

# Impulse response function of climate-carbon cycle models: a model intercomparison study

## Protocol V1.1

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Documents and updates are available online: [http://www.climate.unibe.ch/~joos/IRF\\_Intercomparison](http://www.climate.unibe.ch/~joos/IRF_Intercomparison)

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<sub>2</sub> to an instantaneous release of carbon into the atmosphere, the atmospheric CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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:

$$IRF(t=t_{\text{model}}-2015.0) = (\text{CO}_2(t_{\text{model}})-\text{CO}_{2,\text{ref}})/(100 \text{ GtC}/2.123\text{GtC/ppm}) \quad \text{for } t_{\text{model}} > 2015$$

### Model runs: detailed description

#### A) CO<sub>2</sub> background concentration of 389 ppm

1. PresCO2\_389ppm: The simulation starts from preindustrial conditions. Atmospheric CO<sub>2</sub> is prescribed and compatible emissions (=change in all carbon reservoirs) diagnosed. Atmospheric CO<sub>2</sub> 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<sub>2</sub> is evolving freely. Diagnosed emissions from run PresCO2\_389ppm are used to force the model. (Expected result: the computed CO<sub>2</sub> evolution should be close to the evolution prescribed in run PresCO2\_389ppm, see Figure 1).
3. PresEmiss100\_389ppm: Atmospheric CO<sub>2</sub> 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 at the beginning of year 2015. (Expected results: Atmospheric CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> forcing agents should be included to the extent possible. Non-CO<sub>2</sub> forcing should be kept constant at 2010 level after 2010 (or at the year at which 389 ppm CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>
5. PI100: Freely evolving atm. CO<sub>2</sub>. 100 GtC are released into the atmosphere during year 10 of the control simulation and then continued. (Expected result: atm CO<sub>2</sub> will increase from the preindustrial value of around 280 ppm by about 45 ppm to 325 ppm in year 10. Afterwards, the CO<sub>2</sub> 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<sub>2</sub> and other variables:

- a) IRF\_100GtC\_389ppm: The difference in atm. CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> forcings and land use are preferentially included in run 1 to 3; keep non-CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>, 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](mailto:joos@climate.unibe.ch) and [roth@climate.unibe.ch](mailto:roth@climate.unibe.ch)

### Further Reading

Section 2.10, page 210 ff in:

Forster, P., et al. (2007), Changes in Atmospheric Constituents 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., Fuglestedt, 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<sub>2</sub> background of 389 ppm (R. Roth)

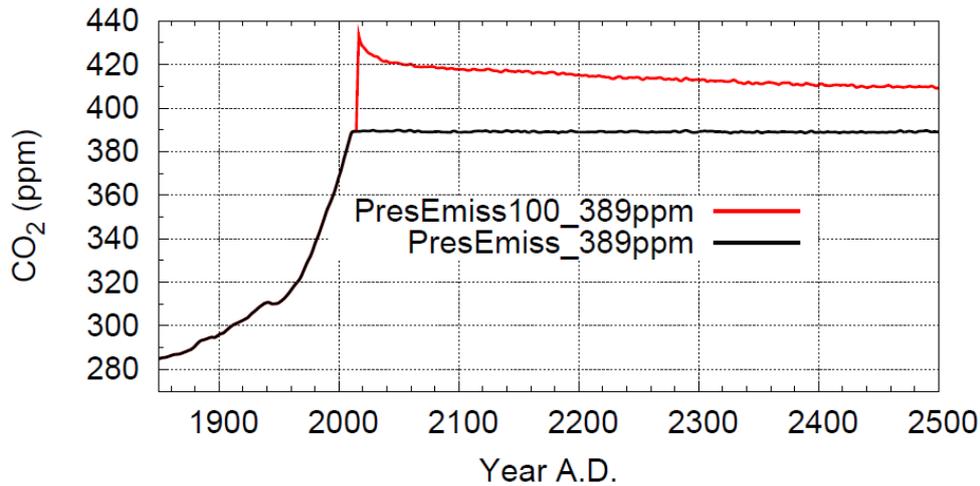


Figure 1: Simulated evolution of atmospheric CO<sub>2</sub> for runs 2 and 3 (PresEmiss\_389ppm PresEmiss100\_389ppm). 100 GtC are instantaneously released at the beginning of year 2015 in simulations PresEmiss100\_389ppm (red) in addition to the emissions prescribed in run PresEmiss\_389ppm (black). Prescribed emissions were diagnosed from a run in which atmospheric CO<sub>2</sub> was prescribed to follow the observed evolution until 2010 and kept constant at 389 ppm after 2010.

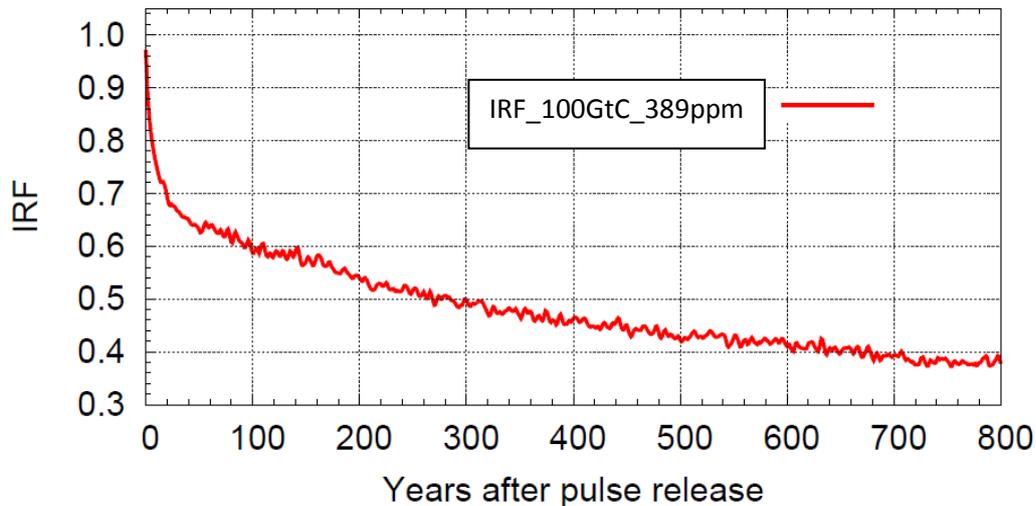
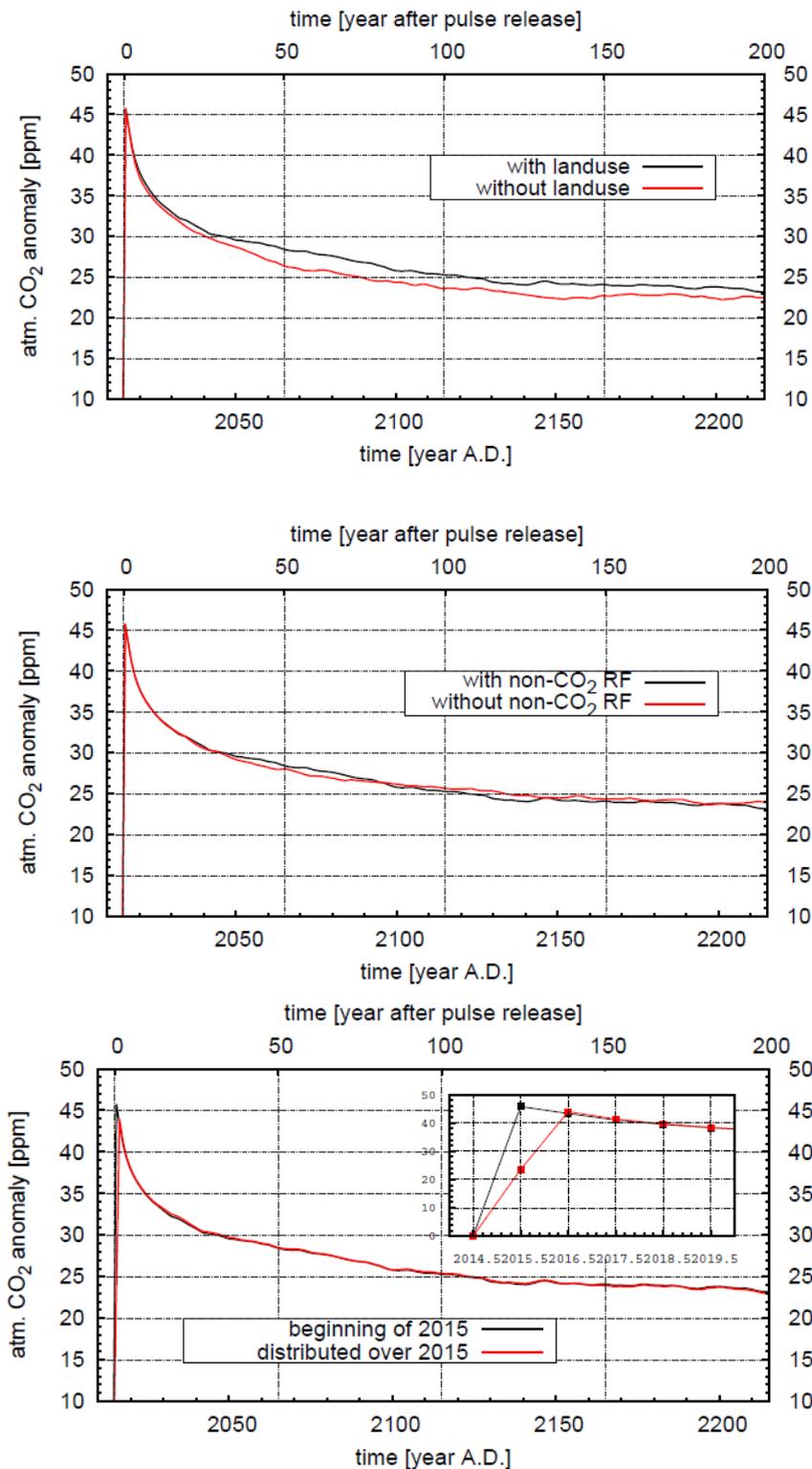


Figure 2: CO<sub>2</sub> impulse response function (IRF) as obtained from the difference of the runs shown in figure 1. The IRF is normalised by the size of the pulse input. Time is shifted such that year 0 corresponds to the time when the pulse of 100 GtC was released into the atmosphere.

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-CO<sub>2</sub> 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<sub>2</sub> to be well mixed in the atmosphere. Thus differences in IRF may be larger for models that feature atmospheric carbon transport.

```
# -----  
# 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
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