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An Empirical Estimate of the Southern Ocean air-sea CO_2 flux

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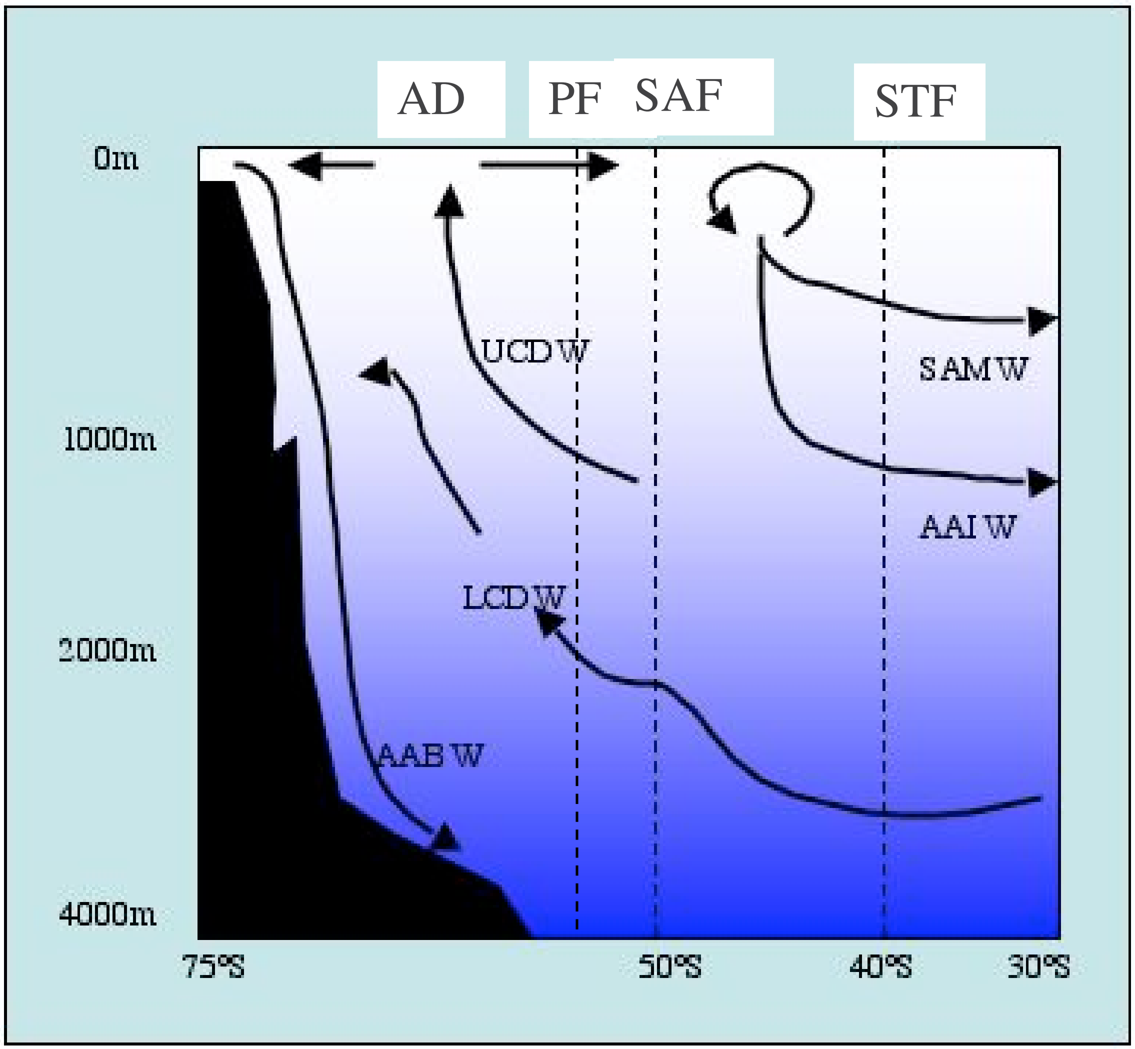
Southern Ocean - Zonation and Circulation



STF- sub-tropical Front

SAF - sub-Antarctic Front

PF - Polar Front

AD - Antarctic Divergence

UCDW - Upper Circumpolar Deep Water

SAMW - sub-Antarctic Mode Water

AAIW - Antarctic Intermediate Water

Most direct way to measure air-sea CO_2 fluxes

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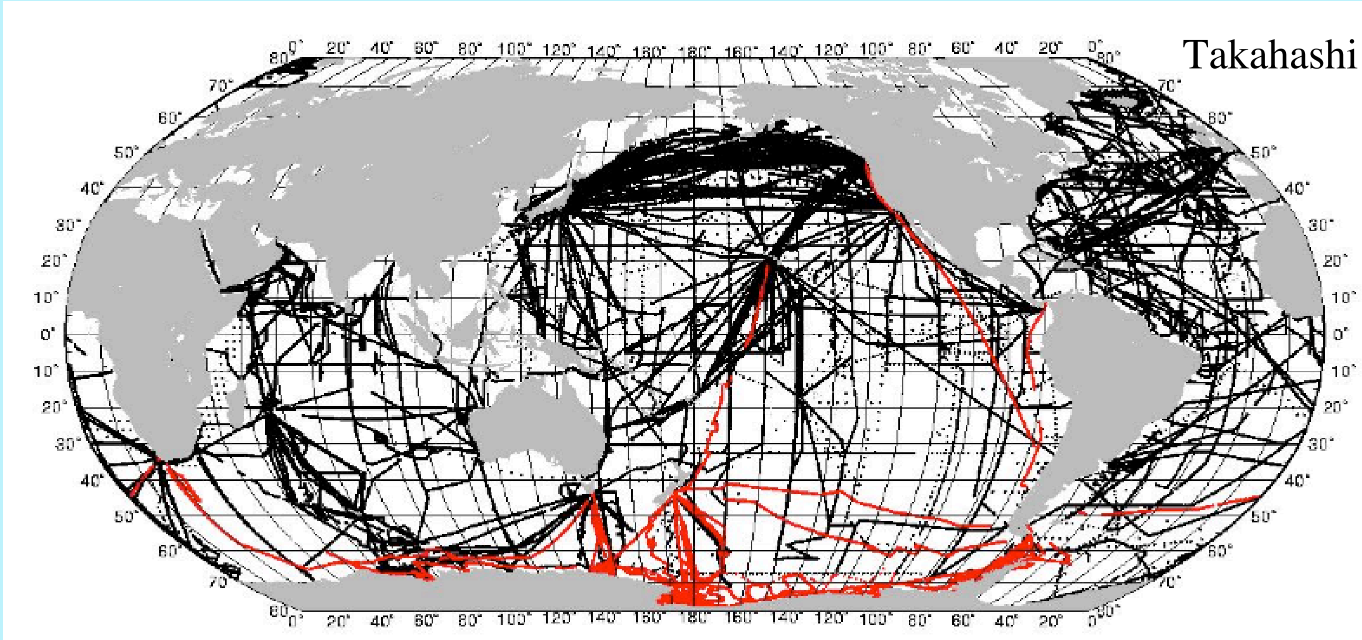


Takahashi et al, 2002

pCO_2

Flux= $\Delta pCO_2 \times k$
(gas-exchange coeff)

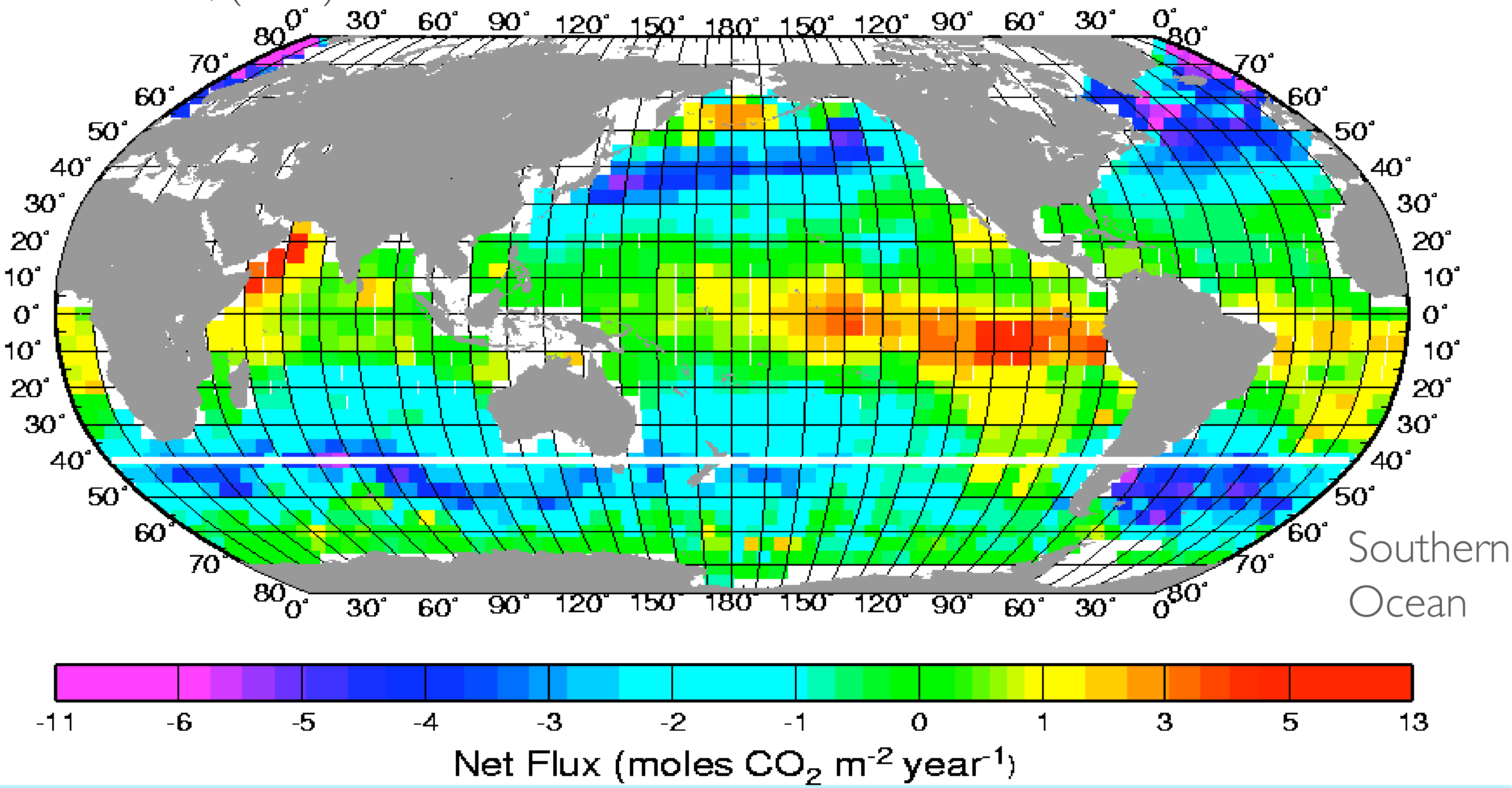
Atmosphere

Surface Ocean

pCO_2

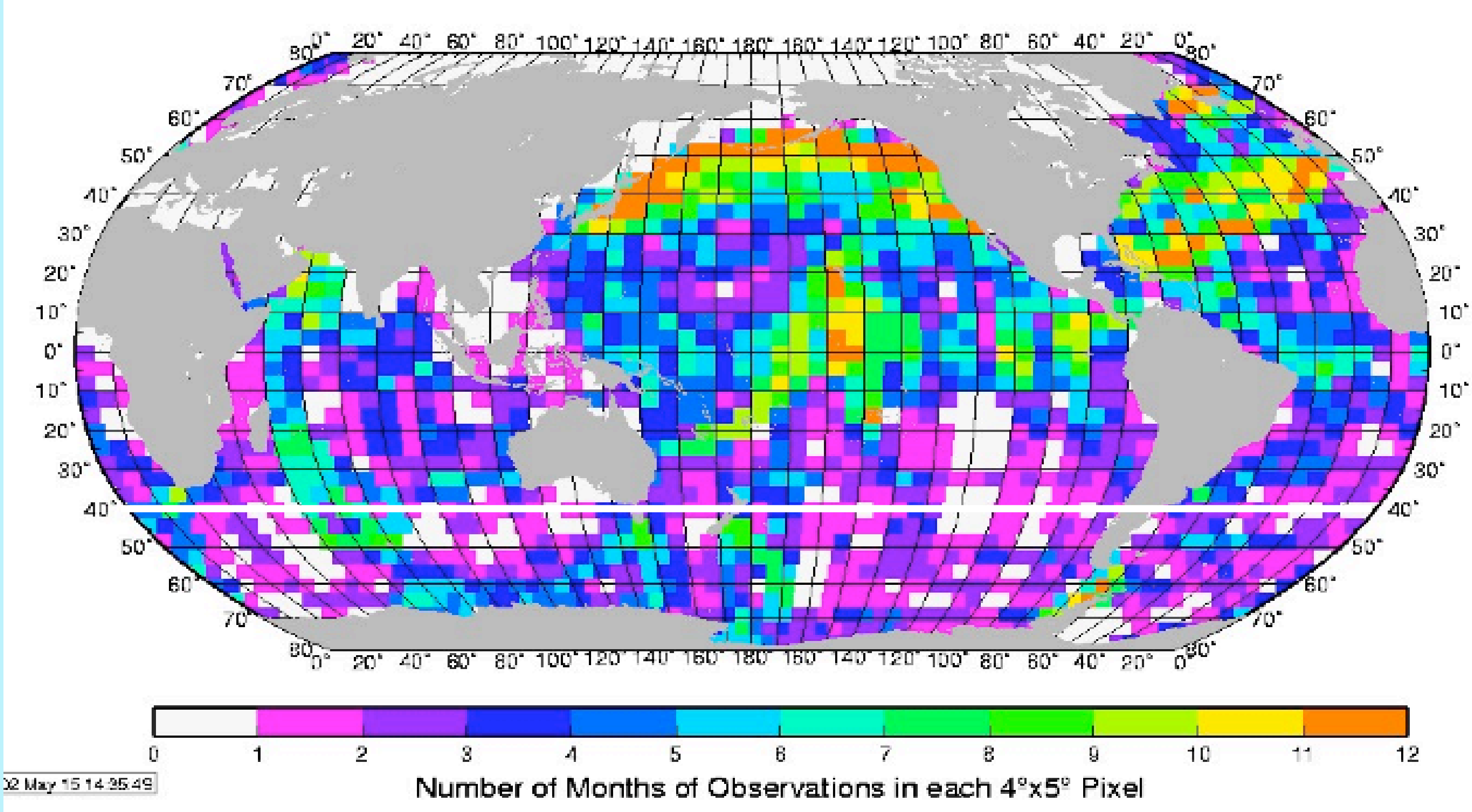
Mean Annual CO_2 Flux via Takahashi pCO_2 database

Takahashi et al, (2002)



- From this, Southern Ocean is a considerable net CO_2 sink (~0.6PgC/yr)
- Most uncertainty in the Southern Ocean CO_2 flux

Problems with the pCO_2 database in the Southern Ocean



Sweeney et al, 2000

- Seasonal sampling bias
- Inter-annual sampling bias

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Concept to estimate the air-sea CO_2 flux

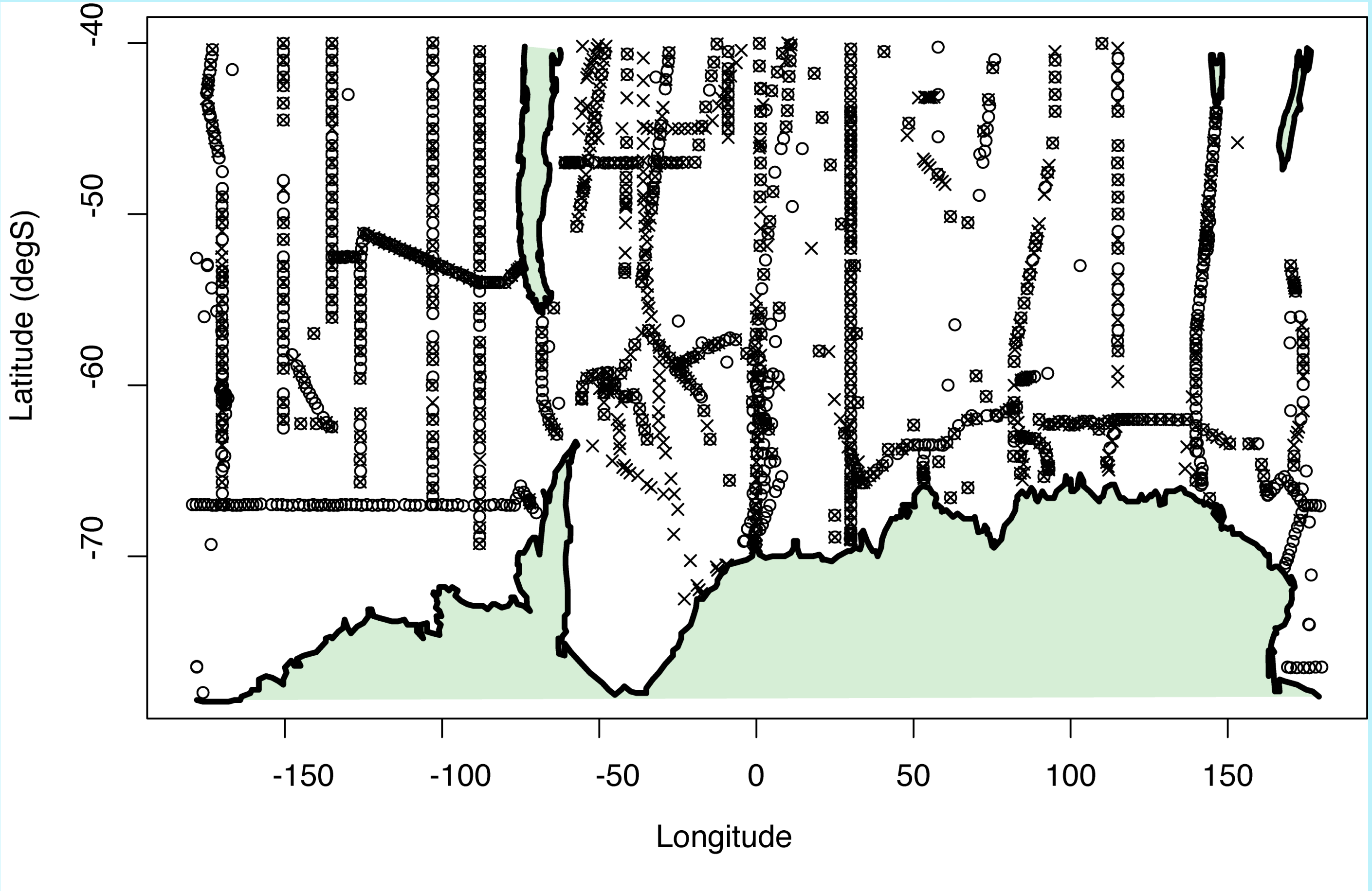
- 1) Gather all available DIC/ALK surface measurements and normalise the anthropogenic CO_2 signal to a given year (1995)
- 2) Derive empirical fits for surface DIC/ALK using standard hydrographic measurements (T,S,nuts). Similar to previous studies that derive these empirical fits (Feely et al, 2002; Millero et al, 1998, Lee et al, 2000)
- 3) Extrapolate these fits using the known seasonal cycles of T,S,nuts from the World Ocean Atlas 2001
- 4) Calculate the seasonal pCO_2 distribution from the extrapolated seasonal cycles of DIC/ALK
- 5) Determine the seasonal and annual air-sea CO_2 flux and associated uncertainties.

Advantage: Not subject to seasonal/interannual biases since the extrapolations are based on standard hydro parameters whose seasaonal cycles are well known

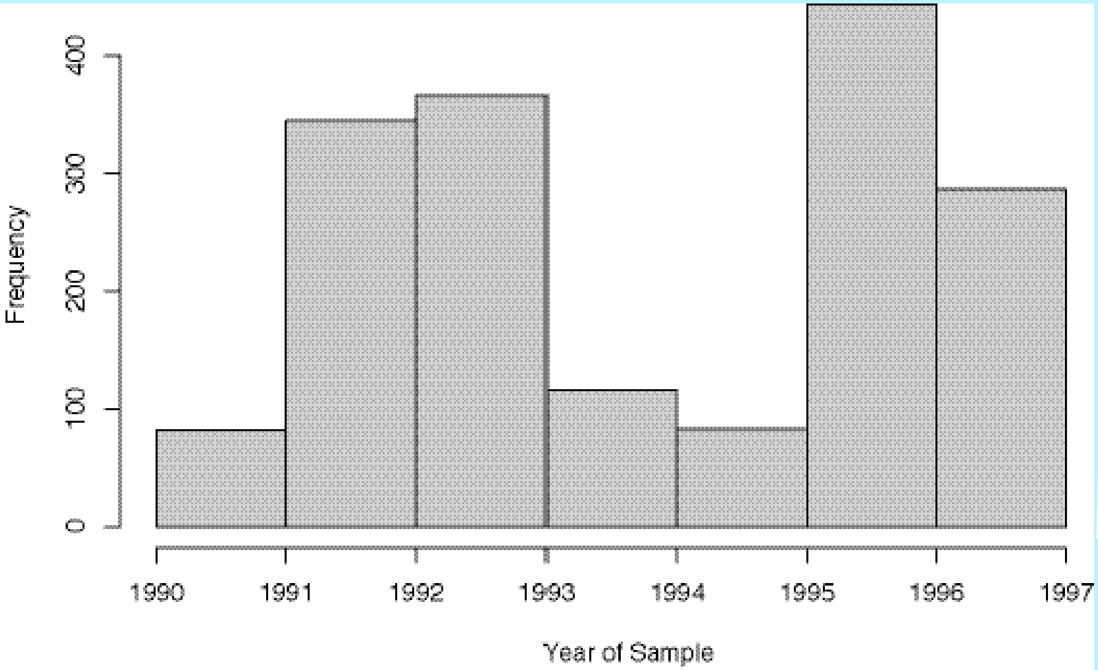
Disadvantage: Indirect determination of pCO_2 and reliant on uncertain choice of CO_2 dissociation constants

Concept for estimating CO_2 flux in the Southern Ocean

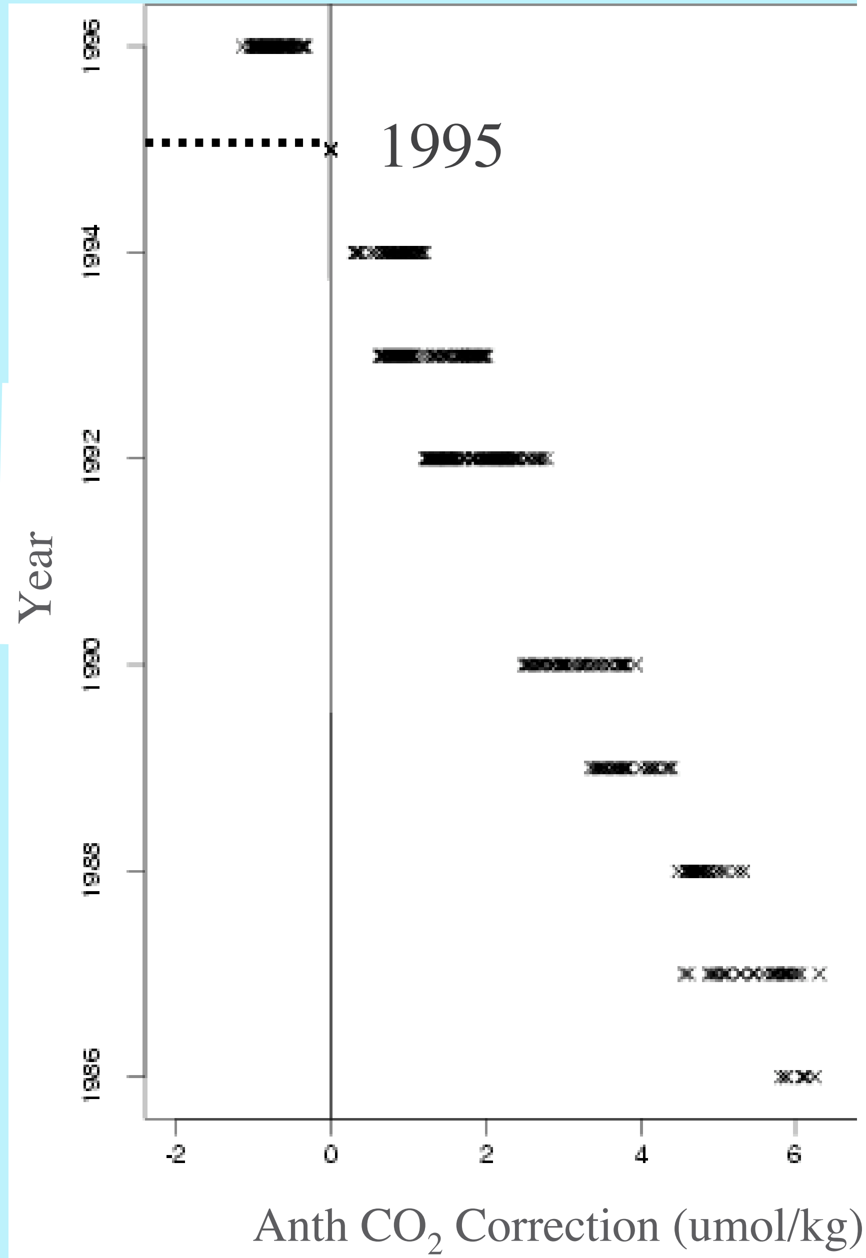
Step 1) Gather all available DIC/ALK surface measurements
Fit surface DIC measurements using more regularly sampled hydrographic measurments (temp, sal, nurients)



Correct for the Anthropogenic CO_2 Component



•DIC concentrations were corrected to the year 1995 using the CFC-age methodology



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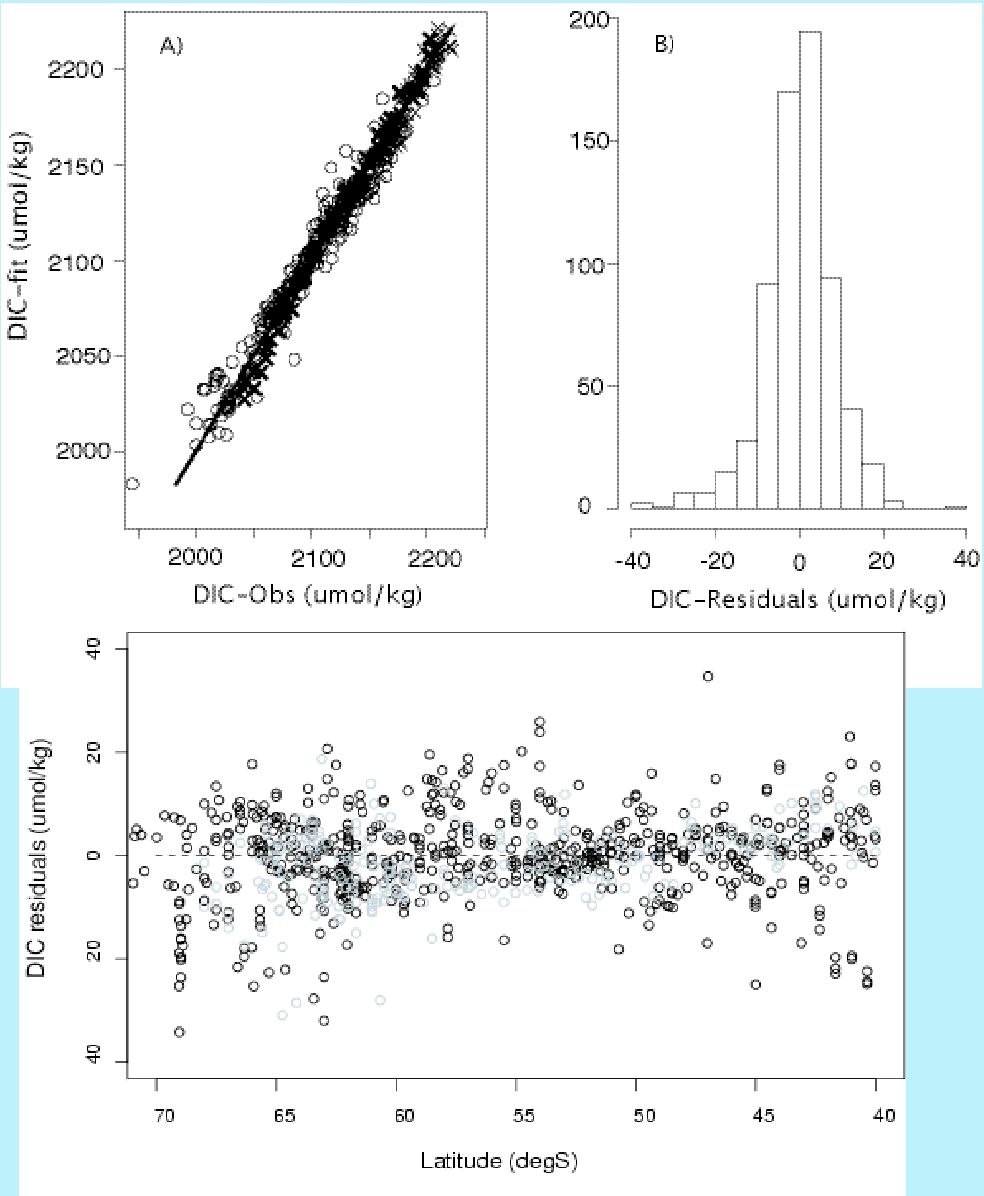
Derive Empirical fits for surface DIC / ALK



$$DIC_{obs} = \alpha_0 + \sum_{i=1}^{n} \alpha_i P_i + \varepsilon$$

DIC= f(temp, sal, nitrate, silicate, oxygen)

S.E = ±8umol/kg

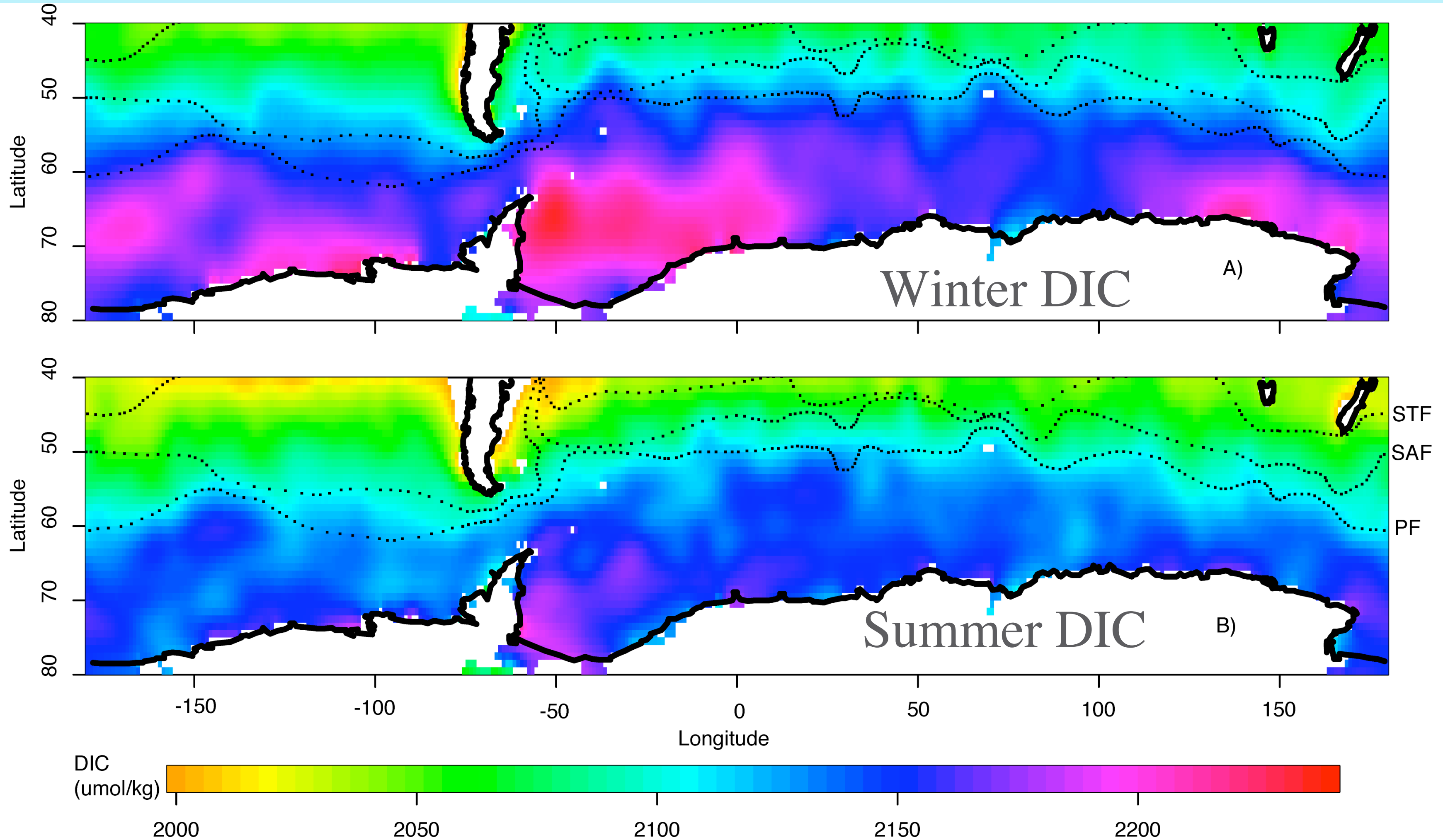
n=668

ALK=f(temp,sal)

S.E= ±9umol/kg

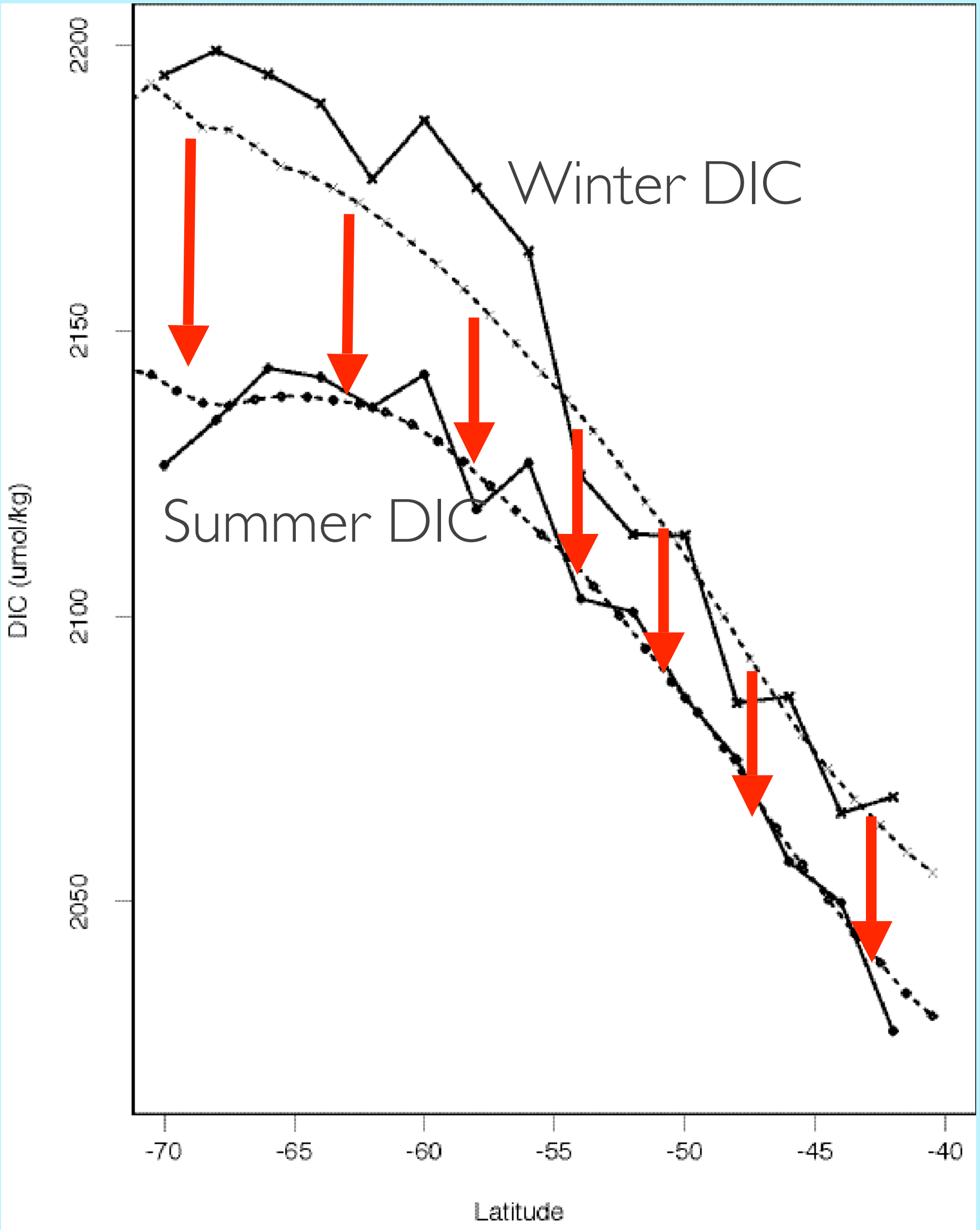
- Similar to previous regression applications only using more data (eg Feely et al, 2002, Lee et al, 2000, Millero et al, 1998)
- No change to the fit with season
- No strong residual pattern indicating potential biases

Step 2) Extrapolate using World Ocean Atlas climatology 2001



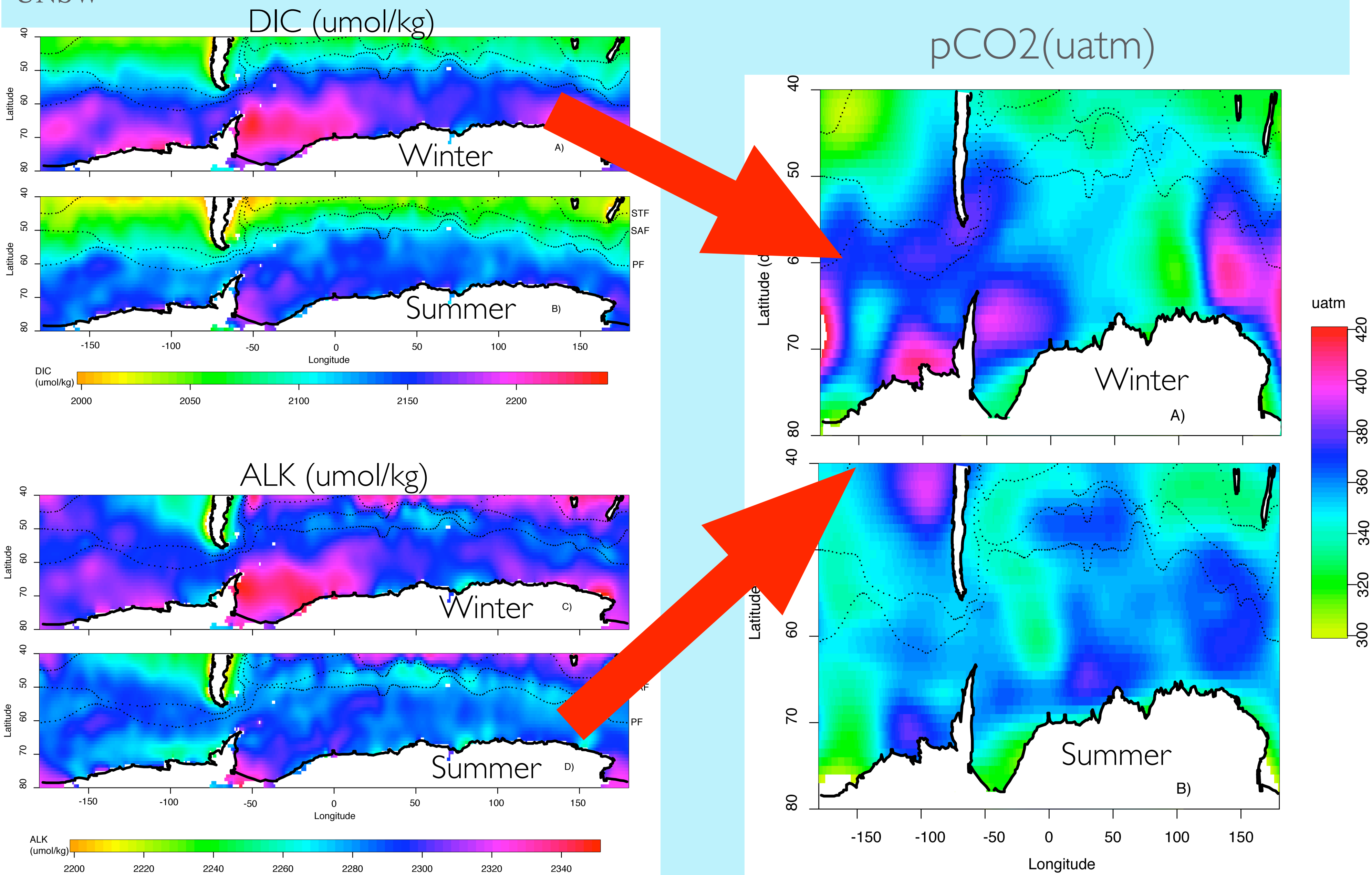
- Results in a full seasonal cycle for DIC and ALK in the Southern Ocean

Test the results with direct DIC observations



- Reproduces the meridional DIC structure and seasonal drawdown quite well
- Winter to summer drawdown of ~30umol/kg

Step 3) Calculate seasonal pCO_2 from DIC/ALK



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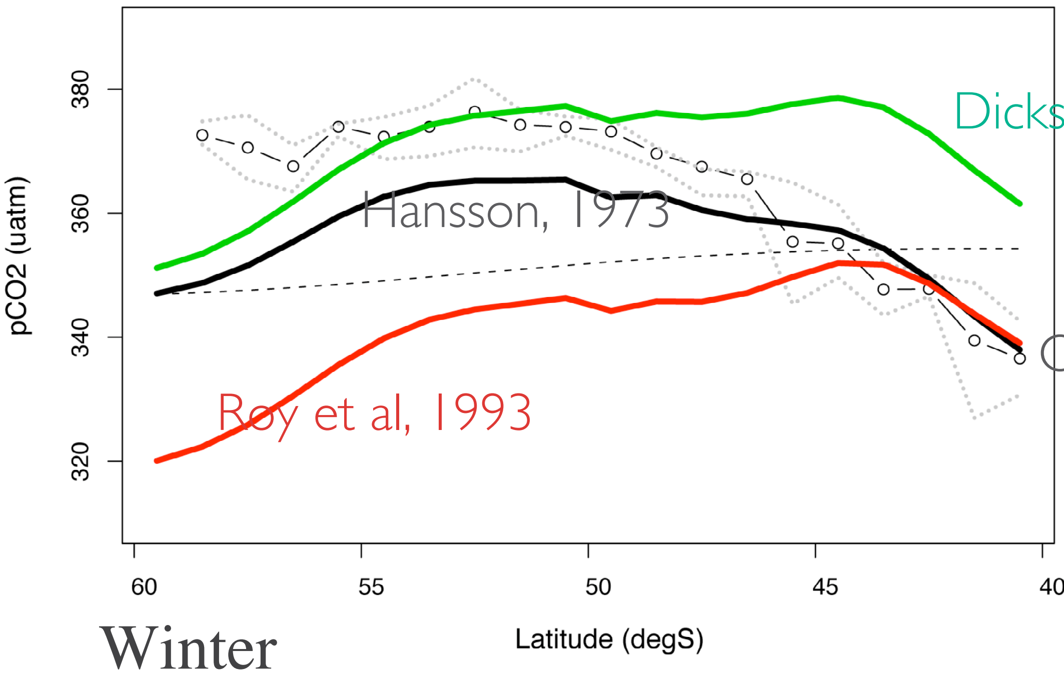
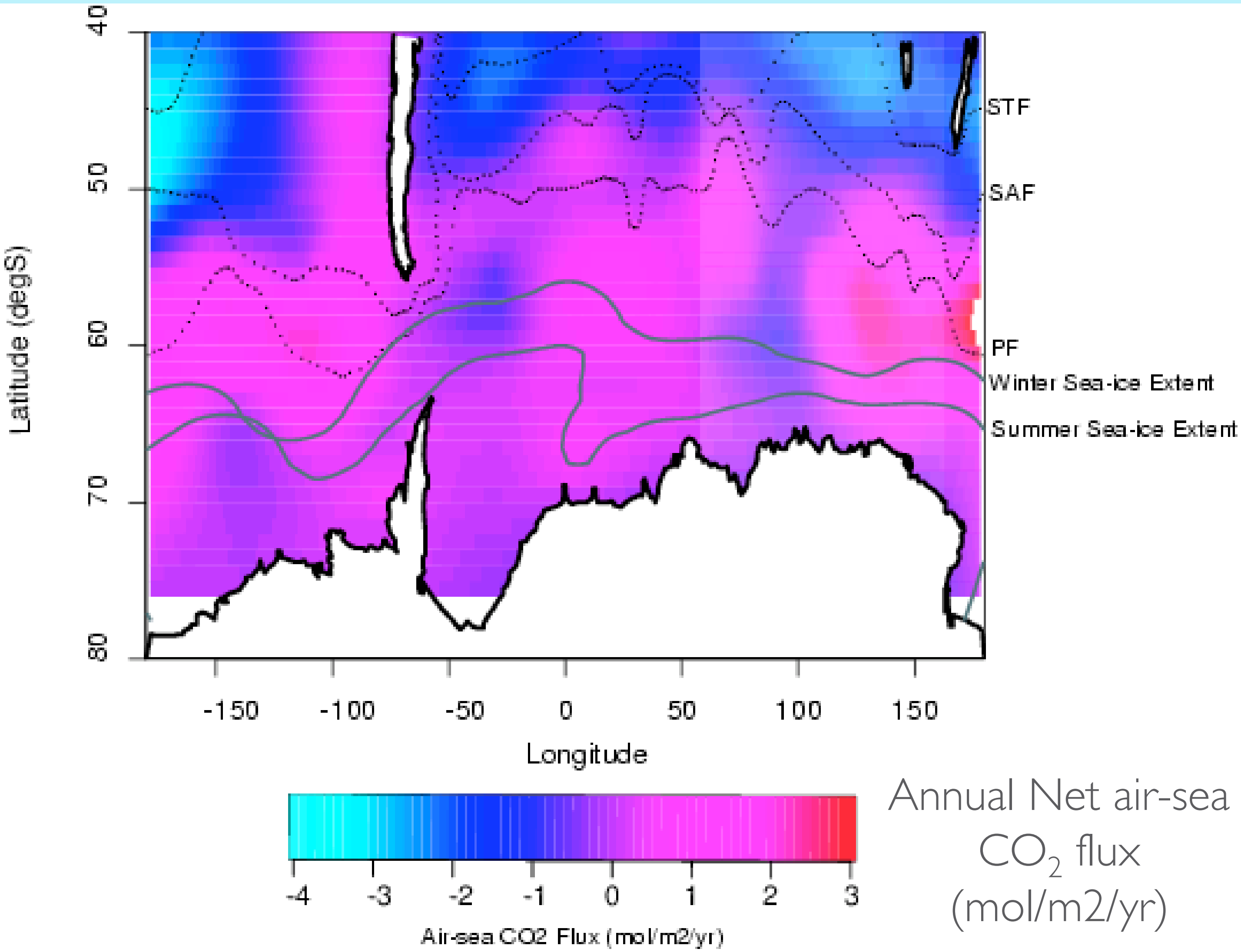
Impact of CO_2 dissociation constants



Winter

- Varies by about ±10uatm
- Used Hansson(1973) - middle estimate
- Not optimal - need tri-carbon sampling strategy of DIC/ALK/pCO_2 for future measurements

Step 4) Calculate the CO_2 flux



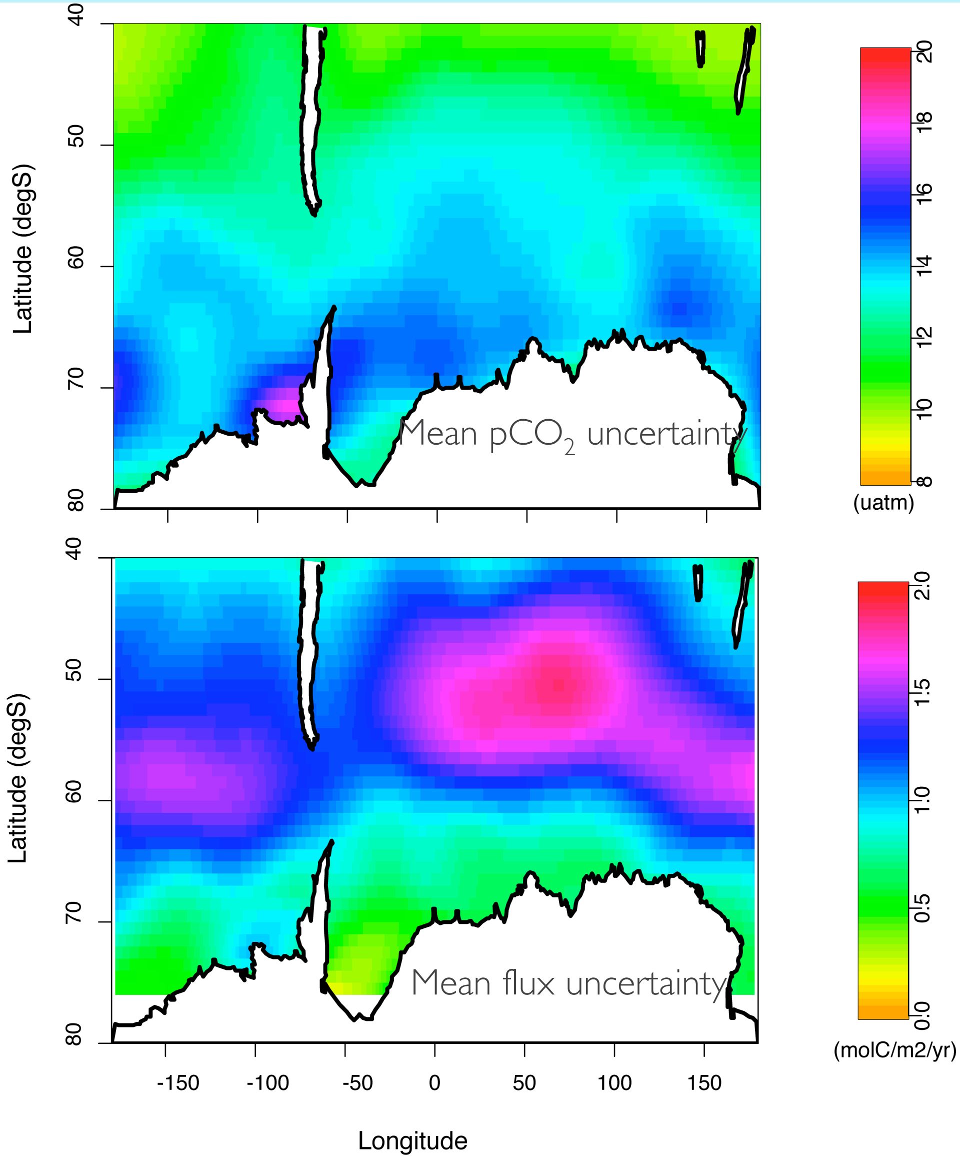
Annual Net air-sea CO_2 flux (mol/m2/yr)

Flux= $\Delta pCO_2 \times k$

- NCEP 10m winds
- Wanninkhof (1992) gas exchange
- Sea-ice concentration taken into account

- Integrating over entire SO implies a moderate CO_2 sink (~0.2PgC/yr)

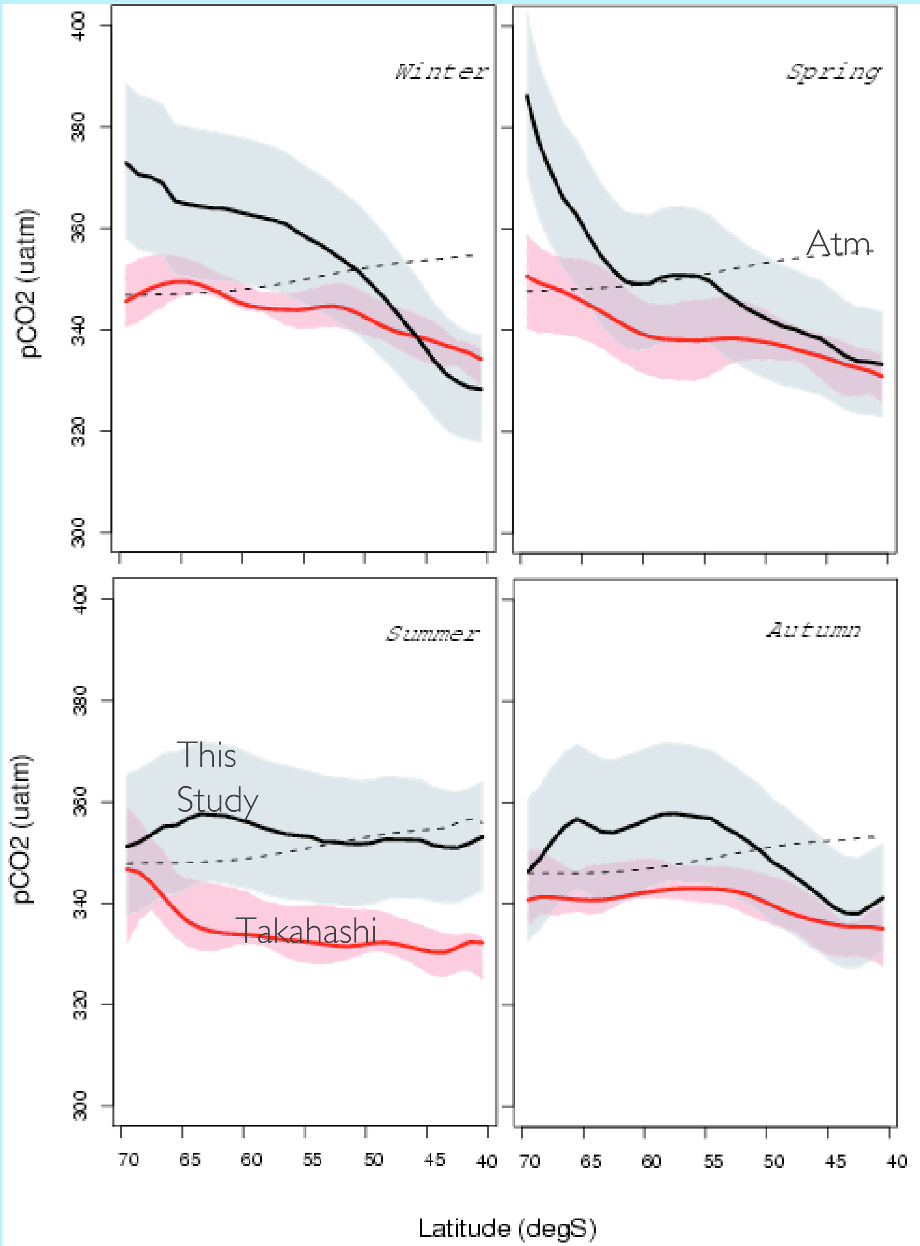
Uncertainty Estimate from Monte-Carlo Analysis



Propagation of uncertainties

- DIC ~ ±8umol/kg, ALK ~ ±9umol/kg
- Wind ~ ±2m/s
- CO_2 dissociation constants ~ ±10uatm
- Final integrated error ~ ±0.26PgC/yr

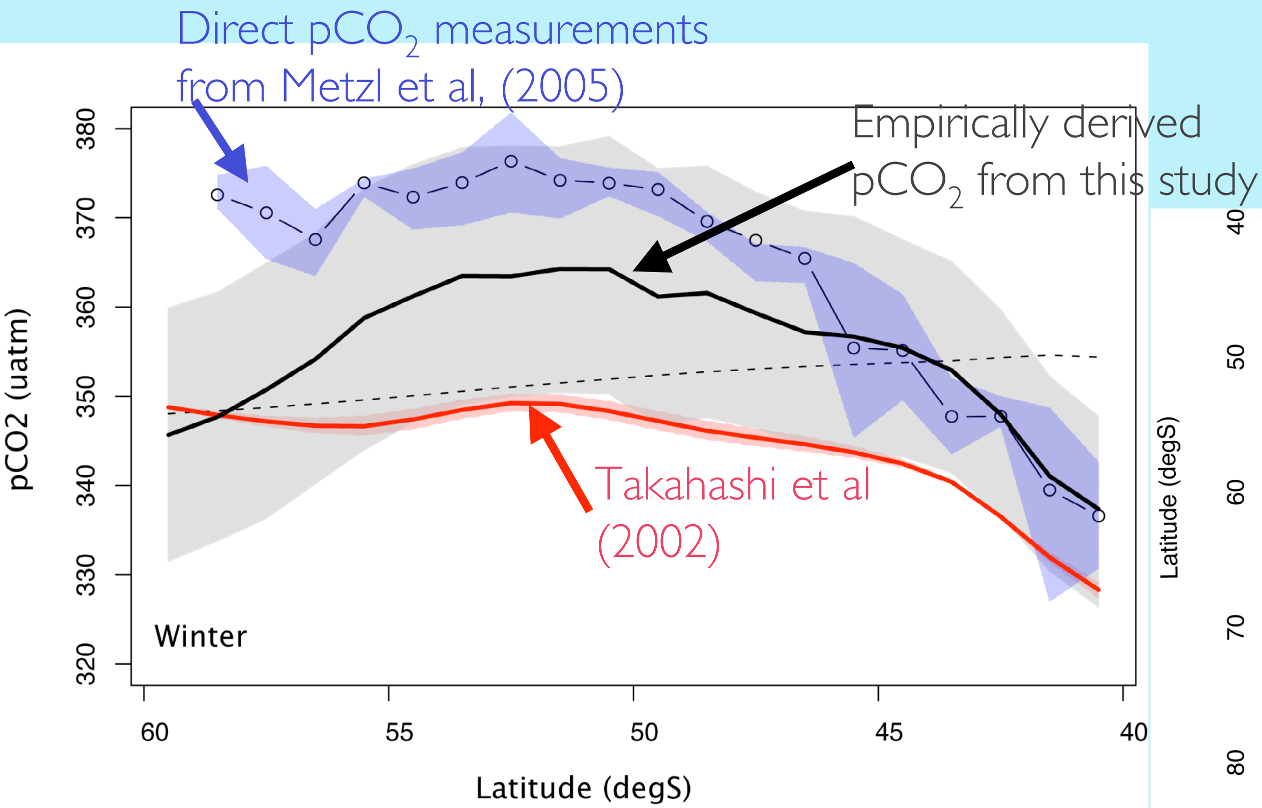
Zonal Comparison with Takahashi pCO_2 database

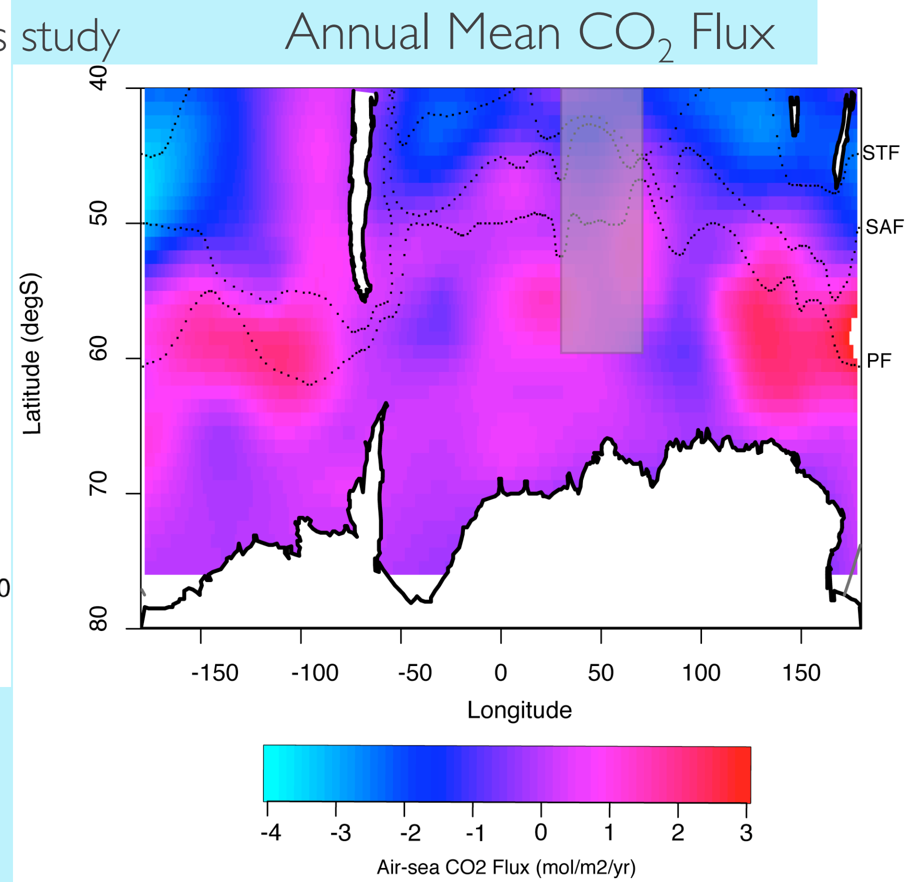


Important Points

- In general higher pCO_2 than Takahashi
- Strong winter pCO_2 source south of the PF (~50degS)

Evidence of strong winter-time source south of PF





- Direct and indirect pCO_2 suggests a source of CO_2 south of the PF
- Probably associated with ventilation of deep waters and inadequate biological drawdown
- Takahashi seems to be underestimating winter source

Southern Ocean Flux Mechanisms

Slightly Revised Schematic from
Niki Gruber

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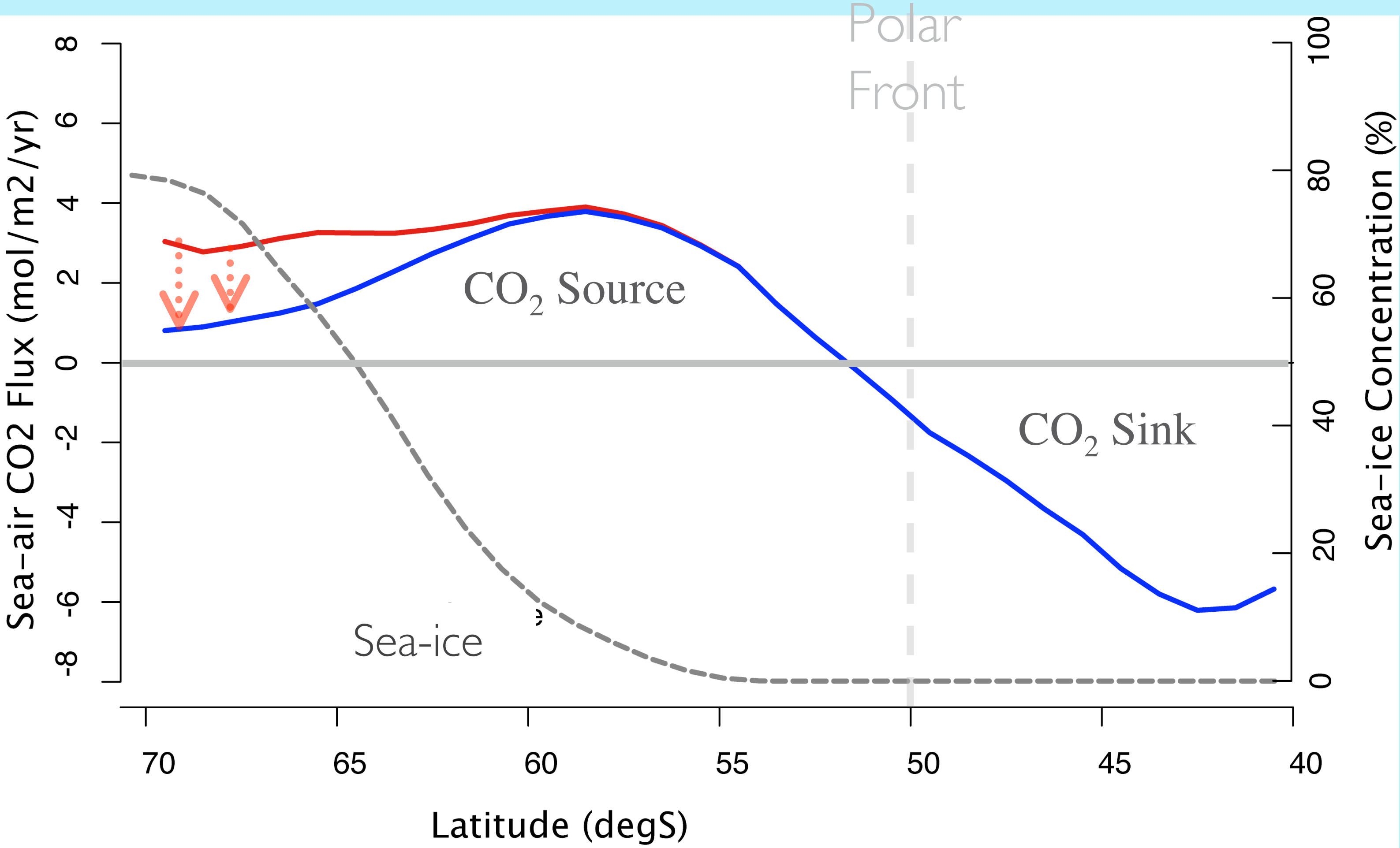
Summary of recent observational estimates for SO CO_2 uptake

Methodology	Reference	Net CO_2 flux (Pg C/yr)		
		40-50°S	50-60°S	60-70°S
Oceanic Inversion	[Gloor et al., 2003]	-0.4		-0.1
TRANSCOM-2 Atmospheric Inversions	[Gurney et al., 2002]	-0.3		-0.1
Atmospheric Inversion	[Roy et al., 2003]		-0.2 ± 0.2	
Oceanic pCO_2 climatology – NCEP 10m winds	[Takahashi et al., 2002] - corrected		-0.45 to –0.35	
Summer/winter pCO_2 measurments	[Metzl et al., 2005]		-0.1	
Summer/winter pCO_2 measurments	[Metzl et al., 1999]	-1		
Oceanic/Atmospheric Inversion	[Jacobson et al., 2005]	-0.4±0.3		
Oceanic DIC/ALK climatology – using NCEP 10m winds and sea-ice effects on air-sea gas exchange	This Study	-0.47±0.25	0.16±0.08	0.12±0.08
		-0.19±0.26		

- Methods are converging suggesting a moderate Southern Ocean CO_2 sink (~0.3PgC/yr)

NB: Needs to be a consistent definition of the Southern Ocean within these methods

Including the effects of sea-ice important



- Sea-ice limits the high latitude outgassing by ~0.1PgC/yr

Importance of including silicate and phosphate when calculating pCO_2 in the Southern Ocean

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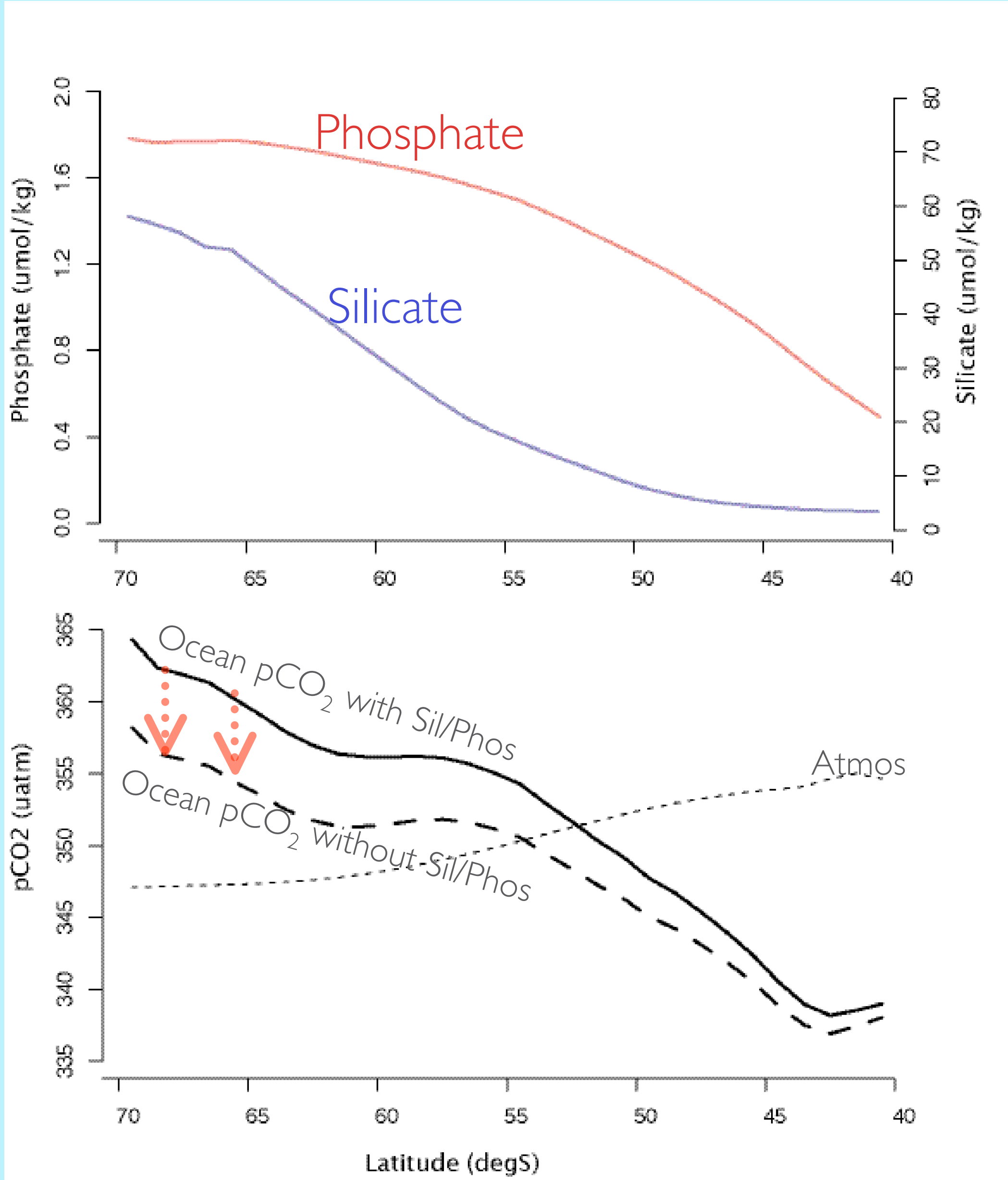
Total Alkalinity

$$ALK_{TOTAL} = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] + [HPO_4^{2-}] + 2[PO_4^{3-}] + [SiO(OH)_3^-] + [NH_3] + [HS^-]..... - [H^+] - [HSO_4^-] - [HF] - [H_3PO_4]$$

- Without including Sil/Phos results in an underestimation of pCO_2 by ~8uatm!
- Models need to include these terms when calculating pCO_2 in the Southern Ocean



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Summary

- Surface DIC can be empirically derived in the Southern Ocean (~8umol/kg), useful for all types of carbon cycle analysis
- Empirically-derived pCO_2 distribution implies a strong sub-Antarctic CO_2 sink (~0.5PgC/yr), which is partially offset by a CO_2 source south of the Polar Front (~0.3PgC/yr)
- Implies the Southern Ocean to be a moderate CO_2 sink (~0.2PgC/yr) and is in relative agreement with other independent methods
- Method could be improved by implementing a tri-carbon sampling strategy for each sample in order find out optimal CO_2 dissociation constants for the SO
- Important to include silicate/phosphate in calculating pCO_2 from DIC/Alk in the Southern Ocean for modelling studies
- Finally, there needs to be a consistent agreement in defining the northern latitude extent of the Southern Ocean for all differing methodologies

Direct way to measure air-sea CO_2 fluxes

Flux= $\Delta pCO_2 \times k$
(gas-exchange coeff)