and the corresponding gene flow[10], the nuclear DNA data nonetheless suggest that a possible male-mediated gene flow between colonies is insufficient to prevent a genetic substructuring even of closely neighbouring colonies.

The consequences for conservation management are obvious. The preprogrammed female reproductive behaviour makes it unlikely that the loss of a breeding habitat (because of human building operations, for example) can be compensated for by emigration to other colonies; that is, the loss of nesting sites is accompanied by the loss of specific genotypes. Thus, to preserve the genetic diversity of the *Caretta* metapopulation one needs to preserve individual nesting sites (attempts to transfer freshly deposited eggs between sites — based on the hope that hatchlings would accept a new hatching site as natal — are controversial). In addition, the described haplotypes may serve as genetic tags to identify the colony membership of individuals offshore or illegally commercialized, and also to complete our knowledge of sea turtle migratory behaviour offshore[11].

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Erratum

In the Scientific Correspondence "Competition for royalty in bees" by R. F. A. Moritz, Per Kryger and Mike H. Allsopp (*Nature* **384**, 31; 1996), the *y*-axis labels of Fig. 2, showing the mean offspring frequencies of various patrilines of a honeybee colony, were printed incorrectly. In the top panel the scale should have read '0–20%', not '0–2%' as printed, and in the middle and bottom panels '0–80%' rather than '0–8%'. ☐

Human effect on global climate?

SIR — The recent pattern-correlation analysis of Santer *et al.*[1] has drawn considerable attention: Nicholls[2], for example, stated that it represents the "clearest evidence yet that humans may have affected global climate". This conclusion is based on the increasing similarity of the vertical temperature pattern in free-atmosphere and global-climate models incorporating combinations of carbon dioxide, sulphate aerosols and stratospheric ozone concentrations as measured by a 'centred' correlation statistic, $R(t)$.

Santer *et al.*[1] found significant increases in $R(t)$ in the 850–50-hPa region of the atmosphere over the period of their study (1963–87) for each of the climate model/atmospheric constituent combinations they analysed (with the exception of a sulphate-only model). We agree with Santer *et al.*[1] that this result stems largely from the pattern of stratospheric and upper tropospheric cooling and a hemispheric asymmetry in the lower and mid-troposphere. But we believe that the reported increases in $R(t)$ are almost totally caused by the higher-altitude temperature changes, and that in the lower levels the results are only a reflection of the time period chosen.

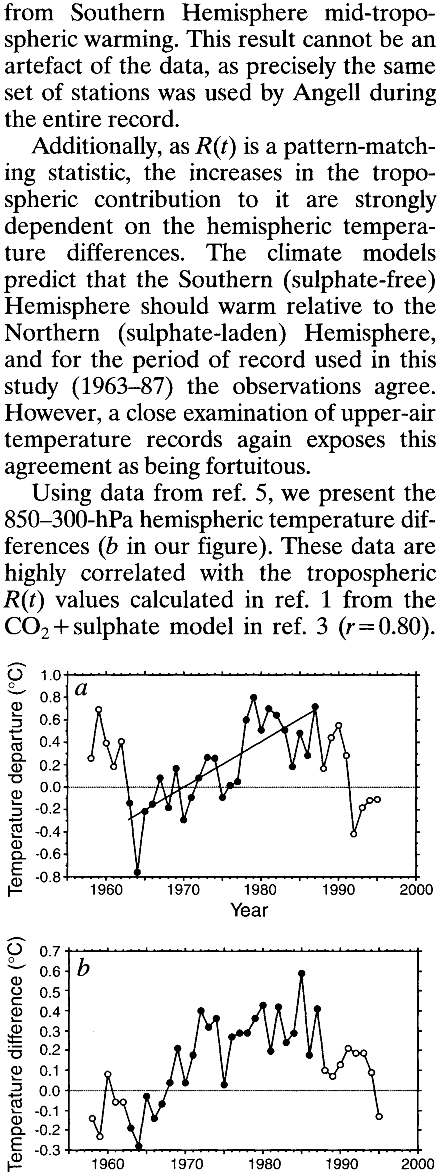
For example, using the carbon dioxide + sulphate model results from Taylor and Penner[3] (Fig. 2 of ref. 1), we can compare the explained variance (obtained by squaring $R(t)$) at the end of the record (1987) between the 850–50-hPa layer (troposphere + stratosphere) to that for the 850–500-hPa layer (lower troposphere only). The values are 64% and 5%, respectively. Thus 92% of the explained variance results from the addition of data above 500 hPa. This result is typical for the models used in this study (with the exception of the sulphate-only model). Further, the calculation of $R(t)$, using four levels above 500 hPa and only two beneath, assures heavy dependence upon the upper troposphere and stratosphere.

The factor that largely constitutes the hemispheric asymmetry is the warming of the mid-troposphere in the Southern Hemisphere, which appears both in the CO_2 + sulphate models (Fig. 1*c*, *e*, *g*–*i* of ref. 1) and in the observations, where it is concentrated between 850 and 300 hPa, 30 to 60° S (Fig. 1*j* of ref. 1). The observed data in ref. 1 are from the record of Oort and Liu[4]. This record extends to 1989 (although annual data to only 1987 are used by Santer *et al.*[1]). The radiosonde record of Angell[5] is longer (1958–95). Over the period of concurrency between refs 1 and 5, the correlation coefficient between annual anomaly values is 0.94 in the Northern Hemisphere and 0.92 in the Southern Hemisphere.

When we examine the period of record used by Santer *et al.* in the context of the longer period available from ref. 5, we find that in the region with the most significant warming (30–60° S, 850–300 hPa) the increase is largely an artefact of the time period chosen (*a* in our figure). Although there is a statistically significant warming in the period from 1963–87, there is no significant change in the entire (1958–95) record. This has considerable bearing on the portion of $R(t)$ in ref. 1 that emanates from Southern Hemisphere mid-tropospheric warming. This result cannot be an artefact of the data, as precisely the same set of stations was used by Angell during the entire record.

Additionally, as $R(t)$ is a pattern-matching statistic, the increases in the tropospheric contribution to it are strongly dependent on the hemispheric temperature differences. The climate models predict that the Southern (sulphate-free) Hemisphere should warm relative to the Northern (sulphate-laden) Hemisphere, and for the period of record used in this study (1963–87) the observations agree. However, a close examination of upper-air temperature records again exposes this agreement as being fortuitous.

Using data from ref. 5, we present the 850–300-hPa hemispheric temperature differences (*b* in our figure). These data are highly correlated with the tropospheric $R(t)$ values calculated in ref. 1 from the CO_2 + sulphate model in ref. 3 ($r = 0.80$).



a, The Angell[5] temperature departure (°C) history for 1958–95 for the 850–300-hPa layer between 30 and 60° S latitudes. Solid circles, years studied in ref. 1. There is a statistically significant (P<0.0001) increase during 1963–87, whereas the overall record exhibits no significant trend. *b*, Annual temperature difference (°C) between Southern and Northern hemispheres in the 850–300-hPa layer, from ref. 5. There is a statistically significant (P< 0.05) downward trend in this data since 1972. Solid circles, period studied by Santer *et al.*

On the basis of this relationship, estimates of $R(t)$ for the period 1988–95, coupled with the observed values in ref. 1, yield a significant downward trend since the early 1970s. This is typical of the models tested.

Even though global temperatures were dramatically reduced by the eruption of Mount Pinatubo in the latter part of this period (1991), the hemispheric temperature difference was relatively unaffected. Therefore, we believe that the eruption would have little effect on the tropospheric values of $R(t)$.

In conclusion, we suggest that the increasing pattern correlation between climate models and observations found by Santer *et al.* is primarily governed by a signal in the upper troposphere and lower stratosphere, and that in the lower and mid-troposphere, the models and observations have been drifting further apart since the early 1970s. Such a result in the troposphere cannot be considered to be a 'fingerprint' of greenhouse-gas-induced climate change. It is therefore apparent that statements about the strength of the evidence for human alteration of lower tropospheric climate must be tempered in the light of more complete data than were analysed by Santer *et al.*

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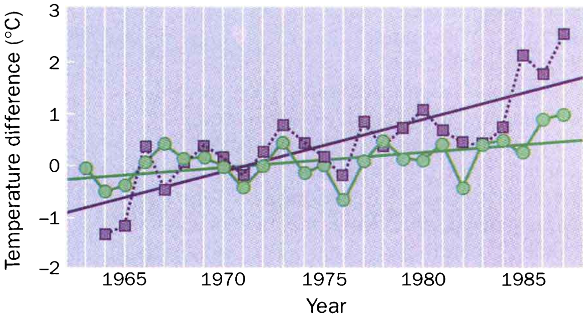
SIR — Santer *et al.*[1] present a statistical analysis in which they compare the model-generated zonal mean vertical thermal structure of the atmosphere in response to the concomitant increase of the concentration of greenhouse gases, sulphur emissions and the observed decrease in stratospheric ozone to the observed thermal structure of the atmosphere between 1963 and 1987. They find that the pattern correlation between the predicted and observed changes in zonal mean latitude height profiles of atmospheric temperature increases with time.

The authors attributed the largest amplitude signals of those trends primarily to two factors: first, the pattern comparison over 50 to 850 hPa (the signal of modelled tropospheric warming and stratospheric cooling); and second, in the troposphere, between 500 and 850 hPa, the disparity between Southern and Northern hemispheric warming due to modelled sulphate aerosol effects.

A well-known tropospheric and stratospheric temperature history for various latitudinal bands between 1958 and 1992 has already been published by Angell[5]; coverage for the Southern Hemisphere stratosphere begins in 1964. Angell's data of the layer 50–100 hPa closely correspond to the stratospheric data used by Santer *et al.*; similarly, Angell's 300–850-hPa data capture the bulk of the troposphere. A signal of tropospheric warming and stratospheric cooling should be visible as an increasing difference between tropospheric warming and stratospheric cooling.

Taking the first point, a trend analysis of Angell's lower stratospheric data for the period 1963–87 (or 1964–87) shows a much larger cooling rate in the Southern than in the Northern Hemisphere (see figure). It appears, therefore, that most (stratospheric cooling in the Southern Hemisphere is about three times as large as in the Northern Hemisphere) of the signal pattern strength in 1963–87 relating to stratospheric/tropospheric trend differences originates in the Southern Hemisphere. This result seems to hold for the 1958–92 period as well, and for trends originating in the mid-1970s and later, which do not show any tropospheric warming in the mid-latitudes of the Southern Hemisphere, but sharply increasing stratospheric cooling and therefore increasing trend differences and strengthening of a pattern of stratospheric/tropospheric differences.



Tropospheric and stratospheric temperature differences in the Northern (green symbols) and Southern (purple symbols) Hemispheres between 1963 and 1987, adapted from ref. 5. The least-squares linear trends (solid lines) are increases of 0.97 °C per decade in the Southern Hemisphere, and 0.27 °C per decade in the Northern Hemisphere.

As Santer *et al.* point out, and as dynamical modelling results seem to suggest[6–9], the cooling of the Southern Hemisphere stratosphere, which increased sharply after about 1983 (ref. 5), may be related to stratospheric ozone depletion, which is most pronounced in the higher latitudes, but also occurs in the mid-latitudes of the Southern Hemisphere[10]. Therefore, the increasing signal pattern strength reported by Santer *et al.*[1] may primarily be related to Southern Hemisphere stratospheric cooling linked to ozone depletion due to CFCs (chlorofluorocarbons)[6–9]. The possible human-induced climate effect alluded to by Santer *et al.* could then largely be attributed to stratospheric cooling by CFCs but not to the warming effect of anthropogenic greenhouse gases.

Turning to the second point, Santer *et al.* report a hemispheric-scale asymmetrical warming signal in 1963–87 only in those modelling experiments that include cooling sulphate aerosol effects. The implication of this result is that the lack of sulphate emissions in the Southern Hemisphere has led to a larger tropospheric warming there.

This interhemispheric difference should be largest in the mid-latitudes, where most of the sulphur emissions occur (Fig. 1 of ref. 1). Although there is a larger 1963–87 warming in Angell's 300–850 hPa mid-latitude data (30–60 °C in both hemispheres) as well, it does not seem to be a permanent feature of the climate system in recent decades. A comparison between Northern and Southern Hemisphere trends ending in 1992 shows that trends beginning after 1964 imply increasingly greater warming in the Northern Hemisphere than in the Southern Hemisphere. This would be incompatible with increasing Northern Hemispheric cooling due to rising sulphur emissions there.

Regarding the role of natural factors, the early years of the period 1963–87 were substantially influenced by tropospheric cooling (and stratospheric warming) following the eruption of Mount Agung[11], whereas the end of that period was influenced by several strong El Niño events[12], which have led to some tropospheric warming and stratospheric cooling, particularly in the southern subtropics of the lower latitudes[5]. Therefore, the general tropospheric warming and stratospheric cooling trend between 1963 and 1987 has

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been accentuated by widely known natural factors[13,14] and could at least partially be explained by them.

In conclusion, the main patterns described by Santer *et al.*[1] — interpreted by some as a sign of a human impact on the climate system — are either not permanent features of the climate system or cannot be ascribed to an increase of man-made greenhouse gases. The possible human impact on climate appears to be restricted to CFCs and the Southern Hemisphere stratosphere.

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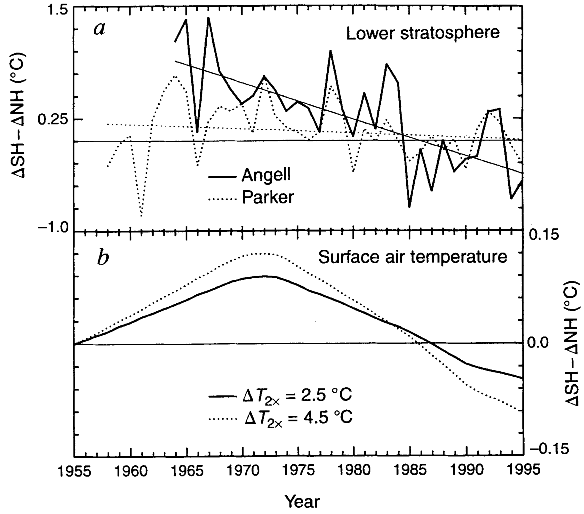

a, Comparison of annual mean changes in hemispheric temperature contrast (Southern Hemisphere minus Northern Hemisphere) in the lower stratosphere in two observed data sets. Data from Angell[5] are virtual temperatures for the 100–50-hPa layer. The Parker radiosonde data[17] are actual temperatures for eight pressure levels; Australian and New Zealand stations were corrected for instrumental biases[20]. To facilitate comparison with Angell's and other data sets, the Parker temperature data were sampled with the channel-4 weighting function of the satellite-based Microwave Sounding Unit (which monitors temperatures in the 120–40-hPa atmospheric layer[18]). Both time series are expressed as anomalies relative to a common reference period average (1979–95). Overall linear trends (over 1964–95 in ref. 5 and 1958–95 in ref. 17) are also shown. *b*, Time series of hemispheric surface air temperature-change differential (Southern Hemisphere minus Northern Hemisphere) predicted by a simple climate model[24] in response to IPCC 'best guess' anthropogenic forcing[25]. Results are shown for two different values of the climate sensitivity. The model prediction in response to purely anthropogenic forcing is qualitatively similar to the observed hemispheric temperature-change contrast in Michaels and Knappenberger's figure *b*.

SANTER *ET AL.* REPLY — Michaels and Knappenberger, and Weber, in their contributions above, criticize our study[1] in which we attempted to identify human influences on climate.

Weber states that the increasing pattern similarity between a model signal and observed data (over 850–50 hPa) that we found may "largely be attributed to stratospheric cooling by CFCs...". He bases this conclusion on larger stratospheric cooling in the Southern Hemisphere. Both Weber and Michaels and Knappenberger argue that the hemispheric asymmetry in 850–500-hPa temperature trends identified in our study is a transient feature unrelated to anthropogenic influences.

To support their arguments, Michaels and Knappenberger and Weber use the virtual temperature data set of Angell[5], which has instrumental biases[15] and known deficiencies in its spatial representativeness[16]. Angell's large asymmetrical cooling in the lower stratosphere (greater cooling in the Southern Hemisphere) is not substantiated by analysis of other data sets — only a small long-term asymmetry trend is evident in the Parker radiosonde data[17] (*a* in our figure). Furthermore, lower stratospheric temperature trends computed from satellite data[18] and a reanalysis of operationally produced climate data[19] show an asymmetry of the opposite sign (greater lower-stratospheric cooling in the *Northern* Hemisphere).

Thus, the basis for Weber's argument for a dominant effect of CFCs is not supported by other available estimates of lower stratospheric temperature change. Furthermore, his proposed mechanism of stratospheric ozone depletion leads to a cooling of the troposphere[20], not a warming as observed. Our own[1] and more recent[20] work finds closest agreement between modelled and observed vertical temperature-change patterns when multiple anthropogenic forcings are considered.

Both Michaels and Knappenberger and Weber claim that our pattern-correlation ($R(t)$) results for the lower atmosphere are merely a manifestation of natural variability. To support this claim, Michaels and Knappenberger use the hemispheric temperature-change difference in the lower atmosphere (850–300 hPa) from Angell's data. They contend that this time series is a reasonable 'proxy' for our 850–500 hPa $R(t)$ results, and hence can be used to extend our correlation analysis beyond 1987.

To test this claim, we used the newly available Parker radiosonde data to extend our $R(t)$ results for the low- to mid-troposphere to the period 1958–95. The time series of $R(t)$ and hemispheric temperature contrast computed with the Parker data are highly correlated ($r = 0.80$), thus confirming Michaels and Knappenberger's supposition. Like the hemispheric temperature-change contrast in the Angell and Parker data sets, the 'updated' $R(t)$ does decrease after 1988.

Contrary to Michaels and Knappenberger's claim, however, such behaviour is consistent with our current understanding of anthropogenic causes. This is because there are temporal changes in the relative strengths of the greenhouse-gas and aerosol forcings, and in their associated (asymmetrical) climate response patterns. Thus, both $R(t)$ and its 'proxy' are *expected* to show periods of increase and decrease (as in Michaels and Knappenberger's figure *b*) as part of an anthropogenic signal[21,22]. Model-based results for the hemispheric temperature-change contrast, based on anthropogenic forcing alone (our figure *b*), are qualitatively similar to the observations shown in Michaels and Knappenberger's figure *b*. Thus, the decadal timescale fluctuations in both the hemispheric temperature differential and in $R(t)$ most probably reflect an anthropogenic signal plus superimposed natural variability noise, and not noise alone, as Michaels and Knappenberger, and Weber, contend.

In summary, the claim by Weber that our 850–50-hPa results reflect only CFC-related stratospheric ozone effects is incorrect and based on suspect data. Nevertheless, stratospheric ozone is an important component of the climate system, and its depletion may well contribute a significant part of the anthropogenic climate-change signal in the lower stratosphere[23]. With regard to the claims in both contributions above that our results depend on the choice of data period, on the contrary, the use of a longer observed record fully supports our earlier 850–50-hPa results. For 850–500 hPa, the changes in $R(t)$ are similar to changes in the hemispheric temperature contrast shown by Michaels and Knappenberger. This is not surprising: we ourselves interpreted our significant 850–500 hPa $R(t)$ results primarily in terms of warming of the Southern Hemisphere relative to the Northern Hemisphere. However, both the recent change in hemispheric temperature contrast and the decline in $R(t)$, rather than being in conflict with the expected effects of anthropogenic forcing, are consistent with those expectations, and the primary conclusions of ref. 1 stand.

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