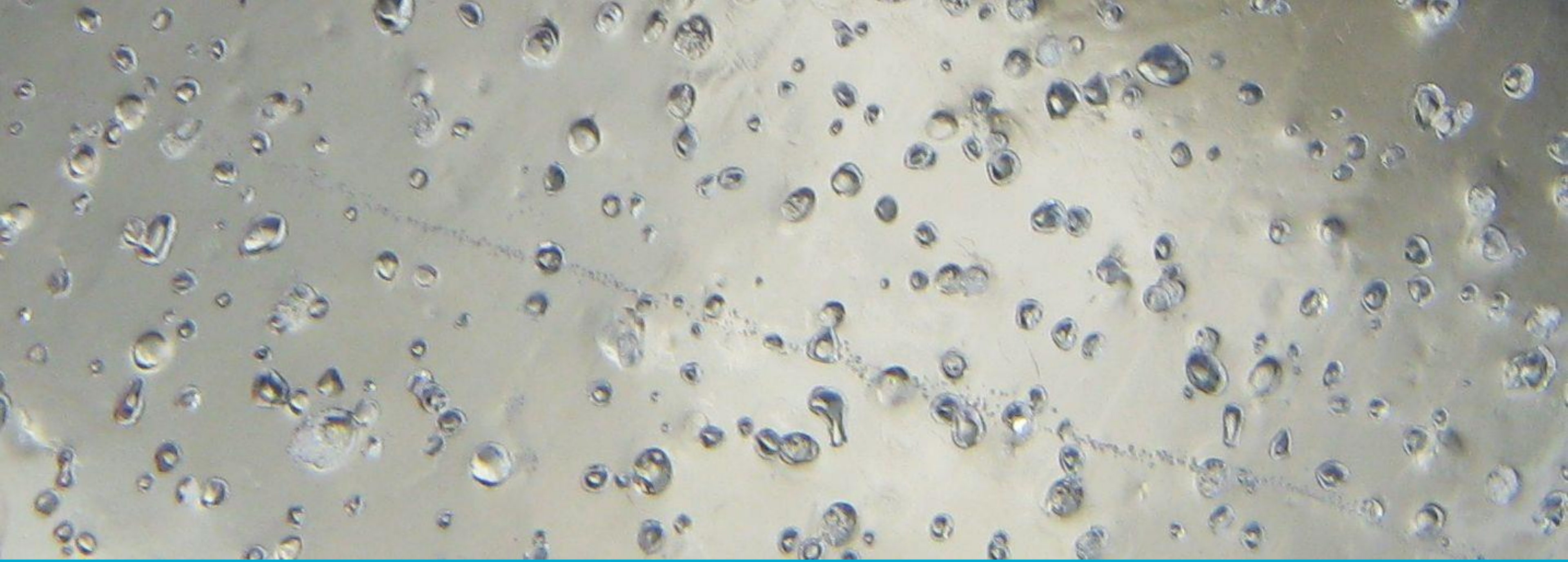
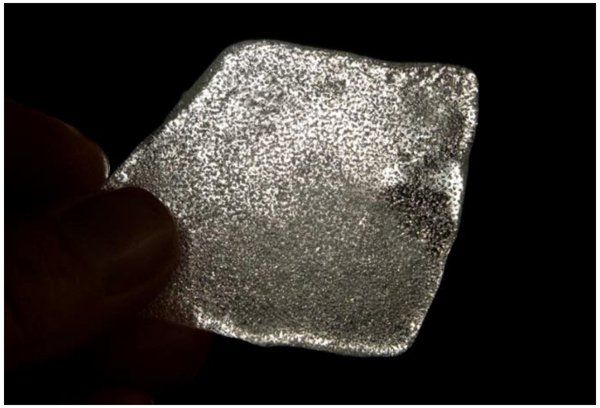


Past atmospheric composition

Cathy Trudinger
17 March 2015

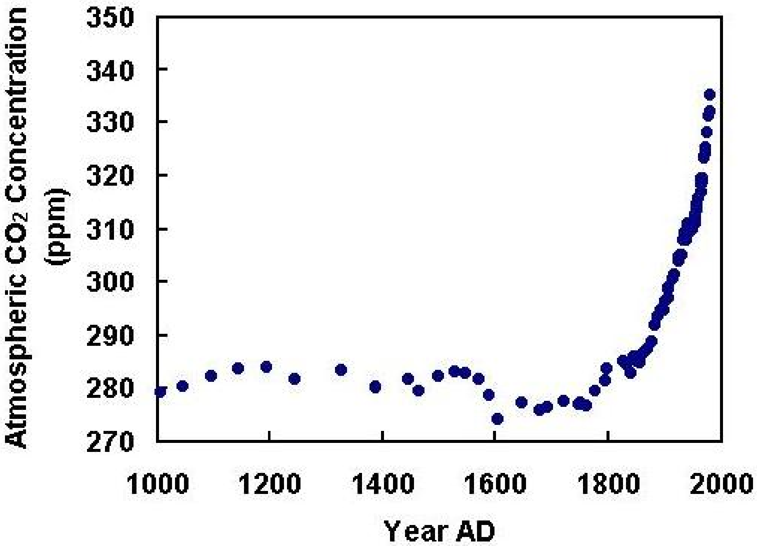
Scope - Interpreting ice core records of CO_2 using:

- Models of bubble trapping
- Box models of the carbon cycle
- Additional observations (isotopes of carbon: ^{13}C and ^{14}C)



Outline

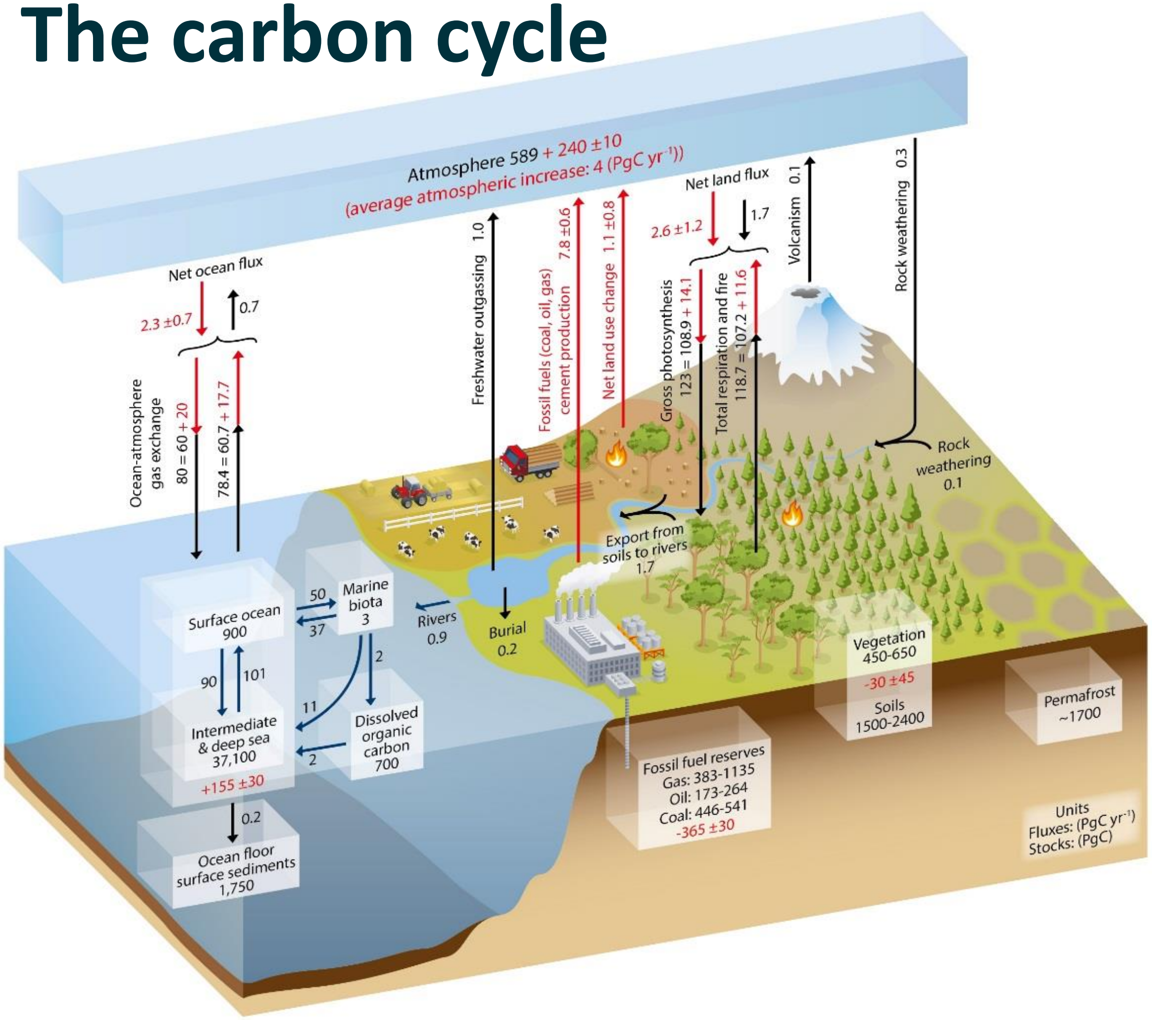
- Background
- Retrospective
- Current problems

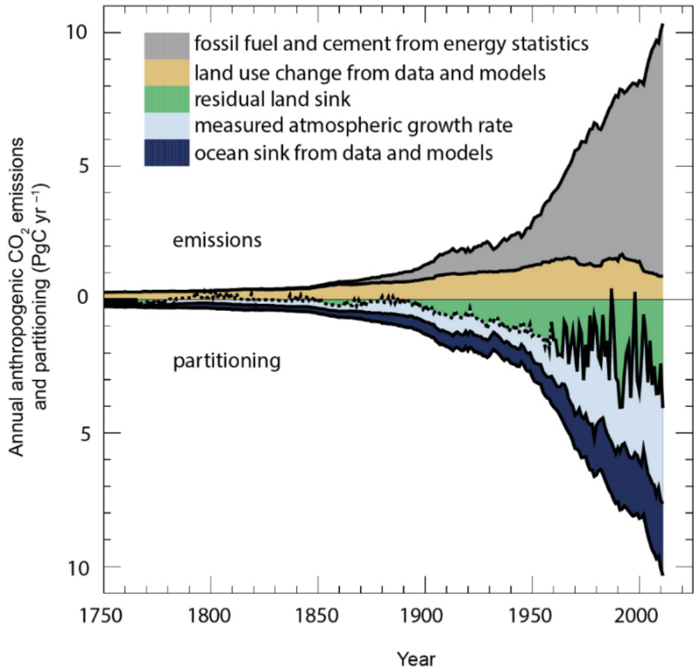


Law Dome CO_2 ice core record

Section 1:
Background

The carbon cycle



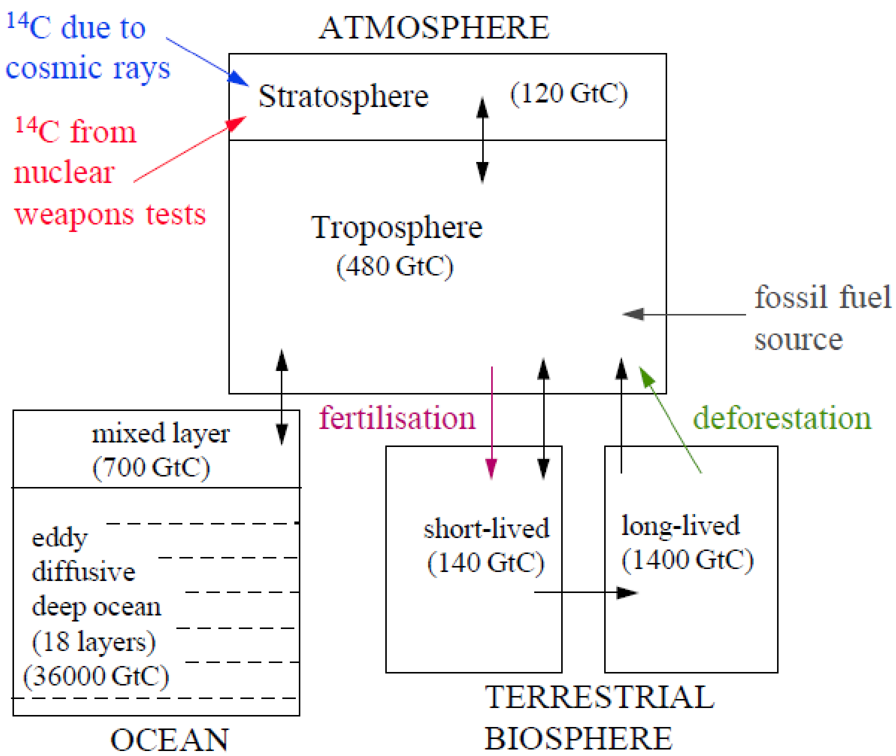


Black = pre-industrial carbon stocks and annual fluxes
Red = anthropogenic (2000-2009) carbon stocks and fluxes (IPCC 2013)

Emissions – fossil fuel and land use change
Partitioning – atmosphere, land and oceans

Understand past to predict future, incl. feedbacks

Box model of the global carbon cycle



CSIRO box diffusion model (Enting and Lassey, 1993)

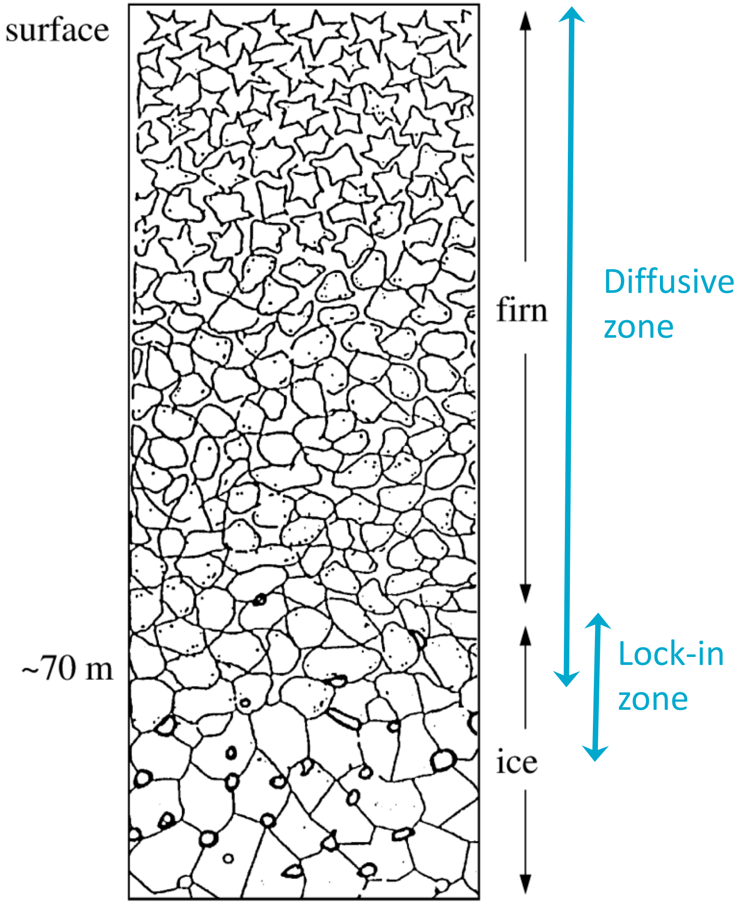
Model C, ^{13}C and ^{14}C:

^{13}C: stable isotope, useful to distinguish uptake by the land and oceans (uptake by the land has a stronger preference for ^{13}C than does uptake by the ocean)

^{14}C: radioactive isotope, useful for calibrating models. Variations in ^{14}C are both natural (cosmic ray flux in stratosphere) and anthropogenic (nuclear weapons tests in 1950s and 60s; fossil fuel emissions are ^{14}C free)

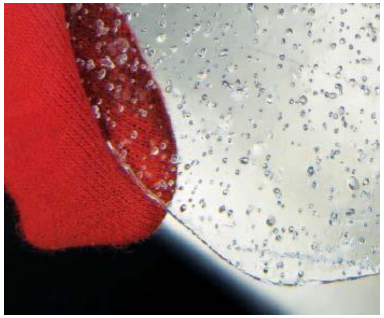
Approx. 99% of atmospheric CO_2 is ^{12}C, 1% is ^{13}C and 1 in 10^{12} is ^{14}C. Isotopes are usually described in terms of ratios to ^{12}C.

Trapping of air into bubbles in ice



Main processes in firn:

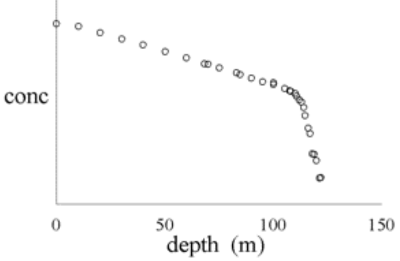
- Advection downwards as new snow falls at the surface
- Diffusive mixing
- Gradual trapping of air into bubbles



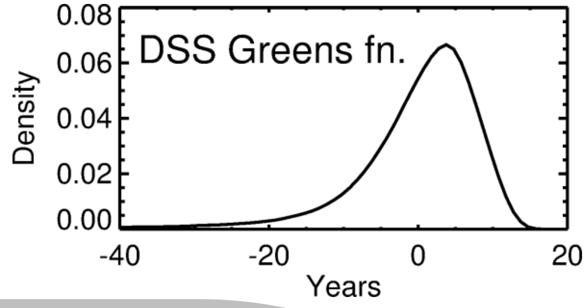
Air in trapped bubbles is younger than host ice.

Bubbles are trapped over a depth range, along with the mixing in firn, causes smoothing of time variations.

Typical concentration-depth profile in firn



Distribution of ages in an ice sample



CSIRO

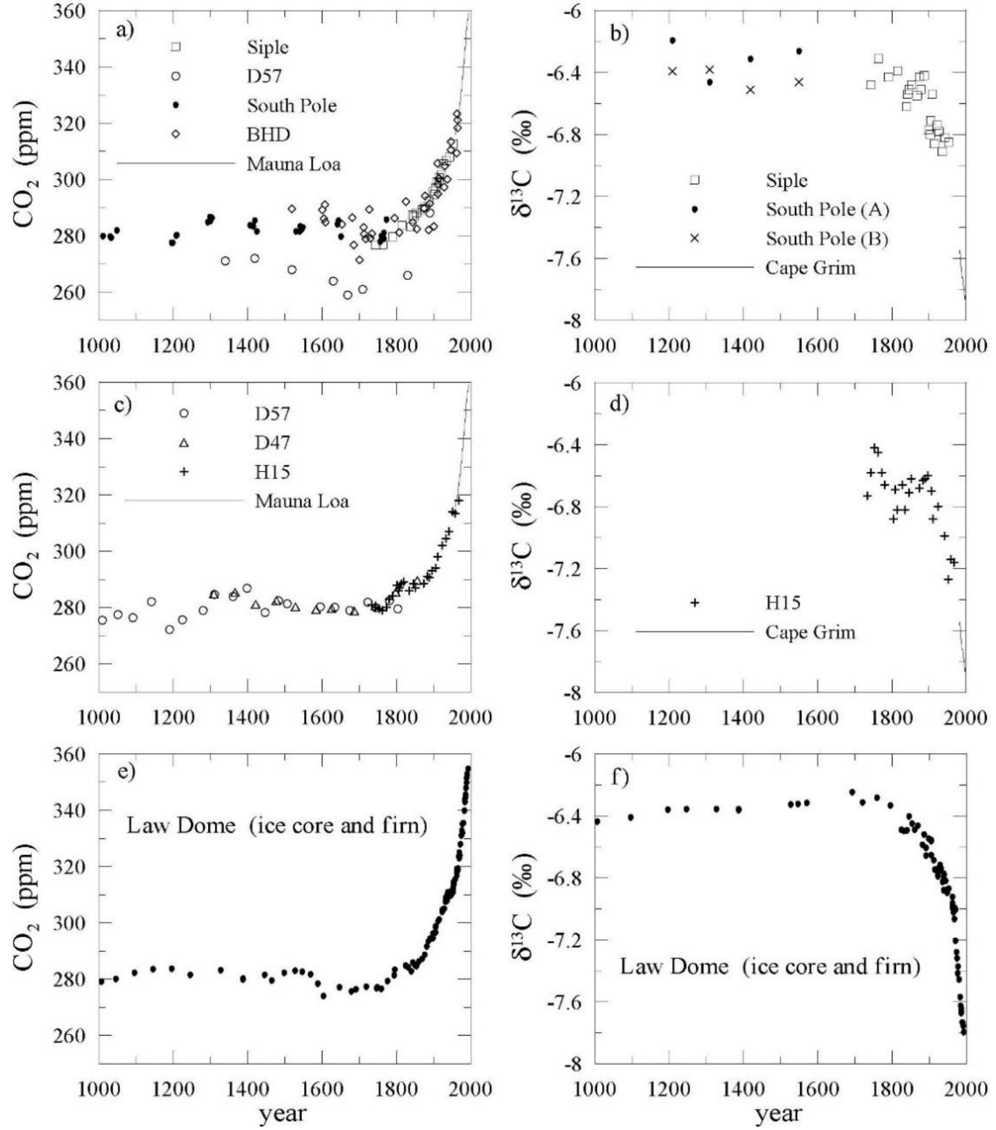
Section 2:
Retrospective

Ice core records of CO_2 and $\delta^{13}CO_2$

1980s

1990s

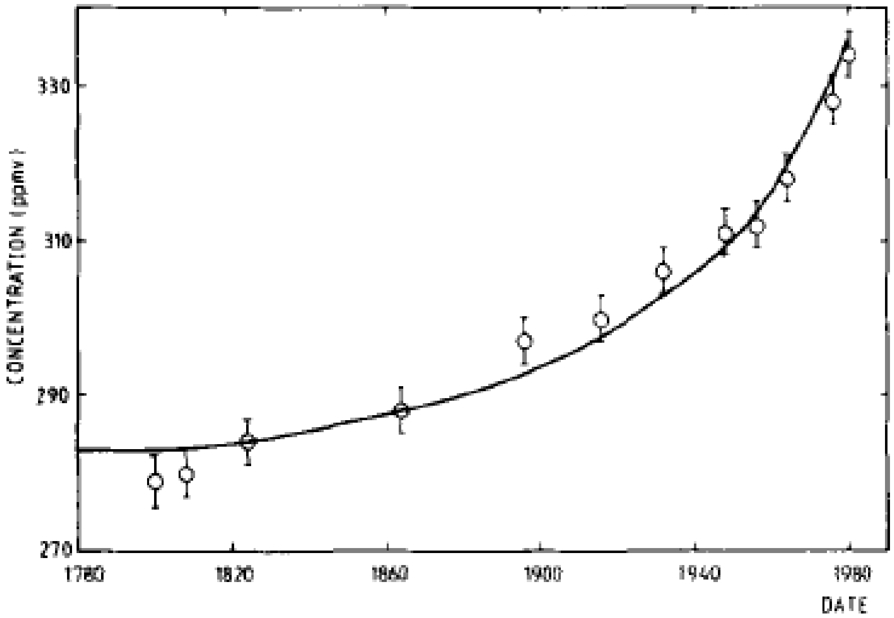
Etheridge et al. (1996)
Francey et al. (1999)

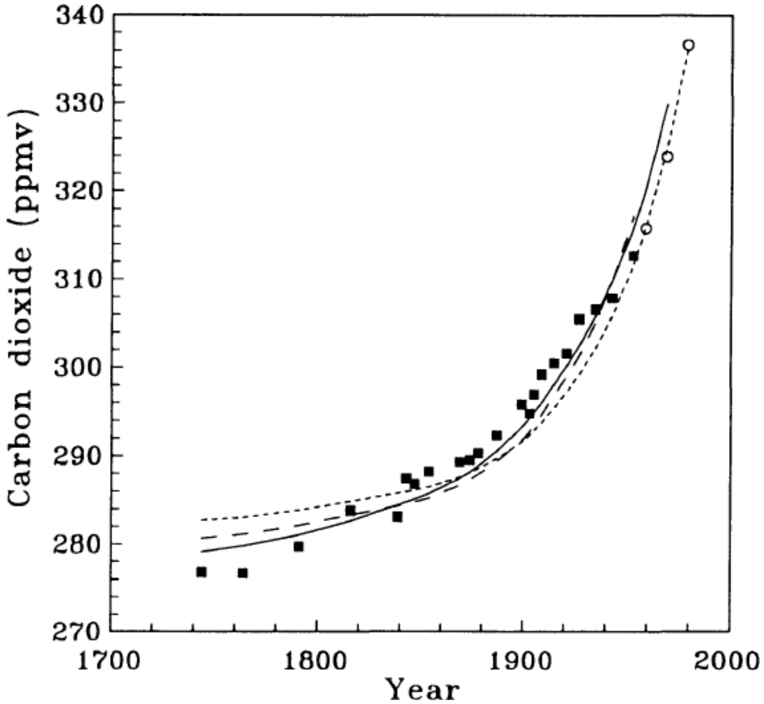


CO_2

$\delta^{13}CO_2$

Quantify measured changes with model



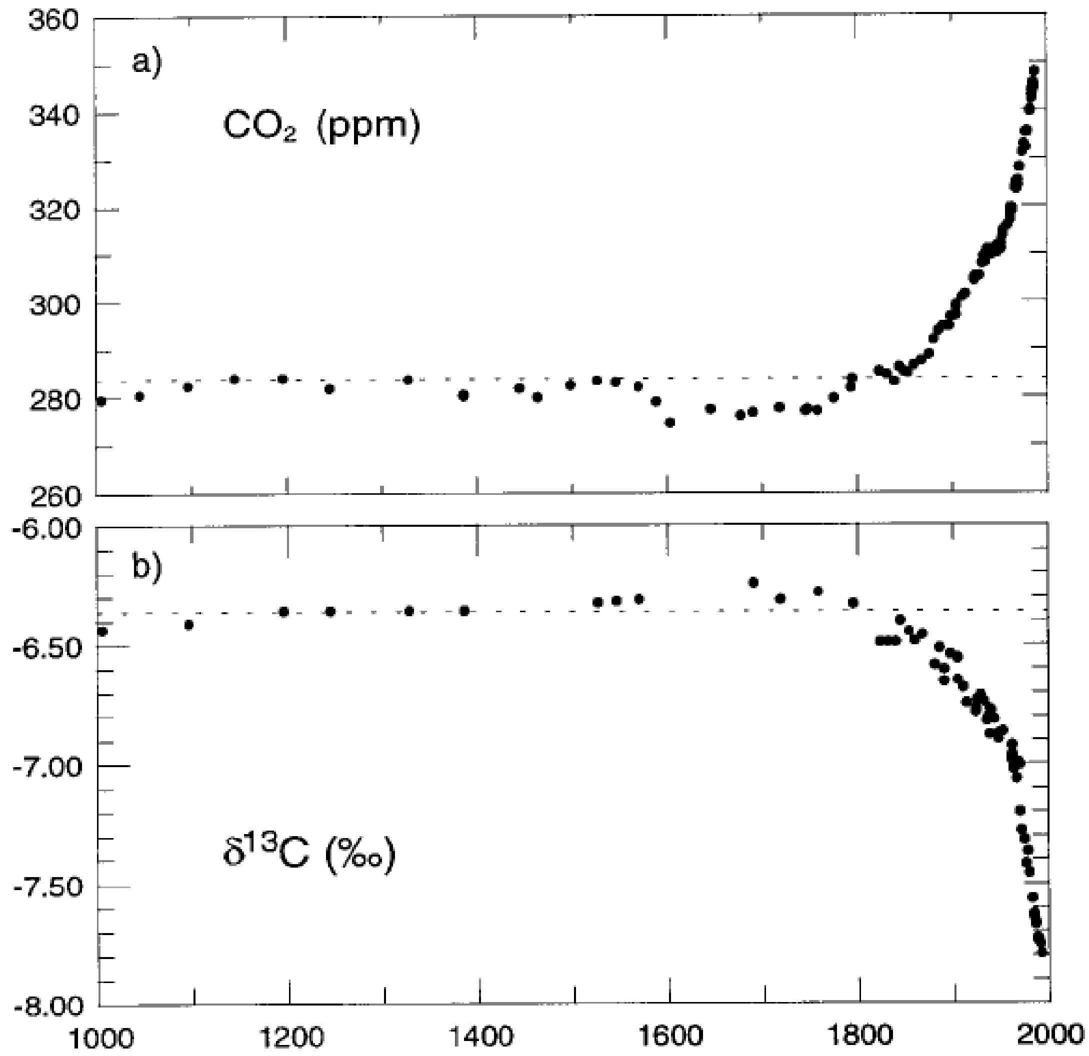


Enting and Mansbridge (1987): ice core CO_2 and history of biotic CO_2 releases from ecosystem modelling are inconsistent with any linear time-invariant model of ocean uptake of CO_2

Enting (1992): Allowing for CO_2-enhanced growth increases the discrepancy. The proposed explanation – the early increase in CO_2 reflects a recovery from a perturbation associated with the Little Ice Age

Little Ice Age

- Little Ice Age = period of reported low temperatures in Europe
- Law Dome ice core record defines Little Ice Age decrease in CO_2.
- Coinciding increase in $\delta^{13}C$, although data is sparse

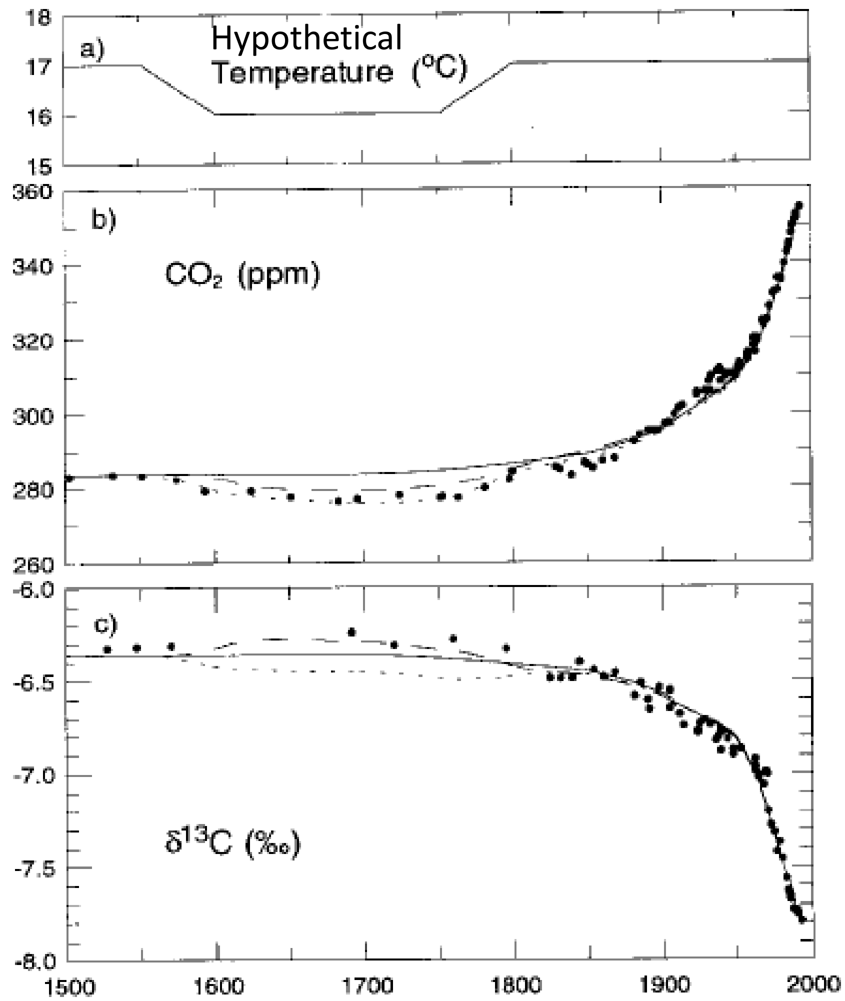


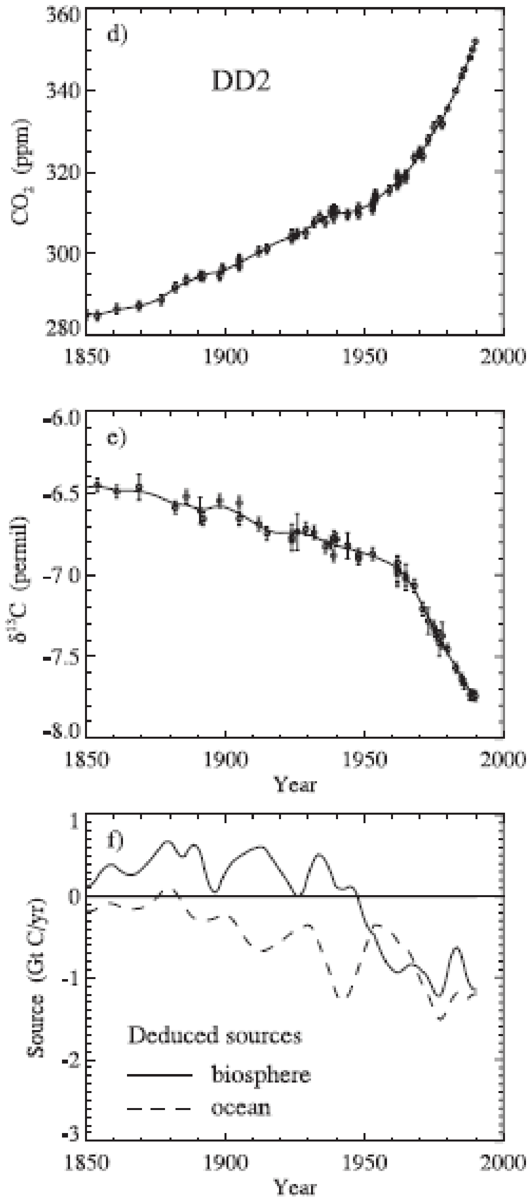
Law Dome ice core CO_2 and $\delta^{13}C$ record

Little Ice Age

Trudinger, Enting et al. (1999)

- With the box diffusion model, we tested the effect of lower temperatures on the land or ocean exchange
- Dotted lines show temperature-dependent ocean exchange (decrease in both CO_2 and $\delta^{13}C$)
- Dashed lines show temperature-dependent land exchange (decrease in CO_2 and increase in $\delta^{13}C$).
- Conclude significant cooling of terrestrial biomes was the dominant cause of the low CO_2 levels





Kalman filter double deconvolution

Double deconvolution – invert CO_2 and $\delta^{13}C$ measurements for net land and ocean fluxes, using carbon cycle model for isotopes (gross fluxes).

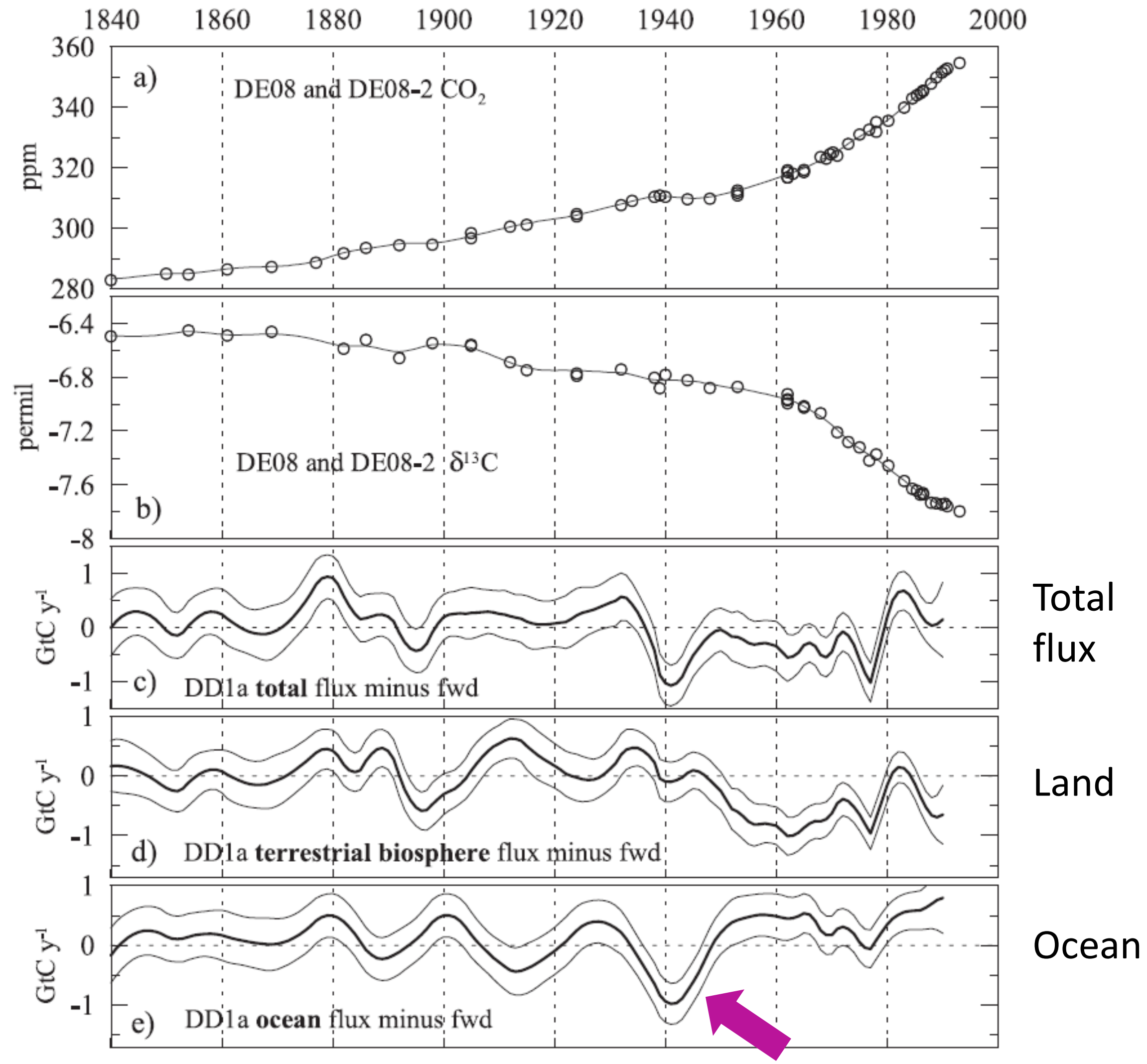
Kalman filter - statistical method, using a state space model. Observations are processed sequentially. Allows estimation of uncertainties.

=> Estimate net fluxes with uncertainties, analysis of the statistics tells you about variability.

Trudinger, Enting et al. (JGR-Atmospheres, 2002a, 2002b)

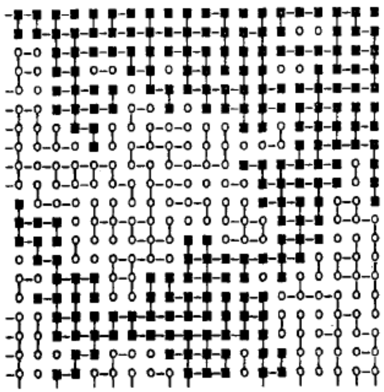
1940s flattening in CO_2

- Flattening in CO_2 in 1940s
- If this were due to terrestrial exchange or fossil emissions, expect corresponding peak in d13C – don't see one
- Double deconvolution suggests a predominantly ocean cause for flattening.

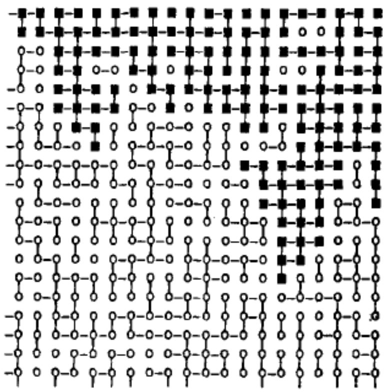


Trudinger, Enting et al. (JGR-Atmospheres, 2002a, 2002b)

Bubble trapping in ice – statistical modelling

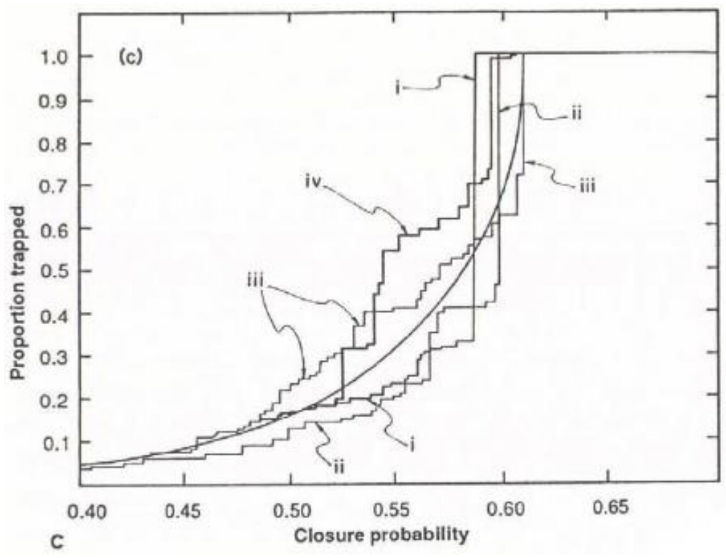


(a) Prob(connected bond) =0.5280



(b) Prob(connected bond) =0.5275

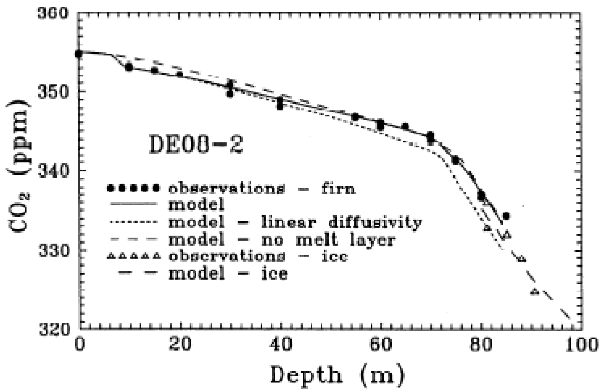
Percolation model from lattice statistics – connected clusters in a lattice.
Points = interstitial cavities in which air is trapped (bubbles)
Bonds (either connected or broken) = connecting pathways that are closed as firn compacts.



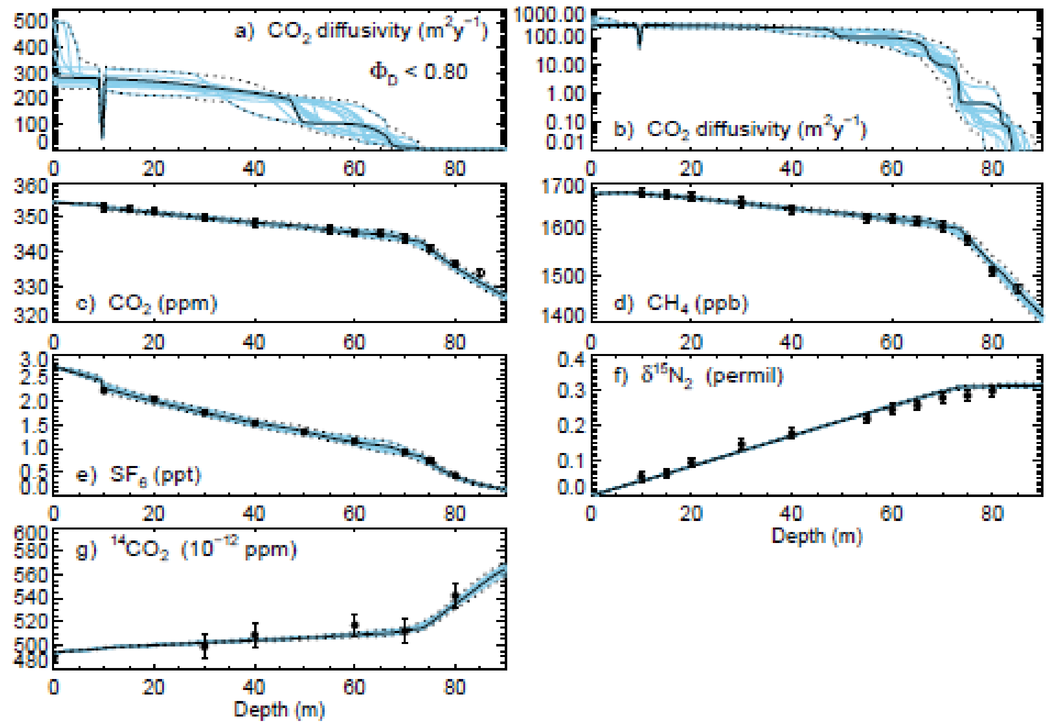
Monte Carlo simulations, showing proportion of trapped bubbles vs bond-closure probability

Enting (1985, 1986, 1987, 1993)

Diffusion in firn



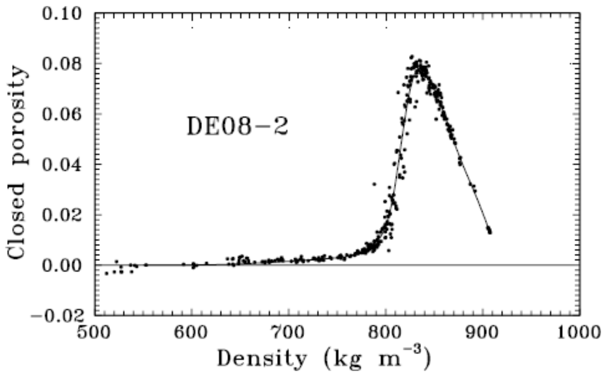
Trudinger, Enting et al. (JGR, 1997)



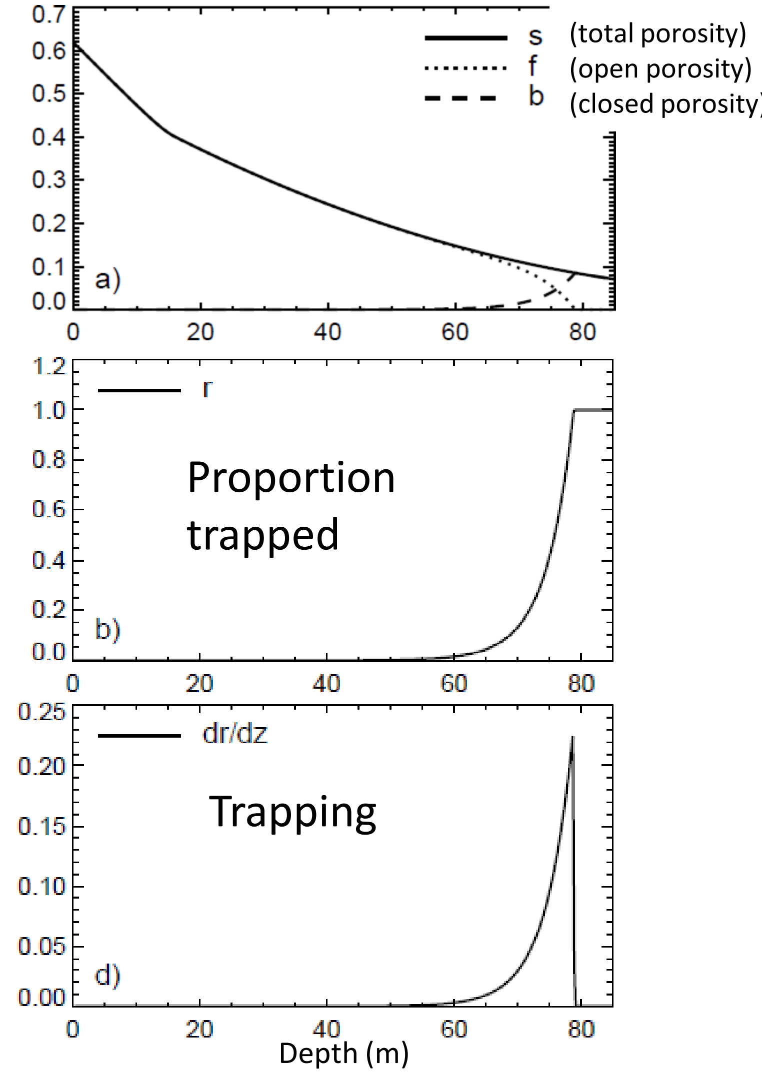
Trudinger, Enting et al. (ACP, 2013)

CSIRO firn model used in many studies to date firn air, provide corrections for isotopes (due to gravity and diffusion), quantify age spread in firn and ice, reconstruct atmospheric histories (synthesis inversion).

Bubble trapping in the CSIRO firn model



Closed porosity measurements
(J.-M. Barnola)



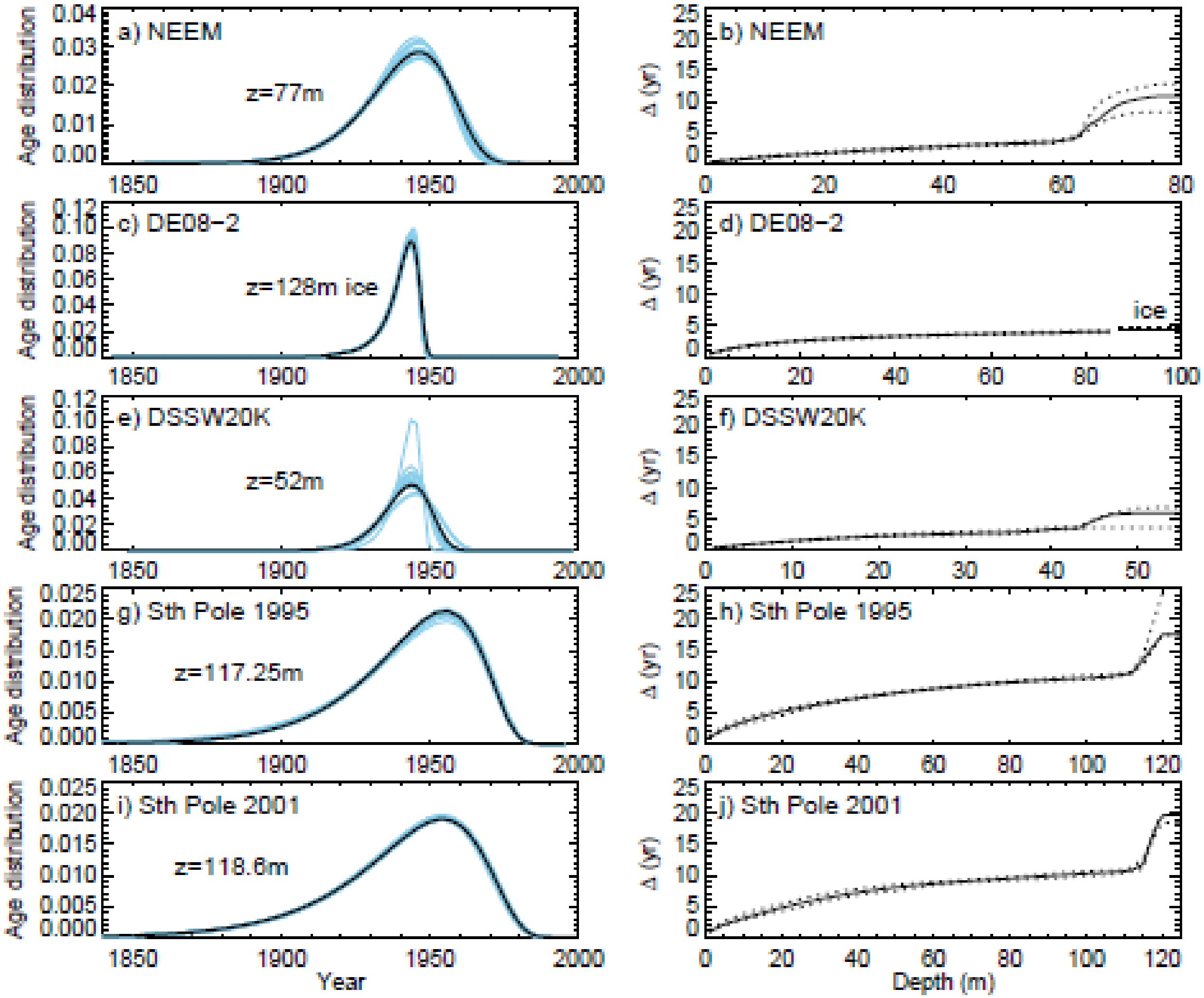
Trapping modelled deterministically.
Trapping = fn(open/closed porosity)
Open/closed porosity = fn(density)

Trudinger, Enting et al. (1997, 2013)

Quantify age distribution at different sites

Depths with mean age of 1940 (ice for DE08-2 and firn for others)

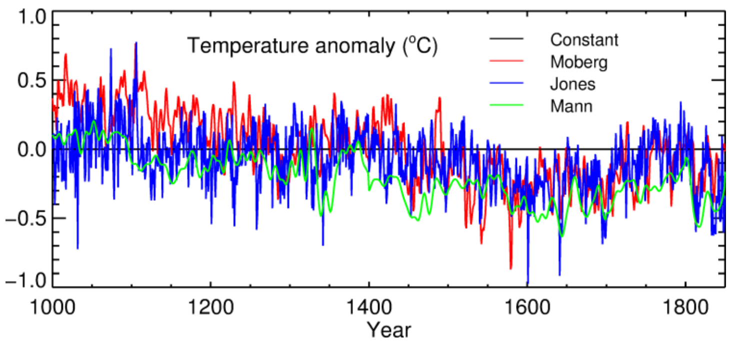
Width depends on snow accumulation rate, depth of firn column, overlap of diffusion and trapping.



Spectral width for the air age distribution is analogous to the standard deviation for a Gaussian distribution

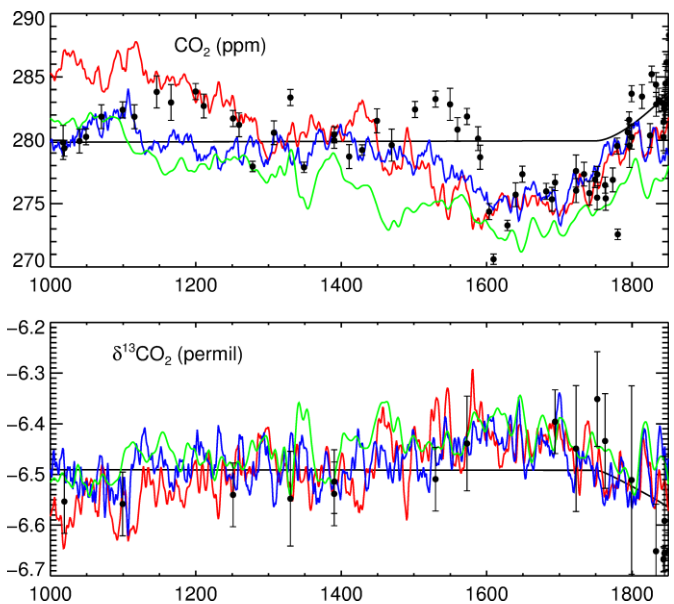
Trudinger, Enting et al. (ACP, 2013)

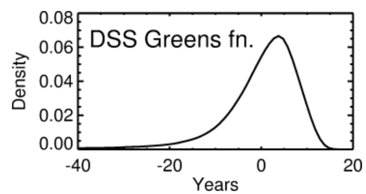
What CO_2 variability do we expect to see at DSS (Law Dome)?



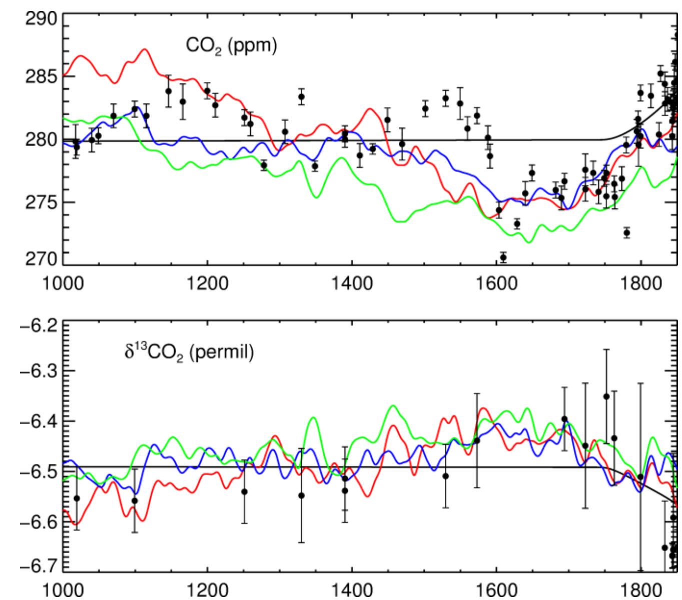
Trudinger et al. (2012, AGU Fall Meeting)

SCCM (Simple Carbon-Climate Model)
(temperature dependent land fluxes)





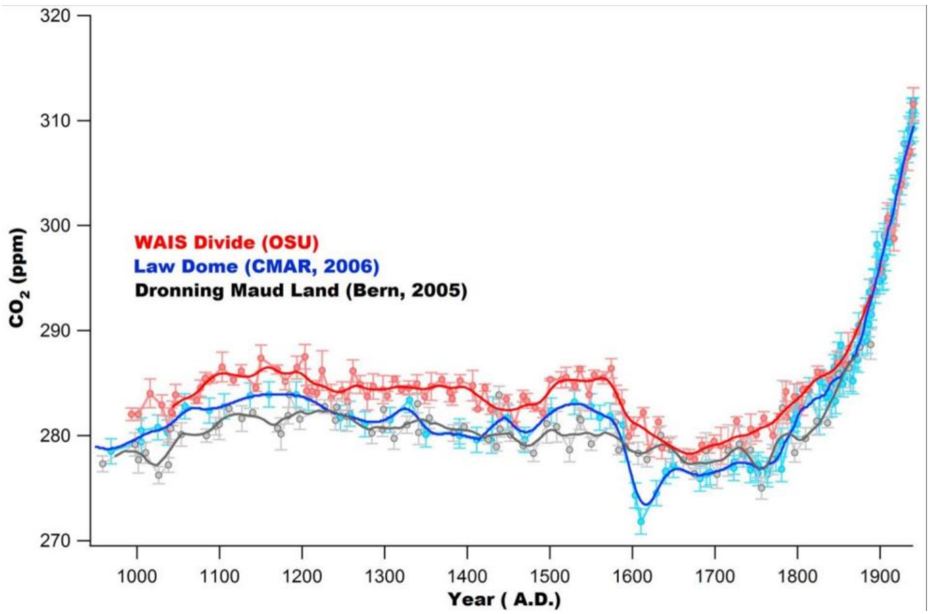
Firn diffusion and trapping model

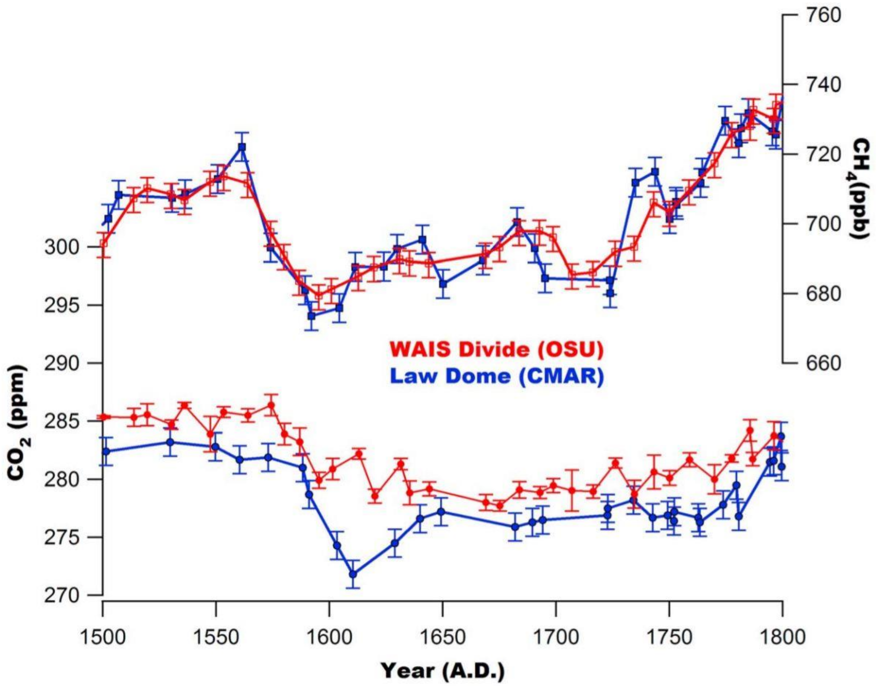


Section 3:
Current problems

New CO_2 ice core records

WAIS Divide, Ahn et al. (2012)

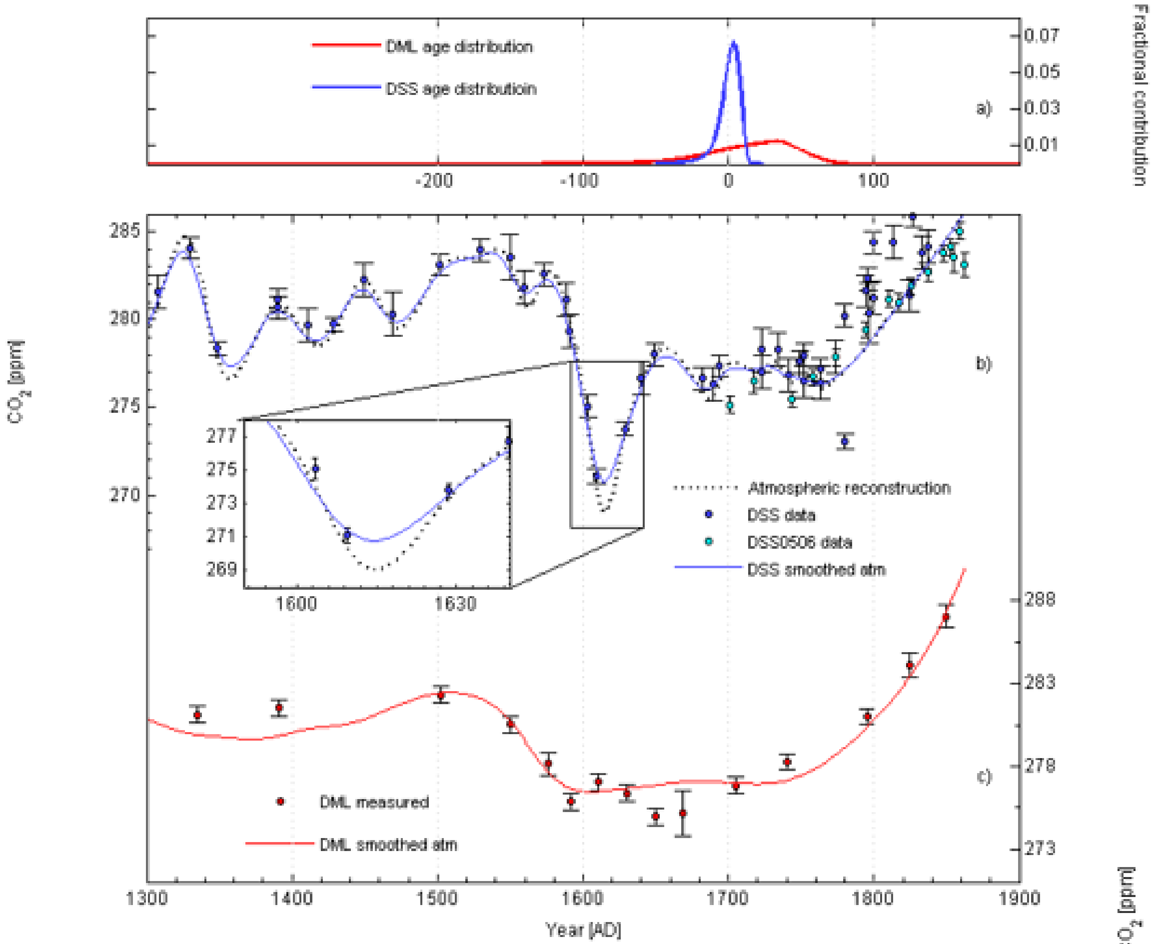




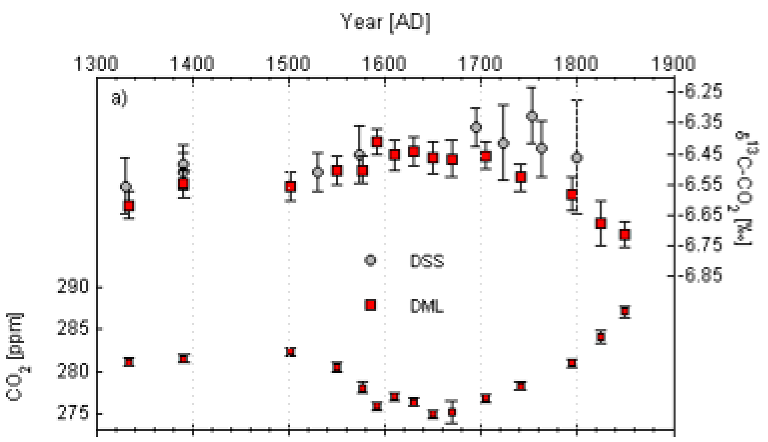
CH_4 shows good agreement between WAIS and Law Dome.
WAIS CO_2 is higher than Law Dome, and does not show the 1600 dip.

New ice core CO_2 records

Rubino, Etheridge, Trudinger et al. (in prep)

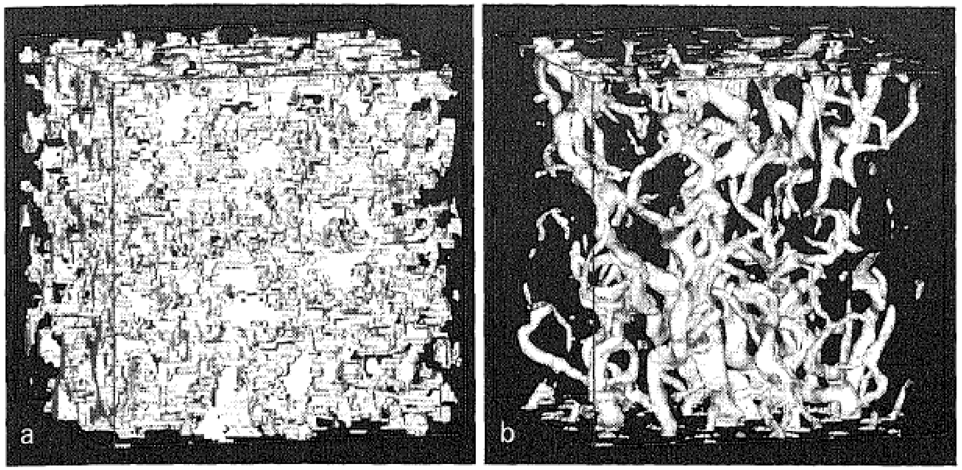


New measurements at DML are consistent with DSS (including the dip at 1600) when age distributions are taken into account



New information on pore close-off

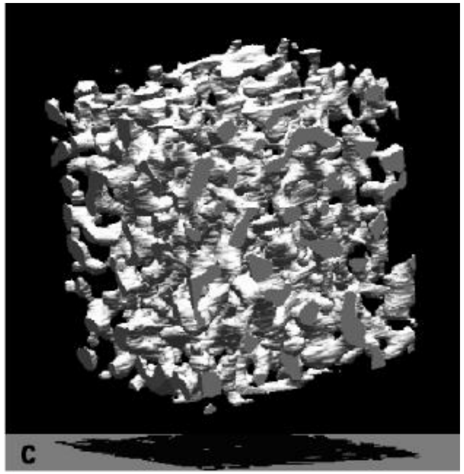
Xray imaging of firn



Pore space

Simulated flow field

Freitag et al. (2002)



Pore space

Freitag et al. (2004)

New information on pore close-off

We have known for years that firn has seasonal density layers, which affect diffusion and trapping, however recent evidence shows

- Layers with lower density near the surface become higher density layers at depth (Freitag et al., 2004; Gregory et al., 2014).
- Impurities in firn have a significant impact on densification (Horhold et al., 2012; Freitag et al., 2013)
- Lower accumulation-rate sites generally have coarser grained firn, and close-off at lower open porosity, than higher accumulation-rate sites which generally have finer-grained layers (Gregory et al., 2014)

Next generation firn models will need to consider these effects

e.g. 3D lattice-Boltzmann model of air flow (Courville et al., 2010); stochastic parameterisation of closed porosity (Mitchell et al., 2015)

Two unsolved problems

- Confirm features and fill in gaps in history of CO_2 and $\delta^{13}C$ over last 1000 years, esp. 1600s, 1940s flattening: [New DSS ice core, precise, high resolution measurements – measure everything we can to understand diffusion and trapping.

- Understanding of bubble trapping: New measurements. Next generation model of diffusion and trapping (statistical? lattice model? impurities? firn microstructure?)

Thank you

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