Chapter 1

Introduction

Over recent centuries, human activities (mainly the burning of fossil fuels) have had a considerable impact on the amount of CO_2 in the atmosphere. The CO_2 concentration has increased by more than 25% since pre-industrial times (Figure 1.1), and will continue to increase in the future. This is of concern because CO_2 is the principal trace gas associated with anthropogenic global warming via the enhanced greenhouse effect. CO_2 is nearly transparent to incoming solar radiation, but strongly absorbs infrared radiation from the earth. Changing the atmospheric CO_2 concentration alters the global radiation balance, which can alter the earth's climate (IPCC, 1996). The possibility of global warming due to the enhanced greenhouse effect was suggested by scientists over 100 years ago (Arrhenius, 1896), but only in recent years has it been widely recognised as a potentially serious problem. In Rio de Janeiro in 1992, representatives from many countries met to negotiate the reduction of CO_2 emissions and put together the Framework Convention on Climate Change.

The ability to predict future CO_2 levels reliably for given emissions is important for setting emission reduction targets. It requires a good quantitative understanding of the carbon cycle. However, despite considerable research effort over recent years, there are still significant uncertainties in the carbon budget. The input of CO_2 to the atmosphere due to fossil fuel burning is quite well known, but not all of this CO_2 stays in the atmosphere. Some of it is taken up by the terrestrial biosphere and the oceans, but the exact amount ending up in each reservoir, the relevant mechanisms and the capacity for uptake in the future are not well enough known.

One of the main objectives in carbon cycle studies, therefore, is estimation of the

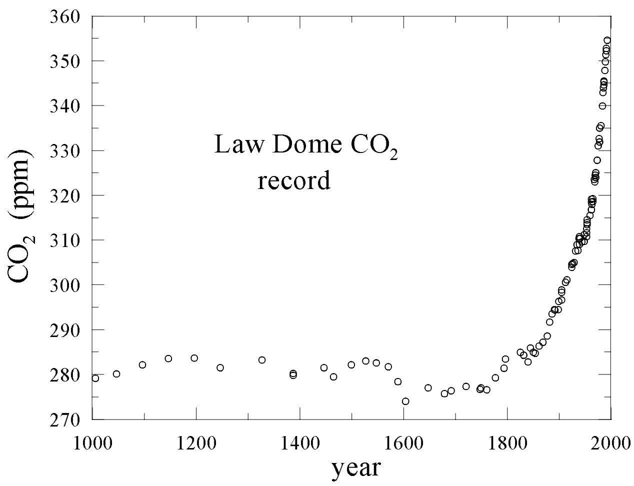

Figure 1.1: Law Dome CO_2 ice core record (Etheridge et al., 1996).

uptake of carbon by the oceans and biosphere and the mechanisms which control it. It is possible to measure fluxes of carbon directly, but they are extremely variable, both spatially and temporally, so that extending direct flux measurements to estimate global budgets directly is not yet practical. Information about sources and sinks must therefore come mostly from interpretation of indirect measurements, usually concentrations. This means that the problem to be solved is an *inverse problem*, because the inference (i.e. sources being estimated from concentrations) is in the opposite direction to natural causality (concentrations are due to sources) (Enting, 2000). A common characteristic of such inverse problems is that small errors in data (concentrations) tend to result in large errors in the unknowns (sources).

There are many different methods that have been used to try to learn more about the carbon cycle, but the different methods have sometimes given inconsistent results. For example, Tans et al. (1990) estimated from the north-south CO_2 gradient in the atmosphere that the biosphere was the major sink for anthropogenic CO_2, and that the oceans took up at most 1 GtC y^{-1}. This ocean uptake is much lower than the 2.0 GtC y^{-1} generally estimated by ocean carbon cycle models (e.g. Sarmiento et al., 1992; Orr, 1993). As well as differences between methods there are differences in the application of a particular method by different researchers. A recent, controversial study by Fan et al. (1998) estimated a large biospheric uptake in North America by inversion of the spatial distribution of CO_2. This result differs from that of a similar type of calculation by Rayner et al. (1999a), which suggests a much lower North American uptake. It makes sense to try to use as much of the available information and as many of the different methods as possible to reduce the uncertainties in the carbon budget.

The particular focus of this thesis is on the information provided about the carbon cycle by inversion of the new CO_2 and ^{13}C ice core records from Law Dome, Antarctica. Measurements from ice cores are an important source of data on CO_2 prior to continuous high quality direct atmospheric measurements that began in 1958. Air trapped in bubbles in polar ice is extracted and measured to reconstruct past atmospheric levels. Dating and interpretation of the measurements as atmospheric levels (also an inverse problem) require consideration of the processes that were involved in storage of the air. Thus, the first step of the analysis will be to develop a model of diffusion and bubble trapping in firn to help in the reconstruction of past atmospheric changes from the ice core measurements.

Globally aggregated box models of the carbon cycle will then be used to interpret the CO_2 and ^{13}C ice core records in terms of uptake of carbon by the oceans and biosphere. ^{13}C is useful for distinguishing uptake by the biosphere and oceans. The anthropogenic perturbation to the carbon cycle sits on top of significant natural variability, and sometimes analysis of these natural variations can provide useful information. Both natural and anthropogenic features in the records over the last 1000 years will be investigated.

The outline of the thesis is as follows. Chapter 2 gives general background information on the carbon cycle, followed by a discussion of CO_2, ^{13}C and their forcing mechanisms over the last 1000 years. Different methods for modelling the observed changes and some previous model results are also discussed. Chapter 3 describes the development of a firn diffusion model and its use in interpreting the Law Dome ice core record. Forward and single deconvolution calculations with a box diffusion carbon cycle model are described in Chapter 4. In Chapter 5, a Kalman filter is used to perform a double deconvolution calculation with the CO_2 and ^{13}C records. Some advantages of the Kalman filter double deconvolution compared to the usual double deconvolution method are discussed. Chapter 6 has general discussion of the carbon cycle over the last 1000 years using the techniques developed and described in the earlier chapters. Chapter 7 summarises the main conclusions and gives suggestions for further work.