Chapter 7

Summary and Further Work

7.1 Summary

Measurements of CO_2 and $\delta^{13}C$ on air extracted from Antarctic ice cores were investigated for natural and anthropogenic variations on a range of time scales. The ice cores come from Law Dome, a coastal Antarctic site, and exhibit high time resolution and recently trapped air overlapping direct atmospheric measurements The link between trapped air and direct records is strengthened by measurements of air pumped from the Law Dome firn. In Chapter 3, a model of firn diffusion and bubble trapping was developed to reconstruct atmospheric histories from the firn and ice core measurements. This model was used to quantify the smoothing due to the firn processes, as well as to correct the $\delta^{13}C$ measurements for fractionating effects in the firn.

In Chapter 4, the CO_2 and $\delta^{13}C$ record was analysed with a box diffusion carbon cycle model. A forward calculation compared the CO_2 variations suggested by the ice core measurements with the variations due to published estimates of anthropogenic fluxes. A single deconvolution calculation showed good agreement with the anthropogenic $\delta^{13}C$ decrease.

Chapter 5 introduced a new double deconvolution method using the Kalman filter. The Kalman filter double deconvolution incorporates statistics into the calculation, and allowed detailed analysis of the source variability and data uncertainties. The firn diffusion and carbon cycle models were then used together to analyse the observed variations in CO_2 and $\delta^{13}C$ in terms of CO_2 fluxes.

Particular findings of this work are:-

- The isotopic diffusion correction, which corrects for the fact that ^{13}C diffuses more slowly than ^{12}C in the firn, is an important correction for $\delta^{13}C$ measured in firn and ice. It depends on the growth rate of CO_2 in the atmosphere, and can be calculated with the firn model

- A $\delta^{13}C$ firn record from South Pole, available through collaboration with the University of Rhode Island, was dated and corrected for gravity and diffusion with the firn model. The South Pole firn record extends back to about 1900, overlapping the Law Dome ice core record. This firn record differs from the Law Dome $\delta^{13}C$ record before 1970 by an amount that increases with depth (and age of the air) up to a value of about 0.2 ‰. The cause of this discrepancy is not known. The smaller pre-industrial – modern $\delta^{13}C$ decrease in the South Pole firn record suggests 0.5 GtC y^{-1} more biosphere uptake, and 0.5 GtC y^{-1} less oceanic uptake, in 1990 in a double deconvolution, compared with the $\delta^{13}C$ decrease measured in the Law Dome record.

- The Law Dome ice core record has low levels of CO_2 and high levels of $\delta^{13}C$ during the Little Ice Age period (approximately 1550–1800). Forward model calculations with a hypothetical 1°C cooling of either the ocean or terrestrial biosphere favour a biospheric response to reduced temperatures rather than an oceanic response. The double deconvolution suggested biospheric uptake and a small oceanic source at this time.

- The Kalman filter double deconvolution method developed here has a number of advantages over the traditional mass balance double deconvolution method for analysis of ice core measurements. It avoids the need to fit smoothing splines to the measurements prior to analysis. It estimates the source uncertainties as part of the calculation, and allows detailed statistical analysis of CO_2, $\delta^{13}C$ and source variability.

- The double deconvolution calculation, DD1a, used the published $\delta^{13}C$ data uncertainties and CO_2 uncertainties that were half the published uncertainties (this was justified by considering the statistics in the Kalman filter). The calculation suggested that natural variability in the CO_2 fluxes may be as large as 1 GtC y^{-1} on time scales of just less than a decade. The uncertainties in the net fluxes from this calculation are around 0.3–0.4 GtC y^{-1} in the industrial period. This calculation assumed that the decadal time scale features in the record, sometimes defined by quite sparse data, are real, and this needs to be confirmed with more frequent sampling of the existing ice cores.

- The DD1a calculation suggested variations in biospheric uptake of CO_2 between 1950 and 1980 that are very similar in both magnitude and temporal evolution to the terrestrial sink estimated by Dai and Fung (1993) using regional climate records to force globally gridded ecosystems.

- A prominent feature in the DE08 and DE08-2 CO_2 measurements is the small reversal in growth rate around the 1940s, at a time when fossil fuel was a significant source to the atmosphere. The firn model showed that this feature was more extreme in the atmosphere than is recorded in the ice core measurements. The firn model and carbon cycle model require uptake of about 3 GtC y^{-1} in the mid-1940s to match the CO_2 measurements. The $\delta^{13}C$ measurements show no evidence of a corresponding feature, suggesting that the uptake was due to the oceans. It is also possible that the uptake was at least two thirds oceanic and up to about one third biospheric, and that a small peak in atmospheric $\delta^{13}C$ (if it existed) was smoothed away by the firn processes and therefore not seen in the ice core record. Processes that could have been responsible for such large oceanic uptake have not yet been identified.

- A review was given of different estimates of the isotopic disequilibrium flux (isoflux). The isoflux, which is needed to solve the ^{13}C budget, arises mainly because atmospheric $\delta^{13}C$ is decreasing due to anthropogenic fluxes, and the oceans and terrestrial biosphere are out of isotopic equilibrium with the atmosphere. Thompson and Randerson (1999) suggested that the isofluxes have significant interannual variability because atmospheric $\delta^{13}C$ variations on the interannual time scale are not mirrored in the ocean or terrestrial biosphere. It was shown here that this can lead to interannual variations in the flux partitioning of up to about 0.4 GtG y^{-1}, which is small compared to interannual variations over recent decades in the net biospheric flux but may be important for oceanic flux variations. This problem can be avoided by taking atmospheric $\delta^{13}C$ variations into account when the isofluxes are estimated.

7.2 Further work

Despite the very high precision and time resolution of the Law Dome CO_2 and $\delta^{13}C$ ice core records compared to previous records, the technology and understanding now exist to improve the data density and measurement precision even further. It is planned at CSIRO Atmospheric Research to make more measurements of CO_2 and $\delta^{13}C$ in the existing Law Dome ice cores. The understanding already gained during the measurement and analysis of $\delta^{13}C$, in particular, will then be very useful. The work presented here has identified some periods where the understanding of CO_2 has been limited because the data density has not been sufficient. It is also hoped that new measurements of firn and ice core $\delta^{13}C$ will clarify the discrepancy between South Pole firn and Law Dome ice core $\delta^{13}C$.

Three periods over the last 1000 years where new ice core measurements would be particularly useful are 1) at the beginning of the Little Ice Age, where there are no reliable $\delta^{13}C$ measurements, 2) between 1800 and 1850, where the CO_2 and $\delta^{13}C$ suggest a complicated beginning to the industrial period, but it is not entirely clear how CO_2 and $\delta^{13}C$ varied and 3) around the 1940s, to confirm the CO_2 record and to give more precise information on $\delta^{13}C$. Better data density and precision through the industrial period, in particular, will allow better determination of oceanic and biospheric fluxes for useful comparison with climate data. This will also help determine the effect of extended El Niño events on the carbon cycle.

This work has assumed that decadal time scale variation in the global isofluxes due to sea surface temperature, sea-ice extent, wind speed, ocean circulation and land-use change is negligible. It should be possible to quantify at least some of these effects with existing data and models. This would give confidence that atmospheric $\delta^{13}C$ variations are in fact associated with net CO_2 fluxes.

In Section 6.4.2, oceanic and biospheric fluxes consistent with the CO_2 and $\delta^{13}C$ measurements around the 1940s and the firn and carbon cycle models were determined by manually iterating with the 2 models. A double deconvolution that took some account of firn smoothing would allow this type of calculation to be done within a single framework. It might be possible, for example, to take into account the effects of the firn processes with the measurement operator in the Kalman filter double deconvolution. This would perhaps be more important for ice core records with higher data density than here, for firn records where smoothing changes with depth, or for using ice core measurements from a number of sites with different smoothing characteristics (e.g DE08/DE08-2 and DSS).

Atmospheric CO_2 and $\delta^{13}C$ were the only measurements used in the Kalman filter double deconvolution calculations described here. It should be possible to use other types of data as well. For example, measurements of mixed layer $\delta^{13}C$ from sponges could be included. The Böhm et al. (2000) sponge record currently has higher data density than the ice core record and similar smoothing in time. It would be possible to tune the offset between the sponge and atmospheric $\delta^{13}C$ measurements, as well as the different anthropogenic changes. If features in the mixed layer $\delta^{13}C$ lag or lead the atmosphere, this may give information on whether the atmosphere is driving the ocean or vice versa. Climate information could also be used in the calculation, perhaps as 'observations' of the fluxes with large uncertainties.

The Kalman filter has been used here to invert for net CO_2 fluxes, with a random walk model describing flux evolution. It would also be possible to use the Kalman filter in a more physically-based model, and to tune model parameters as part of the calculation. This is somewhat similar to what was done by D. Schimel and R. Braswell (pers. comm., 1998) with a Green's function formalism.