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A Combined Mitigation/Geoengineering Approach to Climate Stabilization

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Projected anthropogenic warming and CO_2 concentration increases present a two-fold threat: both from the climate changes, and from CO_2 directly through increasing acidity of the oceans. Future climate change may be reduced through mitigation (greenhouse-gas emissions reductions) or through geoengineering. Most geoengineering approaches, however, do not address the problem of increasing ocean acidity. A combined mitigation/geoengineering strategy could remove this deficiency. We consider here the deliberate injection of sulfate aerosol precursors into the stratosphere. This can significantly offset future warming and provide additional time to reduce dependence on fossil fuels and so stabilize CO_2 concentrations cost-effectively at an acceptable level.

In the absence of policies to reduce the magnitude of future climate change, the globe is expected to warm by approximately 1–6°C over the 21st century (*1*, *2*). Estimated CO_2 concentrations in 2100 lie in the range from 540 ppm to 970 ppm, sufficient to cause substantial increases in ocean acidity (*3*–*6*). Mitigation directed towards stabilizing CO_2 concentrations (*7*) addresses both problems; but presents considerable economic and technological challenges (*8*, *9*). Geoengineering (*10*–*17*) could help reduce future climate change, but does not address the ocean acidity problem. Mitigation is therefore necessary, but geoengineering could provide additional time to address the economic and technological challenges faced by a mitigation-only approach.

The geoengineering strategy examined here is the injection of aerosol or aerosol precursors (such as sulfur dioxide, SO_2) into the stratosphere to provide a negative forcing of the climate system and so offset part of the positive forcing due to increasing greenhouse-gas concentrations (*18*). Volcanic eruptions provide ideal experiments that can be used to assess the effects of large anthropogenic emissions of SO_2 on stratospheric aerosols and climate. We know, for example, that an eruption like that of Mt. Pinatubo [June 1991 (*19*, *20*)] caused detectible short-term cooling (*19*–*21*), but did not seriously disrupt the climate system. Deliberately adding aerosols or aerosol precursors to the stratosphere so that the loading is similar to the maximum loading from Pinatubo should therefore present minimal climate risks.

Increased sulfate aerosol loading of the stratosphere may present other risks, such as through the influence on stratospheric ozone. This particular risk, however, is likely to be small. The effect of sulfate aerosols depends on the chlorine loading (*22*–*24*). With current elevated loadings there would be enhanced ozone loss. This would delay the recovery of stratospheric ozone slightly, but only until anthropogenic chlorine loadings returned to 1980 levels (expected by the late 2040s).

Figure 1 shows the effect of multiple sequential eruptions of Pinatubo, every year, every two years and every four years. The Pinatubo forcing used here has a peak annual-mean value of –2.97 W/m^2 (*20*, *21*). The climate simulations were carried out using an upwelling-diffusion, energy balance model [MAGICC (*2*, *25*, *26*)] with a chosen climate sensitivity of 3°C equilibrium warming for a CO_2 doubling. Figure 1 suggests that a sustained stratospheric forcing of around –3 W/m^2 (the average asymptotic forcing for the biennial eruption case) would be sufficient to offset much of the anthropogenic warming expected over the next century. Figure 1 also shows how rapidly the aerosol-induced cooling disappears once the injection of material into the stratosphere stops, as might become necessary should unexpected environmental damages arise.

To illustrate possible options for the timing and duration of aerosol injections, three scenarios are considered. In each case, the loading of the stratosphere begins in 2010 and ramps up linearly to –3 W/m^2 over 30 years. The scenarios depart from each other after this date (Fig. 2). These geoengineering cases are complemented by three future CO_2 emissions scenarios: a central "no-climate-policy" scenario from the SRES (*27*) set, viz. the A1B scenario; an ambitious CO_2 stabilization scenario stabilizing at 450 ppm (the present level is about 380 ppm), WRE450 (*7*); and an overshoot CO_2 concentration case rising to 530 ppm in 2080 before declining to 450 ppm. (Note that even 450 ppm "produces both calcite and aragonite undersaturation in most of the deep ocean" (*4*), so a level even less than this may ultimately be desirable.)

CO_2 concentrations and corresponding fossil-fuel emissions for these three CO_2 cases are shown in Fig. 3. Emissions for the stabilization cases were calculated using an inverse version of MAGICC, accounting for climate feedbacks on the carbon cycle. The WRE450 case is an archetypal mitigation-only case, stabilizing at a level that many believe would avoid "dangerous anthropogenic interference" with the climate system (*28*). The overshoot case is introduced here to be considered in conjunction with the three geoengineering options. The overshoot case allows much larger CO_2 emissions, and a much slower departure from the A1B no-policy baseline. Although the rate of decline of emissions in the mid to late 21st century is more rapid than in WRE450, these reductions begin 15–20 years later allowing additional time both to phase out existing CO_2-emitting fossil-fuel energy technologies and to develop and deploy energy sources that have net-zero CO_2 emissions (*7*–*9*).

Figure 4 shows global-mean temperature and sea level projections for (i) the no-policy (A1B) case, (ii) the mitigation-only (WRE450) case, and (iii) the overshoot CO_2 case combined with the three alternative geoengineering options (labeled "HIGH GEO", "MID GEO" and "LOW GEO"). For the early decades after 2010, changes in aerosol forcing in all three "GEO" scenarios occur more rapidly than forcing changes for the CO_2 scenarios, so the net effect is cooling. After 2040, the HIGH GEO cooling tends to balance the warming from the overshoot CO_2 stabilization scenario, eventually leading to a slight cooling that would bring global-mean temperatures back to near their pre-industrial level. The MID and LOW GEO cases lead to temperatures roughly stabilizing at 1°C and 2°C relative to 2000 (*29*). After 2100, LOW GEO (where injection into the stratosphere is ramped down to zero by 2090) closely matches the WRE450 mitigation-only case, but requires less stringent emissions reductions.

The sea level results, using models employed in the IPCC Third Assessment Report (*30*, *31*), show the much larger inertia of this part of the climate system. LOW GEO and WRE450 again are similar, with neither tending towards stabilization. Even the HIGH GEO case shows a continuing (but slow) sea level rise at the end of the study period, but the rate of rise is small even relative to observed changes over the 20th century (*30*, *32*).

A combined mitigation/geoengineering approach to climate stabilization has a number of advantages over either employed separately. A relatively modest geoengineering investment (*33*, *34*) corresponding to the present LOW GEO case could reduce the economic and technological burden on mitigation substantially by deferring the need for immediate or near-future cuts in CO_2 emissions. More ambitious geoengineering, when combined with mitigation, could even lead to stabilization of global-mean temperature at near-present levels and reduce future sea level rise to a rate much less than observed over the 20th century – aspects of future change that are virtually impossible to achieve through mitigation alone.

As a guide to the amount of SO_2 required, the eruption of Pinatubo injected about 10 TgS into the stratosphere (*35*, *36*), and the analysis here suggests that an annual flux of half that amount would have a significant influence. Smaller aerosols would have longer lifetimes and require still smaller injection rates (*15*). 5 TgS/yr is only about 7% of current SO_2 emissions from fossil-fuel combustion (*37*, *38*). Further analysis is required to assess the technological feasibility of the suggested injections of SO_2 [or of more radiatively efficient material (*34*)] into the stratosphere, the economic costs of this option relative to the reduced costs of mitigation that an overshoot CO_2 stabilization pathway would allow, and the detailed effects of the proposed SO_2 injections and CO_2 concentration changes on climate [cf. (*39*)] and stratospheric chemistry.

References and Notes

1. U. Cubasch, G. A. Meehl, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge University Press, Cambridge, UK, 2001), pp. 525–582.
2. T. M. L. Wigley, S. C. B. Raper, *Science* **293**, 451 (2001).
3. K. Caldeira, M. E. Wickett, *Nature* **425**, p. 365 (2003).
4. K. Caldeira, M. E. Wickett, *J. Geophys. Res.* **110**, C09S04, doi:10.1029/2004JC002671 (2005).
5. J. C. Orr *et al.*, *Nature* **437**, 681 (2005).
6. A. J. Andersson, F. T. Mackenzie, A. Lerman, *Global Biogeochem. Cycles* **20**, doi:10.1029/2005GB002506 (2006).
7. T. M. L. Wigley, R. Richels, J. A. Edmonds, *Nature* **379**, 240 (1996).
8. M. I. Hoffert *et al.*, *Nature* **395**, 881 (1998).
9. M. I. Hoffert *et al.*, *Science* **298**, 981 (2002).
10. Geoengineering refers to engineering aimed at counteracting the undesired side effects of other human activities (*11*). Two classes may be distinguished: climate engineering (*12*–*15*), and carbon cycle engineering [e.g., through modifying ocean alkalinity; (*16*, *17*)]. Here, the word geoengineering refers specifically to climate engineering, i.e., direct and intentional management of the climate system.
11. D. W. Keith, *Ann. Rev. Energy Environ.* **25**, 245 (2000).
12. S. H. Schneider, *Nature* **409**, 417 (2001).
13. National Academy of Sciences, *Policy Implications of Greenhouse Warming: Mitigation, Adaptation and the Science Base*, Ch. 28 "Geoengineering", (National Academy Press, Washington, DC, 1992), pp. 433–464.
14. B. P. Flannery *et al.*, in *Engineering Response to Global Climate Change: Planning a Research and Development Agenda*, R. G. Watts, Ed. (Lewis Publishers, Boca Raton, Florida, 1997), pp. 379–427.
15. P. J. Crutzen, *Climatic Change* **76**, doi:10.1007/s10584-006-9101-y (2006).
16. H. S. Kheshgi, *Energy* **20,** 915 (1995).

17. K. S. Lackner, *Ann. Rev. Energy Environ.* **27**, 193 (2002).
18. M. I. Budyko, *Climate Changes* (Amer. Geophys. Union, Washington, DC, 1977: English translation of 1974 Russian text), 244 pp.
19. A. Robock, *Rev. Geophys.* **38**, 191 (2000).
20. C. M. Ammann, G. A. Meehl, W. M. Washington, C. S. Zender, *Geophys. Res. Lett.* **30**,1657, doi:10.1029/2003GL016875 (2003).
21. T. M. L. Wigley, C. M. Ammann, B. D. Santer, S. C. B. Raper, *J. Geophys. Res.* **110**, D09107, doi:10.1020/2004JD005557 (2005).
22. X. Tie, G. Brasseur, *Geophys. Res. Lett.* **22**, 3035 (1995).
23. S. Solomon *et al.*, *J. Geophys. Res.* **101**, 6713 (1996).
24. R. W. Portmann *et al.*, *J. Geophys. Res.* **101**, 22991 (1996).
25. MAGICC is a suitable tool because it reproduces the results from more complex coupled ocean/atmosphere general circulation models (AOGCMs) for both volcanic timescale (*21*) and long-term (*26*) forcing.
26. S. C. B Raper, J. M. Gregory, T. J. Osborn, *Climate Dynamics* **17**, 601 (2001).
27. N. Nakićenović, R. Swart, Eds., *Special Report on Emissions Scenarios* (Cambridge University Press, Cambridge, UK, 2000).
28. Avoiding dangerous anthropogenic interference with the climate system is one of the primary guidelines for climate policy espoused in Article 2 of the UN Framework Convention on Climate Change.
29. In all cases there is a residual warming tendency arising from the emissions of non- CO_2 gases (CH_4, N_2O, halocarbons, tropospheric aerosols). Emissions from these sources are assumed simply to follow A1B to 2100 and then remain constant, leading to a slow but long-term increase in radiative forcing.
30. J. A. Church, J. M. Gregory, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge University Press, Cambridge, UK, 2001), pp. 639–694.
31. T. M. L. Wigley, S. C. B. Raper, *Geophys. Res. Lett.* **32**, L05704, doi:10.1029/2004GL021238 (2005).
32. A. Cazenave, R. S. Nerem, *Rev. Geophys.* **42**, RG3001, doi:10.1029/2003RG000139 (2004).
33. Teller *et al.* (*34*) point out that sulfate aerosols are "grossly non-optimized" as scatterers of short-wave radiation, and that metallic or resonant scatterers offer large mass savings. Although emplacement costs for such scatterers would be higher, they estimate net costs (for metals) to be "as much as five times less" than for sulfate aerosols.
34. E. Teller, R. Hyde, L. Wood, *Active Climate Stabilization: Practical Physics-Based Approaches to Prevention of Climate Change*, Preprint UCRL-JC-148012, LLNL, Livermore, CA (2002).
35. G. J. S. Bluth, S. D. Doiron, C. C. Schnetzler, A. J. Krueger, L. S. Walter, *Geophys. Res. Lett.* **19**, 151–154 (1992).
36. S. Guo, G. J. S. Bluth, W. I. Rose, I. M. Watson, A. J. Prata, *Geochem. Geophys. Geosystems* **5**, Q04001, doi:10.1029/2003GC000654 (2004).
37. S. J. Smith, H. Pitcher, T. M. L. Wigley, *Global and Planetary Change* **29**, 99–119 (2001).
38. At steady-state, an injection of 5 TgS/yr into the stratosphere would increase the flux into the troposphere by the same amount, with larger fluxes in high latitudes. Given current emissions, the consequences of this extra flux are likely to be minor, but this aspect warrants further attention.
39. B. Govindasamy, K. Caldeira, *Geophys. Res. Lett.* **17**, 2151 (2000).
40. NCAR is supported by the U.S. National Science Foundation.

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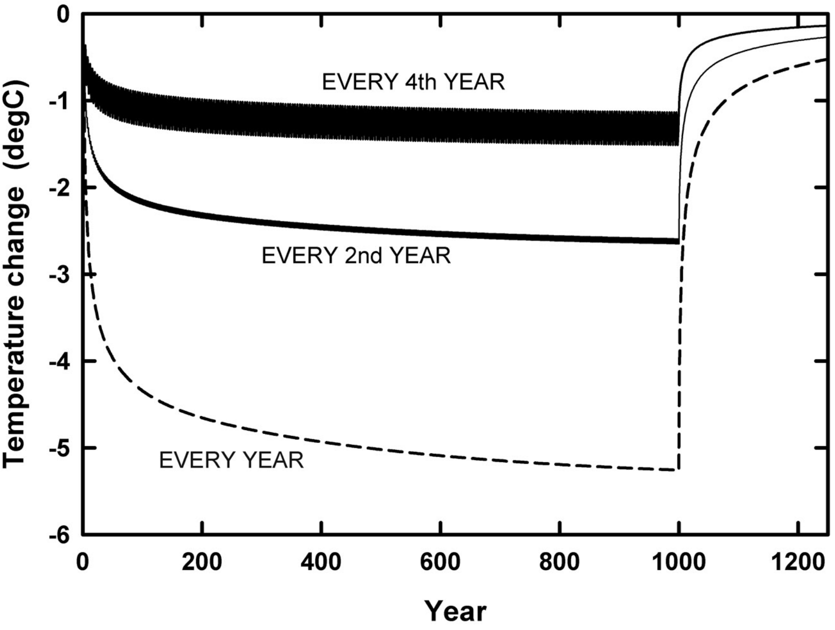
Fig. 1. Global-mean temperature response to multiple volcanic eruptions. The "standard" eruption used is Mt. Pinatubo [forcing data from Ammann *et al.* (*20*, *21*)], and eruptions are assumed to occur every four years (top curve), every two years, or every year. The results shown are annual-mean values plotted year by year. In the two- and (especially) four-year cases the forcing varies considerably from year to year, leading to noticeable interannual temperature variations. These appear as bands of values because the abscissa scale in the graph is insufficient to resolve these rapid variations. A climate sensitivity of 3°C equilibrium warming for $2xCO_2$ is assumed.

Fig. 2. Radiative forcing scenarios for the three geoengineering cases considered. The HIGH GEO case corresponds approximately to the steady-state forcing that would result from eruptions of Pinatubo every two years.

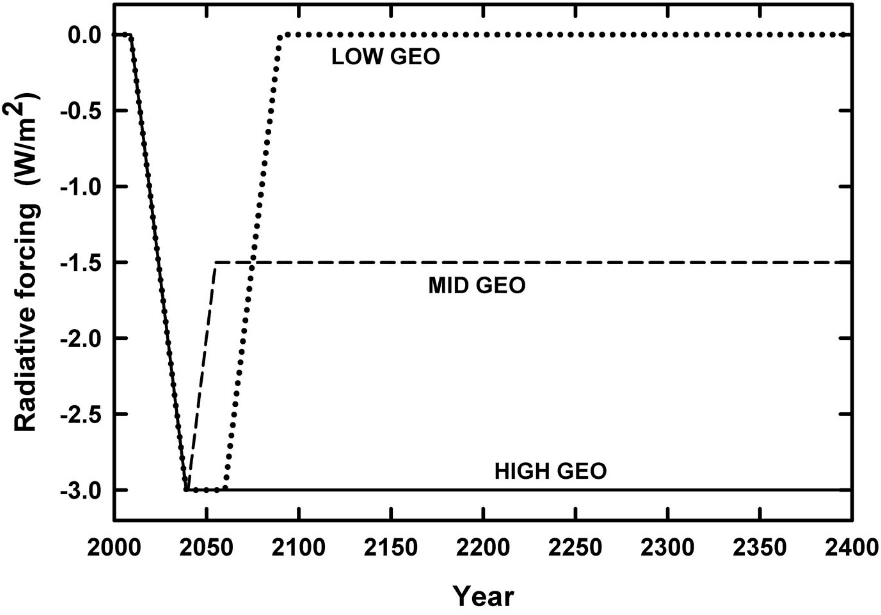
Fig. 3. (**A**) CO_2 concentration projections used in the analysis together with (**B**) corresponding fossil-fuel emissions. "A1B" is a central scenario from the SRES "no-climate-policy" set (*27*). "WRE450" is a concentration stabilization case from ref. (*7*), used as a mitigation-only example. "Overshoot" is a case with CO_2 concentrations stabilizing at 450 ppm but with less mitigation (higher emissions) than in WRE450. This is the case that is used in conjunction the three geoengineering cases shown in Fig. 2. A climate sensitivity of 3°C equilibrium warming for $2xCO_2$ is assumed. CO_2 emissions

results depend on the climate sensitivity because of climate feedbacks on the carbon cycle.

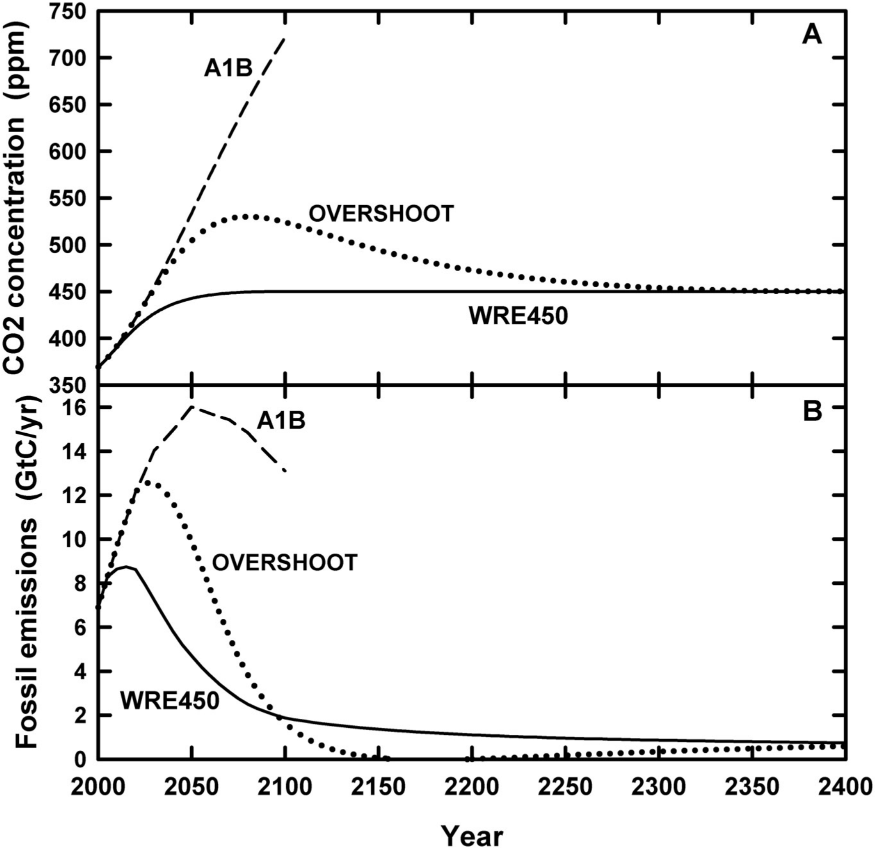
Fig. 4. Global-mean temperature (**A**) and sea level changes (**B**) for the baseline “no-climate-policy” scenario (A1B), a mitigation-only scenario stabilizing at 450 ppm (WRE450), and three scenarios combining both mitigation and geoengineering. The latter employ the overshoot (reduced mitigation) scenario (“Overshoot” in Fig. 3) and increasingly strong geoengineering cases from Fig. 2 (LOW GEO, MID GEO and HIGH GEO). A climate sensitivity of 3°C equilibrium warming for $2xCO_2$ is assumed.



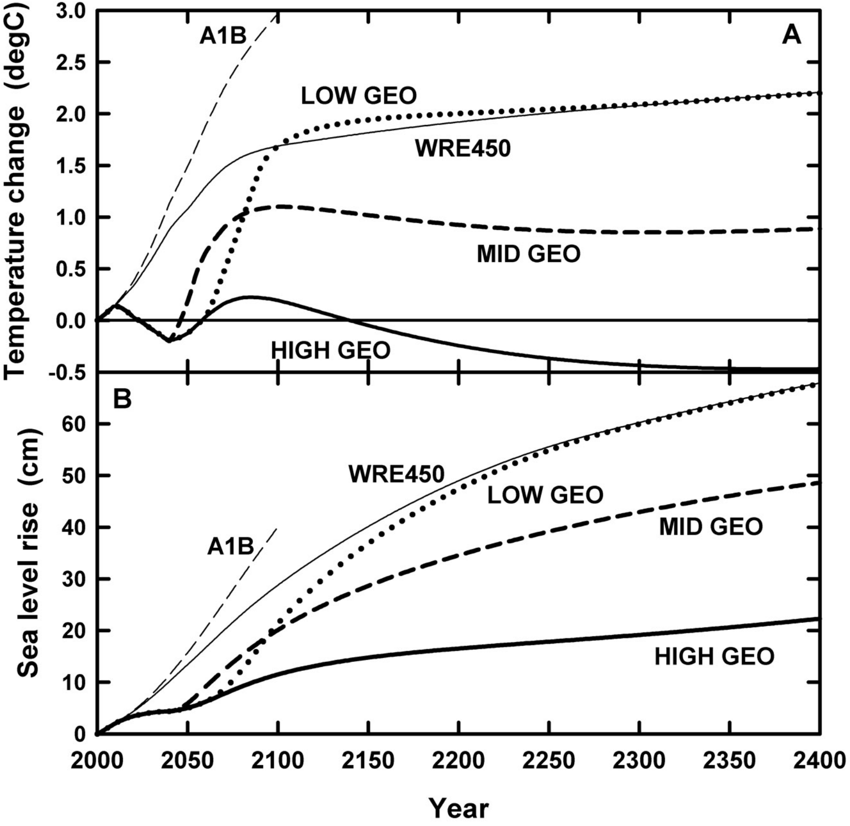
Temperature change (degC)
Year
EVERY 4th YEAR
EVERY 2nd YEAR
EVERY YEAR
0
-1
-2
-3
-4
-5
-6
0
200
400
600
800
1000
1200



Radiative forcing (W/m2)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
2000
2050
2100
2150
2200
2250
2300
2350
2400
Year
LOW GEO
MID GEO
HIGH GEO



A
B
A1B
OVERSHOOT
WRE450
CO2 concentration (ppm)
Fossil emissions (GtC/yr)
Year
750
700
650
600
550
500
450
400
350
16
14
12
10
8
6
4
2
0
2000
2050
2100
2150
2200
2250
2300
2350
2400



Temperature change (degC)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
A
A1B
LOW GEO
WRE450
MID GEO
HIGH GEO
B
Sea level rise (cm)
60
50
40
30
20
10
0
WRE450
LOW GEO
A1B
MID GEO
HIGH GEO
2000
2050
2100
2150
2200
2250
2300
2350
2400
Year