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1991 ERUPTION OF MOUNT PINATUBO
ON THE OCEANIC UPTAKE OF CO₂**

by

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An Assessment Of The Effect Of The 1991 Eruption Of Mount Pinatubo On The Oceanic Uptake Of CO₂

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Abstract

An ocean carbon cycle model, coupled to an ocean general circulation model, was used to assess the effect of a reduction in solar radiation after June 1991 on the oceanic uptake of atmospheric carbon dioxide through cooling of the surface temperature and deepening of the mixed layer. By comparing a simulation in which the solar forcing was reduced by up to 4.5 W m^{-2} against a control simulation in which no such reduction occurred, it was found that a 30% increase in the net CO₂ flux into the ocean was achievable. This translates into a fall in the de-trended atmospheric pCO₂ of 0.36 ppm by the end of 1993, which is approximately five times smaller than the observed decrease. The reason for the observed atmospheric CO₂ anomaly is therefore highly unlikely to have been an enhanced oceanic CO₂ flux due to Pinatubo cooling, and the cause must be sought elsewhere. Since it seems unlikely that erroneous emissions data could account for a perturbation of this size, the most likely place to look for the cause of the anomaly is the marine and terrestrial biosphere.

Introduction

An interesting puzzle has been posed by the observed slowdown in the rate of accumulation of atmospheric CO₂ since 1989. Peaks and troughs in the atmospheric CO₂ accumulation rate tend to be associated with El Nino (Keeling *et al.*, 1989), and a fall from 1989 to 1990 followed by a short-lived rise during the first part of 1991 is in line with predictions based on the El Nino - Southern Oscillation (ENSO) cycle (Sarmiento, 1993). Since July 1991, however, the atmospheric CO₂ accumulation has fallen particularly sharply at a time when it had been expected to rise as the climate system entered the El Nino of 1992 (see Figure 1). The timing of the sudden fall in July 1991 is suggestive of a link with the large volcanic eruption of Mount Pinatubo which occurred then. One mechanism proposed to account for the observed pattern since 1991 involves the cooling effect at the sea surface induced by the release of aerosols into the stratosphere as Pinatubo erupted and the reduction in direct solar radiation at the surface (Sarmiento, 1993). The consequent fall in sea surface temperature (SST) and deepening of the surface mixed layer of the ocean would enable a stronger uptake of CO₂ by the oceans to occur, thus causing a reduction in atmospheric CO₂.

In order to quantify the magnitude of this effect, a simple experiment was undertaken using a carbon cycle model coupled to an ocean general circulation model. The model was used to simulate, in a somewhat crude manner, the effect of a reduction in short-wave heating comparable in timing and magnitude to that caused by the Pinatubo eruption on the transfer of CO₂ between atmosphere and ocean. By comparing the results with those obtained from a control run in which no reduction in solar heating was made, the impact of the cooling could be directly measured.

The Experiment

The model used was a global ocean carbon cycle model coupled to a 3-dimensional ocean general circulation model, developed at the Hadley Centre for studies of the ocean carbon cycle (Taylor 1995). The model includes the physical and chemical mechanisms of oceanic carbon uptake, but does not include biological effects. The

circulation model is based on the Bryan-Cox model (Cox, 1984) with the addition of an embedded mixed layer scheme, isopycnal diffusion of tracers, and a thermodynamic sea-ice model. The carbon cycle model itself computes the 3-D distribution of dissolved inorganic carbon within the ocean, and uses this, in combination with the SST predicted by the circulation model, to calculate the partial pressure of CO₂ at the sea surface, and the associated flux of CO₂ into, or out of, the ocean at each grid point according to the difference in atmospheric and oceanic partial pressures. The transfer formulation used for these runs is that of Wanninkhof (1992). Further details of the model may be found in Taylor (1995).

To obtain a starting point for the Pinatubo experiment, the model was firstly used to simulate the period from 1765 to 1991. Seasonally varying climatological forcing was used to drive the ocean model, and the atmospheric CO₂ concentration was prescribed as the observed history (Neftel *et al* 1985). Heat fluxes from Esbensen and Kushnir (1981) were applied as two separate components: the net longwave heating flux was applied only at the sea surface, whereas shortwave solar radiation was allowed to penetrate below the sea surface according to the double exponential decay function of Paulson and Simpson (1977). Surface fresh water fluxes were obtained by combining the Jaeger (1976) precipitation dataset with evaporation derived from the Esbensen and Kushnir fluxes. Wind stresses were taken from Hellerman and Rosenstein (1983). During this period of the run, the model's sea surface temperature and salinity were forced to lie close to the climatological values of Levitus (1982), by use of a relaxation term in the surface forcing. The model's atmosphere-to-ocean CO₂ flux was 2.0 GtC yr⁻¹ for the decade 1980-1990 relative to 1840, which is very close to the IPCC estimate for the same period (IPCC, 1990). The use of relaxation terms during this spinup phase introduces a feedback term into the model forcing which prevents the ocean model from drifting away from the climatological state. However, this technique would have been unsuitable for the experimental phase described later, because the model would have reacted to the Pinatubo perturbation by increasing the restoring terms, and the Pinatubo signal would have been lost.

The Pinatubo experiment was started from the beginning of 1991. The period from 1991 to the end of 1993 was

simulated using climatological forcing as before, except that the relaxation terms used for the spinup were removed from the model equations. Instead, the heat and salt fluxes needed to keep the model close to the climatological state were diagnosed from the last five years of the spinup run, and these fluxes were added in to the climatological forcing as corrections. This is equivalent to the flux correction technique used routinely in coupled ocean-atmosphere models (Sausen *et al.*, 1988). It differs from the relaxation technique used for the spinup run in that there is no feedback between model drift and the corrective terms, so that the model is free to evolve away from its initial state if the forcing changes. Flux correction was performed only for temperature and salinity. No correction was applied for sea-ice. A pair of runs was carried out. Firstly, a control simulation was performed in which the forcing consisted of climatological forcing plus flux correction. Then a perturbation run was done in which the penetrative solar radiation at the sea surface was modified to simulate the effect of the Pinatubo eruption after June 1991. For this, the surface solar radiation (S) was reduced according to the formula

$$\Delta S = 4.5 a t^b \exp(-bt/\tau)$$

where t is the time in months since the eruption, assumed to have started at the beginning of June 1991. The coefficients a , b , and τ were chosen to provide a fit to observations of the departure of the observed aerosol optical thickness from two-year mean zonal values (Halpert and Ropelewski, 1993 - data provided by L. Stowe). The perturbation was applied in three distinct zonal bands with coefficients set as follows:

60 °S-40 °S	$a=0.33$	$b=0.9$	$\tau=5.0$
40 °S-40 °N	$a=0.91$	$b=0.8$	$\tau=3.0$
40 °N-60 °N	$a=0.1$	$b=1.7$	$\tau=8.0$

The functional form of the perturbation is shown in Figure 2. The maximum reduction of 4.5 W m^{-2} occurs in

the tropics three months after the start of the eruption. The southern hemisphere perturbation peaks two months later in November, and the northern mid-latitudes receives its maximum reduction after a further 3 months in February 1992. Observations from satellites and airborne instruments measure aerosol cloud and its effects at the tropopause, whereas the variable needed for driving the model is the solar radiation reaching the sea surface. Russell *et al* (1993) estimated that the change in net shortwave flux at the tropopause at the Mauna Loa Observatory in September 1991 was between -5.8 and -7.2 W m^{-2} , depending on what assumptions are made about the effective radius of the aerosol particles. These figures were converted to equivalent values at the surface by taking the output from a ten-year run of the latest version of the Hadley Centre atmospheric model, and comparing the solar radiation reaching the sea surface with the difference between incoming and outgoing shortwave radiation at the top of the atmosphere. The ratio thus obtained had an average value in the latitude band 40°S - 40°N of 0.74. This figure was used to scale down the estimates of Russell *et al* to between 4.3 and 5.3 W m^{-2} , and a peak value of 4.5 W m^{-2} chosen as a conservative estimate.

While the main effect of the aerosol is to reflect a greater proportion of incident solar radiation out to space, it also traps more of the outgoing infra-red radiation. This would partially offset the cooling due to reduced solar radiation, but is neglected in this simulation. Based on the calculations provided by Russell *et al*, it is estimated that inclusion of the effects of IR would lower the perturbation by approximately 20%. Heating due to absorption at the altitude of the aerosol, and the consequent reduction in heating of the lower atmosphere due to loss of solar radiation will produce changes in cloud distribution which will influence the penetration of solar radiation to sea level. It is assumed that, while the cloud may be redistributed, there is no change in the mean amount. It also seems reasonable to assume as a first approximation that the effect on solar radiation reaching the sea surface follows a similar functional form to the aerosol optical thickness.

Results

A basic problem that arises when forcing ocean models using direct observations of atmospheric fluxes is "model drift". Estimates of the turbulent heat fluxes for the N Atlantic, which is the most densely-sampled ocean, can

vary by as much as 30% (Kent and Taylor, 1995). This uncertain knowledge of the forcing fluxes makes it necessary to adjust the heat balance of ocean models by relaxing the surface values of temperature and salinity back towards observations (which are known to a greater degree of certainty than heat fluxes). This technique has the drawback for climate change studies that the surface climatology of the model is tied closely to the observations and the model is inhibited from evolving away from its initial state. An alternative technique which is more usually used for coupled ocean-atmosphere models is to introduce flux correction terms into the model equations as described earlier. These extra terms neutralise the model drift and allow a realistic reference climate to be obtained which retains its responsiveness to perturbations. To check on the success of this technique I computed the difference between the annual mean SST for 1990 (when the model SST was forced to be close to climatology) and 1992 (two years after the imposition of flux correction) in the control run. Over most of the globe this was found to be small (less than 0.2 °C), indicating that the use of flux correction in preventing excessive drift away from a sensible reference climatology was successful. There is, however, a rapid warming trend which occurs in sea-ice-covered regions, as well as a succession of alternately warm and cold anomalies (of magnitude up to 3 or 4 °C) along the path of the Antarctic Circumpolar Current (ACC) between the latitudes 40 °S and 60 °S. The drift in SST beneath the sea-ice is due to the fact that the scheme used for applying the flux correction is very simple and takes no account of the additional flux required to keep the depth of sea-ice at its climatological value. If the run had been continued for a longer period of time, the ice would have eventually melted away. However, over the length of this experiment the covering of sea-ice, although thinner, is always present, and so there is no exchange of CO₂ between atmosphere and ocean in this region. Hence the temperature drift beneath the ice has no effect on CO₂ uptake. The succession of warm and cold areas south of 40 °S is due to meandering of the ACC, which is permitted to occur in the flux-corrected run, but was prevented from happening during the spinup run. This pushes cold water north and warm water south. Other experiments indicate that very long (~1000 year) integrations are required to establish an equilibrium flux correction in this region (C. Gordon, personal communication). These drifts are present in both the control and perturbation runs, and because the results reported here depend on differences between the two runs, any possible effect that the drifts could have is cancelled out.

Figure 3a shows the change in the annual-mean sea surface temperature between the perturbation (ie. with Pinatubo) and control (without Pinatubo) runs for 1992. Most of the tropics show cooling in excess of 0.2 °C, with a cooling of as much as 0.4 °C or more in some areas. The reduction in solar radiation has the greatest impact along two bands either side of the equator, in regions where the surface mixed layer is quite shallow. Along the equator in the Pacific, however, where the mixed layer is at its shallowest, the cooling is relatively modest. This is presumably because equatorial dynamics are more important than surface fluxes in this region (Philander *et al.*, 1987). The largest differences occur in the regions where the climate drift is smallest, confirming that the drift associated with the imposition of flux correction has only a minor effect on these results.

Is this simulated reduction in SST realistic? Figure 4 shows the zonally-averaged observed SST anomalies from 1990 through 1992 relative to the climatology for the period 1951 to 1981 (Parker *et al.*, 1994). The data are complicated by the presence of the ENSO cycle and other agents of SST variability, which are not present in the model, and which make a comparison difficult. Nevertheless, there is clearly a transition between July and October 1991 from warm conditions to cooler conditions. This is particularly evident in the mid-latitudes of the Northern hemisphere, where the cooling shown by the data is considerably greater than that in the model. The model, on the other hand, shows the greatest amount of cooling occurs in the tropics. However, direct comparison of the model with observations in this region cannot be made because of the neglect of ENSO in the model. Robock and Mao (1994) have attempted to remove the ENSO signal from climate records of the past 140 years in order to isolate the impact of major volcanic eruptions on surface temperatures. Their data shows a fall in globally averaged ocean temperature of about -0.15 °C following the Mt Pinatubo eruption, which compares reasonably well with the model's average for 1992 of -0.21 °C. A map of the difference in mixed layer depth between anomaly and control runs, similar to that shown in Figure 3a for SST, showed a less coherent pattern than SST. The annual mean mixed layer deepened by less than 5m over most of the world with the biggest changes of more than 20m occurring for the most part close to the Labrador sea and immediately

to the south of Australia.

The change in atmosphere-to-ocean CO₂ flux for 1992 is shown in Figure 3b. Surface gas exchange is determined in the model as the product of a wind-dependent transfer coefficient and the difference between atmosphere and ocean partial pressure of CO₂ (or pCO₂). Oceanic pCO₂ is determined mainly by solubility, and so a map of the change in pCO₂ generally follows the same pattern as the SST difference chart. The CO₂ flux chart, although broadly similar to the SST map, also betrays the effect of wind-speed in enhancing the gas exchange. This is particularly apparent in the way that the flux over the North Atlantic is increased whereas the change in SST in that region is not especially large. The largest increase in flux occurs in the central North Atlantic at 50 °N, where the increase is about 0.2 mol m⁻² yr⁻¹. This is in a region where the SST difference is only 0.2 °C. The annually-averaged oceanic uptake of CO₂ for 1992 increased by about 0.1 mol m⁻² yr⁻¹ over much of the ocean between 60 °N and 60 °S. Figure 5 shows the zonally-averaged change in CO₂ flux for the entire length of the experiment. The excess flux peaks in the northern sub-tropics in October 1991, and in the southern hemisphere sub-tropics and mid-latitudes in February 1992. A further peak occurs in the summer of 1992 in the northern mid-latitudes, and the effect has diminished substantially by the end of 1992.

Discussion

To evaluate the significance of the induced perturbation in the model's carbon cycle on a global scale, the global net atmosphere-ocean CO₂ flux has been calculated for the two runs. The difference between them is plotted in Figure 6, in units of GtC yr⁻¹. The flux difference reached a peak of 0.59 GtC yr⁻¹ at the start of 1992, declining approximately exponentially to 0.1 GtC yr⁻¹ by the end of 1993. This is an extremely large perturbation, since the peak value is some 30% of the IPCC global estimate of 2.0 ±0.8 GtC yr⁻¹ (IPCC, 1990). Figure 6 also breaks this figure down by region, the regions being as defined in Taylor (1995). For the first four months after the eruption, the equatorial zone (between 15 °S and 15 °N), Southern hemisphere gyres and North Pacific account for roughly equal proportions of the perturbation. After that time, the relative contribution of the

tropics decreases whereas the other two zones increase dramatically. The Southern Gyres region accounts for more than 40% of the peak perturbation in early 1993. The effect that a perturbation of this magnitude would have on the atmospheric CO₂ concentration is illustrated in Figure 7. This shows the decrease in atmospheric pCO₂ computed by accumulating the changes in CO₂ flux shown in Figure 6 and adjusting the atmospheric CO₂ concentration accordingly. The atmospheric pCO₂ has fallen by 0.36 ppm by the end of 1993, which is not sufficiently large to account for the observed drop in atmospheric CO₂ accumulation. The observed carbon anomaly was -1.5ppm in May 1993 (see Figure 1), which compares with a value estimated from the model of -0.32 ppm at this time. The simulated decrease is about 5 times smaller than what is required, and so the effect of SST anomalies cannot explain the drop in pCO₂. In fact the discrepancy is likely to be even larger than this since the model is forced by climatology and so does not include the effects of the ENSO cycle on pCO₂. The warm phase of ENSO tends to be followed by an sharp increase in atmospheric pCO₂ of between 1.0 and 1.5 ppm, over a period of about a year (see Figure 1). On this basis, one would have expected to see a rise of approximately 1.5 ppm during 1992 if the EL Nino-induced effect on pCO₂ was of a similar magnitude to that which occurred after the 1986-87 El Nino, since the SST anomalies were similar in magnitude for the two events. Thus if we take the ENSO cycle into account we are seeking to explain a Pinatubo-induced decrease in pCO₂ of around -2.5 ppm, which is almost an order of magnitude larger than the decrease which can be explained by a reduction in SST due to Pinatubo cooling. Furthermore, the solar radiation anomaly used to force the model did not take into account the effect of a reduction in outgoing longwave radiation which would offset the shortwave cooling by as much as 20%. Thus, although the model does give an enhanced oceanic CO₂ sink, it is of insufficient magnitude and duration to account for the observed drop in atmospheric CO₂ accumulation. Explanations for the check in CO₂ increase must therefore be sought elsewhere.

One possibility lies in the reduction in CO₂ emissions from the countries of Central and Eastern Europe after 1989 due to a combination of the depressed economy and a series of mild winters. Marland *et al* (1994) estimate global emissions for the years 1989-1991 of 6.07, 6.10, and 6.19 GtC respectively. That is, according

to these figures, the global trend was still rising in 1991. On the other hand, Grubb (1994) describes alternative estimates (of 6.04, 6.08, 6.01 GtC for 1989-1991 and 6.03 GtC for 1992) which indicate that the decline in emissions from this region was large enough to cause a reversal in the global trend. Uncertainty in the estimates of CO₂ contributions from the Central/East European countries might mean that the fall shown in Figure 1 is exaggerated due to an over-estimate of the trend used to derive it. However, this effect is almost certainly too small to explain away the observed pCO₂ anomaly. The difference between the two emissions estimates for 1991 is 0.18 GtC, and the corresponding figure for 1992 is about 0.25 GtC (obtained by projecting the trend for 1990-1991 forward to 1992 in the Marland *et al* figures). This gives a total of 0.43 GtC as a possible overestimate of CO₂ emissions by the end of 1992, which translates to just 0.2 ppm. Thus this explanation is also an order of magnitude smaller than what is required. We are seeking to explain an extra sink of order 4 GtC over two years, while Eastern European emissions contributed approximately 1.3 GtC to global emissions for 1990. An error of order 100% in the estimates is required to explain the data, which seems unlikely.

Sarmiento (1993) mentions other possible geophysical causes of the anomaly. These include an increase in oceanic biological production and uptake of atmospheric CO₂, possibly stimulated by enrichment of the supply of the limiting nutrient iron (in the fall-out from the volcanic eruption) to surface waters where other nutrients are abundant. However, recent sea-going experiments in the equatorial Pacific ocean in which a small patch of water was enriched with iron (Watson *et al*, 1994) argue against this explanation. They found that the lowering of pCO₂ caused by addition of a pulse of iron was between 4 and 15 ppm, which was a small fraction of the potential fall of 125 ppm if all the nutrients had been fully utilized. A sustained lowering of surface pCO₂ in the equatorial ocean by 125 ppm would represent a shift in the carbon balance large enough to account for the observed atmospheric anomaly. Watson *et al* point out that their results may have been affected by the time over which iron was added. A longer-lasting source of iron (such as would be provided by a volcanic eruption) may have a larger effect on pCO₂. Further experiments of this nature involving longer releases of iron would be useful in this regard. The stimulation of primary production needed to account for the increased CO₂ drawdown would have been easily detectable in images of ocean colour, and so it is unfortunate that we have no satellite

measurements of primary productivity over this period.

Cooling and changes in rainfall could have affected uptake by the terrestrial biosphere, by lowering the rate of respiration. For instance, a simple "q10" model of respiration yields a reduction in respiration of 1.4% in response to a cooling of 0.2 °C (Peter Cox, personal communication). This corresponds to a reduction of order 1.5 GtC yr⁻¹, which is of the right order of magnitude. A third possibility would be a decline in deforestation and biomass burning. Although the size of this source is estimated to be only about 1.7 GtC in 1990, the estimates are notoriously uncertain and an error of 30% corresponding to a reduction of 0.5 GtC yr⁻¹ is not beyond the bounds of possibility. It could therefore be a significant contributor, but would not explain the entire anomaly. Reduced biomass burning would also help account for an observed fall in the gas carbon monoxide since 1988 (Khalil and Rasmussen, 1994).

What is the mechanism for the enhanced oceanic sink seen in the model? Scatter diagrams of the regional correlation between CO₂ flux anomalies and SST and mixed layer depth anomalies showed that, whereas an increase in CO₂ flux is associated with a decrease in SST, no clear relationship holds for CO₂ flux and mixed layer depth. This would seem to indicate that the increased CO₂ flux obtained is due more to a simple cooling of the ocean surface rather than to a deepening of the surface mixed layer (and consequent increase in the volume of water in contact with the atmosphere). In fact, this is rather similar to the thermal skin effect reported by Robertson and Watson (1992). They found that the consideration that the top 1mm of the oceans is generally cooler than the bulk mixed layer by about 0.3 °C would result in an increase in computations of the atmosphere-ocean CO₂ flux of about 0.7 GtC yr⁻¹.

Summary and Conclusions

We have used a model of the inorganic carbon cycle coupled to an ocean GCM in a crude attempt to simulate the effect of changes in solar radiation due to the eruption of Mt Pinatubo on the oceanic uptake of CO₂. By

forcing the model with climatological forcing adjusted to take account of a reduction in solar radiation after June 1991 and by comparing the results against those from a control simulation with no reduction in solar radiation, it was found that the model predicted a large increase in CO₂ uptake which at its peak was 30% above its unperturbed value. However, by accumulating the change in CO₂ flux, and converting to an equivalent atmospheric CO₂ change, it was calculated that there would be a drop in atmospheric pCO₂ of just 0.36ppm by the end of 1993 due to this effect. This figure is relative to the longer-term trend due to increasing fossil fuel emissions and to short-term effects such as El Nino episodes. When due allowance is made for the El Nino event of 1992, the predicted figure is roughly an order of magnitude smaller than the observed atmospheric pCO₂ anomaly.

From this study we can say that the sharp fall in atmospheric CO₂ accumulation is unlikely to have been due to an increased oceanic flux through the mechanism of enhanced oceanic CO₂ uptake investigated here. Although the experiment performed was somewhat idealised, and did not include many of the processes which may have played an important role, it has demonstrated that the SST anomaly effect is of insufficient magnitude to account for the observed drop in atmospheric pCO₂ and can be ruled out as a significant player. Similarly, deepening of the oceanic mixed layer as a consequence of the Pinatubo cooling is small, and has almost no influence on the oceanic CO₂ uptake. The cause (or causes) of the CO₂ anomaly must be sought elsewhere. An overestimate of the emissions from industry and land-use changes seem unlikely to provide a full explanation for the anomaly, although they may have contributed to it. The most promising area of research seems to lie within the biota, both marine and terrestrial. Our present inability to pin down the precise causes of such a large CO₂ anomaly highlights the need for an global observing system for the carbon cycle that can monitor the build-up of CO₂ in the ocean and terrestrial biosphere.

Although atmosphere-ocean CO₂ flux is clearly very sensitive to changes in sea surface temperature, the anomalies need to be present for several years before having a significant impact on atmospheric CO₂. Nevertheless, the sensitivity of the ocean carbon cycle to SST variations will have implications for longer-lived

climate fluctuations. The results described here suggest that, assuming that no significant ocean circulation changes took place, a CO₂-induced climatic warming of similar magnitude (but opposite sign) to the Pinatubo eruption would reduce the sink strength of the ocean for CO₂ by some 30%, and there would be a positive feedback effect as more CO₂ would be left in the atmosphere to increase the radiative forcing. The anomaly would have to persist for 3 years to change the atmospheric CO₂ concentration by 1 ppm. Similarly, cooling conditions at the onset of an ice age would increase the oceanic CO₂ uptake, and feed back to the climate in such a way as to accelerate the cooling.

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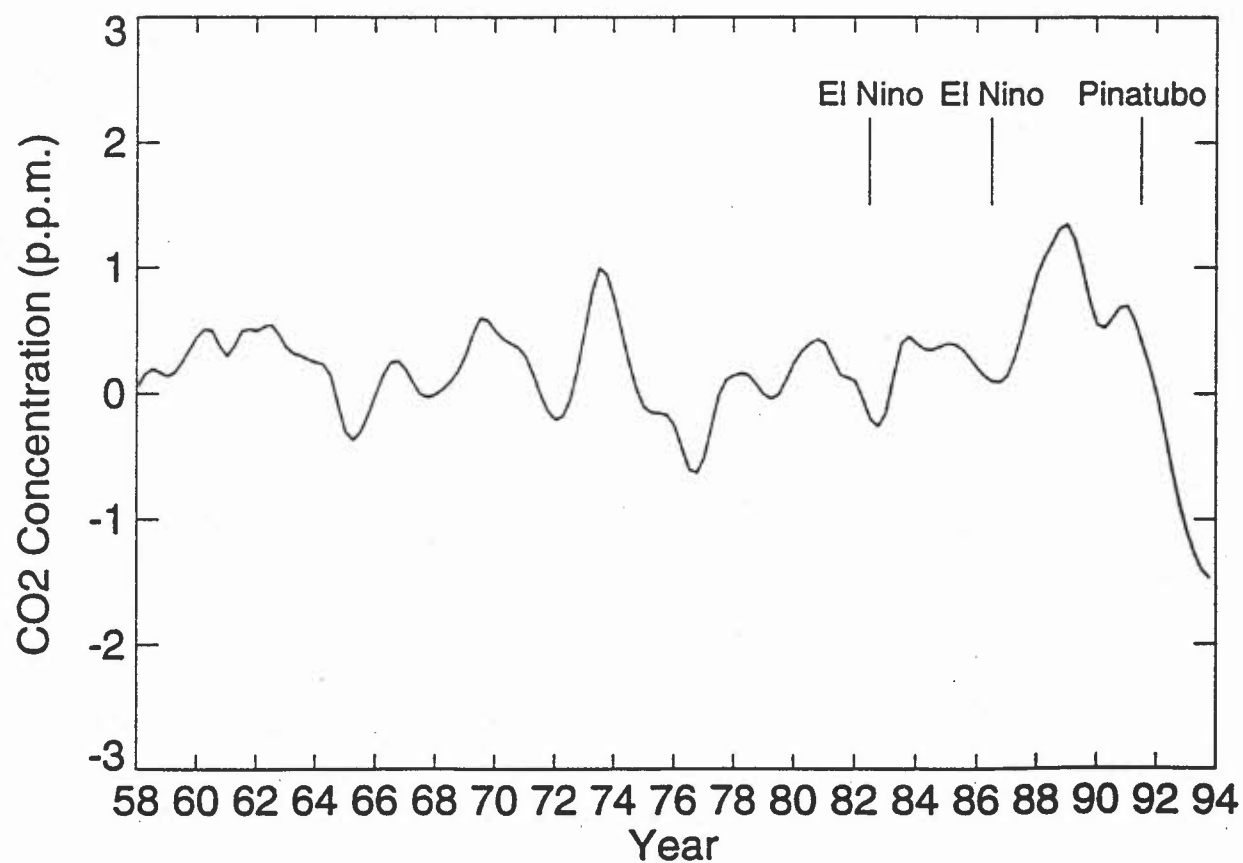


Fig. 1 - Atmospheric CO2 anomaly recorded at Mauna Loa Observatory, obtained by removing the seasonal signal and detrending the remaining signal using a constant airborne fraction (58.58%) of the industrial release. The times of the 1982-83 and 1986-87 El Nino events and the Mt Pinatubo eruption are marked. Redrawn from Sarmiento (1993).

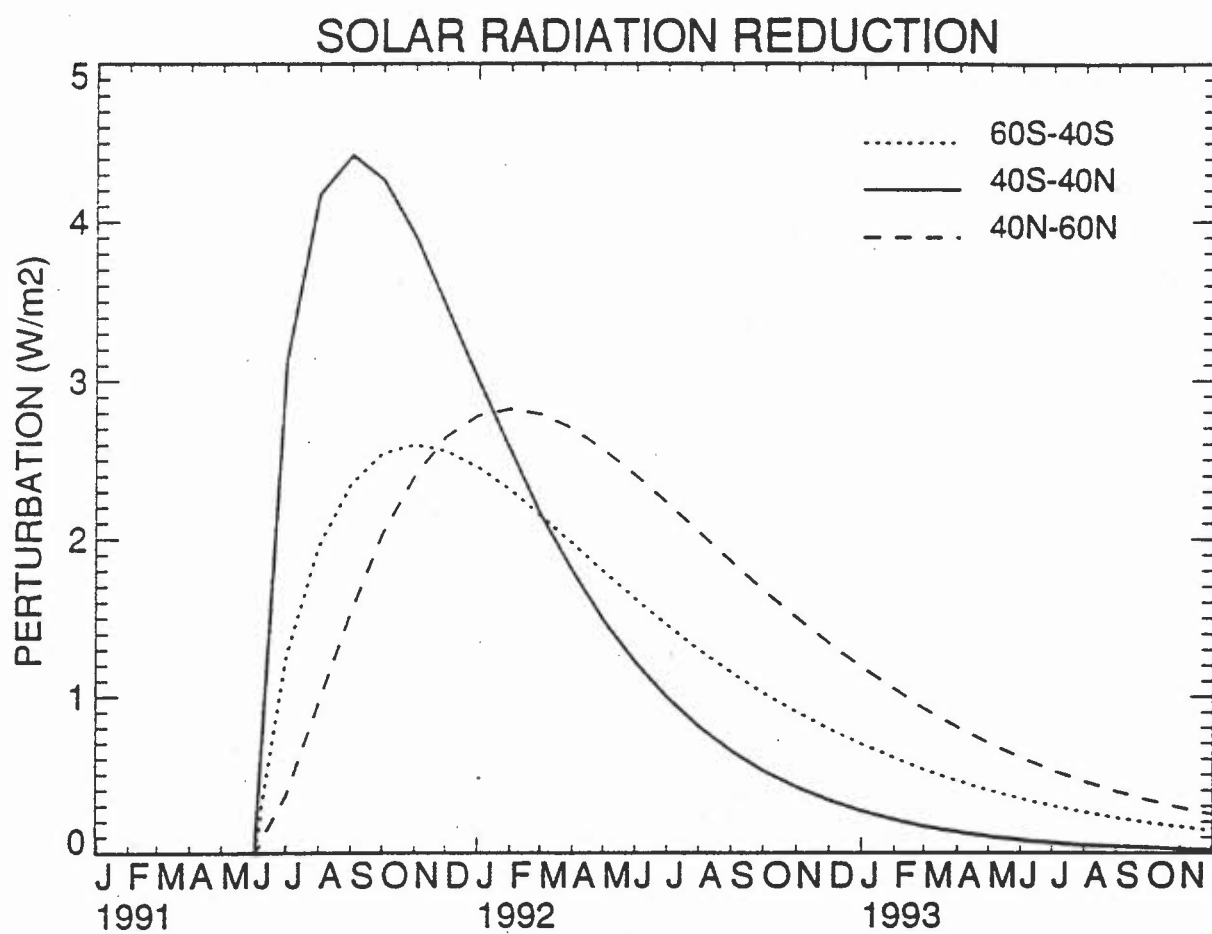


Fig. 2 - Solar radiation perturbation applied to the model. The perturbation was applied separately for three different latitude bands: 60 °S - 40 °S, 40 °S - 40 °N, and 40 °N - 60 °N. Outside these regions no perturbation was applied.

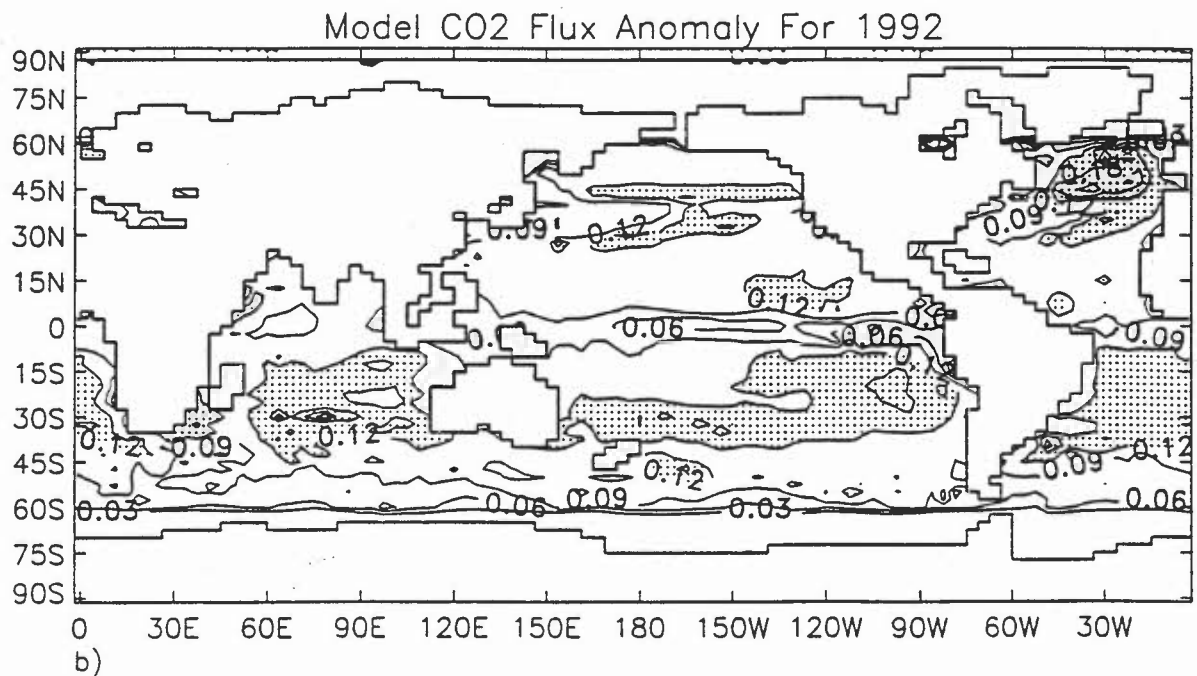
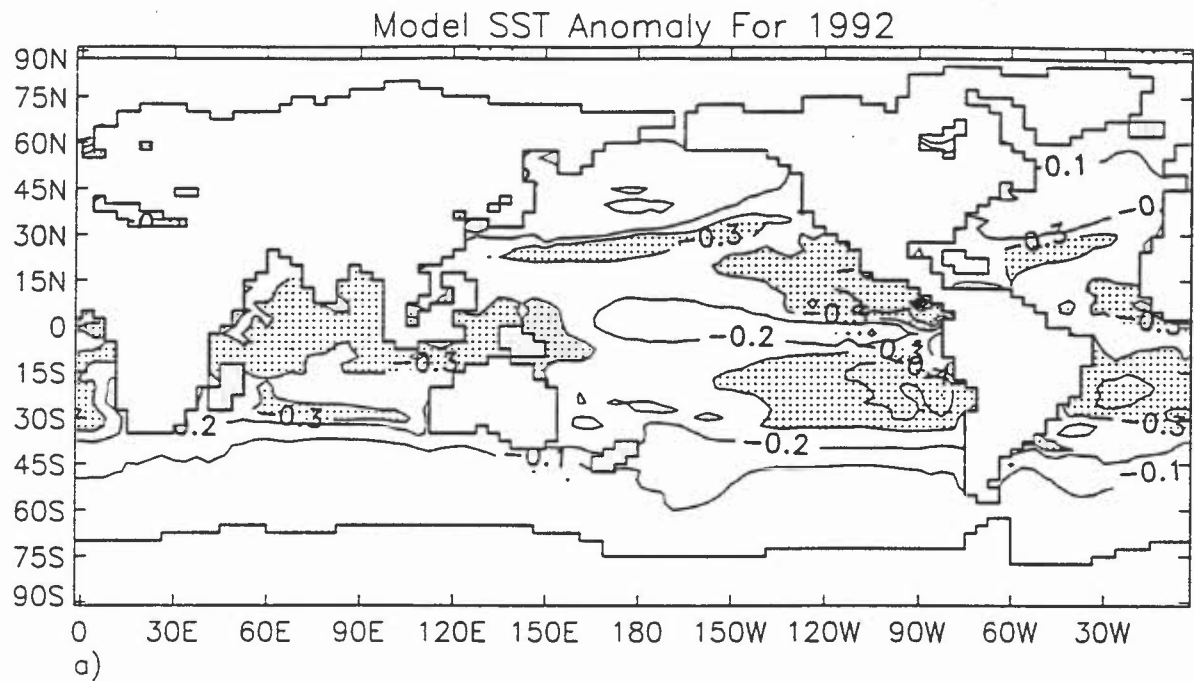


Fig. 3 - Difference in a) SST and b) atmosphere-ocean CO₂ flux between control and perturbation runs for 1992. Contour intervals are 0.1 °C and 0.03 mol m⁻² yr⁻¹ respectively. SST anomalies in excess of 0.3 °C and CO₂ flux anomalies greater than 0.12 mol m⁻² yr⁻¹ are shaded. The largest cooling occurs in the tropics. The CO₂ flux pattern largely follows the SST anomaly pattern, but is enhanced in regions of high wind speed.

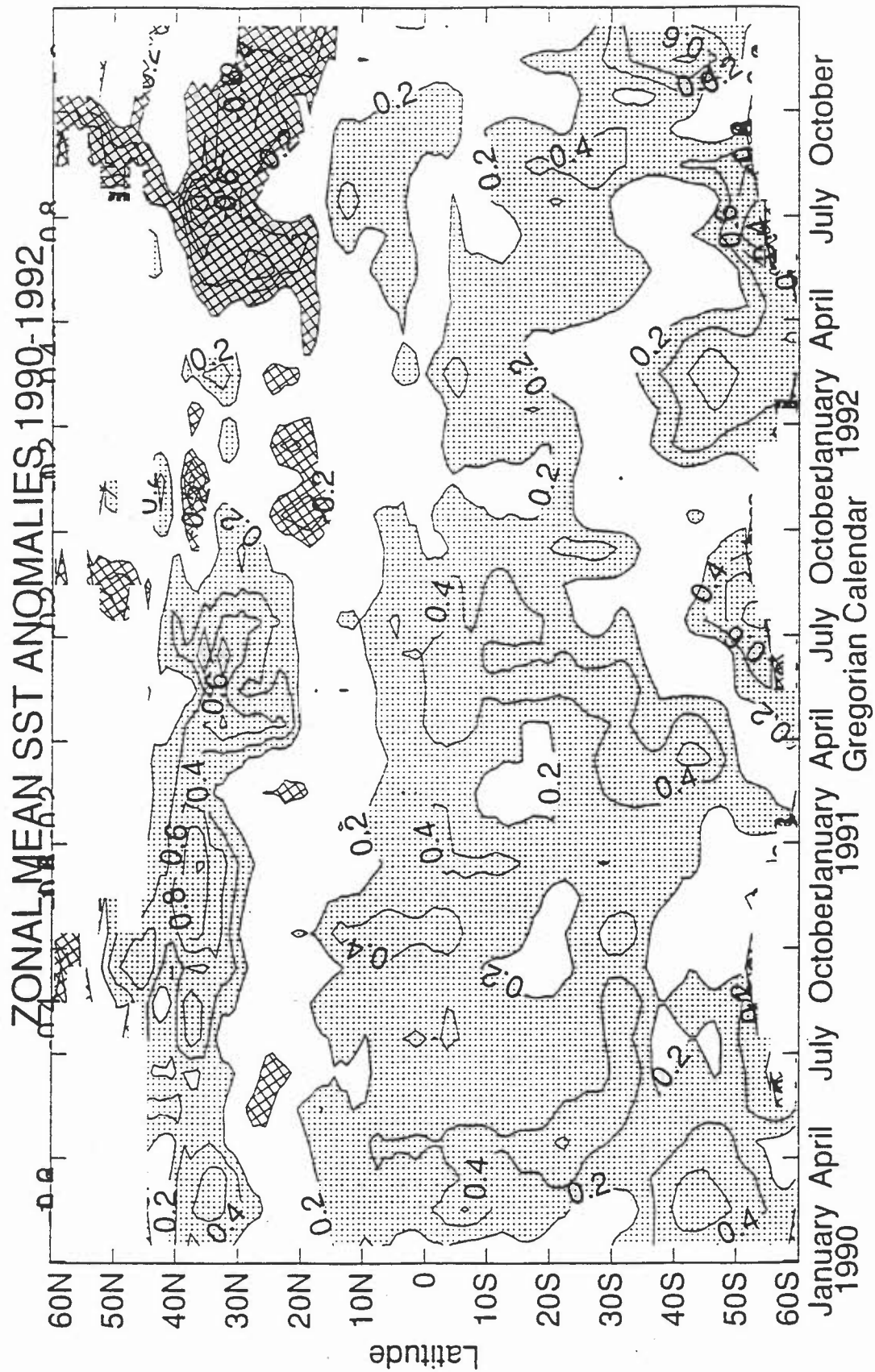


Fig. 4 - Zonally-averaged SST anomalies for the period 1990-1992 relative to the climatology based on the period 1951-1981. Contour interval is 0.2 °C. Warm anomalies are lightly stippled; cold anomalies are cross-hatched. Source: Parker *et al* (1994).

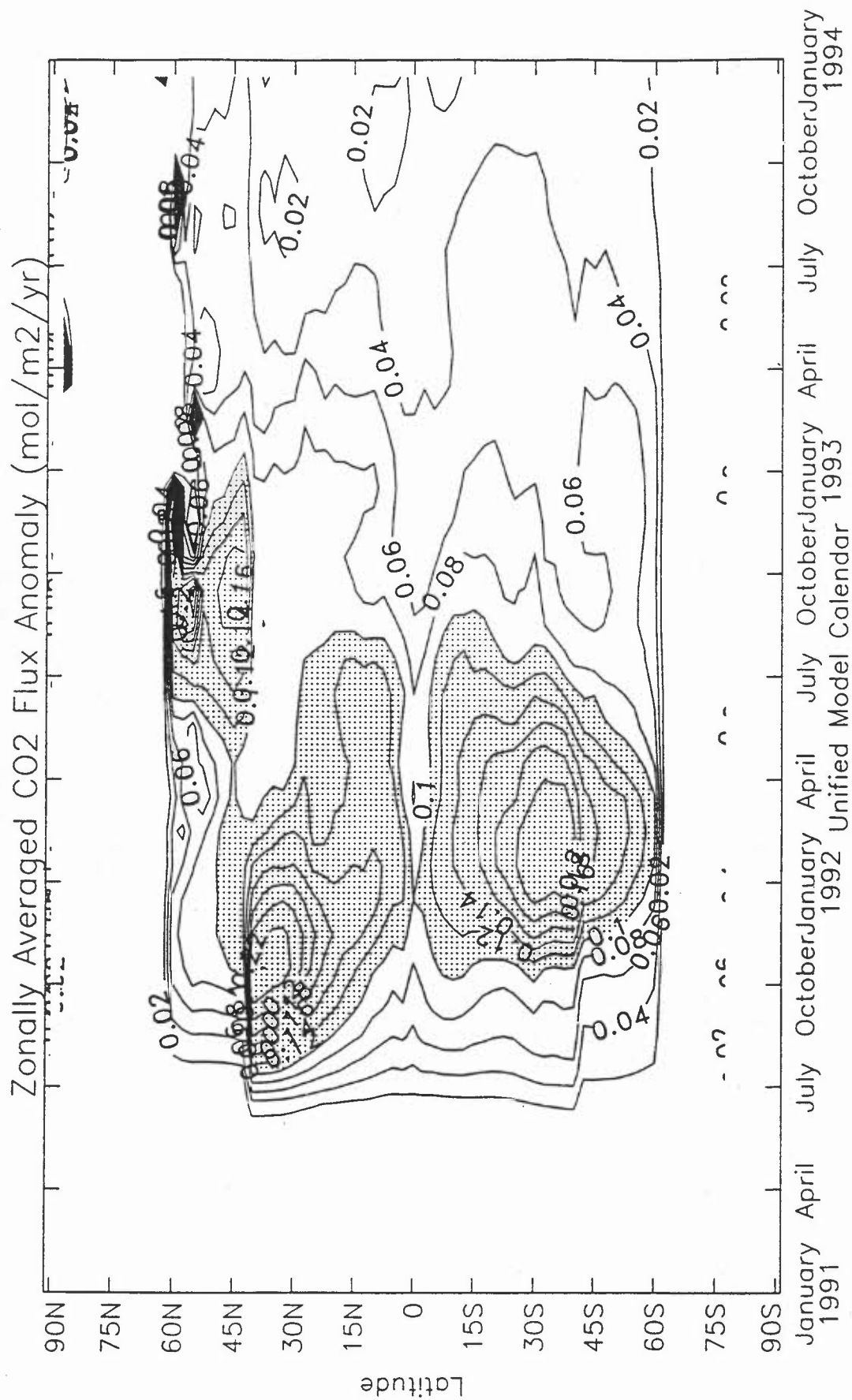


Fig. 5 - Zonally-averaged difference in CO₂ flux in mol m⁻² yr⁻¹ between perturbation and control experiments from 1991 to 1994. Contour interval is 0.02 mol m⁻² yr⁻¹. Values in excess of 0.1 mol m⁻² yr⁻¹ are shaded.

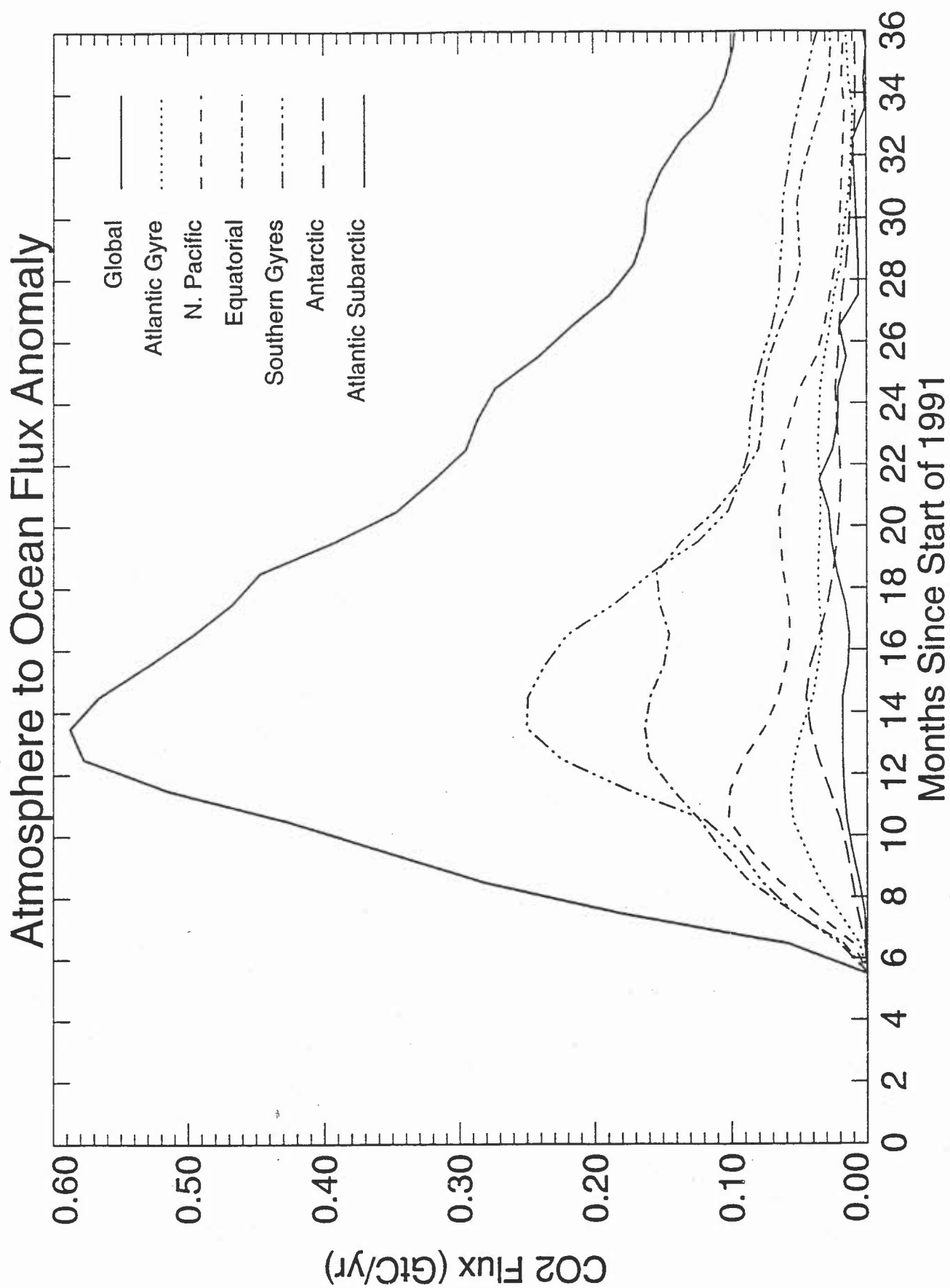


Fig. 6 - Difference in net CO₂ flux in GtC yr⁻¹ between control and perturbation runs for various regions and globally from 1991 to 1993.

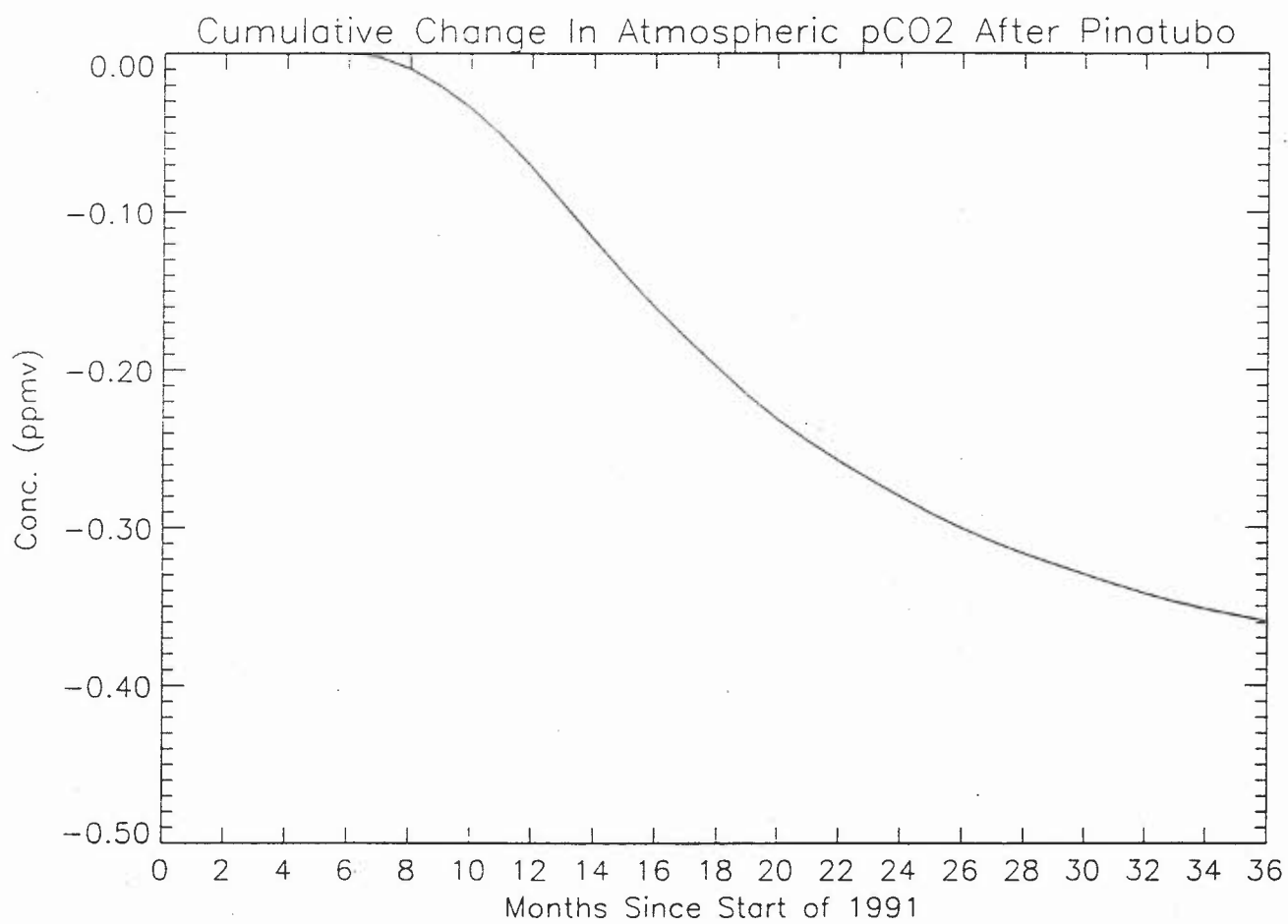


Fig. 7 - Computed effect of the increased atmosphere-ocean CO₂ flux on atmospheric pCO₂ in ppm. By the end of the experiment (1993), atmospheric pCO₂ has fallen by 0.36 ppm.

