a critical determinant of T_{FH} cell generation. It will be interesting to see how different environmental cues affect the balance between these two transcriptional antagonists.

Uncontrolled generation of T_{FH} cells could be fatal, causing systemic autoimmunity by increasing antibody production. Therefore, expression of Blimp-1 may help maintain tolerance by inhibiting Bcl6 expression and the differentiation of T_{FH} cells. But if Bcl6 suppresses the generation of T_H1 and T_H17 cells by binding to their master transcription factors, then how are B cells stimulated to produce antibodies in response to inteferon-γ and IL-17, the cytokines that these T cell subtypes secrete? One possibility is that B cells are induced to make these antibodies by T_H1 and T_H17 cells, instead of T_{FH} cells, outside of germinal centers (*13*). Alternatively, differentiating T_H1, T_H2, and T_H17 cells may express low amounts of Bcl6, which might allow them to acquire the T_{FH} cell phenotype and induce B cells to make these antibodies. Johnston *et al.* show that a T cell–B cell interaction is essential for Bcl6 expression in activated $CD4^+$ T cells, which in turn could initiate differentiation into T_{FH} cells. It might be possible that activated T_H1, T_H2, and T_H17 cells express Bcl6 upon interaction with B cells, causing them to become $T_{FH}1$, $T_{FH}2$, and $T_{FH}17$ cells. They could then affect antibody production by B cells through the cytokines they produce.

The transcription factor cMaf also plays an essential role in generating T_{FH} cells (*14*). cMaf primarily activates IL-21 expression in $CD4^+$ T cells, and thus provides an autocrine growth factor for T_{FH} cell development (*15*). Bcl6 and cMaf may synergize to generate T_{FH} cells by regulating the expression of critical factors such as IL-21, the IL-21 receptor, and CXCR5. The balance among the transcription factors in the differentiation of T_{FH} cells, particularly between Bcl6 and Blimp-1, could be exploited in various autoimmune and infectious diseases.

References and Notes

1. L. J. McHeyzer-Williams, M. G. McHeyzer-Williams, *Annu. Rev. Immunol.* **23**, 487 (2005).
2. R. J. Johnston *et al.*, *Science* **325**, 1006 (2009); published online 16 July 2009 (10.1126/science.1175870).
3. R. I. Nurieva *et al, Science* **325**, 1001 (2009); published online 23 July 2009 (10.1126/science.1176676).
4. D. Yu *et al.*, *Immunity* 10.1016/j.immuni.2009.07.002 (2009).
5. N. Fazilleau *et al.*, *Immunity* **30**, 324 (2009).
6. A. G. Zaretsky *et al.*, *J. Exp. Med.* **206**, 991 (2009).
7. T. Korn *et al.*, *Nature* **448**, 484 (2007).
8. R. Nurieva *et al.*, *Nature* **448**, 480 (2007).
9. R. I. Nurieva *et al.*, *Immunity* **29**, 138 (2008).
10. A. Vogelzang *et al.*, *Immunity* **29**, 127 (2008).
11. T. Chtanova *et al.*, *J. Immunol.* **173**, 68 (2004).
12. T. Korn, E. Bettelli, M. Oukka, V. K. Kuchroo, *Annu. Rev. Immunol.* **27**, 485 (2009).
13. J. M. Odegard *et al.*, *J. Exp. Med.* **205**, 2873 (2008).
14. A. T. Bauquet *et al.*, *Nat. Immunol.* **10**, 167 (2009).
15. C. Pot *et al.*, *J. Immunol.* **183**, 797 (2009).

16. We thank J. Hulin and A. C. Anderson for their critical reading of this manuscript.

10.1126/science.1178752

CLIMATE CHANGE

Risks of Climate Engineering

Gabriele C. Hegerl[1] and Susan Solomon[2]

Observations indicate that attempts to limit climate warming by reducing incoming shortwave radiation risk major precipitation changes.

As the risks of climate change and the difficulty of effectively reducing greenhouse gas emissions become increasingly obvious, potential geoengineering solutions are widely discussed. For example, in a recent report, Blackstock *et al.* explore the feasibility, potential impact, and dangers of shortwave climate engineering, which aims to reduce the incoming solar radiation and thereby reduce climate warming (*1*). Proposed geoengineering solutions tend to be controversial among climate scientists and attract considerable media attention (*2*, *3*). However, by focusing on limiting warming, the debate creates a false sense of certainty and downplays the impacts of geoengineering solutions.

Discussions of "dangerous" levels of interference with the climate system often use warming as a proxy for the seriousness of greenhouse gas–induced climate change. However, climate change impacts are driven not only by temperature changes, but also by change in other aspects of the climate system, such as precipitation and climate extremes. If geoengineering studies focus too heavily on warming, critical risks associated with such possible "cures" will not be evaluated appropriately. Here, we present an example illustrative of the need for greater emphasis not only on possible benefits but also on the risks of geoengineering—in particular, the risks already suggested by observations of climate system change.

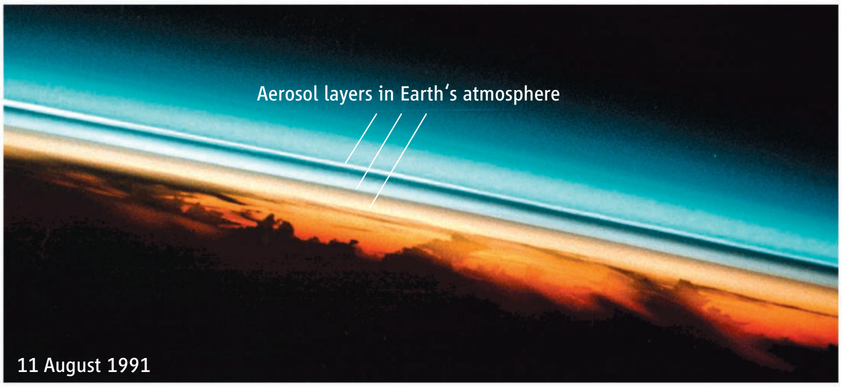
Carbon dioxide increases cause a reduction in outgoing longwave radiation, thus changing the heat balance of the planet. Several proposed geoengineering solutions aim to avoid the resulting energy imbalance that will lead to warming by reducing incoming solar radiation. This may be achieved by, for example, increasing the number of atmospheric reflecting particles in the stratosphere or by placing reflecting "mirrors" outside the atmosphere. These measures are indeed expected to reduce the projected warming (*1*, *2*). Blackstock *et al.* focus on this particular example of geoengineering, with the rationale that it may allow rapid action to be taken if a threat of catastrophic climate change emerges. Such emerging threats could, for example, be rapidly disintegrating ice sheets, or warming that is more rapid than expected (*4*). One of the attractions of shortwave climate engineering is the effectiveness and rapidity with which it could reduce warming, but it is also connected with considerable risks.

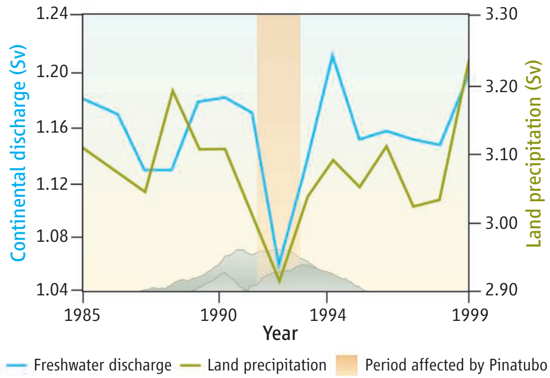
It is clear that reducing incoming shortwave radiation would lead to decreases in temperature. Volcanic eruptions in the 20th century led to substantial coolings that occurred within months after the eruption and lasted several years (*5*, *6*). Strong volcanic eruptions have in the past led to anomalously cold conditions: The year without a summer (1816) noted in North America and Europe followed the eruption of Tambora in Indonesia the year before, which was the largest volcanic event observed in recent centuries (*5*). However, volcanic eruptions also affect precipitation (*7*). The 1991 eruption of Mount Pinatubo led to substantial decreases in global stream flow and to increases in the incidence of drought (see the figure) (*8*). An analysis of 20th-century observations indicates that volcanic eruptions caused detectable decreases in global land precipitation (*9*, *10*). The reason is that with reduced incoming shortwave radiation and surface cooling, less energy is available for evaporation.

Greenhouse gas increases also influence precipitation, through two mechanisms: directly through reducing outgoing longwave radiation, and indirectly through warming (*11*–*13*). Warming increases evaporation, thus

[1]Grant Institute, Kings Buildings, West Mains Road, Edinburgh EH9 3JW, UK. [2]National Oceanic and Atmospheric Administration, Earth System Research Laboratory, 325 Broadway R/CSD, Boulder, CO 80305–3337, USA. E-mail: gabi.hegerl@ed.ac.uk; susan.solomon@noaa.gov

Published by AAAS





Aerosol effects. The eruption of Mount Pinatubo in June 1991 led to aerosol layering in the stratosphere (**A**) and to global reductions in precipitation (**B**). Optically thick layers of stratospheric aerosol cause the dark layers seen in the photo in (A), taken from the space shuttle on 11 August 1991. The data in (B) are averaged over the annual water year (October through September values); 1 Sv = 10^6 m^3/s. Aerosol inserted into the stratosphere as part of geoengineering solutions may have similar effects on precipitation.

making more water available globally for precipitation. However, because greenhouse gases reduce outgoing longwave radiation, they also reduce the effectiveness with which the atmosphere radiates out latent heat of condensation. This reduces precipitation. The net result of the two mechanisms is a relatively small increase in global precipitation in the early stages of greenhouse warming simulations (*12*).

The 20th-century climate record shows the different effects of shortwave and longwave forcing on temperature and on precipitation. Global surface temperature responds in a quite straightforward way to changes in the energy budget, irrespective of whether shortwave or longwave radiation changes are involved. Thus, temperatures in the latter part of the 20th century were dominated by anthropogenic warming (interspersed with short-term cooling after volcanic eruptions) (*14*). In contrast, precipitation reacts more strongly to reductions in incoming shortwave radiation, such as volcanic eruptions or shortwave climate engineering, than to reductions in outgoing longwave radiation associated with greenhouse gas forcing. Thus, global land precipitation changes over the 20th century correlate with model-simulated precipitation changes, largely because both show decreases in precipitation after volcanic eruptions (*9*, *12*). In contrast, greenhouse gas–induced precipitation changes so far are smaller on the global land average (*10*, *15*).

Models have been able to capture the patterns of precipitation changes with greenhouse warming (*14*, *15*) but appear to underestimate the magnitude of precipitation changes over the 20th century in response to both shortwave and longwave forcing. Patterns of precipitation changes over the 20th century already show contributions by human influences (*15*). The observed precipitation patterns with latitude were qualitatively captured in the average change simulated by multiple climate models, but the magnitude of simulated changes was significantly underestimated. Similarly, the observed global land precipitation response to volcanic forcing over the 20th century was much stronger than that simulated by present climate models (*9*, *10*).

Satellite data also suggest that climate models underestimate the magnitude of forced changes and of variations in precipitation extremes (*16*, *17*). Although these data are limited (*13*), they all suggest that precipitation changes are being underestimated. Missing external forcings (such as by absorbing aerosols) or errors in observations could contribute to the discrepancy between observations and model simulations. However, until these discrepancies are fully resolved, models cannot reliably predict how shortwave engineering can target precipitation and temperature simultaneously (*18*), implying that very large risks are associated with any such geoengineering scheme.

Some models suggest a large degree of cancellation between changes in warming and in precipitation in a shortwave climate-engineered world (*18*). However, models have been shown to have problems simulating past precipitation variability as well as trends. Furthermore, the combination of a strong greenhouse effect with a reduction of incoming radiation could have substantial effects on regional precipitation (*19*), including reductions that would rival those of past major droughts (*20*). Geoengineered changes in the environment could thus lead not only to "winners and losers" but even to conflicts over water resources (*19*) and the potential for migration and instability, making shortwave climate engineering internationally very controversial.

Blackstock *et al.* call for a study phase, during which the possible impacts of geoengineering options could be investigated. This is clearly necessary, and optimism about a geoengineered "easy way out" should be tempered by examination of currently observed climate changes. Climate change is about much more than temperature change, and using temperature alone as a proxy for its effects represents an inappropriate risk to the health of our society and to the planet.

References

1. J. J. Blackstock *et al.*, *Climate Engineering Responses to Climate Emergencies* (Novim, 2009), available at http://arxiv.org/pdf/0907.5140.
2. P. J. Crutzen, *Clim. Change* **77**, 211 (2006).
3. A. Robock, *Bull. At. Sci.* **64**, 14 (2008).
4. G. A. Meehl *et al.*, in *Climate Change 2007: The Fourth Scientific Assessment*, S. Solomon *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2007), pp. 747–845.
5. A. Robock, *Rev. Geophys.* **38**, 191 (2000).
6. G. C. Hegerl *et al.*, *Geophys. Res. Lett.* **30**, 1242 (2003).
7. A. Robock, Y. Liu, *J. Clim.* **7**, 44 (1994).
8. K. E. Trenberth, A. Dai, *Geophys. Res. Lett.* **34**, L15702 (2007).
9. N. P. Gillett, A. J. Weaver, F. W. Zwiers, M. F. Wehner, *Geophys. Res. Lett.* **31**, L12217 (2004).
10. F. H. Lambert, N. P. Gillett, D. A. Stone, C. Huntingford, *Geophys. Res. Lett.* **32**, L18704 (2005).
11. J. F. B. Mitchell, C. A. Wilson, W. M. Cunnington, *Q. J. R. Meteorol. Soc.* **113**, 293 (1987).
12. M. R. Allen, W. J. Ingram, *Nature* **419**, 223 (2002).
13. F. H. Lambert, A. R. Stine, N. Y. Krakauer, J. C. H. Chang, *Eos* **89**, 193 (2008).
14. G. C. Hegerl *et al.*, in *Climate Change 2007: The Fourth Scientific Assessment*, S. Solomon *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2007), pp. 663–745.
15. X. Zhang *et al.*, *Nature* **448**, 461 (2007).
16. F. J. Wentz, L. Ricciardulli, K. Hilburn, C. Mears, *Science* **317**, 233; published online 30 May 2007.
17. R. P. Allan, B. J. Soden, *Science* **321**, 1481; published online 7 August 2008.
18. K. Caldeira, L. Wood, *Philos. Trans. R. Soc. London Ser. A* **366**, 4039 (2008).
19. A. Robock, L. Oman, G. L. Stenchikov, *J. Geophys. Res.* **113**, D16101 (2008).
20. G. T. Narisma, J. A. Foley, R. Licker, N. Ramankutty, *Geophys. Res. Lett.* **34**, L06710 (2007).

10.1126/science.1178530