1. Funch, P. & Kristensen, R. M. *Nature* **378,** 711–714 (1995).
2. Funch, P. & Kristensen, R.M. in *Microscopic Anatomy of Invertebrates 13: Lophophorates, Entoprocta and Cycliophora* (eds Harrison, F.W. & Woollacott, R.M.) 409–474 (Wiley-Liss, New York, 1997).
3. Funch, P. *J. Morphol.* **230,** 231–263 (1996).
4. Conway Morris, S. *Nature* **378,** 661–662 (1995).
5. d'Hondt, J.-L. *Bull. Mens. Soc. Linn. Lyon* **66,** 12–22 (1997).
6. Van de Peer, Y., Caers, A., De Rijk, P. & De Wachter, R. *Nucleic Acids Res.* **26,** 179–182 (1998).
7. Kumar, S., Tamura, K. & Nei, M. *MEGA: Molecular Evolutionary Genetics Analysis Version 1.0: Manual* (Pennsylvania State Univ., Pennsylvania, 1993).
8. Bremer, K. *Evolution* **42,** 795–803 (1988).
9. Lorenzen, S. in *The Origins and Relationships of Lower Invertebrates* (eds Conway Morris, S., George, J. D., Gibson, R. & Platt, H. M.) 210–223 (Clarendon, Oxford, 1985).
10. Garey, J. R., Near, T. J., Nonnemacher, M. R. & Nadler, S. A. *J. Mol. Evol.* **43,** 287–292 (1996).
11. Ahlrichs, W. H. *Zoomorphology* **117,** 41–48 (1997).
12. Brusca, R. C. & Brusca, G. J. *Invertebrates* (Sinauer, Sunderland, 1990).
13. Kimura, M. *J. Mol. Evol.* **16,** 111–120 (1980).
14. Jukes, T. H. & Cantor, C. R. in *Mammalian Protein Metabolism* (ed. Munro, H. N.) 21–132 (Academic, New York, 1969).
15. Van de Peer, Y., Van der Auwera, G. & De Wachter, R. *J. Mol. Evol.* **42,** 201–210 (1996).

Gulf Stream shifts following ENSO events

Over the past three decades the annual mean latitude of the Gulf Stream off the coast of the United States has been forecastable from the intensity of the North Atlantic Oscillation (NAO)[1], the predictions accounting for more than half the variance. Here we show that much of the unexplained variance can be accounted for by the Southern Oscillation in the Pacific, the Gulf Stream being displaced northwards following El Niño–Southern Oscillation (ENSO) events. This provides a link between events in the equatorial Pacific and the circulation and weather conditions of the North Atlantic.

Monthly charts showing the position of the north wall of the Gulf Stream since 1966 have been used to study its long-term variations[2,3] and to construct an index of its latitude by principal components analysis[1]. Ocean circulation theory predicts that the path of the Gulf Stream is set by the line of zero Ekman pumping, where there is no wind-driven convergence or divergence of water at the ocean surface[4]. The position of the Gulf Stream will therefore vary with the intensity of the North Atlantic Oscillation, the dominant mode of mid-latitude atmospheric variation in the North Atlantic, and indeed 60% of the annual variance in the latitude of the north wall 1966–96 is predictable from an NAO index[1,5].

Another source of fluctuation in the Gulf Stream is the subtropical and tropical trade wind belt. This is a region that is strongly affected by ENSO events in the Pacific Ocean, their influence appearing in African weather patterns[6]. Figure 1a shows that the residuals from a multiple regression prediction of the Gulf Stream position based on the NAO index are correlated with the values from two years earlier of one measure of ENSO variations, the September-to-February averages of the Southern Oscillation (SO) index (the difference in sea-level pressure anomalies between Tahiti and Darwin). The SO index is uncorrelated with the NAO index[7].

We used a stepwise regression analysis to relate the annual Gulf Stream position during 1966–97 to the previous year's position (to take account of persistence between years) and the NAO and SO indices at lags of up to two years. For each of these indices, the largest and most significant contribution was made by the value of the index from two years previously, there being no significant contributions from the NAO and SO index at a one-year lag or from the unlagged SO index. The predictions of the regression equation (F-ratio = 22.7, $P < 0.01$) are shown in Fig. 1b. The two-year time lag is consistent with an earlier study of the latitude at which the Gulf Stream separates from the coast of the United States. Gangopadhyay *et al.*[4] found that the theoretically predicted latitudes during 1977–88 only agreed with those observed if the wind forcing was integrated over about three years, a delay they attributed to the adjustment time of the ocean circulation.

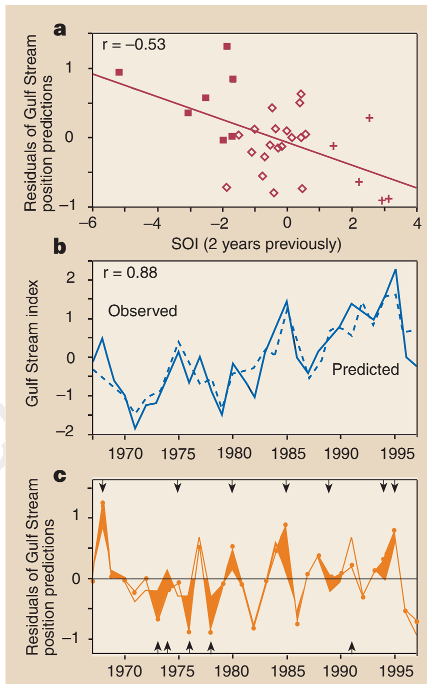

Figure 1 Observed and predicted Gulf Stream positions. **a,** Scatter plot comparing observed and predicted Gulf Stream positions (1966–97)[1] with the SO index two years previously (index has been allocated to the year of the January data). The prediction was based on a multiple regression equation using the NAO index[5] and its value two years before, and the previous year's position. A regression line through the points is shown. Filled squares, the El Niño years (1966, 1973, 1978, 1983, 1987 and 1992–93); crosses, the La Niña years (1971–72, 1974, 1976 and 1989); diamonds, years belonging to neither group. **b,** Latitude of Gulf Stream 1966–97 (solid line) compared with the predictions of the regression equation (broken line) in which the delayed effect of the SO is added to the variables in **a**. The units of the index are equivalent to 0.03° at 79° W and 0.3° at 65° W. **c,** Reduction of regression residuals when delayed effect of the SO is considered (filled circles, original regression results). Downward arrows, two years after an El Niño; upward arrows, two years after a La Niña. Shaded regions, associated reductions of residuals. Correlation coefficients (r) both have $P < 0.01$. (All significance levels corrected for lag 1 serial correlation[11].)

Because of intercorrelation between the variables, it is not possible to obtain a unique value for the contribution of the SO index to the predictions in Fig. 1b. Thus the stepwise regression indicates that the index accounts for 9% of the variance, but the partial correlation coefficient between the Gulf Stream index and the SO index is 0.4, which indicates that the percentage could be larger. Figure 1c shows how including the lagged SO index reduces the regression residuals: after El Niño or La Niña events, the residual is reduced in the direction of the arrows.

Averaging the data from ref. 1 over the region from 65° to 79° W shows that the mean latitude of the Gulf Stream two years after ENSO events was 0.2° further north than after non-event years ($P < 0.001$). These displacements represent two-thirds of a standard deviation (the southward shift following La Niña events, 0.05°, was not significant). The displacements may be accompanied by larger shifts further east, where the Stream's path is less constrained, or by more substantial circulation changes elsewhere.

The position of the Gulf Stream affects the waters over the continental shelf from Cape Hatteras to the Grand Banks in several ways[8] and may influence storm tracks over the northwest Atlantic[9,10] The results in Fig. 1 indicate that these processes may be linked to ocean–atmosphere events in the tropical Pacific.

Arnold H. Taylor, Michael B. Jordan, John A. Stephens
NERC Centre for Coastal and Marine Sciences, Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth PL1 3DH, UK
e-mail: aht@pml.ac.uk

1. Taylor, A. H. & Stephens, J. A. *Tellus* **50 A,** 134–142 (1998).
2. Miller, J. L. *J. Geophys. Res.* **99,** 5057–5064 (1994).
3. Drinkwater, K. F., Myers, R. A., Pettipas, R. G. & Wright, T. L. *Can. Data Rep. Hydrogr. Ocean Sci.* **125,** 1–103 (1994).
4. Gangopadhyay, A., Cornillon, P. & Watts, R. D. *J. Phys. Oceanogr.* **22,** 1286–1301 (1992).
5. Hurrell, J. W. *Science* **269,** 676–679 (1995).
6. Cane, M. A., Eshel, G. & Buckland, R. W. *Nature* **370,** 204–205 (1994).
7. Rogers, J. C. *Mon. Weath. Rev.* **112,** 1999–2015 (1984).
8. Myers, R. A. & Drinkwater, K. F. *J. Mar. Res.* **47,** 635–656 (1989).
9. Dickson, R. R. & Namias, J. *Mon. Weath. Rev.* **104,** 1255–1265 (1976).
10. Cione, J. J., Raman, S. & Pietrafesa, L. J. *Mon. Weath. Rev.* **121,** 421–430 (1993).
11. Taylor, A. H. *ICES J. Mar. Sci.* **52,** 711–721 (1995).