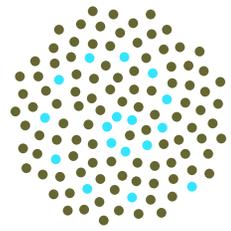


Forty years of global CO₂ inversions: what have we learned?

Ian G. Enting

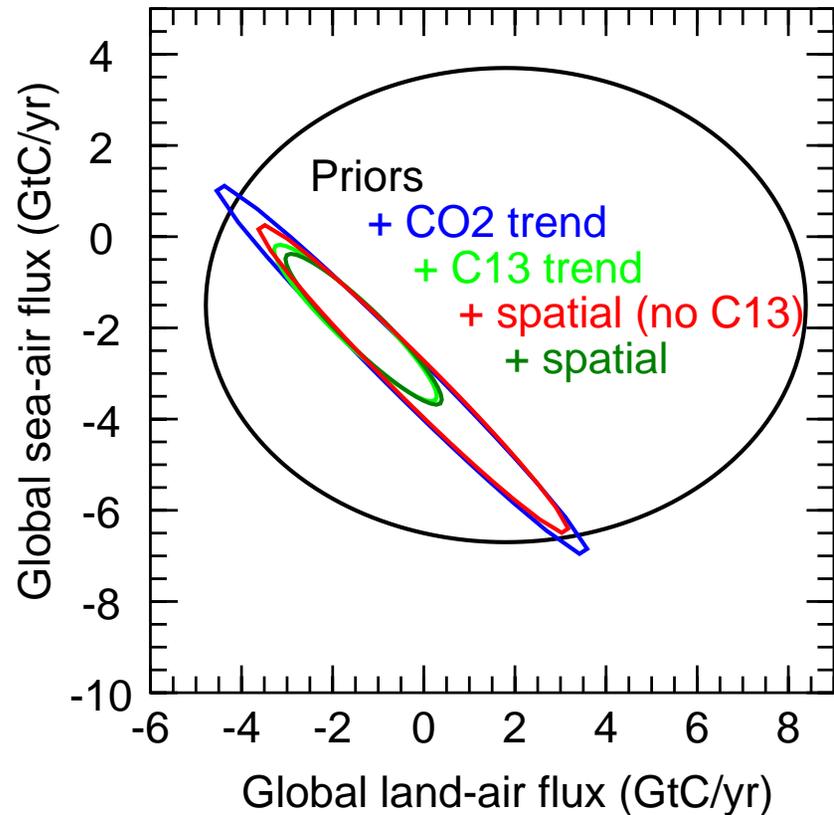
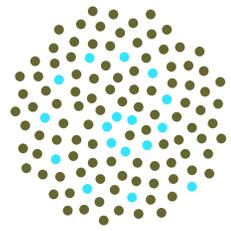
Centre of Excellence in Mathematics and Statistics of Complex Systems

Overview



- ▶ Objectives
 - ▶ Budgets → Processes → projections
- ▶ Inverse Problems
 - ▶ Estimations → Resolution
- ▶ Cases:
 - ▶ Tropical source
 - ▶ Ocean sink
 - ▶ Northern sinks
 - ▶ Internannual variability

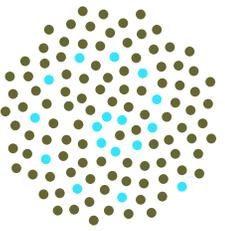
Objectives of inversion



- ▶ Understand budgets
 - ▶ Better projections
- but**
- ▶ Most global information is in global trends
 - ▶ N-S is poor proxy for air-sea

Philosophy is an attempt to transmit all we know into what we would like to know. (Valery).

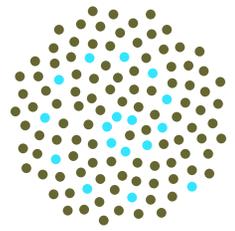
Evolving views of carbon cycle



- ▶ circa 1975: models calibrated by ^{14}C reveal “missing sink”
- ▶ 1990: conflicting estimates of ocean sink, from inversions
- ▶ 1992: conflicting estimates of ocean sink from isotopes
- ▶ 1995: conflicting isotopic estimates of interannual variability
- ▶ circa 2000: concern about feedbacks, increased focus on processes

(more in book, chapter 14, concept from R Francey)

Consistency requirements



Time :

- ▶ Time
- ▶ Averaging: period and type of smoothing

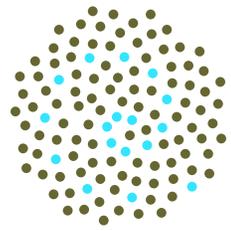
Space :

- ▶ Location
- ▶ Form and scale of averaging

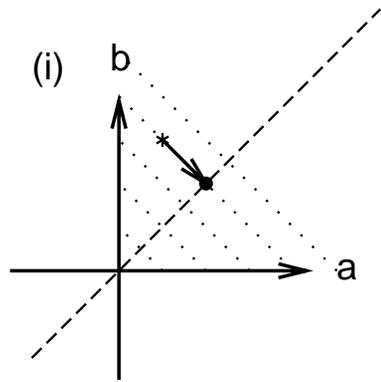
Process :

- ▶ CO₂ vs. carbon fluxes
- ▶ Flux vs. storage budgets.

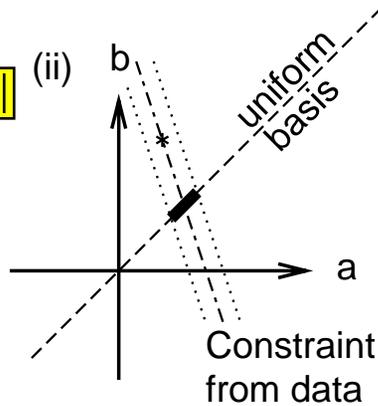
Truncation error: idealised



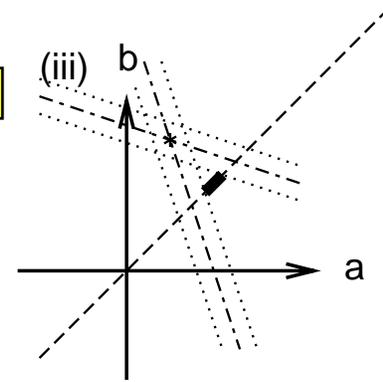
Seeking projection • from unknown 'true' value *



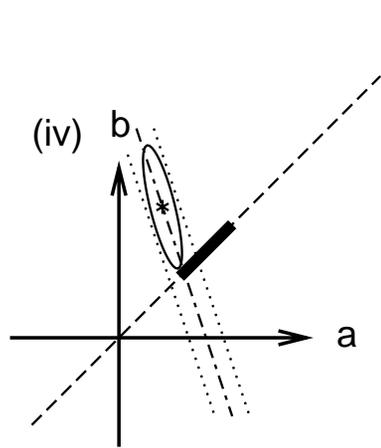
desired solution



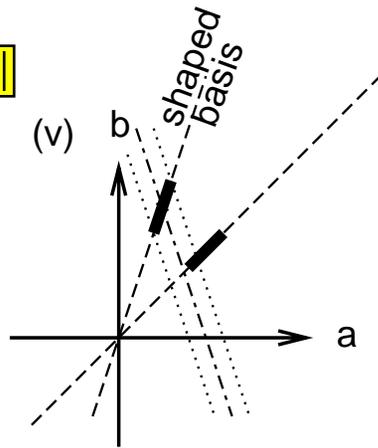
solution from biased data



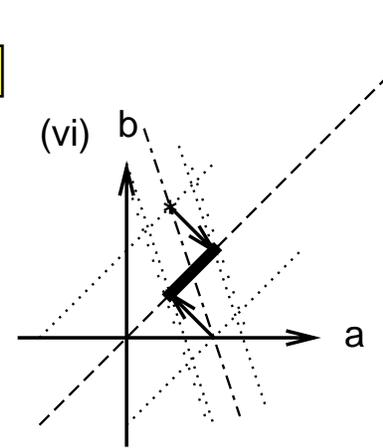
solution from unbiased data



project from full space



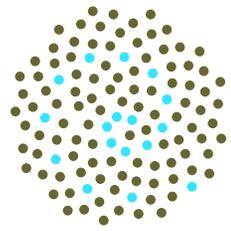
work in target space



apply truncation error to data

- i objective
- ii the risk
- iii the hope
- iv Wunsch
- v Strong prior
- vi correction

Ill-conditioning



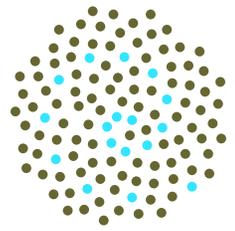
Bolin and Keeling, 1963: “*no details of the sources and sinks are reliable*”

Junge and Czeplak, 1967: “*It seems hardly likely that detailed information could be obtained on the latitudinal dependence of K and the CO_2 source function from atmospheric CO_2 observations, even if the number and quality of the data were very considerably increased.*”

Pearman (WMO report, 1980): “*over 100 stations to determine air-surface exchange within regions with significant anthropogenic influence*”

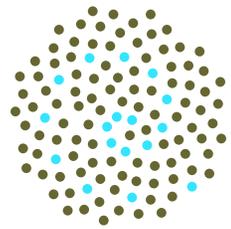
- ▶ Use Bayesian estimation to stabilise inversion.

Inversion as estimation



- ▶ Inversion should be process of statistical estimation
 - ▶ or hypothesis testing, if detecting discrepancies!
- ▶ Only limited number of modes can be estimated (or detected):
 - ▶ these need to be determined by data (Backus Gilbert, Wunsch and Minster)
 - ▶ use non-parametric statistics to avoid building in the solution (Evans and Stark)

Autocorrelation in estimates



Zones 90S to 48S to 12S to 12N to 48N to 90N

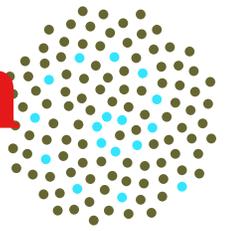
$$\begin{bmatrix} 0.21 & -0.37 & 0.22 & -0.06 & 0.01 \\ -0.37 & 1.04 & -0.53 & -0.04 & -0.07 \\ 0.22 & -0.53 & 1.75 & -1.37 & 0.00 \\ -0.06 & -0.04 & -1.37 & 2.43 & -0.86 \\ 0.01 & -0.07 & 0.00 & -0.86 & 0.94 \end{bmatrix}$$

covariance of zonal flux

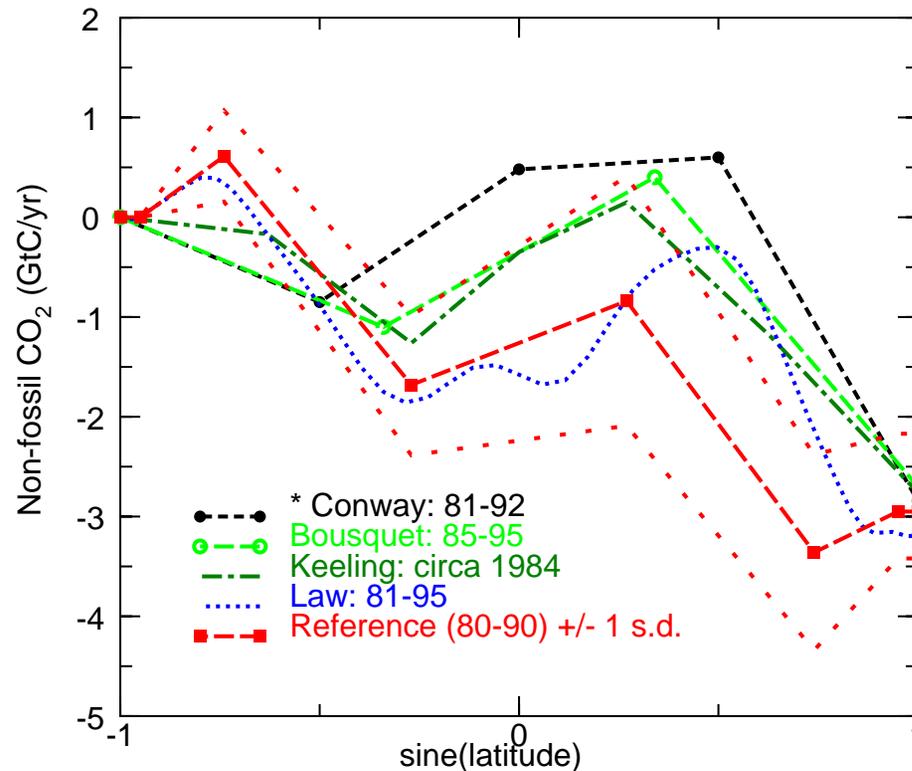
$$\begin{bmatrix} 0.21 & -0.16 & 0.06 & 0.00 & 0.01 \\ -0.16 & 0.50 & 0.18 & 0.09 & 0.03 \\ 0.06 & 0.18 & 1.64 & 0.16 & 0.10 \\ 0.00 & 0.09 & 0.16 & 1.12 & 0.20 \\ 0.01 & 0.03 & 0.10 & 0.20 & 0.23 \end{bmatrix}$$

covariance of integrated flux

Circumventing autocorrelation

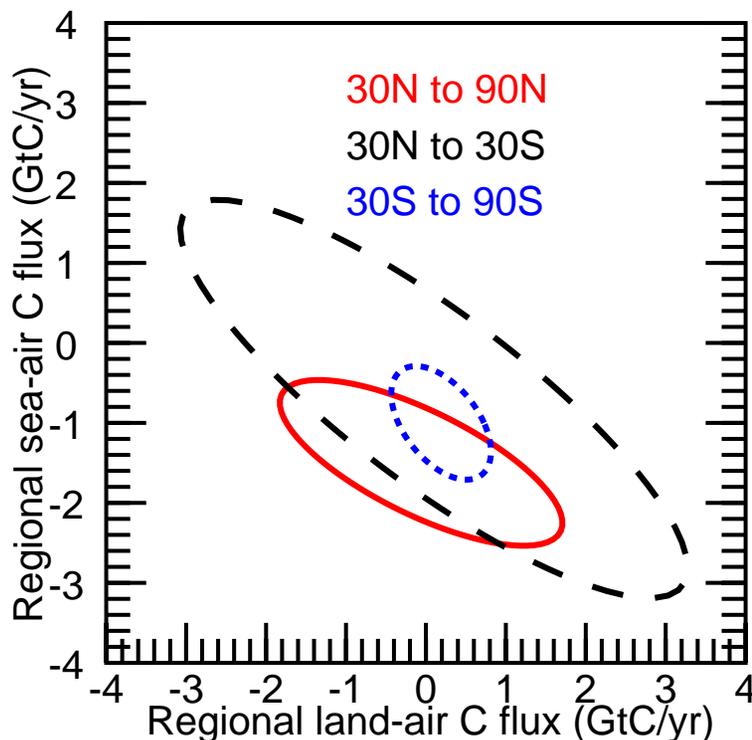
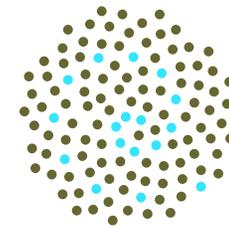


Cumulative CO₂ flux, integrated south to north



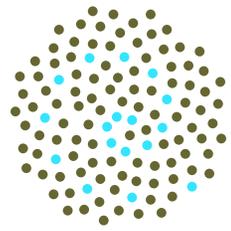
- ▶ Compare different discretisations using integrated fluxes.
- and
- ▶ Illustrates robust features that are obscured when considering each region separately.

Tropical CO₂ fluxes



- ▶ Tropical fluxes are important, but poorly determined by inversions
- due to
- ▶ Sparse observing network
 - ▶ Circulation transports 'signal' vertically, away from observing sites.

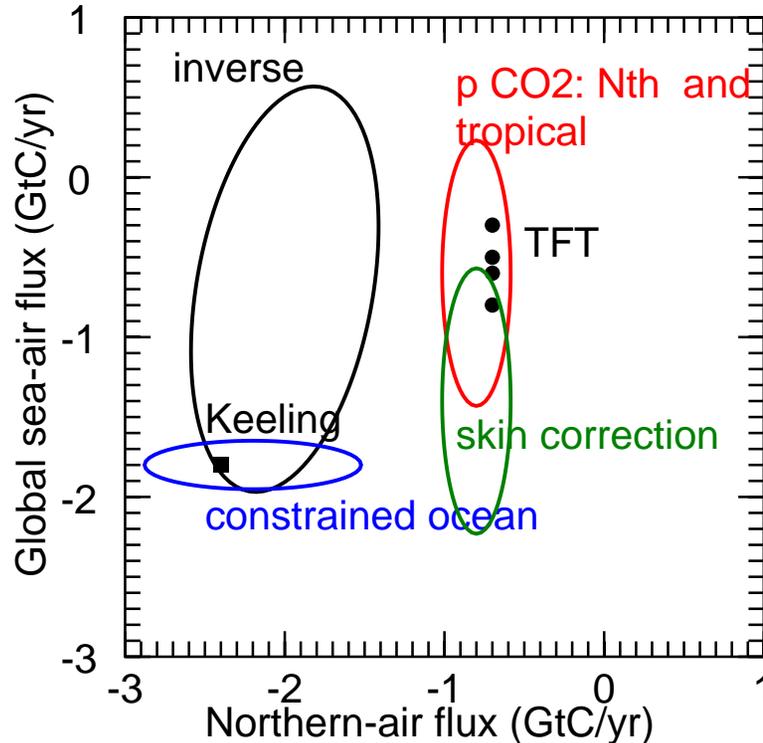
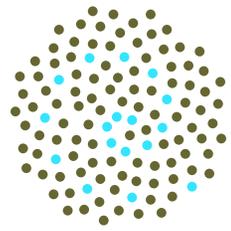
Tropical fluxes



Tropical fluxes are hard to estimate from inversion **but**

- ▶ tropical flux seems less than expected from ocean outgassing plus deforestation (Tans et al., 1989, plus most subsequent studies)
- ▶ Ocean p_{CO_2} can provide constraint on ocean contribution
- ▶ there is a strong ENSO effect in the ocean flux (and possibly terrestrial flux)

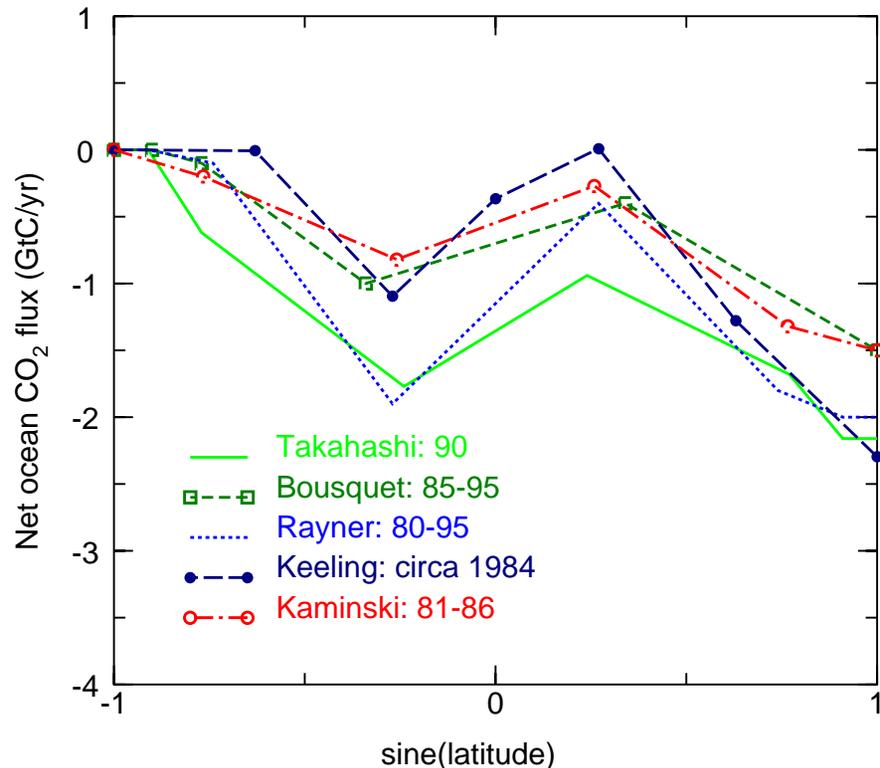
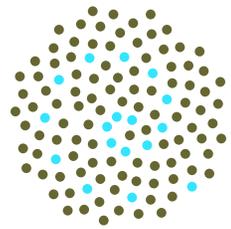
Oceans: 1990 perspective



Conflicting views of ocean flux:
high vs. low uptake

- ▶ inversions alone are weak constraint
- ▶ global ocean constraint achieved by high Nth uptake
- ▶ direct constraint from p_{CO_2} favours low uptake.
- ▶ correction for p_{CO_2} skin effect reduces discrepancy

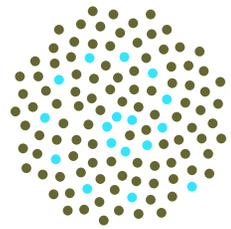
Ocean fluxes



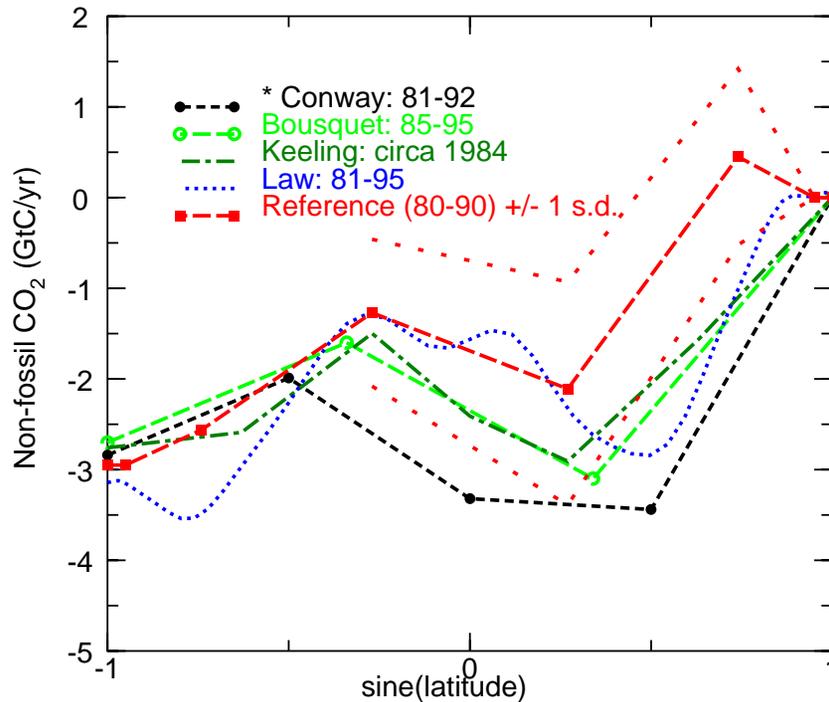
- ▶ Global isotopic budgets also split between low (Tans et al) and high (Quay et al) ocean uptake
- ▶ Resolved by flux vs. storage distinction (and skin effect and CO)
- ▶ Inversions often have same assumptions as global budgets

Most inversions give smaller SH sink than implied by (sparse) p_{CO_2} data.

Northern sink

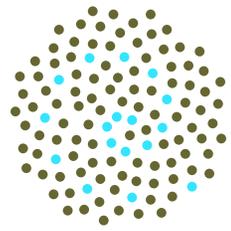


Cumulative CO₂ flux, from north to south



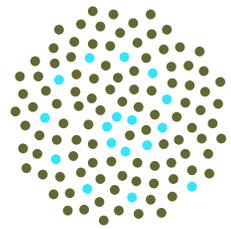
- ▶ Northern sink is robust feature
- ▶ Attribution to ocean (Keeling) driven by global budget
- ▶ Identified as terrestrial (Ciais, 95, also using ¹³C)
- ▶ Attributed to Nth American biota (Fan et al)
- ▶ More even America–Eurasia split in most other inversions.

Interannual variability



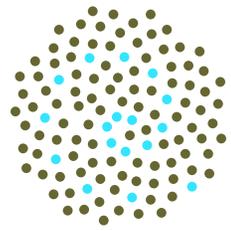
- ▶ Joint global budgets of CO₂ and ¹³CO₂ indicate high interannual variability of CO₂ fluxes.
 - ▶ SIO and CSIRO budgets disagree (mainly in early years) attributable to calibration
- but
- ▶ For surface sources, variability of surface mean is greater than variability of atmospheric mean.
 - ▶ time-dependent inversions give interannual variability closer to direct estimates

The role of TransCom



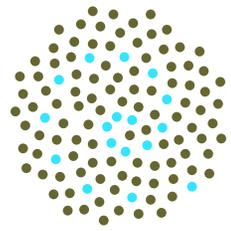
- ▶ Model error is comparable to data error
 - ▶ Tarantola says this is normal
- ▶ Therefore, in the absence of model improvement, adding data may not reduce real uncertainties
- ▶ Most 'synthetic data' experiments carry the assumption of an ideal model
 - ▶ This may be acceptable if one is evaluating data streams well in advance of actual availability

Notes for internet version



- ▶ Prof. Enting's attendance at TransCom-Tsukuba was funded by the Global Carbon Program.
- ▶ A number of the diagrams are from the book *Inverse Problems in Atmospheric Constituent Transport* by I. Enting, CUP, 2002, and are subject to copyright.
- ▶ This presentation was prepared in LaTeX, using the prosper class with a hack of the gyom style. All graphics are hand-coded postscript.

Some references



- ▶ Bolin and Keeling. J. Geophys Res. 68, p3899, 1963.
- ▶ Tans Fung and Takahashi, Science, 247, p1431, 1980.
- ▶ Sarmiento and Sundquist, Nature, 356, 589, 1992.
- ▶ Ciais et al, Science, 269, p1098, 1995.
- ▶ Fan et al, Science, 282, p442, 1998.
- ▶ Evans and Stark, Inverse Problems, 18, R55, 2002.