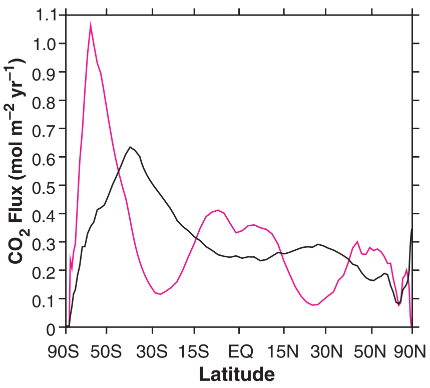

Fig. 3. Zonal mean anthropogenic CO_2 accumulation rate in the ocean (black line) and zonal mean anthropogenic CO_2 flux into the ocean (magenta line), by latitude band (averaged over land and ocean areas for 1995). The latitude axis is scaled so that equal horizontal distances represent equal areas on Earth's surface. On this scale, the total flux or accumulation into the ocean is proportional to the area under the appropriate curve. The Southern Ocean is an area with the highest anthropogenic CO_2 fluxes, but the Antarctic Convergence is the area with the largest anthropogenic CO_2 accumulation.

ern Ocean was much more vigorous in the period from ~1350 to 1880 A.D. than in the recent past. Our simulations reflect primarily late–20th century oceanographic conditions and support the conclusion of a subordinate role for deep convection in the Southern Ocean during this time period (*21*).

Our conclusion that present-day Southern Ocean uptake of anthropogenic carbon is large, but Southern Ocean storage is relatively small, has implications for the mechanisms governing future changes in the ocean carbon cycle. If most of the anthropogenic carbon entering the Southern Ocean is being transported northward isopycnally to the Antarctic Convergence, then a reduction in deep convection would have little impact on Southern Ocean uptake of anthropogenic carbon. Thus, the particular scenario described in (*6*) seems unlikely to occur. Changes in ocean circulation, reduction in sea ice coverage, temperature-dependent changes in CO_2 solubility, and changes in biological activity will impact oceanic CO_2 uptake (*6, 15*). Nevertheless, if global climate change reduces the density of surface waters in the Southern Ocean (*6, 15*), isopycnal surfaces that are now ventilated would become isolated from the atmosphere; this would tend to diminish Southern Ocean carbon uptake.

References and Notes

1. J. L. Sarmiento and E. T. Sundquist, *Nature* **356**, 589 (1992); C. D. Keeling, S. C. Piper, M. Heimann, in *Aspects of Climate Variability in the Pacific and Western Americas*, vol. 55 of *Geophysical Monograph Series*, D. H. Peterson, Ed. (American Geophysical Union, Washington, DC, 1989), pp. 305–363; P. P. Tans, I. Y. Fung, T. Takahashi, *Science* **247**, 1431 (1990).
2. C. L. Sabine *et al.*, *Global Biogeochem. Cycles* **13**, 179 (1999).
3. E. Maier-Reimer and K. Hasselmann, *Clim. Dyn.* **2**, 63 (1987).
4. U. Siegenthaler and J. L. Sarmiento, *Nature* **365**, 119 (1993).
5. J. L. Sarmiento, J. C. Orr, U. Siegenthaler, *J. Geophys. Res.* **97**, 3621 (1992); J. L. Sarmiento, C. Le Quere, S. W. Pacala, *Global Biogeochem. Cycles* **9**, 121 (1995).
6. J. L. Sarmiento, T. M. C. Hughes, R. J. Stouffer, S. Manabe, *Nature* **393**, 245 (1998).
7. N. Gruber, J. L. Sarmiento, T. S. Stocker, *Global Biogeochem. Cycles* **10,** 809 (1996).
8. N. Gruber, *Global Biogeochem. Cycles* **12**, 165 (1998).
9. A. Poisson and C.-T. Chen, *Deep Sea Res. Part A* **34**, 1255 (1987); P. P. Murphy, R. A. Freely, R. H. Gammon, K. C. Kelly, L. S. Waterman, *Mar. Chem.* **35**, 77 (1991).
10. P. B. Duffy and K. Caldeira, *Geophys. Res. Lett.* **24**, 1323 (1997); K. Caldeira and P. B. Duffy, *Geophys. Res. Lett.* **25**, 1003 (1998). Our simulations tend to have slow and shallow North Atlantic Deep Water, but they represent the Southern Ocean relatively well.
11. R. Pacanowski, K. Dixon, A. Rosati, *The G.F.D.L. Modular Ocean Model Users Guide version 1.0, GFDL Ocean Group Technical Report 2* (NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, 1991).
12. J. M. Oberhuber, *J. Phys. Oceanogr.* **23**, 808 (1993).
13. P. B. Duffy, M. Eby, A. J. Weaver, *Geophys. Res. Lett.* **26**, 1739 (1999).
14. D. G. Martinson, *J. Geophys. Res.* **95**, 11641 (1990). The horizontal sizes of regions of brine-induced convection are very small in comparison to the grid cells in our model. Thus, a first-order representation of this subgrid-scale convection process is to sink rejected salt without mixing other tracers (*10, 13*).
15. F. Joos, G.-K. Plattner, T. F. Stocker, O. Marchal, A. Schmittner, *Science* **284**, 464 (1999); R. J. Matear and A. C. Hirst, *Tellus Ser. B* **51**, 722 (1999).
16. R. Wanninkhof, *J. Geophys. Res.* **97**, 7373 (1992).
17. S. Levitus and T. P. Boyer, *Temperature*, vol. 4 of *World Ocean Atlas 1994*, *NOAA Atlas NESDIS 4* (National Oceanographic Data Center, Silver Spring, MD, 1994).
18. K. Bryan, *J. Phys. Oceanogr.* **14**, 666 (1984).
19. Evidence of deep penetration of CFCs in the Southern Ocean [A. H. Orsi, G. C. Johnson, J. L. Bullister, *Prog. Oceanogr.* **43**, 55 (1999)] may appear to contradict the conclusions drawn here. However, CFCs equilibrate with the atmosphere much more rapidly than CO_2 does, and the solubility of CFCs is much more sensitive to changes in temperature than the solubility of CO_2 is. These two factors increase the ratio of CFC to anthropogenic CO_2 concentrations in the Southern Ocean.
20. W. S. Broecker, S. Sutherland, T.-H Peng, *Science* **286**, 1132 (1999).
21. These conclusions are echoed by a study showing deep convection to play a subordinate role in tracer transport in the North Atlantic [A. J. Watson *et al.*, *Nature* **401**, 902 (1999)].

22. We thank N. Gruber, R. M. Key, and C. L. Sabine for their insightful papers and access to the data underlying them. K.C. was supported by the NASA Oceanography Program and the U.S. Department of Energy Center for Research on Ocean Carbon Sequestration. P.B.D. was supported by the Lawrence Livermore National Laboratory Laboratory Directed Research and Development program.

15 July 1999; accepted 2 December 1999

Nanotube Molecular Wires as Chemical Sensors

Jing Kong,[1]* Nathan R. Franklin,[1]* Chongwu Zhou,[1] Michael G. Chapline,[1] Shu Peng,[2] Kyeongjae Cho,[2] Hongjie Dai[1]†

Chemical sensors based on individual single-walled carbon nanotubes (SWNTs) are demonstrated. Upon exposure to gaseous molecules such as NO_2 or NH_3, the electrical resistance of a semiconducting SWNT is found to dramatically increase or decrease. This serves as the basis for nanotube molecular sensors. The nanotube sensors exhibit a fast response and a substantially higher sensitivity than that of existing solid-state sensors at room temperature. Sensor reversibility is achieved by slow recovery under ambient conditions or by heating to high temperatures. The interactions between molecular species and SWNTs and the mechanisms of molecular sensing with nanotube molecular wires are investigated.

Carbon nanotubes are molecular-scale wires with high mechanical stiffness and strength. A SWNT can be metallic, semiconducting, or semimetallic, depending on its chirality (*1*). Utilization of these properties has led to applications of individual nanotubes or ensembles of nanotubes as scanning probes (*2, 3*), electron field emission sources (*4*), actuators (*5*), and nanoelectronic devices (*6*). Here, we report the realization of individual semiconducting-SWNT (S-SWNT)–based chemical sensors capable of detecting small concentrations of toxic gas molecules.

Sensing gas molecules is critical to environmental monitoring, control of chemical processes, space missions, and agricultural and medical applications (*7*). The detection of NO_2, for instance, is important to monitoring environmental pollution resulting from combustion or automotive emissions (*8*). Detection of NH_3 is needed in industrial, medical, and living environments (*9*). Existing electrical sensor materials include semicon-

[1]Department of Chemistry, [2]Department of Mechanical Engineering, Stanford University, Stanford, CA 94305, USA.

*These authors contributed equally to this work.
†To whom correspondence should be addressed. E-mail: hdai@chem.stanford.edu