusion presented here that the ARTP appears to be relatively robust across models is an encouraging sign for ongoing efforts to provide sub-global metrics.

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Table 1. RTP coefficients (regional response per W m^{-2} forcing in the indicated area relative to global sensitivity).

Forcing region	SHext	Tropics	NHml	Arctic	Global
Response region					
SHext	0.38	0.02	0.05	0.00	0.74
Tropics	0.19	0.51	0.15	0.08	1.03
NHml	0.11	0.55	0.49	0.16	1.06
Arctic	0.14	0.36	0.43	0.77	1.58

Global sensitivity is defined here as global mean temperature response per W m^{-2} global quasi-uniform forcing, making the RTP coefficients dimensionless. Values are derived from responses to sulfate, except for SHext and global forcing, for which CO_2 forcing was used (Shindell and Faluvegi, 2009). Note that regional responses to global forcing are provided for comparison only and are not used in the ARTP calculation.

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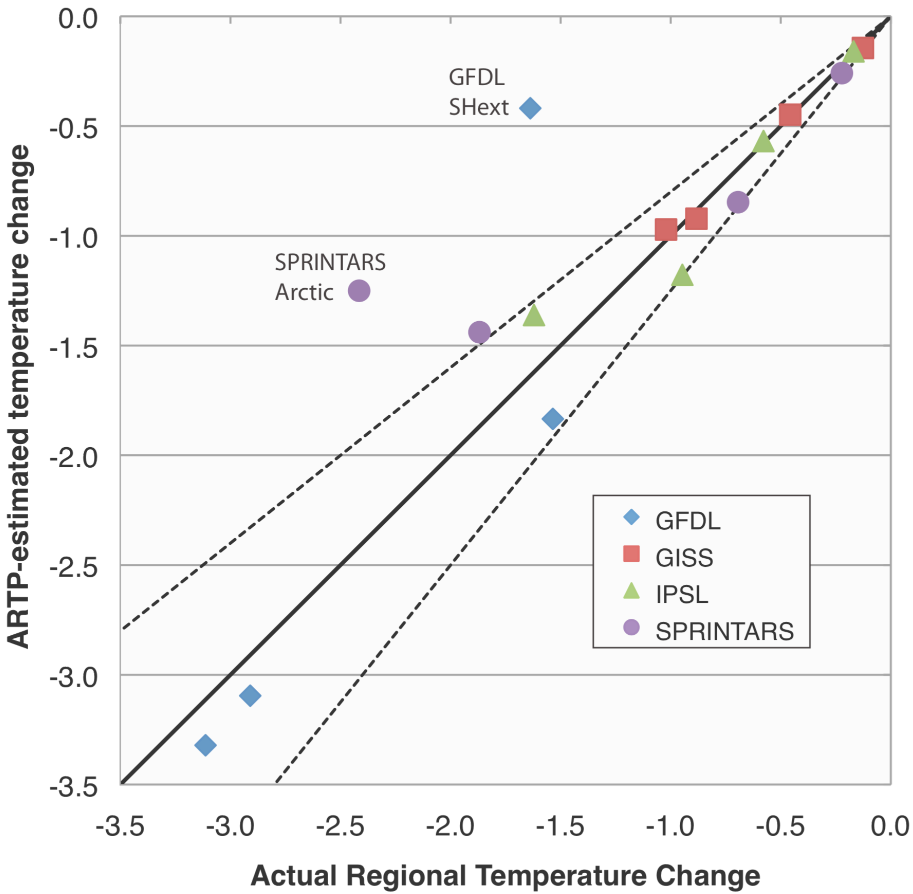

Fig. 1. Regional temperature changes in the indicated models from the actual simulations (horizontal axis) compared with the responses estimated using the ARTP methodology (vertical axis). Dashed lines show ±20 % agreement thresholds.

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