Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis

Supplementary Information Part A: Protocol V1.1

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Global warming potentials (GWP) of different gases are used as a metric to compare emissions of various greenhouse gases in the Kyoto Basket approach. The response in atmospheric CO_2 to an instantaneous release of carbon into the atmosphere, the atmospheric CO_2 impulse response function (IRF), is used for the computation of global warming potentials (GWP) and global temperature change potential (GTP) (Shine et al., 2005).

The goal of this exercise is to determine the atmospheric CO_2 impulse response function (IRF) by a suite of carbon-cycle climate models to explore model-model differences. Results will be written up for publication in a peer-reviewed journal in spring 2012 (IPCC AR5 WG1 deadline is summer 2012) in order to be available for calculations of GWPs in IPCC AR5. The results will also be useful for metrics and simplified climate models in other contexts.

Model requirements

The model must be able to compute the redistribution of anthropogenic carbon among the principal carbon reservoirs atmosphere, land biosphere, and ocean. Further compartments such as ocean sediments may also be included. Preferentially, the model simulates changes in climate in response to CO_2 radiative forcing and includes a representation of the relevant carbon cycle-climate feedbacks.

Model runs: overview

The scenario setup is inspired by the calculation of the IRF function as done for the Second Assessment Report (SAR) and as used in the Kyoto GWP with the Bern SAR model version and as repeated in preparation of the Fourth Assessment. The setup relies on that described in Enting, Wigley, Heimann, CSIRO Division of Atmospheric Research. Technical Paper No 31, 1994:

Three simulations are performed:
(a) The model is forced with historical concentration up to a reference year (here t_{ref}=2010) and then concentration are kept fixed thereafter at a constant value (here $CO_{2,ref}$=389 ppm). The allowed emission are calculated from the change in total inventory (prescribed atmospheric change plus modelled ocean and terrestrial uptake)
(b) A simulation with prescribed emissions from (a)
(or concentration prescribed up to the reference year and emissions prescribed thereafter)
(c) same as (b) but an impulse of carbon, here of 100 GtC, added instantaneously to the atmosphere five years after the reference year (here in 2015).

The normalised IRF is then approximately:

$IRF(t{=}t_{\mathrm{model}}\text{-}2015.0) = (CO_2(t_{\mathrm{model}})\text{-}CO_{2,\mathrm{ref}})/(100\ \mathrm{GtC}/2.123\mathrm{GtC/ppm})$ for $t_{\mathrm{model}} > 2015$

Model runs: detailed description

A) CO_2 *background concentration of* 389 *ppm*

1. PresCO2_389ppm: The simulation starts from preindustrial conditions. Atmospheric CO_2 is prescribed and compatible emissions (=change in all carbon reservoirs) diagnosed. Atmospheric CO_2 is prescribed to follow the historical evolution up to year 2010. After 2010, the concentration is kept fixed at the value of 389.0 ppm. The diagnosed emissions should be written frequently (at least annually); these will be used to drive the model in run 2 and 3. An input file with the historical concentrations is provided
(file name: co2ccn_irf_850_2010_v1.0.dat).
A restart file may be written in 2010 to start simulation 2 and 3 in 2010
2. PresEmiss_389ppm: run 2 may either start in 2010 as a continuation of run 1 or at the same preindustrial initial conditions used in run 1. Atmospheric CO_2 is evolving freely. Diagnosed emissions from run PresCO2_389ppm are used to force the model. (Expected result: the computed CO_2 evolution should be close to the evolution prescribed in run PresCO2_389ppm, see Figure 1).
3. PresEmiss100_389ppm: Atmospheric CO_2 is evolving freely. Diagnosed emissions from run PresCO2_389ppm are used to force the model as in run PresEmiss_389ppm. In addition, 100 GtC are released <u>at the beginning</u> of year 2015. (Expected results: Atmospheric CO_2 will increase by 47.1032 ppm above the background concentration (~389 ppm) in 2015 and then slowly decline over the coming decades, see Figure 1)

Remarks:

- It is crucial that the carbon pulse will be added to a constant background concentration of 389 ppm for comparability (roughly 2010 value).
- run 1 (PresCO2_389ppm): An existing run or setup from the CMIP or EMIC Intercomparison projects may be used up to a concentration of 389 ppm.
- run 3 (PresEmiss100_389ppm): The atmospheric CO_2 concentration should be increased at the beginning of year 2015 by 47.1032 ppm (100 GtC/2.123 GtC/ppm) in all atmospheric grid cells.
- non-CO_2 forcing agents should be included to the extent possible. Non-CO_2 forcing should be kept constant at 2010 level after 2010 (or at the year at which 389 ppm CO_2 is reached).
- land use and land use changes should be included to the extent possible. Land use area should be kept constant at 2010 level after 2010.
- If CPU time is an issue and if a group is sure that CO_2 remains at a constant value with the emissions diagnosed in run #1, run#2 may be skipped. This may only apply to ESMs and it is strongly recommended to perform run #2 to avoid problems with model drift.

B) *Preindustrial Set*

Runs 4 to 5 start from preindustrial conditions

4. CTRL: Control simulation with constant boundary conditions and freely evolving atm. CO_2
5. PI100: Freely evolving atm. CO_2. 100 GtC are released into the atmosphere during year 10 of the control simulation and then continued. (Expected result: atm CO_2 will increase from the preindustrial value of around 280 ppm by about 45 ppm to 325 ppm in year 10. Afterwards, the CO_2 concentration will then decrease due to uptake by the ocean and the land biosphere).
6. PI5000: as PI100, but 5000 GtC are released instead of 100 GtC

Remark: an available control simulation may be used to minimize work

Resulting IRFs

We will use your results to compute impulse response functions for CO_2 and other variables:

a) IRF_100GtC_389ppm: The difference in atm. CO_2 of run PresEmiss100_389ppm and PresEmiss_389ppm divided by the pulse size of 47 ppm will yield the (normalized) IRF for a background concentration of 389 ppm and a pulse size of 100 GtC (see Figure 2)
b) IRF_100GtC_PI: The difference in atm. CO_2 of run PI100 and CTRL will yield the IRF for preindustrial background conditions and a pulse size of 100 GtC
c) IRF_5000GtC_PI: The difference in atm. CO_2 of run PI5000 and CTRL will yield the IRF for preindustrial background conditions and a pulse size of 5000 GtC

Duration of runs

Preferentially, simulations are run for 2000 years after the pulse release until a complete equilibrium between atmosphere-ocean-land biosphere is re-established. If this is not feasible, runs of shorter duration are also welcome. Usually models are close to equilibrium after 1000 years. Global Warming Potentials for which the IRFs will be used were tabulated in past IPCC reports for 500, 100, and 20 years. A time horizon of 100 years is used in the Kyoto protocol.

A minimum of 100 years after the pulse release is requested.

Models that include ocean sediments and/or weathering and that are cost-efficient enough may also be run over many millennia (e.g. 100 ka).

Priority of runs

The *top priority* is to get results needed to compute the IRF for a background concentration of 389 ppm (IRF_100GtC_389ppm). For this, *runs 1, 2, and 3* are required.
Alternative: If computing requirements are too high for run 1 to 3, please provide at least results for runs 4 and 5 (PI100, CTRL).

Conversion factor GtC to ppm

Please use a conversion factor of 2.123 GtC per ppm

Preindustrial condition

It is up to the researcher to define the exact preindustrial state and the exact evolution how to reach the 2010 atmospheric CO_2 value of 389 ppm. However, model runs should start before 1900 AD and concentration should be kept fixed at a value of 389 ppm a few years before and during the pulse release. The idea is that the carbon pulse is added for the same background concentration of 389 ppm in all models.

Other forcings

Non-CO_2 forcings and land use are preferentially included in run 1 to 3; keep non-CO_2 forcing and land use area constant after 2010 at the level of year 2010. A suitable set of forcing is provided by the EMIC Intercomparison Project (http://climate.uvic.ca/EMICAR5/forcing).

Output

Ascii files with global mean values, provide at least 5 significant digits for each run.

a) File name: RUNNAME_MODELNAME_Modelversion_startyear_endyear.dat, e.g. "PresCO2_2010_Bern3DLPX_v1.0_1750_4015.dat" for run 1 with the Bern3DLPX model, version 1.0 and simulation starting at 1750 AD and ending at 4015
b) Header:
   - start each comment line with: #
   - indicate run name
   - provide contact address,
   - indicate model name and version and model components included,
   - indicate climate sensitivity of model
   - conversion factor used to convert GtC into ppm and/or pulse size in ppm
   - description of non-CO_2 forcing applied
   - indicate whether tabulated data show annual averages or instantaneous values
   - column headers with units

c) Tabulated data including year, global mean values of atmospheric CO_2 in ppm (CO2atm), global mean net air-to-sea carbon flux in GtC per year (Fas,net), global mean net air-to-land carbon flux in GtC per year (Fab,net), global mean surface temperature in Celsius (T) , global mean sea level rise in cm (SLR), ocean heat content in Joule (Heat)
   # year CO2atm [ppm] Fas,net [GtC/yr] Fab,net [GtC/yr] T [deg Celsius] SLR[cm] Heat[J]

A text file in ascii describing the model, model resolution, model components, climate sensitivity, and appropriate references. File name: MODELNAME_Modelversion_description.txt. Include contact address.

It is assumed that group will store more output individually than just the few global numbers that we ask for as output. It is anticipated that the runs may be very useful to diagnose response patterns for a wide range of variables. In additions to IRFs for CO_2, temp, and sea level, one may also want to analyze pH, precip, etc.

Deadlines

Please let us know by *15 December 2011* whether you plan to contribute and submit the runs until **15 February 2012** to joos@climate.unibe.ch and roth@climate.unibe.ch

Further Reading

Section 2.10, page 210 ff in:

Forster, P., et al. (2007), Changes in Atmospheric Constitutents and in Radiative Forcing, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, pp. 129-234, Cambridge United Kingdom and New York, NY, USA, New York, NY, USA.

Enting, I.G., Wigley, T.M.L., Heimann, M., 1994. Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses. CSIRO Division of Atmospheric Research Technical Paper no. 31.

Shine, K., Fuglestvedt, J., Hailemariam, K., and Stuber, N.: Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases, Climatic Change, 68, 281-302, 10.1007/s10584-005-1146-9, 2005

Results obtained with the Bern3D-LPJ model for a CO_2 background of 389 ppm (R. Roth)

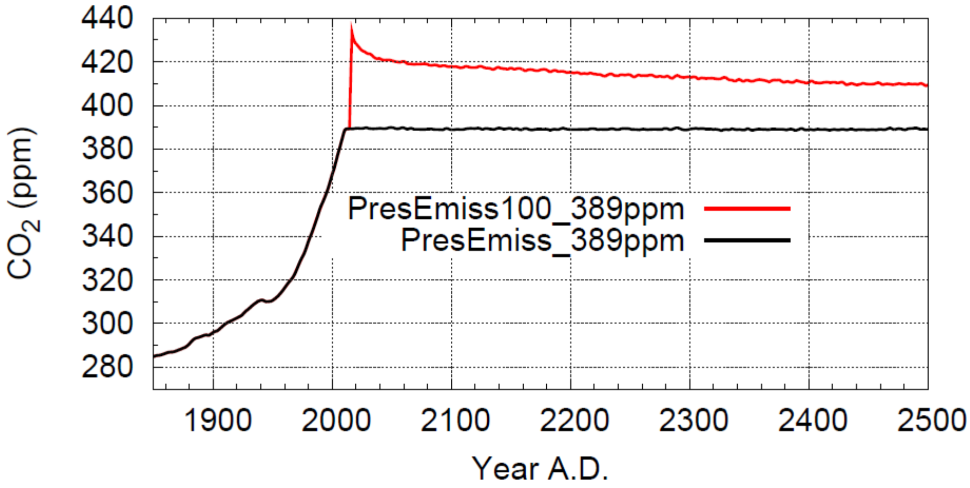


Figure 1: Simulated evolution of atmospheric CO_2 for runs 2 and 3 (PresEmiss_389ppm PresEmiss100_389ppm). 100 GtC are instantaneously released at the beginning of year 2015 in simulations PresEmiss100_389ppm (red) in addition to the emissions prescribed in run PresEmiss_389ppm (black). Prescribed emissions were diagnosed from a run in which atmospheric CO_2 was prescribed to follow the observed evolution until 2010 and kept constant at 389 ppm after 2010.

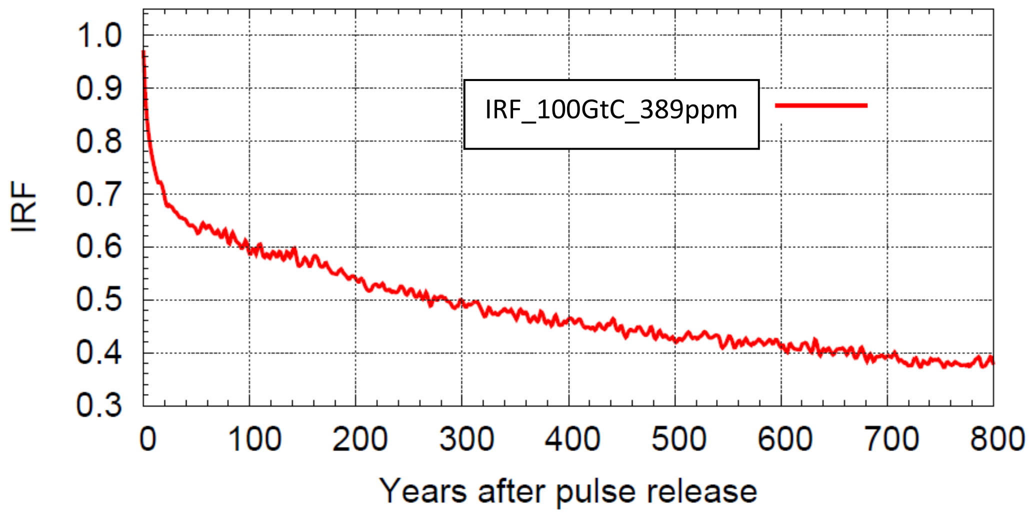
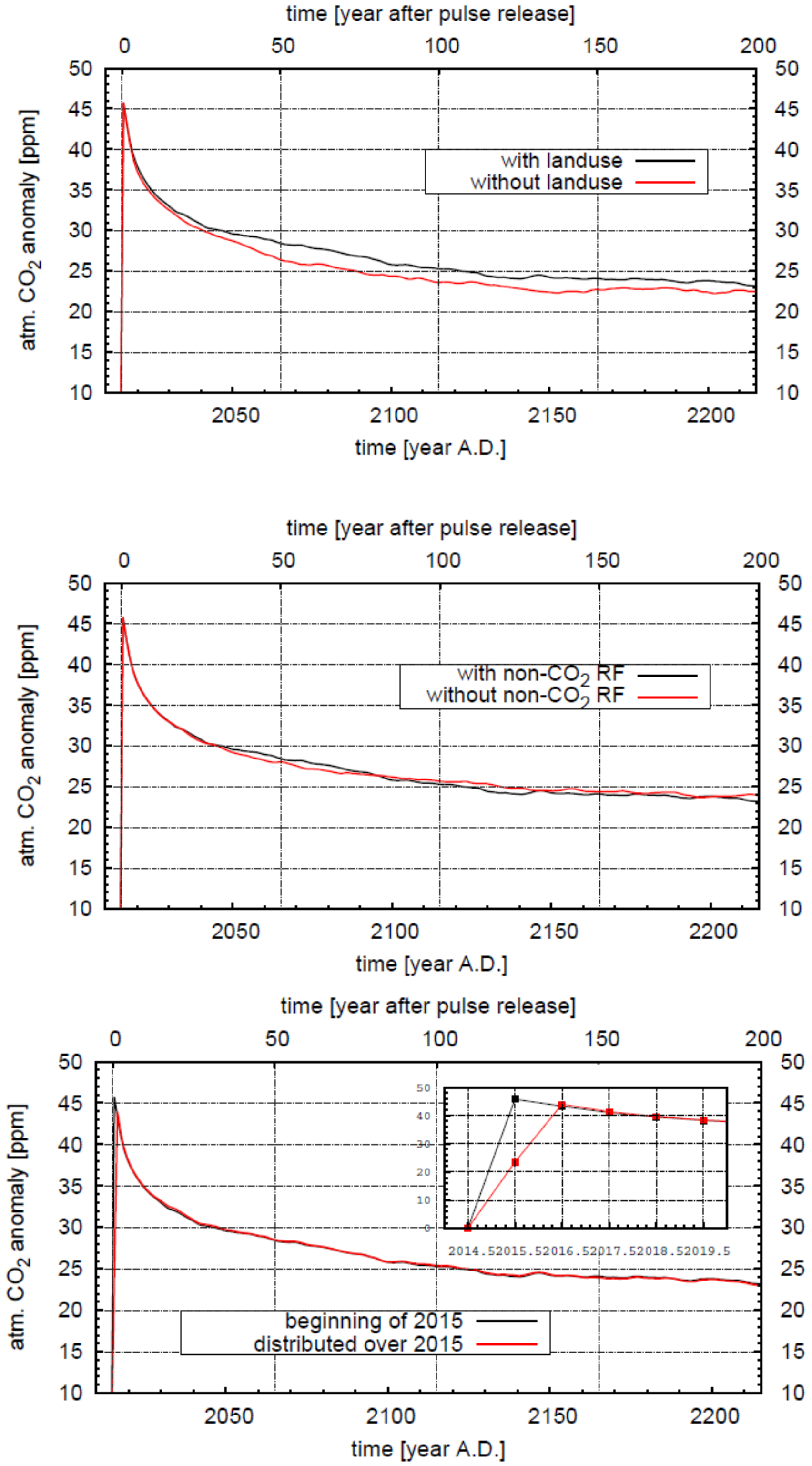


Figure 2: CO_2 impulse response function (IRF) as obtained from the difference of the runs shown in figure 1. The IRF is normalised by the size of the pulse input. Time is shifted such that year 0 corresponds to the time when the pulse of 100 GtC was released into the atmosphere.

Results of sensitivity runs with the Bern3D-LPJ model (Raphael Roth)



Differences in Impulse Response Function computed with the Bern3D-LPX model for different model setups. Top: Results from simulations with and without anthropogenic land use. Middle: Results from simulations with and without non-CO2 forcings. Bottom: release of pulse emissions at the beginning of the year versus a release of 100 GtC over one year. Note that the Bern3D-LPX model considers CO_2 to be well mixed in the atmosphere. Thus differences in IRF may be larger for models that feature atmospheric carbon transport.

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# ------------------------------------------------------------

# midyear CO2 concentrations 850-2010
# to be used for the IRF intercomparison experiment "PresCO2_389ppm"
#

# author: Raphael Roth, roth@climate.unibe.ch
# date:   24/11/2011
# ------------------------------------------------------------
#
# data used:
# from 850 - 2005 EMIC AR5 forcing was used
(http://climate.uvic.ca/EMICAR5/data/UVic_data/co2ccn_850-2005.nc.gz)
#     -->PMIP3 CO2 concentration (850 to 1800) and the CMIP5 historical
CO2 concentration (1765 to 2005).
#     -->The data sets were linearly blended between 1765 and 1800.
#
# from 2005-2010, RCP6.0 midyear CO2-concentration
#                 (value from 2010.5 of 389.072 was rounded to 389.00)
# from 2010-      constant value of 389.00 ppm
#
#
#
# year  co2 [ppm]
#
 850.5  279.266
 851.5  279.272
 852.5  279.277
 853.5  279.281
 854.5  279.284
 855.5  279.286
 856.5  279.287
 857.5  279.287
 858.5  279.285
 859.5  279.283
 860.5  279.279
 861.5  279.274
 862.5  279.268
 863.5  279.261
 864.5  279.254
 865.5  279.245
 866.5  279.236
 867.5  279.226
 868.5  279.216
 869.5  279.204
 870.5  279.193
 871.5  279.181
 872.5  279.169
 873.5  279.156
 874.5  279.143
 875.5  279.130
 876.5  279.117
 877.5  279.103
 878.5  279.090
 879.5  279.077
 880.5  279.064
 881.5  279.051
 882.5  279.038
 883.5  279.026
```

884.5	279.014
885.5	279.002
886.5	278.991
887.5	278.980
888.5	278.970
889.5	278.961
890.5	278.953
891.5	278.945
892.5	278.938
893.5	278.932
894.5	278.927
895.5	278.923
896.5	278.920
897.5	278.919
898.5	278.918
899.5	278.919
900.5	278.921
901.5	278.924
902.5	278.928
903.5	278.932
904.5	278.938
905.5	278.945
906.5	278.952
907.5	278.960
908.5	278.968
909.5	278.977
910.5	278.987
911.5	278.996
912.5	279.007
913.5	279.017
914.5	279.027
915.5	279.038
916.5	279.048
917.5	279.059
918.5	279.069
919.5	279.079
920.5	279.089
921.5	279.099
922.5	279.108
923.5	279.116
924.5	279.124
925.5	279.132
926.5	279.139
927.5	279.145
928.5	279.150
929.5	279.154
930.5	279.157
931.5	279.160
932.5	279.161
933.5	279.161
934.5	279.159
935.5	279.157
936.5	279.153
937.5	279.147
938.5	279.140
939.5	279.132
940.5	279.121
941.5	279.109
942.5	279.095

943.5	279.079
944.5	279.062
945.5	279.042
946.5	279.020
947.5	278.997
948.5	278.973
949.5	278.947
950.5	278.920
951.5	278.893
952.5	278.865
953.5	278.837
954.5	278.809
955.5	278.781
956.5	278.754
957.5	278.727
958.5	278.701
959.5	278.677
960.5	278.654
961.5	278.633
962.5	278.613
963.5	278.596
964.5	278.581
965.5	278.568
966.5	278.559
967.5	278.552
968.5	278.549
969.5	278.549
970.5	278.553
971.5	278.560
972.5	278.570
973.5	278.584
974.5	278.600
975.5	278.620
976.5	278.642
977.5	278.666
978.5	278.694
979.5	278.724
980.5	278.755
981.5	278.790
982.5	278.826
983.5	278.864
984.5	278.904
985.5	278.946
986.5	278.989
987.5	279.034
988.5	279.080
989.5	279.128
990.5	279.176
991.5	279.226
992.5	279.276
993.5	279.328
994.5	279.379
995.5	279.432
996.5	279.484
997.5	279.538
998.5	279.591
999.5	279.644
1000.5	279.697
1001.5	279.750

1002.5	279.803
1003.5	279.856
1004.5	279.907
1005.5	279.959
1006.5	280.009
1007.5	280.059
1008.5	280.107
1009.5	280.154
1010.5	280.199
1011.5	280.243
1012.5	280.285
1013.5	280.325
1014.5	280.363
1015.5	280.398
1016.5	280.431
1017.5	280.461
1018.5	280.488
1019.5	280.513
1020.5	280.533
1021.5	280.551
1022.5	280.564
1023.5	280.574
1024.5	280.580
1025.5	280.581
1026.5	280.579
1027.5	280.573
1028.5	280.565
1029.5	280.556
1030.5	280.549
1031.5	280.544
1032.5	280.543
1033.5	280.546
1034.5	280.557
1035.5	280.575
1036.5	280.603
1037.5	280.641
1038.5	280.691
1039.5	280.752
1040.5	280.822
1041.5	280.901
1042.5	280.987
1043.5	281.081
1044.5	281.180
1045.5	281.283
1046.5	281.391
1047.5	281.500
1048.5	281.612
1049.5	281.724
1050.5	281.836
1051.5	281.947
1052.5	282.055
1053.5	282.160
1054.5	282.260
1055.5	282.355
1056.5	282.444
1057.5	282.526
1058.5	282.599
1059.5	282.662
1060.5	282.717

1061.5	282.764
1062.5	282.802
1063.5	282.833
1064.5	282.857
1065.5	282.874
1066.5	282.885
1067.5	282.891
1068.5	282.891
1069.5	282.886
1070.5	282.877
1071.5	282.863
1072.5	282.847
1073.5	282.827
1074.5	282.805
1075.5	282.781
1076.5	282.755
1077.5	282.728
1078.5	282.701
1079.5	282.673
1080.5	282.645
1081.5	282.618
1082.5	282.592
1083.5	282.567
1084.5	282.545
1085.5	282.525
1086.5	282.508
1087.5	282.494
1088.5	282.484
1089.5	282.478
1090.5	282.476
1091.5	282.478
1092.5	282.483
1093.5	282.491
1094.5	282.502
1095.5	282.516
1096.5	282.533
1097.5	282.552
1098.5	282.573
1099.5	282.597
1100.5	282.622
1101.5	282.649
1102.5	282.678
1103.5	282.708
1104.5	282.739
1105.5	282.772
1106.5	282.805
1107.5	282.838
1108.5	282.872
1109.5	282.907
1110.5	282.943
1111.5	282.978
1112.5	283.014
1113.5	283.050
1114.5	283.086
1115.5	283.123
1116.5	283.159
1117.5	283.195
1118.5	283.231
1119.5	283.267

1120.5	283.302
1121.5	283.337
1122.5	283.372
1123.5	283.406
1124.5	283.439
1125.5	283.472
1126.5	283.504
1127.5	283.535
1128.5	283.565
1129.5	283.594
1130.5	283.622
1131.5	283.649
1132.5	283.674
1133.5	283.698
1134.5	283.721
1135.5	283.743
1136.5	283.763
1137.5	283.781
1138.5	283.797
1139.5	283.812
1140.5	283.826
1141.5	283.838
1142.5	283.849
1143.5	283.858
1144.5	283.867
1145.5	283.874
1146.5	283.880
1147.5	283.886
1148.5	283.891
1149.5	283.895
1150.5	283.898
1151.5	283.901
1152.5	283.904
1153.5	283.906
1154.5	283.908
1155.5	283.910
1156.5	283.911
1157.5	283.913
1158.5	283.915
1159.5	283.917
1160.5	283.919
1161.5	283.922
1162.5	283.925
1163.5	283.928
1164.5	283.931
1165.5	283.935
1166.5	283.938
1167.5	283.942
1168.5	283.946
1169.5	283.949
1170.5	283.953
1171.5	283.956
1172.5	283.959
1173.5	283.962
1174.5	283.965
1175.5	283.967
1176.5	283.969
1177.5	283.970
1178.5	283.971

1179.5	283.972
1180.5	283.972
1181.5	283.972
1182.5	283.970
1183.5	283.969
1184.5	283.966
1185.5	283.963
1186.5	283.958
1187.5	283.953
1188.5	283.948
1189.5	283.941
1190.5	283.933
1191.5	283.924
1192.5	283.914
1193.5	283.903
1194.5	283.891
1195.5	283.877
1196.5	283.862
1197.5	283.845
1198.5	283.827
1199.5	283.807
1200.5	283.786
1201.5	283.763
1202.5	283.737
1203.5	283.709
1204.5	283.680
1205.5	283.648
1206.5	283.613
1207.5	283.576
1208.5	283.537
1209.5	283.495
1210.5	283.451
1211.5	283.404
1212.5	283.355
1213.5	283.305
1214.5	283.254
1215.5	283.200
1216.5	283.146
1217.5	283.090
1218.5	283.034
1219.5	282.977
1220.5	282.919
1221.5	282.862
1222.5	282.804
1223.5	282.746
1224.5	282.688
1225.5	282.631
1226.5	282.575
1227.5	282.519
1228.5	282.464
1229.5	282.410
1230.5	282.358
1231.5	282.308
1232.5	282.259
1233.5	282.212
1234.5	282.167
1235.5	282.124
1236.5	282.084
1237.5	282.046

1238.5	282.012
1239.5	281.980
1240.5	281.952
1241.5	281.927
1242.5	281.905
1243.5	281.887
1244.5	281.874
1245.5	281.864
1246.5	281.858
1247.5	281.858
1248.5	281.861
1249.5	281.866
1250.5	281.874
1251.5	281.883
1252.5	281.892
1253.5	281.900
1254.5	281.906
1255.5	281.909
1256.5	281.909
1257.5	281.904
1258.5	281.893
1259.5	281.876
1260.5	281.854
1261.5	281.826
1262.5	281.794
1263.5	281.758
1264.5	281.718
1265.5	281.676
1266.5	281.630
1267.5	281.583
1268.5	281.534
1269.5	281.484
1270.5	281.434
1271.5	281.384
1272.5	281.334
1273.5	281.285
1274.5	281.238
1275.5	281.193
1276.5	281.150
1277.5	281.110
1278.5	281.073
1279.5	281.040
1280.5	281.009
1281.5	280.982
1282.5	280.958
1283.5	280.937
1284.5	280.920
1285.5	280.907
1286.5	280.897
1287.5	280.892
1288.5	280.889
1289.5	280.891
1290.5	280.897
1291.5	280.907
1292.5	280.921
1293.5	280.940
1294.5	280.962
1295.5	280.990
1296.5	281.021

1297.5	281.058
1298.5	281.099
1299.5	281.144
1300.5	281.195
1301.5	281.250
1302.5	281.311
1303.5	281.376
1304.5	281.447
1305.5	281.523
1306.5	281.605
1307.5	281.691
1308.5	281.783
1309.5	281.879
1310.5	281.977
1311.5	282.078
1312.5	282.180
1313.5	282.281
1314.5	282.382
1315.5	282.481
1316.5	282.577
1317.5	282.669
1318.5	282.757
1319.5	282.838
1320.5	282.913
1321.5	282.979
1322.5	283.037
1323.5	283.086
1324.5	283.123
1325.5	283.148
1326.5	283.161
1327.5	283.161
1328.5	283.145
1329.5	283.114
1330.5	283.066
1331.5	283.001
1332.5	282.919
1333.5	282.823
1334.5	282.712
1335.5	282.591
1336.5	282.458
1337.5	282.316
1338.5	282.167
1339.5	282.012
1340.5	281.852
1341.5	281.689
1342.5	281.524
1343.5	281.359
1344.5	281.196
1345.5	281.035
1346.5	280.878
1347.5	280.727
1348.5	280.583
1349.5	280.448
1350.5	280.323
1351.5	280.210
1352.5	280.106
1353.5	280.013
1354.5	279.930
1355.5	279.856

1356.5	279.791
1357.5	279.735
1358.5	279.687
1359.5	279.647
1360.5	279.614
1361.5	279.588
1362.5	279.569
1363.5	279.556
1364.5	279.549
1365.5	279.547
1366.5	279.551
1367.5	279.558
1368.5	279.570
1369.5	279.586
1370.5	279.605
1371.5	279.627
1372.5	279.651
1373.5	279.678
1374.5	279.707
1375.5	279.736
1376.5	279.767
1377.5	279.798
1378.5	279.829
1379.5	279.860
1380.5	279.891
1381.5	279.920
1382.5	279.948
1383.5	279.973
1384.5	279.997
1385.5	280.017
1386.5	280.035
1387.5	280.049
1388.5	280.059
1389.5	280.065
1390.5	280.066
1391.5	280.062
1392.5	280.053
1393.5	280.039
1394.5	280.022
1395.5	280.001
1396.5	279.977
1397.5	279.951
1398.5	279.924
1399.5	279.895
1400.5	279.866
1401.5	279.837
1402.5	279.809
1403.5	279.782
1404.5	279.757
1405.5	279.734
1406.5	279.714
1407.5	279.698
1408.5	279.686
1409.5	279.678
1410.5	279.676
1411.5	279.680
1412.5	279.690
1413.5	279.707
1414.5	279.730

1415.5	279.760
1416.5	279.796
1417.5	279.839
1418.5	279.888
1419.5	279.944
1420.5	280.006
1421.5	280.074
1422.5	280.149
1423.5	280.230
1424.5	280.318
1425.5	280.412
1426.5	280.512
1427.5	280.619
1428.5	280.731
1429.5	280.850
1430.5	280.975
1431.5	281.098
1432.5	281.213
1433.5	281.316
1434.5	281.409
1435.5	281.491
1436.5	281.563
1437.5	281.624
1438.5	281.675
1439.5	281.715
1440.5	281.745
1441.5	281.765
1442.5	281.775
1443.5	281.775
1444.5	281.764
1445.5	281.745
1446.5	281.715
1447.5	281.675
1448.5	281.626
1449.5	281.568
1450.5	281.500
1451.5	281.424
1452.5	281.340
1453.5	281.250
1454.5	281.155
1455.5	281.056
1456.5	280.954
1457.5	280.849
1458.5	280.745
1459.5	280.640
1460.5	280.536
1461.5	280.435
1462.5	280.338
1463.5	280.245
1464.5	280.158
1465.5	280.077
1466.5	280.004
1467.5	279.941
1468.5	279.887
1469.5	279.844
1470.5	279.814
1471.5	279.796
1472.5	279.789
1473.5	279.795

1474.5	279.810
1475.5	279.837
1476.5	279.872
1477.5	279.917
1478.5	279.970
1479.5	280.032
1480.5	280.100
1481.5	280.176
1482.5	280.258
1483.5	280.345
1484.5	280.438
1485.5	280.535
1486.5	280.637
1487.5	280.742
1488.5	280.849
1489.5	280.959
1490.5	281.071
1491.5	281.184
1492.5	281.298
1493.5	281.412
1494.5	281.525
1495.5	281.638
1496.5	281.749
1497.5	281.857
1498.5	281.963
1499.5	282.066
1500.5	282.165
1501.5	282.260
1502.5	282.349
1503.5	282.434
1504.5	282.513
1505.5	282.588
1506.5	282.658
1507.5	282.723
1508.5	282.784
1509.5	282.840
1510.5	282.892
1511.5	282.940
1512.5	282.983
1513.5	283.023
1514.5	283.059
1515.5	283.092
1516.5	283.121
1517.5	283.147
1518.5	283.169
1519.5	283.188
1520.5	283.204
1521.5	283.217
1522.5	283.228
1523.5	283.236
1524.5	283.241
1525.5	283.244
1526.5	283.245
1527.5	283.244
1528.5	283.240
1529.5	283.235
1530.5	283.228
1531.5	283.219
1532.5	283.209

1533.5	283.196
1534.5	283.182
1535.5	283.165
1536.5	283.147
1537.5	283.126
1538.5	283.103
1539.5	283.077
1540.5	283.049
1541.5	283.018
1542.5	282.985
1543.5	282.949
1544.5	282.909
1545.5	282.867
1546.5	282.822
1547.5	282.774
1548.5	282.722
1549.5	282.667
1550.5	282.609
1551.5	282.547
1552.5	282.483
1553.5	282.419
1554.5	282.355
1555.5	282.292
1556.5	282.232
1557.5	282.176
1558.5	282.125
1559.5	282.080
1560.5	282.042
1561.5	282.013
1562.5	281.992
1563.5	281.978
1564.5	281.970
1565.5	281.966
1566.5	281.965
1567.5	281.967
1568.5	281.969
1569.5	281.971
1570.5	281.972
1571.5	281.969
1572.5	281.963
1573.5	281.951
1574.5	281.933
1575.5	281.907
1576.5	281.871
1577.5	281.824
1578.5	281.764
1579.5	281.690
1580.5	281.599
1581.5	281.491
1582.5	281.364
1583.5	281.216
1584.5	281.045
1585.5	280.850
1586.5	280.630
1587.5	280.383
1588.5	280.107
1589.5	279.800
1590.5	279.467
1591.5	279.112

1592.5	278.741
1593.5	278.358
1594.5	277.963
1595.5	277.562
1596.5	277.156
1597.5	276.748
1598.5	276.342
1599.5	275.939
1600.5	275.543
1601.5	275.156
1602.5	274.781
1603.5	274.421
1604.5	274.080
1605.5	273.758
1606.5	273.461
1607.5	273.190
1608.5	272.948
1609.5	272.739
1610.5	272.565
1611.5	272.429
1612.5	272.331
1613.5	272.268
1614.5	272.240
1615.5	272.243
1616.5	272.275
1617.5	272.334
1618.5	272.418
1619.5	272.525
1620.5	272.652
1621.5	272.798
1622.5	272.960
1623.5	273.136
1624.5	273.323
1625.5	273.521
1626.5	273.725
1627.5	273.935
1628.5	274.148
1629.5	274.361
1630.5	274.574
1631.5	274.784
1632.5	274.991
1633.5	275.193
1634.5	275.390
1635.5	275.581
1636.5	275.764
1637.5	275.939
1638.5	276.105
1639.5	276.259
1640.5	276.403
1641.5	276.534
1642.5	276.652
1643.5	276.759
1644.5	276.853
1645.5	276.936
1646.5	277.008
1647.5	277.069
1648.5	277.119
1649.5	277.159
1650.5	277.189

1651.5	277.210
1652.5	277.221
1653.5	277.224
1654.5	277.220
1655.5	277.207
1656.5	277.188
1657.5	277.163
1658.5	277.132
1659.5	277.096
1660.5	277.056
1661.5	277.011
1662.5	276.963
1663.5	276.911
1664.5	276.858
1665.5	276.802
1666.5	276.745
1667.5	276.688
1668.5	276.630
1669.5	276.572
1670.5	276.515
1671.5	276.460
1672.5	276.406
1673.5	276.355
1674.5	276.307
1675.5	276.263
1676.5	276.222
1677.5	276.186
1678.5	276.156
1679.5	276.131
1680.5	276.113
1681.5	276.101
1682.5	276.097
1683.5	276.100
1684.5	276.110
1685.5	276.126
1686.5	276.148
1687.5	276.173
1688.5	276.202
1689.5	276.234
1690.5	276.267
1691.5	276.301
1692.5	276.336
1693.5	276.370
1694.5	276.403
1695.5	276.435
1696.5	276.466
1697.5	276.496
1698.5	276.525
1699.5	276.553
1700.5	276.581
1701.5	276.607
1702.5	276.634
1703.5	276.660
1704.5	276.686
1705.5	276.712
1706.5	276.738
1707.5	276.764
1708.5	276.790
1709.5	276.818

1710.5	276.845
1711.5	276.874
1712.5	276.903
1713.5	276.934
1714.5	276.965
1715.5	276.998
1716.5	277.032
1717.5	277.068
1718.5	277.106
1719.5	277.145
1720.5	277.187
1721.5	277.230
1722.5	277.276
1723.5	277.324
1724.5	277.374
1725.5	277.425
1726.5	277.474
1727.5	277.521
1728.5	277.563
1729.5	277.600
1730.5	277.630
1731.5	277.651
1732.5	277.661
1733.5	277.659
1734.5	277.644
1735.5	277.614
1736.5	277.571
1737.5	277.518
1738.5	277.457
1739.5	277.390
1740.5	277.320
1741.5	277.250
1742.5	277.181
1743.5	277.117
1744.5	277.058
1745.5	277.005
1746.5	276.957
1747.5	276.912
1748.5	276.871
1749.5	276.832
1750.5	276.796
1751.5	276.761
1752.5	276.727
1753.5	276.695
1754.5	276.665
1755.5	276.638
1756.5	276.614
1757.5	276.595
1758.5	276.582
1759.5	276.575
1760.5	276.576
1761.5	276.585
1762.5	276.604
1763.5	276.634
1764.5	276.675
1765.5	276.728
1766.5	276.830
1767.5	276.943
1768.5	277.067

1769.5	277.202
1770.5	277.344
1771.5	277.493
1772.5	277.648
1773.5	277.809
1774.5	277.974
1775.5	278.143
1776.5	278.319
1777.5	278.501
1778.5	278.689
1779.5	278.882
1780.5	279.077
1781.5	279.275
1782.5	279.478
1783.5	279.685
1784.5	279.897
1785.5	280.115
1786.5	280.338
1787.5	280.565
1788.5	280.793
1789.5	281.016
1790.5	281.232
1791.5	281.440
1792.5	281.638
1793.5	281.828
1794.5	282.009
1795.5	282.180
1796.5	282.341
1797.5	282.494
1798.5	282.638
1799.5	282.773
1800.5	282.899
1801.5	283.007
1802.5	283.111
1803.5	283.211
1804.5	283.307
1805.5	283.400
1806.5	283.490
1807.5	283.578
1808.5	283.661
1809.5	283.735
1810.5	283.797
1811.5	283.847
1812.5	283.889
1813.5	283.926
1814.5	283.963
1815.5	284.001
1816.5	284.043
1817.5	284.086
1818.5	284.129
1819.5	284.167
1820.5	284.198
1821.5	284.223
1822.5	284.244
1823.5	284.263
1824.5	284.281
1825.5	284.300
1826.5	284.320
1827.5	284.340

1828.5	284.360
1829.5	284.380
1830.5	284.400
1831.5	284.385
1832.5	284.280
1833.5	284.125
1834.5	283.975
1835.5	283.825
1836.5	283.675
1837.5	283.525
1838.5	283.425
1839.5	283.400
1840.5	283.400
1841.5	283.425
1842.5	283.500
1843.5	283.600
1844.5	283.725
1845.5	283.900
1846.5	284.075
1847.5	284.225
1848.5	284.400
1849.5	284.575
1850.5	284.725
1851.5	284.875
1852.5	285.000
1853.5	285.125
1854.5	285.275
1855.5	285.425
1856.5	285.575
1857.5	285.725
1858.5	285.900
1859.5	286.075
1860.5	286.225
1861.5	286.375
1862.5	286.500
1863.5	286.625
1864.5	286.775
1865.5	286.900
1866.5	287.000
1867.5	287.100
1868.5	287.225
1869.5	287.375
1870.5	287.525
1871.5	287.700
1872.5	287.900
1873.5	288.125
1874.5	288.400
1875.5	288.700
1876.5	289.025
1877.5	289.400
1878.5	289.800
1879.5	290.225
1880.5	290.700
1881.5	291.200
1882.5	291.675
1883.5	292.125
1884.5	292.575
1885.5	292.975
1886.5	293.300

1887.5	293.575
1888.5	293.800
1889.5	294.000
1890.5	294.175
1891.5	294.325
1892.5	294.475
1893.5	294.600
1894.5	294.700
1895.5	294.800
1896.5	294.900
1897.5	295.025
1898.5	295.225
1899.5	295.500
1900.5	295.800
1901.5	296.125
1902.5	296.475
1903.5	296.825
1904.5	297.200
1905.5	297.625
1906.5	298.075
1907.5	298.500
1908.5	298.900
1909.5	299.300
1910.5	299.700
1911.5	300.075
1912.5	300.425
1913.5	300.775
1914.5	301.100
1915.5	301.400
1916.5	301.725
1917.5	302.075
1918.5	302.400
1919.5	302.700
1920.5	303.025
1921.5	303.400
1922.5	303.775
1923.5	304.125
1924.5	304.525
1925.5	304.975
1926.5	305.400
1927.5	305.825
1928.5	306.300
1929.5	306.775
1930.5	307.225
1931.5	307.700
1932.5	308.175
1933.5	308.600
1934.5	309.000
1935.5	309.400
1936.5	309.750
1937.5	310.000
1938.5	310.175
1939.5	310.300
1940.5	310.375
1941.5	310.375
1942.5	310.300
1943.5	310.200
1944.5	310.125
1945.5	310.100

1946.5	310.125
1947.5	310.200
1948.5	310.325
1949.5	310.500
1950.5	310.750
1951.5	311.100
1952.5	311.500
1953.5	311.925
1954.5	312.425
1955.5	313.000
1956.5	313.600
1957.5	314.225
1958.5	314.848
1959.5	315.500
1960.5	316.272
1961.5	317.075
1962.5	317.795
1963.5	318.397
1964.5	318.925
1965.5	319.647
1966.5	320.647
1967.5	321.605
1968.5	322.635
1969.5	323.902
1970.5	324.985
1971.5	325.855
1972.5	327.140
1973.5	328.677
1974.5	329.742
1975.5	330.585
1976.5	331.747
1977.5	333.272
1978.5	334.848
1979.5	336.525
1980.5	338.360
1981.5	339.728
1982.5	340.793
1983.5	342.198
1984.5	343.783
1985.5	345.283
1986.5	346.797
1987.5	348.645
1988.5	350.737
1989.5	352.487
1990.5	353.855
1991.5	355.017
1992.5	355.885
1993.5	356.777
1994.5	358.128
1995.5	359.837
1996.5	361.462
1997.5	363.155
1998.5	365.323
1999.5	367.348
2000.5	368.865
2001.5	370.467
2002.5	372.522
2003.5	374.760
2004.5	376.813

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2005.5  378.813
2006.5  380.828
2007.5  382.777
2008.5  384.800
2009.5  386.935
2010.5  389.000
999999. 389.000
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Supplementary Information: Part B

Responses in CO_2 for the 100 GtC emission pulse added to a constant background of 389 ppm (PD100 case) are fitted by a sum of exponentials:

$$IRF_{\mathrm{CO2}}(t) = a_0 + \sum_{i=1}^{3} a_i \cdot \exp\left(\frac{-t}{\tau_i}\right) \qquad \text{for } 0 \le t \le nryears \quad . \tag{S1}$$

For IRF_{CO2} the conditions is applied that the sum of the coefficients a_i equals 1. Note that the fits only apply for the period from 0 to *nryears*, where *nryears* is the number of available output years.

The mean relative error, *mre*, in permil is calculated from annual values:

$$mre = \frac{1}{nryears} \sum_{i=1}^{nryears} \frac{|f_i - m_i|}{m_i} \cdot 1000\text{permil} \ , \tag{S2}$$

where f_i are the annual data from the fit and m_i from the model output.

Table S1: Coefficients to fit model responses in CO_2 (IRF_{CO2}) for the PD100 case. The mean relative error (mre) is given in permil.

model	*nryears*	*mre*	a_0	a_1	a_2	a_3	τ_1	τ_2	τ_3
NCAR CSM1.4	289	11	2.935E-07	3.665E-01	3.542E-01	2.793E-01	1.691E+03	2.836E+01	5.316E+00
HadGEM2-ES	101	40	4.340E-01	1.973E-01	1.889E-01	1.798E-01	2.307E+01	2.307E+01	3.922E+00
MPI-ESM	101	16	1.252E-07	5.864E-01	1.826E-01	2.310E-01	1.781E+02	9.039E+00	8.989E+00
Bern3D-LPJ (reference)	1000	5	6.345E-10	5.150E-01	2.631E-01	2.219E-01	1.955E+03	4.583E+01	3.872E+00
Bern3D-LPJ (ensemble)	585	3	2.796E-01	2.382E-01	2.382E-01	2.440E-01	2.762E+02	3.845E+01	4.928E+00
Bern2.5D-LPJ	1000	9	2.362E-01	9.866E-02	3.850E-01	2.801E-01	2.321E+02	5.850E+01	2.587E+00
CLIMBER2-LPJ	1000	20	2.318E-01	2.756E-01	4.900E-01	2.576E-03	2.726E+02	6.692E+00	6.692E+00
DCESS	1000	4	2.159E-01	2.912E-01	2.410E-01	2.518E-01	3.799E+02	3.631E+01	3.398E+00
GENIE (ensemble)	1000	5	2.145E-01	2.490E-01	1.924E-01	3.441E-01	2.701E+02	3.932E+01	4.305E+00
LOVECLIM	1000	58	8.539E-08	3.606E-01	4.503E-01	1.891E-01	1.596E+03	2.171E+01	2.281E+00
MESMO	1000	1	2.848E-01	2.938E-01	2.382E-01	1.831E-01	4.543E+02	2.500E+01	2.014E+00
UVic2.9	1000	4	3.186E-01	1.748E-01	1.921E-01	3.145E-01	3.046E+02	2.656E+01	3.800E+00
ACC2	985	4	1.779E-01	1.654E-01	3.796E-01	2.772E-01	3.862E+02	3.689E+01	3.723E+00
Bern-SAR	1000	3	1.994E-01	1.762E-01	3.452E-01	2.792E-01	3.331E+02	3.969E+01	4.110E+00
MAGICC6 (ensemble)	604	1	2.051E-01	2.533E-01	3.318E-01	2.098E-01	5.961E+02	2.197E+01	2.995E+00
TOTEM2	984	2	7.177E-06	2.032E-01	6.995E-01	9.738E-02	8.577E+04	1.118E+02	1.583E-02
multi-model mean	1000	6	2.173E-01	2.240E-01	2.824E-01	2.763E-01	3.944E+02	3.654E+01	4.304E+00

Table S2: Coefficients to fit model responses in CO_2 (IRF_{CO2}) for the PI100 and PD100 cases with and without climate feedbacks and for the Bern3D-LPJ(reference). The mean relative error (mre) is given in permil.

	nryears	*mre*	a_0	a_1	a_2	a_3	τ_1	τ_2	τ_3
					PI100				
With climate feedback	1000	4	1.266E-01	2.607E-01	2.909E-01	3.218E-01	3.028E+02	3.161E+01	4.240E+00
Without climate feedback	1000	3	1.332E-01	1.663E-01	3.453E-01	3.551E-01	3.133E+02	2.999E+01	4.601E+00
					PD100				
With climate feedback	1000	5	6.345E-10	5.150E-01	2.631E-01	2.219E-01	1.955E+03	4.583E+01	3.872E+00
Without climate feedback	1000	0.02	2.123E-01	2.444e-01	3.360e-01	2.073e-01	3.364e+02	2.789e+01	4.055e+00

Figure S1: Responses in IRF_{CO2} from individual models (black) and corresponding fits (red).