The Meridian Integral: A potential new tool for assessing ocean model air-sea gas exchange

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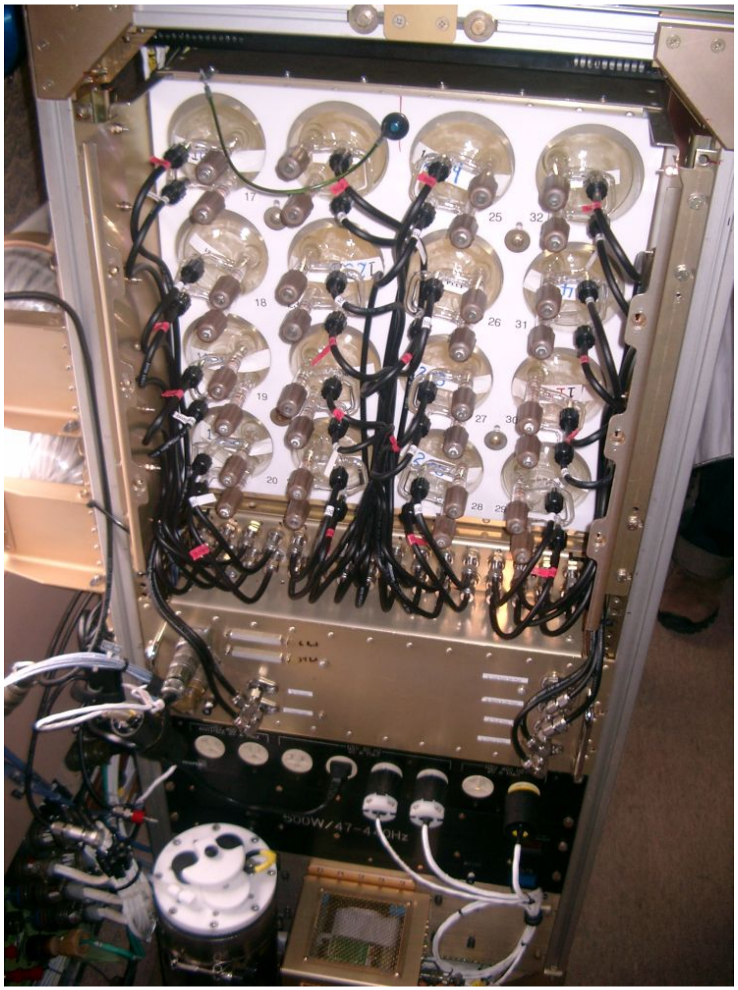
NCAR/SIO HIPPO Contribution 1: AO2

- Developed by Britt Stephens, Steve Shertz, Andy Watt
- Measures $\delta(O_2/N_2)$ with a Vacuum Ultraviolet Absorption technique
- 1Hz+ real-time in situ data
- Measures CO_2 at 2Hz with LiCor NDIR

NCAR/SIO HIPPO Contribution 2: MEDUSA



- Samples up to 32 flasks per research flight (up to 350 per campaign)
- Fills flasks to atmospheric pressure
- Measures $\delta(O_2/N_2)$, CO_2, $\delta(Ar/N_2)$, and ^{13}C and ^{18}O isotopes of carbon dioxide.
- Flasks are shipped to SIO for analysis
- Only considering Southern Ocean flasks for this study

Scientific Context:

Atmospheric Potential Oxygen

(Equation: Keeling et al. 1998)

Oxygen adds a constraint to the carbon system, is not buffered by carbonate

APO ~ O2+CO2, or the O2 you remaining in an air sample if land photosynthesis drew CO2 down to 0

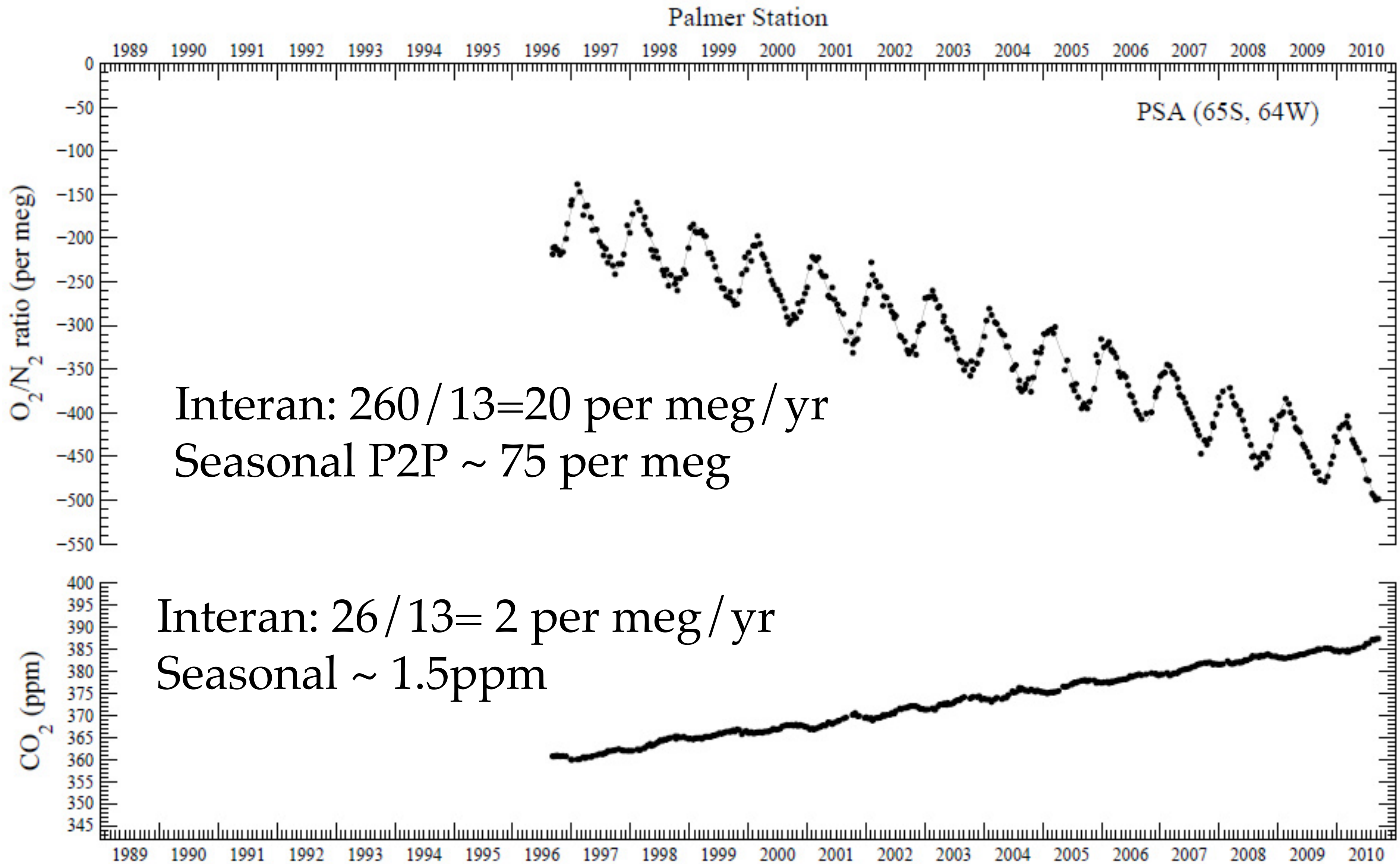
An ocean biogeochemistry tracer (biology + temp effects + ventilation) which is conservative with respect to land processes

$$\text{APO} = \delta(O_2/N_2) + \frac{R_{O_2:C}}{0.2095} X_{CO_2}$$

Measured in "per meg" (i.e. per mil*1000): useful for measuring exceedingly small changes to a large reservoir.

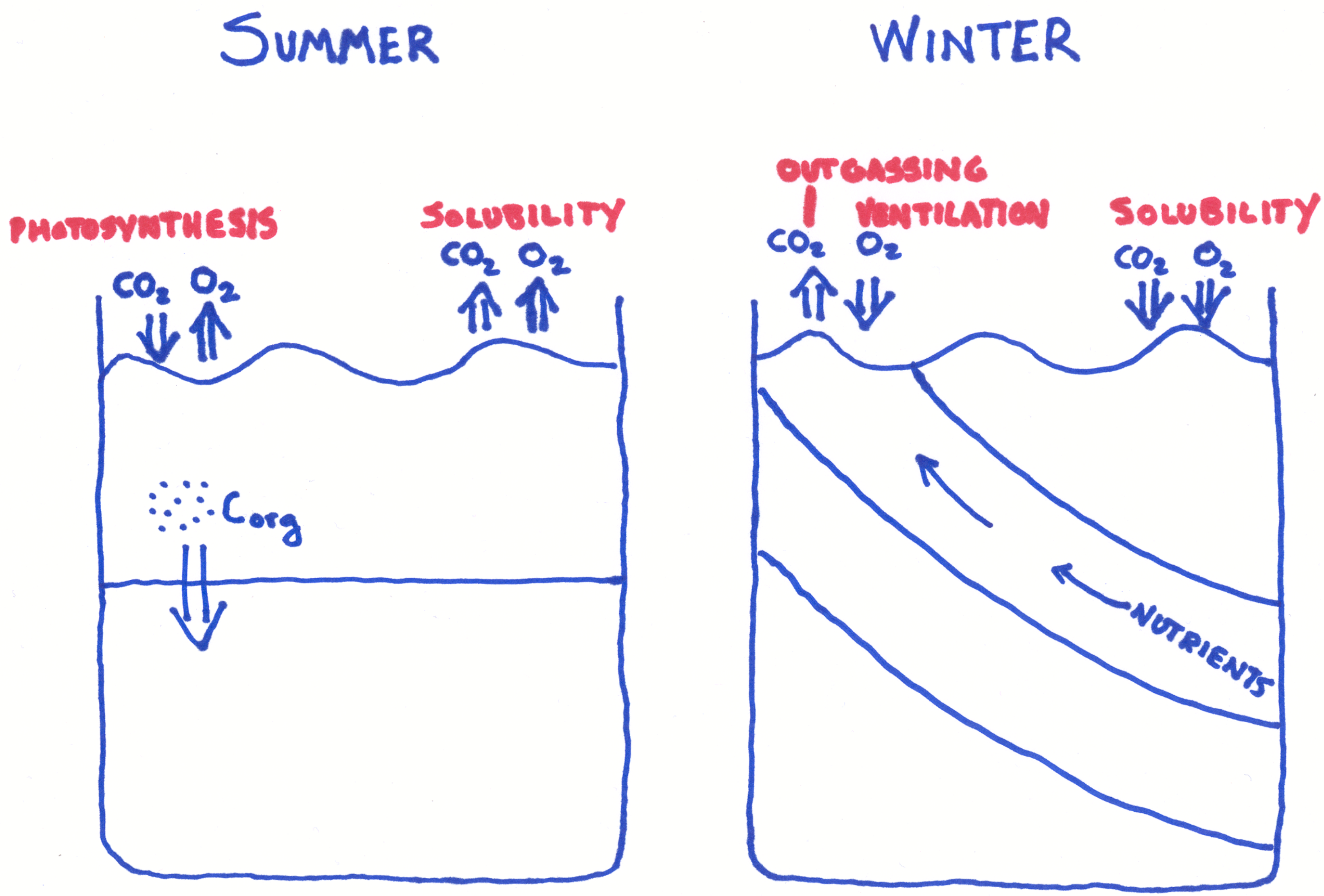
Southern Ocean Seasonal Cycles

(Figure: http://bluemoon.ucsd.edu;)



Southern Ocean O_2,CO_2 Air-Sea Exchange:

Marine biology and temperature forcings to seasonal signals

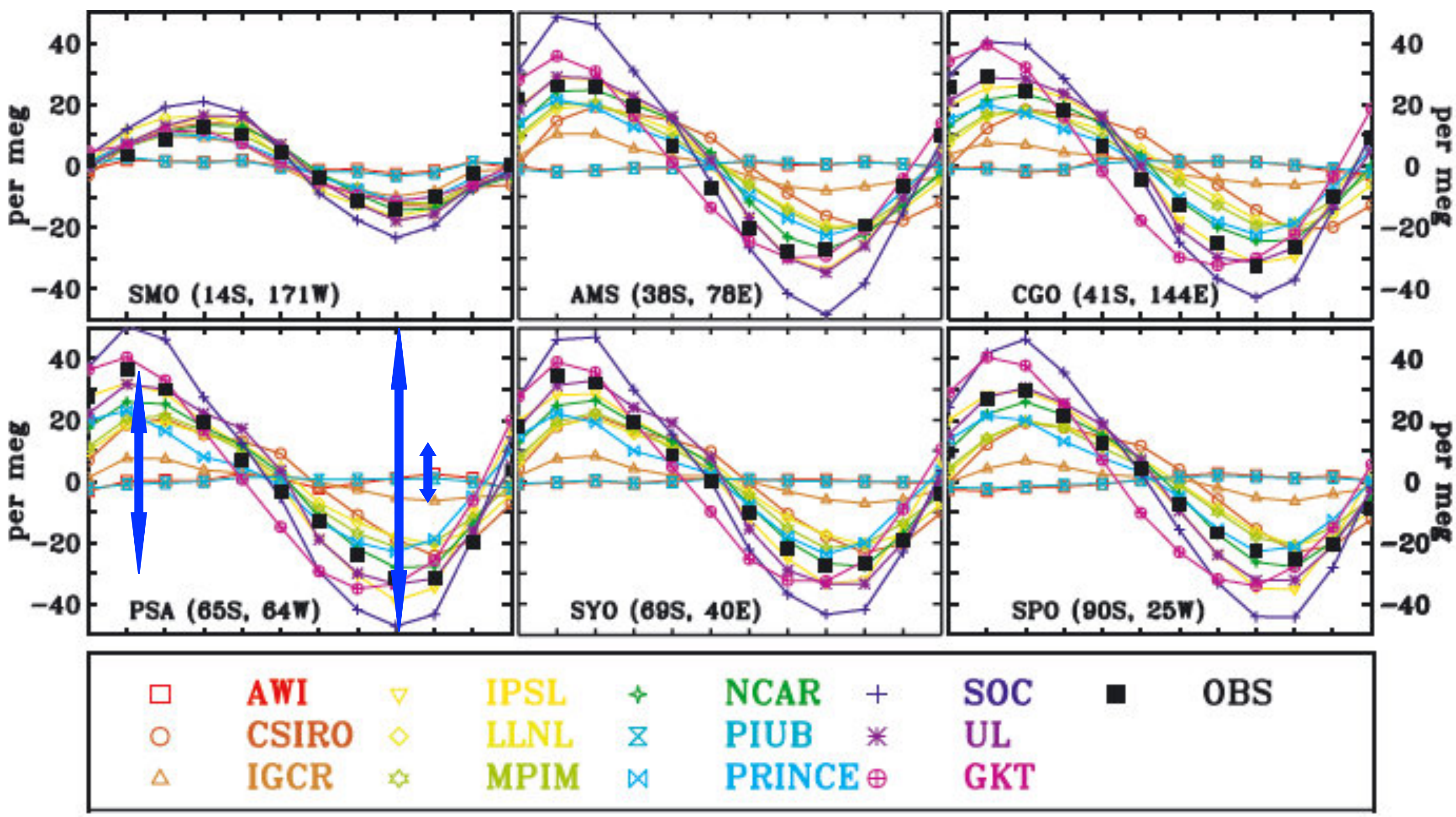


Modeling and TransCom: The Atmospheric Tracer Transport Model Intercomparison Project

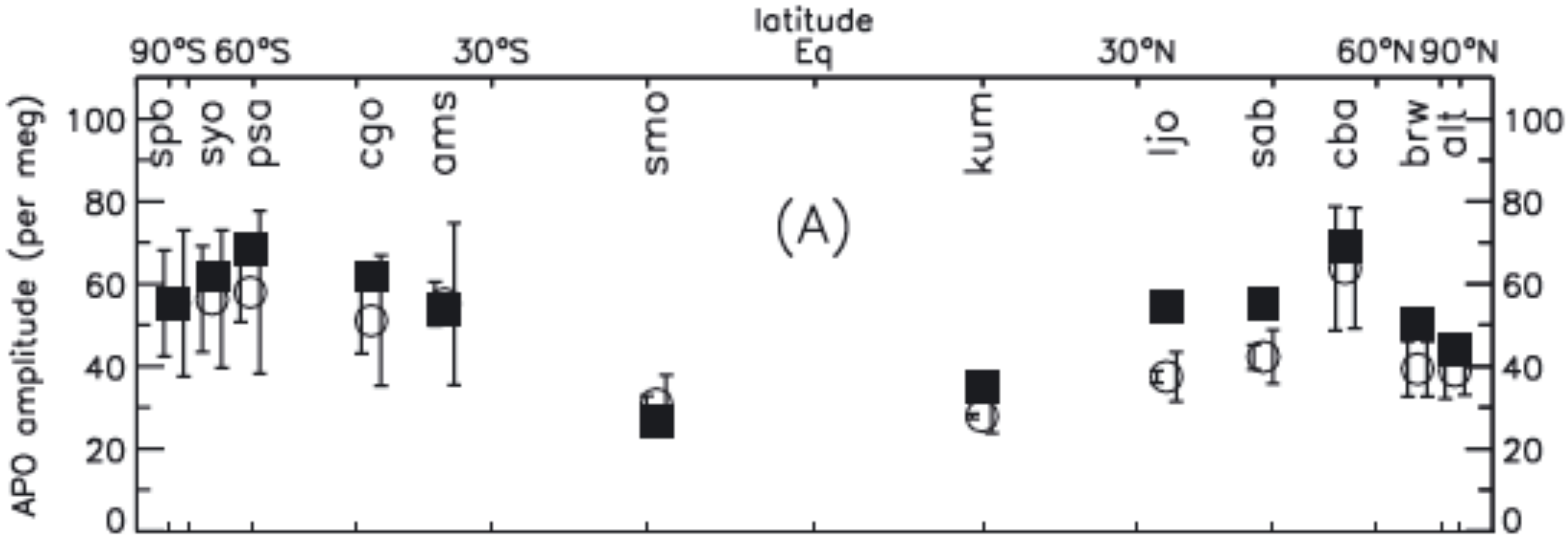
- What is the season O_2 flux in/out of the Southern Ocean
- Ocean Biogeochemistry Models or Dissolved Climatologies generate fluxes
- Atmospheric Transport Models distribute them atmosphere

- TransCom: ~16 ATMs with common input data and shared output meant to diagnose uncertainty (primarily in CO_2) in ATMs
- Blaine (2005), used TransCom ATMs, but drove them with Garcia and Keeling (2001) fluxes (instead of the usual inversion for just CO_2).
- Cindy Nevison and others have continued to consider these APO TransCom results.

Naegler et al. 2007 & The Modeling Impasse



Naegler et al. 2007 (cont.)

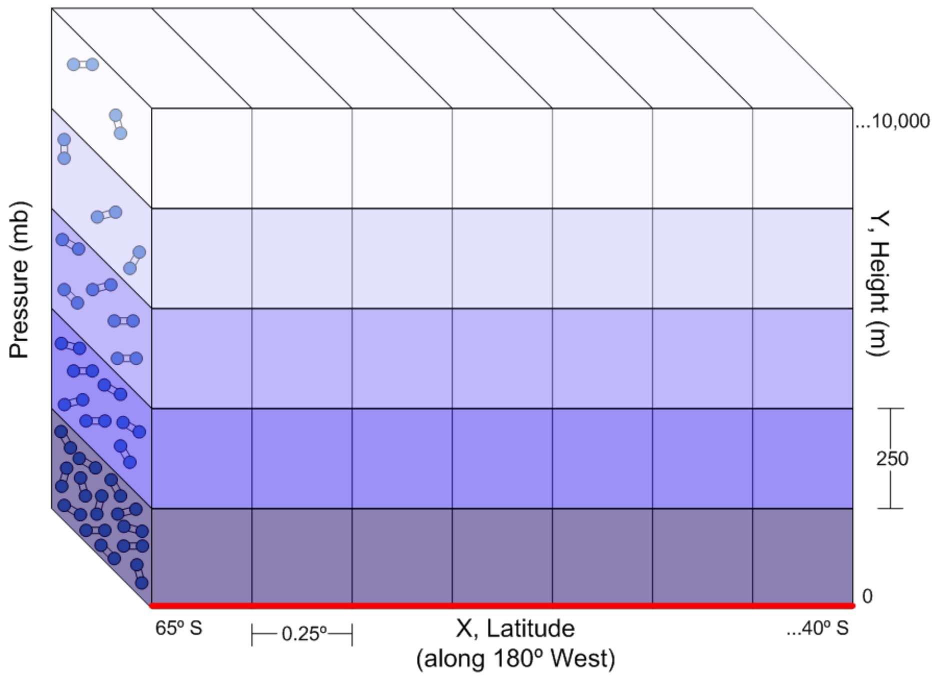


"We conclude that it is difficult to validate ocean models based on APO because shortcomings in atmospheric transport models and problems with data representivity cannot be distinguished from ocean model deficiencies."

-Naegler et al. 2007

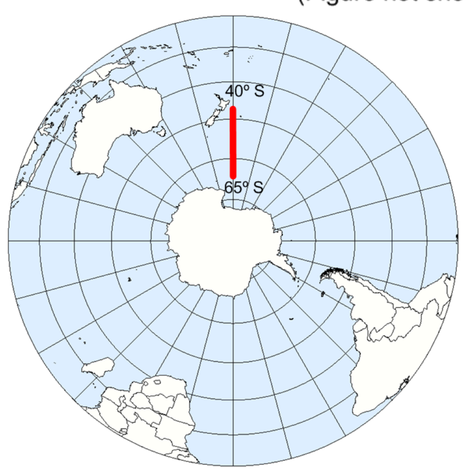
Left error bar: d(TM2/TM3)
Right error bar: Ocean Model Spread

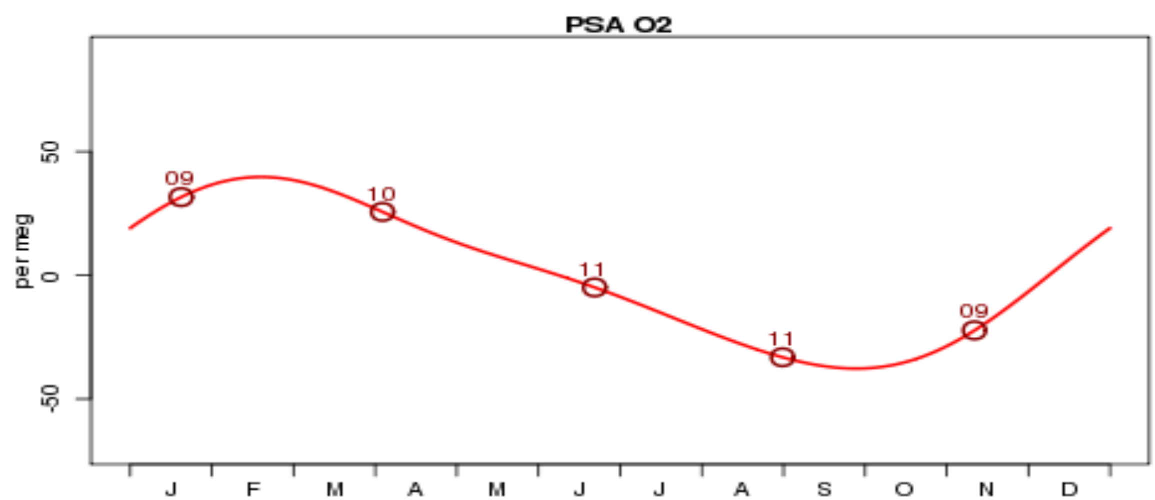
Southern Ocean "Meridian Integral"



- To address the question of vertical mixing in ATMs, air-sea fluxes in OBMs, FFMs
- Reduces the need to specify vertical mixing (as per ATMs) because, regardless of how the APO signal is vertically distributed, the integral constrains the TOTAL seasonal flux

(Figure not shown to scale)





Work Summary

Task	Completion
Flying HIPPO Missions	H1-3 Flown; H4-5 in 2011
Data consolidation and Analysis	Most of code written; More robust scheme to come; Much analysis still to so
Calculation, Evaluation of Meridian Integral	Prelim MED, AO2 vals for H1-3 Rough projected values for H4-5
Comparison with Blaine output	Promising
Evaluating, Rescaling G&K	None
Evaluating OBMs	None
Comparison with ATMs	H1-3, very prelim with TM3
Scoring OBMs, ATMs by agreement	None

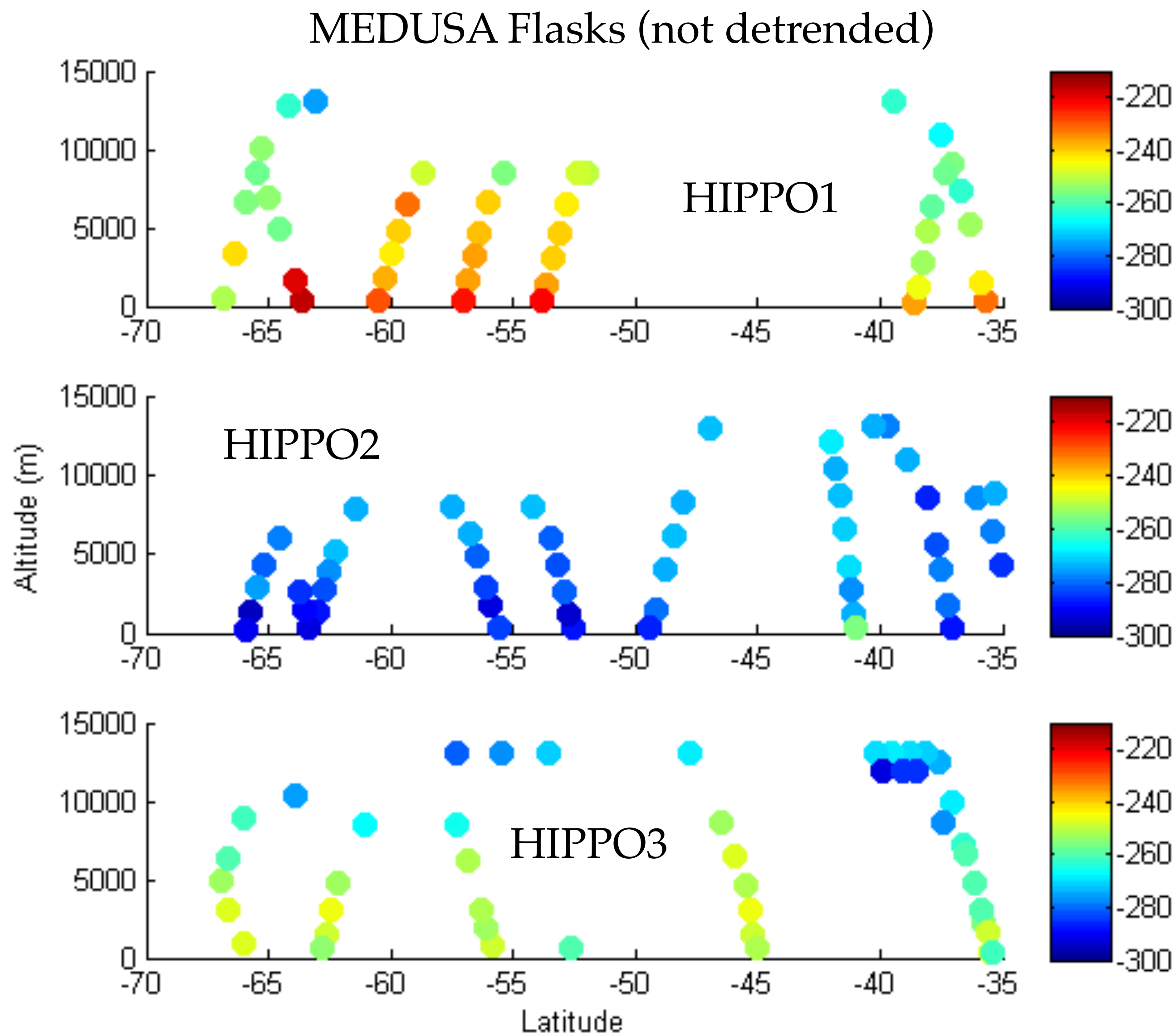
APO Results: S. Ocean Data

MEDUSA flasks:

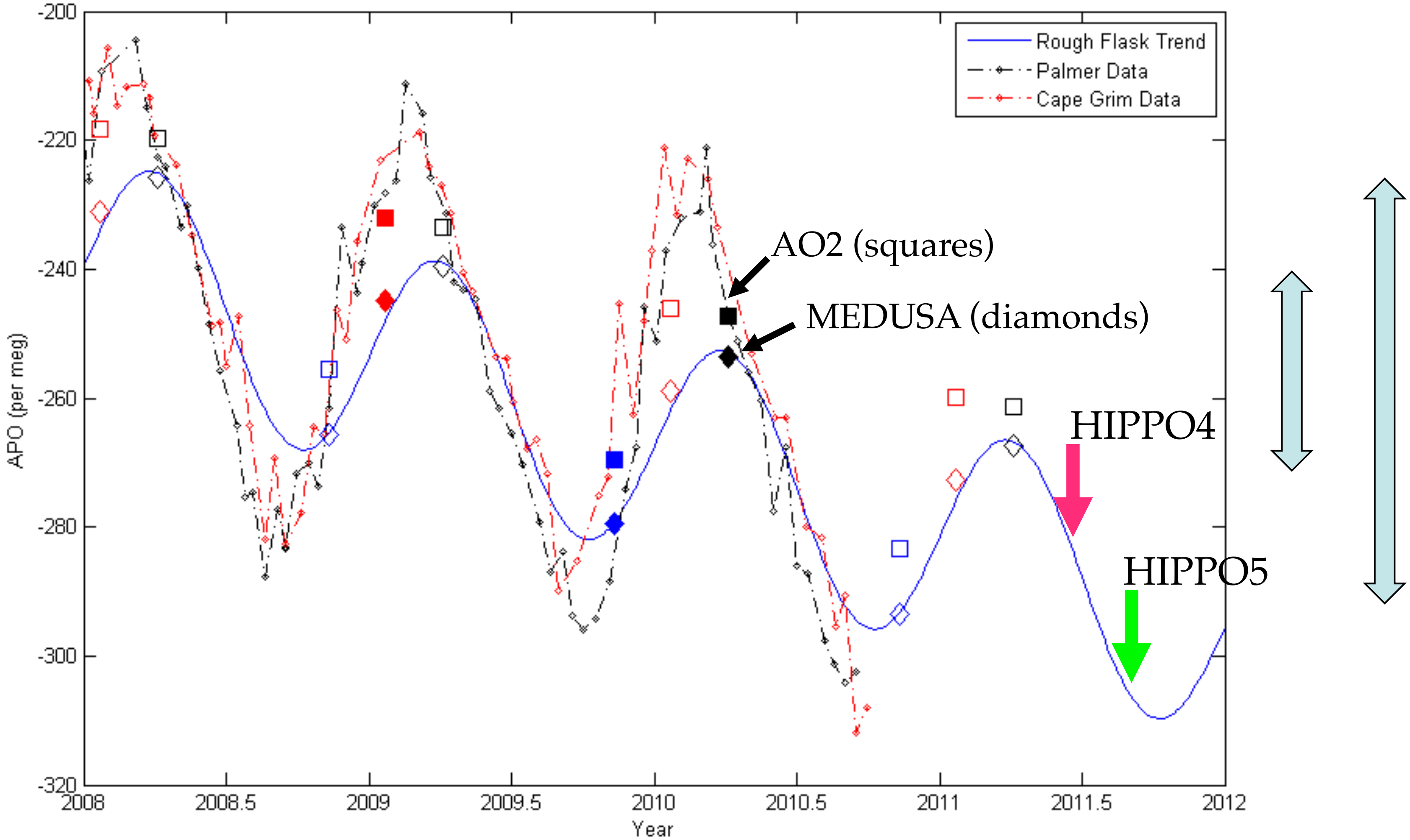
- HIPPO1: 42
- HIPPO2: 51
- HIPPO3: 49

Vertical grads up to 70 per meg

Surface APO is typically higher for H1,3; lower for H2.

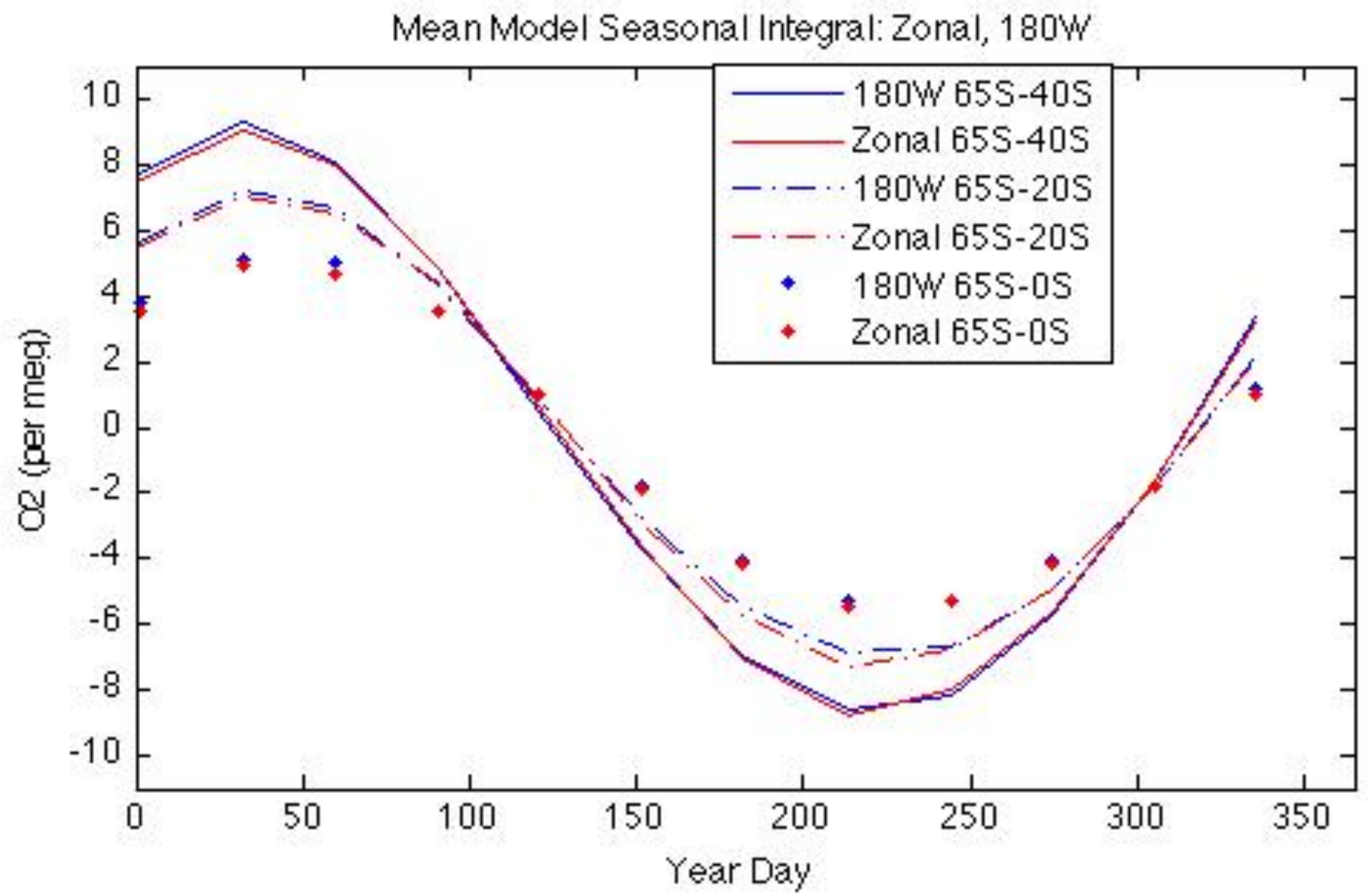


The Meridian Integral: Current and Projected

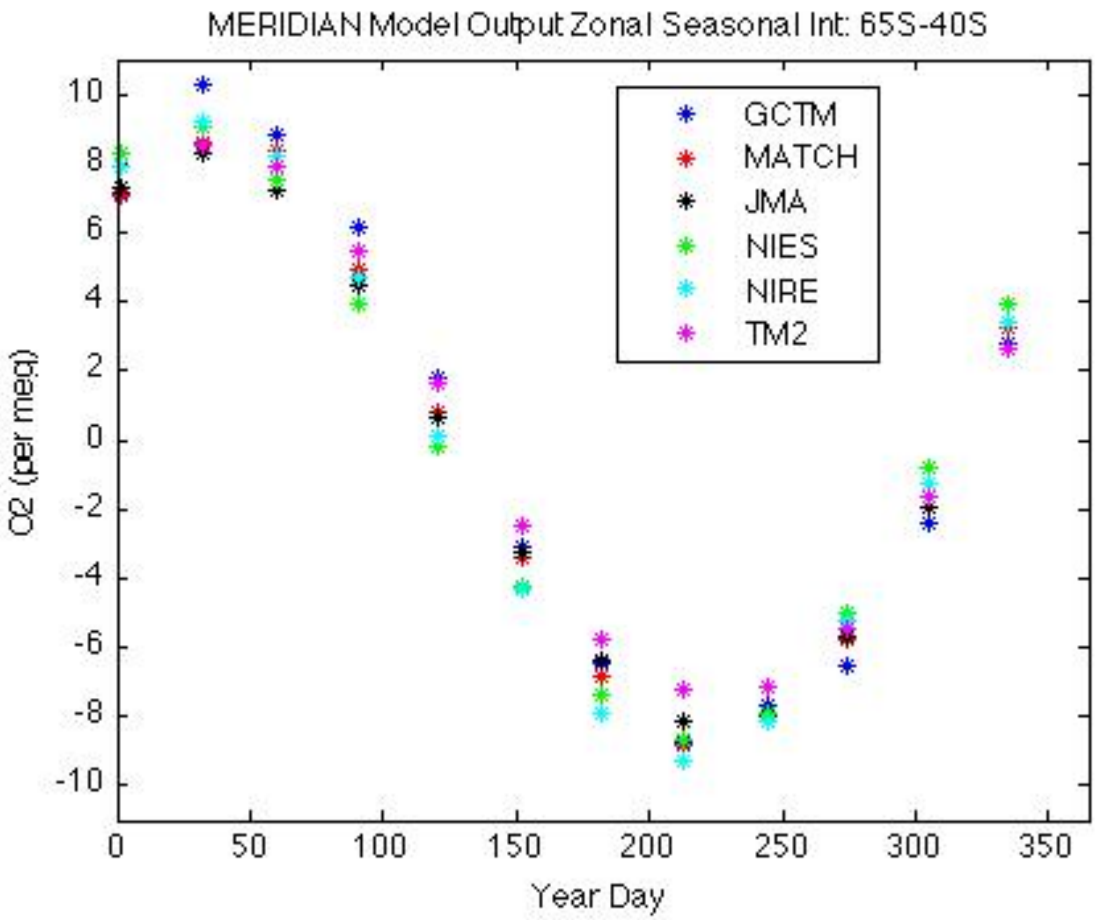


H1: Red H2: Blue H3: Black H4: Magenta H5: Green

TransCom Seasonal Integral (mean of models): Zonal vs. 180W



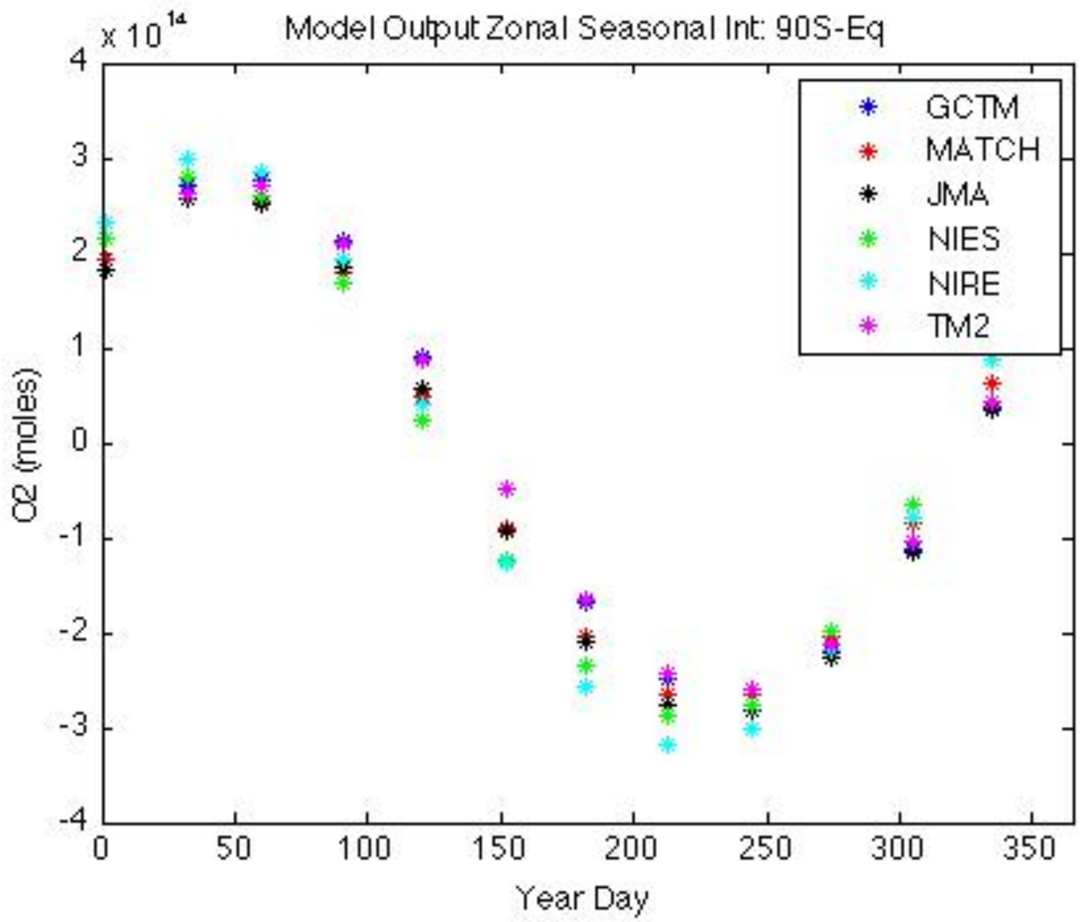
TransCom Meridian Integral

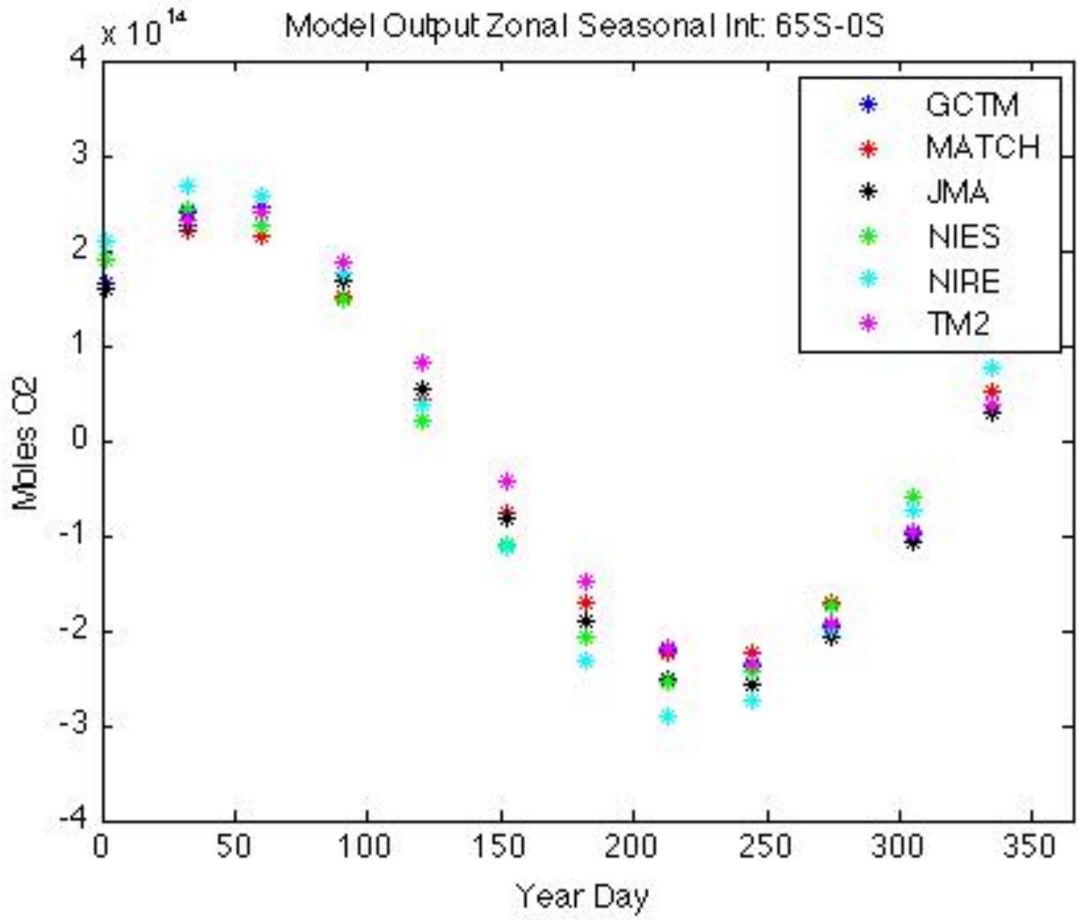


Conclusions

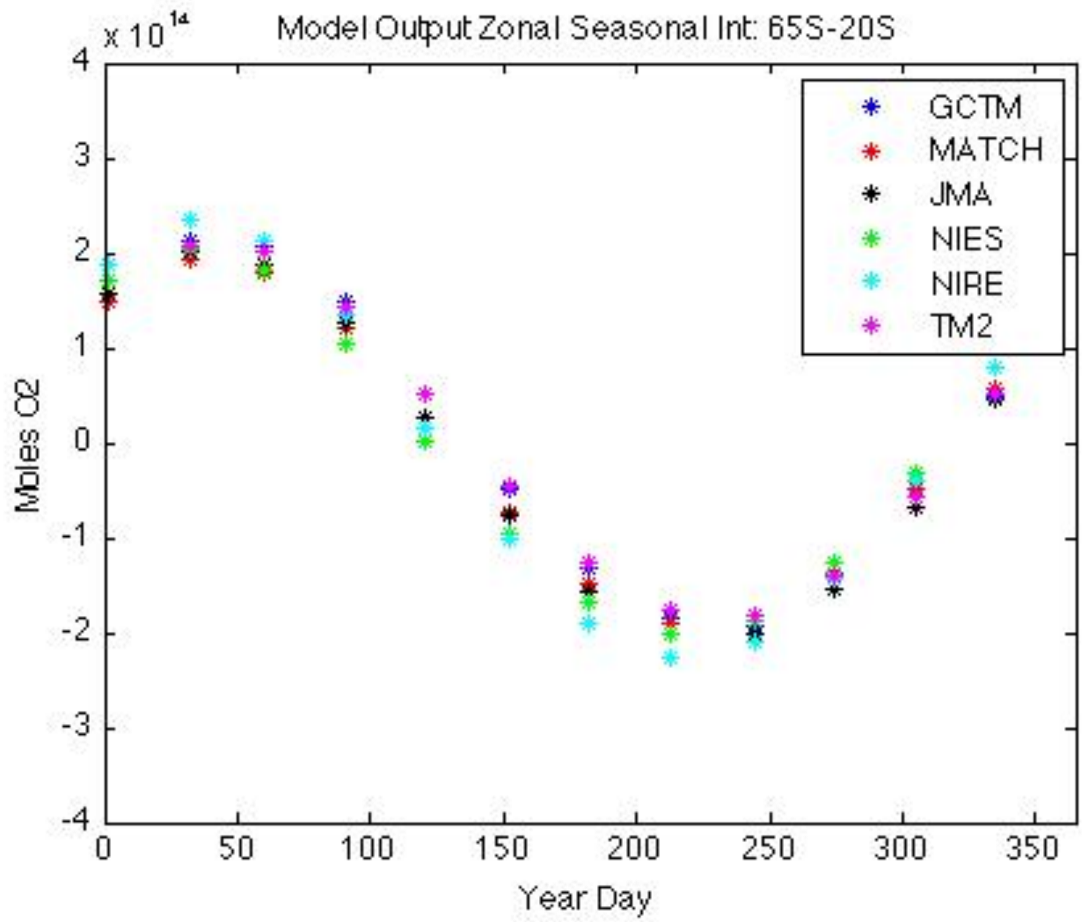
- Atmospheric Potential Oxygen has potential as a conservative tracer of ocean biogeochemistry
- Recent papers assert that APO is presently unable to identify the source of model-data discrepancy when models are coupled
- HIPPO airborne data have the potential to resolve this question by comprehensively describing the vertical structure of the Southern Ocean atmosphere
- The Meridian Integral may be able to calculate total APO flux without knowledge of vertical mixing
- Initial TransCom results support the notion of the MI
- These data should allow us to evaluate and score the representivity of OBMs, FFMs, and ATMs

TRANSCOM model comparison

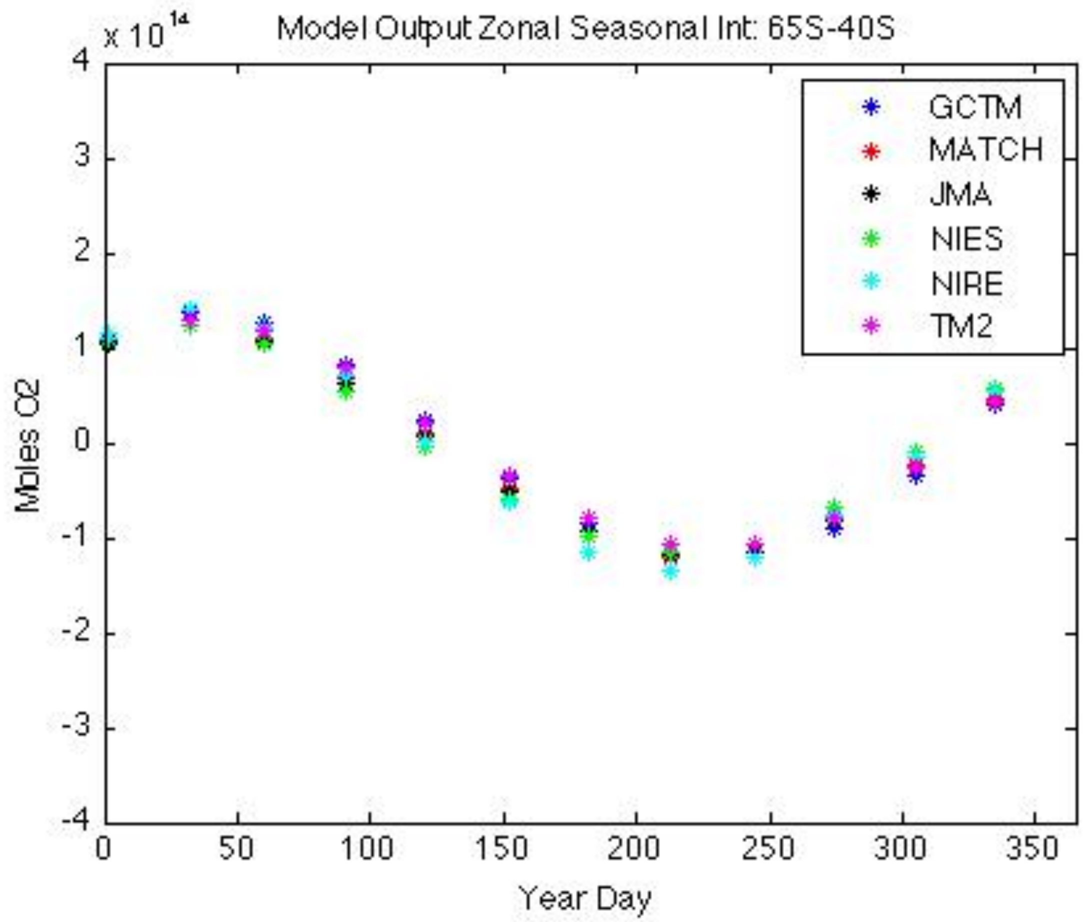




Model Output Zonal Seasonal Int: 65S-0S
x 10^14
4
3
2
1
0
-1
-2
-3
-4
Moles O2
0
50
100
150
200
250
300
350
Year Day
GCTM
MATCH
JMA
NIES
NIRE
TM2

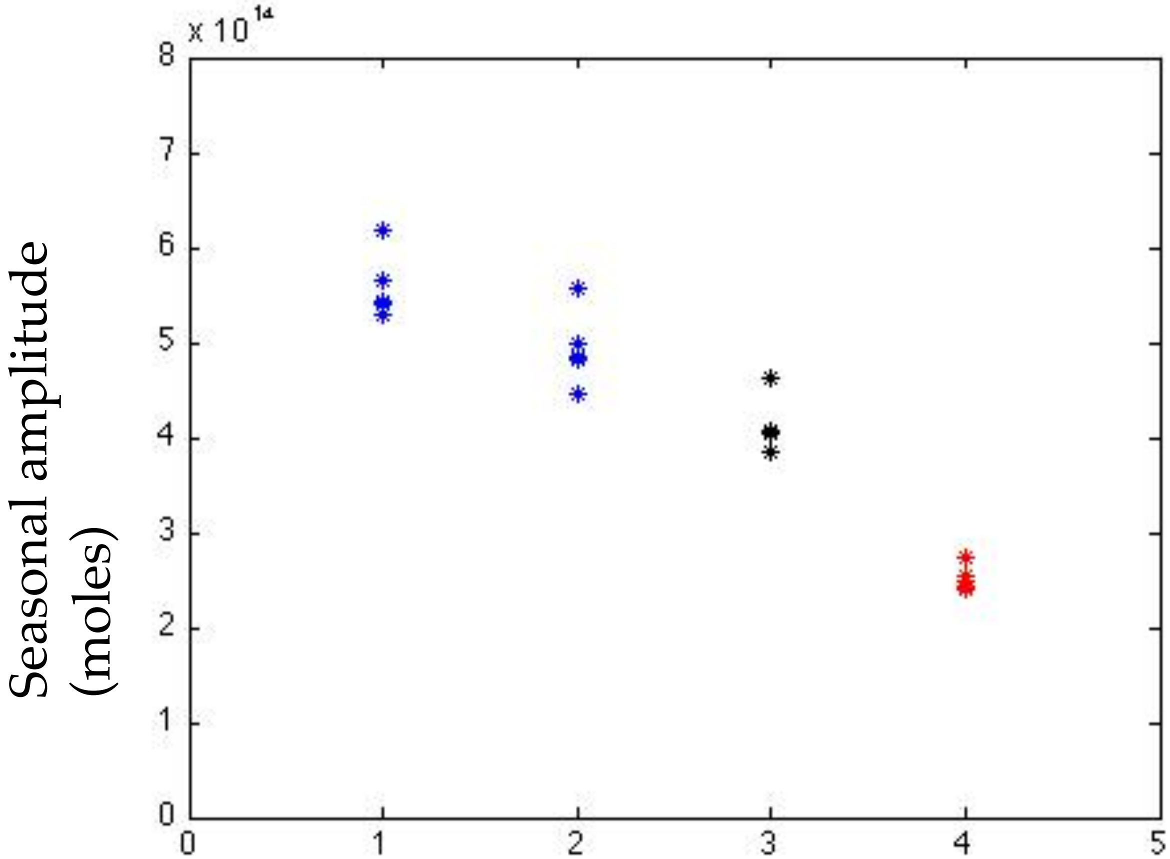


Model Output Zonal Seasonal Int: 65S-20S
x 10^14
Moles C02
Year Day
GCTM
MATCH
JMA
NIES
NIRE
TM2
4
3
2
1
0
-1
-2
-3
-4
0
50
100
150
200
250
300
350



Model Output Zonal Seasonal Int: 65S-40S
x 10^14
Moles O2
Year Day
GCTM
MATCH
JMA
NIES
NIRE
TM2
4
3
2
1
0
-1
-2
-3
-4
0
50
100
150
200
250
300
350

Southern Hemisphere O2 inventories by model and latitude band



Modeling the Southern Ocean

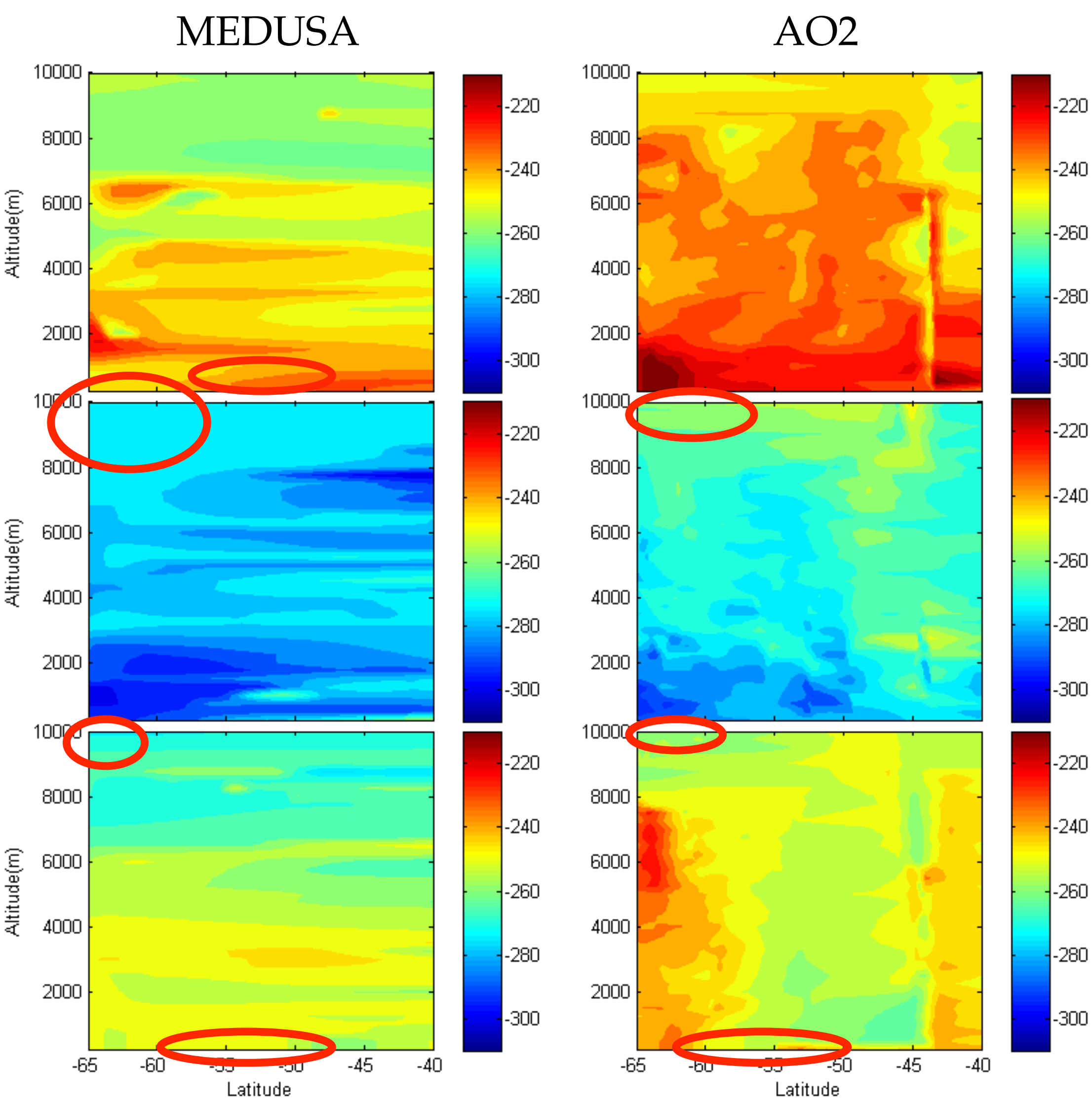
Easy

- Little land effect on signals in Southern Hemisphere
- Good zonal mixing

Hard

- Most ocean pCO2, O2 measurements are in summertime
- Verification of vertical profiles impossible: virtually no airborne data
- Sparse meteorological data

MEDUSA, AO2 Southern Ocean Transects



- Non-detrended H1-3
- AO2 data reflect an Ar-correction; MED do not
- AO2 has considerably more detail
- Some minor boundary extrapolation has been necessary for the Meridian Integral calculation
- (AO2 data: Britt Stephens)

Evaluating Meridian Integral

Potential Problems

- Latitudinal mixing into box
- Interpolating data introduces uncertainty

Supportive

- Zonal mixing
- Consistent sample offsets don't affect flux values (Δ)
- Stephen Walker's Harmonic Fits

Principal Diagnostic

Do the TransCom ATMs Blaine (2005) drove with Garcia and Keeling (2001) fluxes reproduce the same seasonal APO signal when the Meridian integral is calculated?

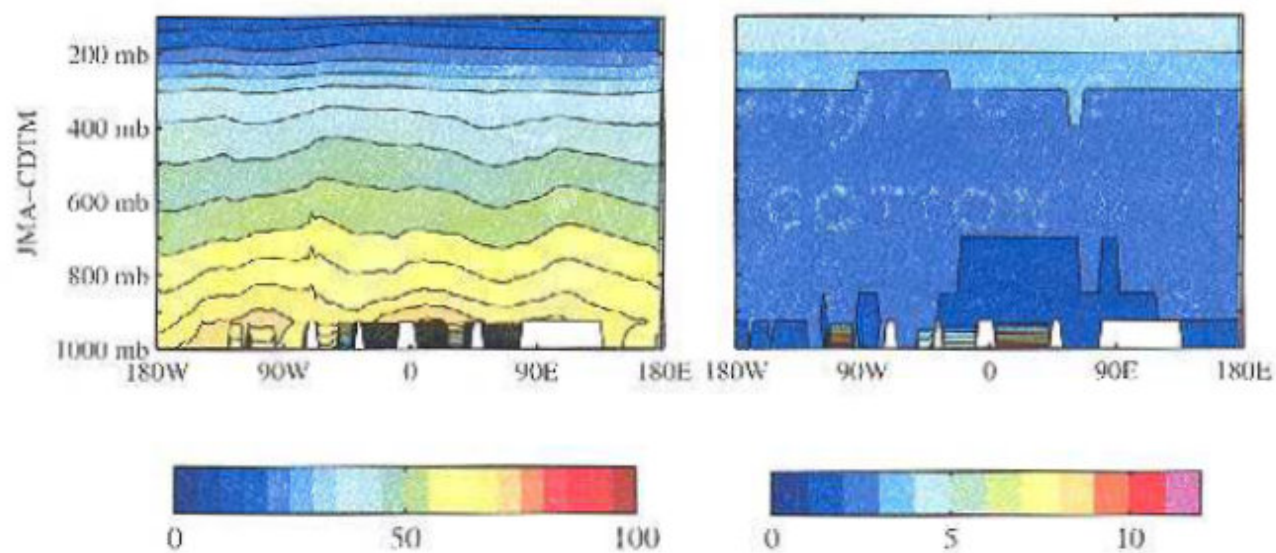
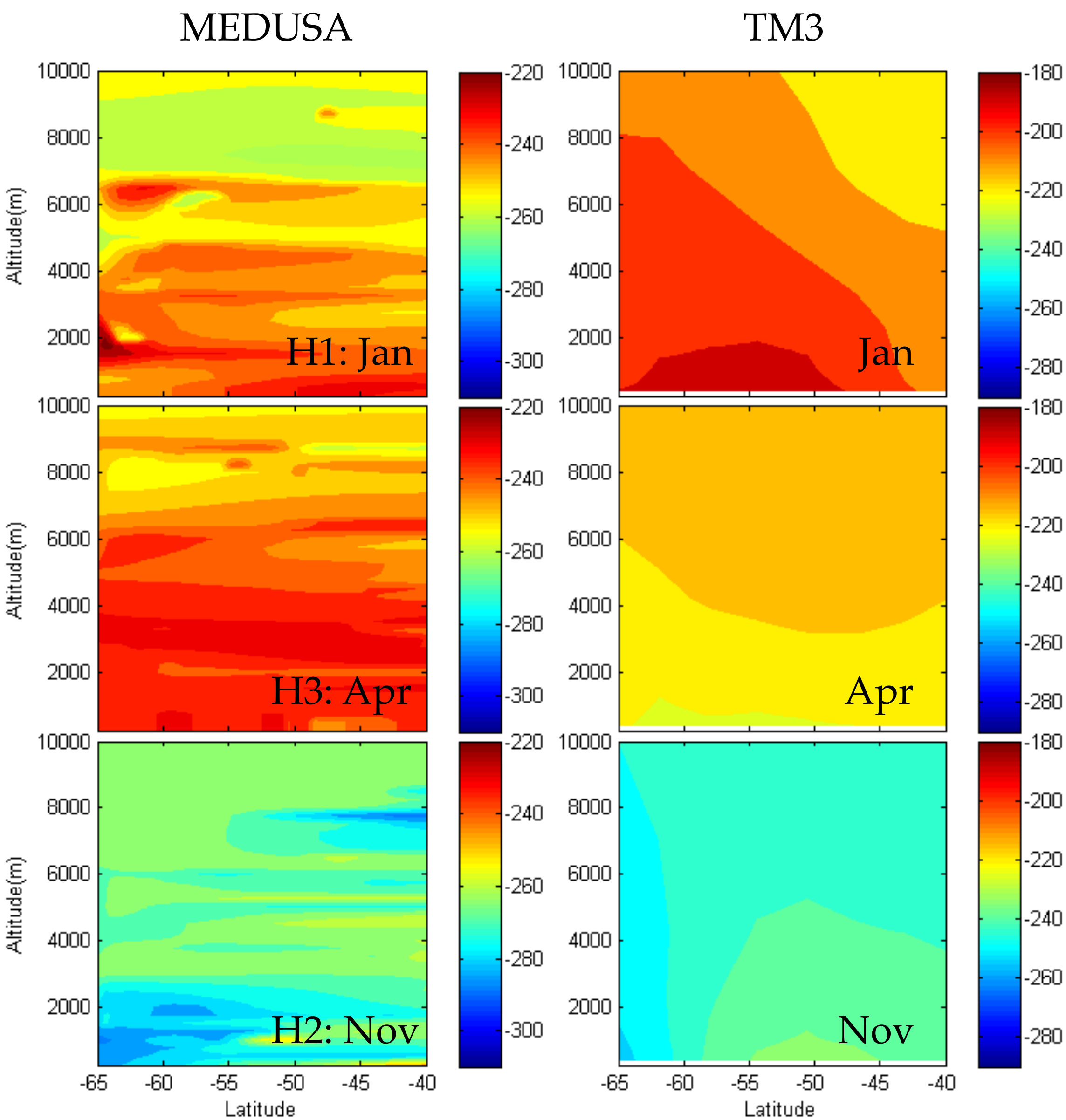


Figure 2.14. Representative transects of the annual peak-to-peak amplitude and phasing at 60°S.

Evaluating ATMs: Early TM3 Comparison



- Detrended
- TM3 output using Takahashi (2009) and Garcia and Keeling (2001) flux fields provided by Sara Mikaloff-Fletcher, Britt Stephens
- APO vals for TM3 are arbitrary; colorbar is adjusted to H1

Model Evaluation

Do APO signals from Blaine (2005) TransCom output reproduce the seasonal amplitude determined in HIPPO?

Use TransCom output, Meridian integral to establish the average seasonal cycle expected by Garcia and Keeling (2001) in form:

$$APO(t) = (\alpha_{apo} * \cos(t-\Phi_p)*(\omega)\text{-const.})$$

Evaluate and scale G&K α, Φ_p to match HIPPO

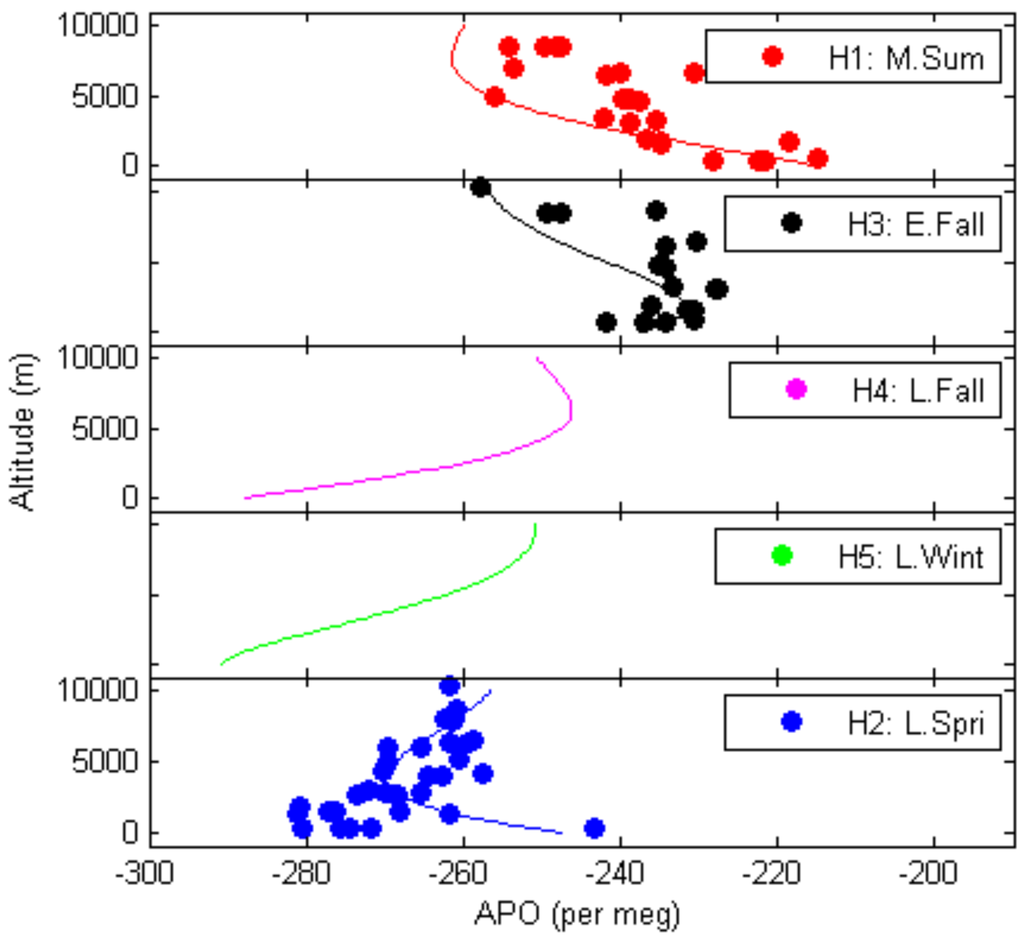
Generate new G&K flux fields

Use new flux fields to drive ATMs

Establish which OBMs best match Meridian integral air-sea fluxes

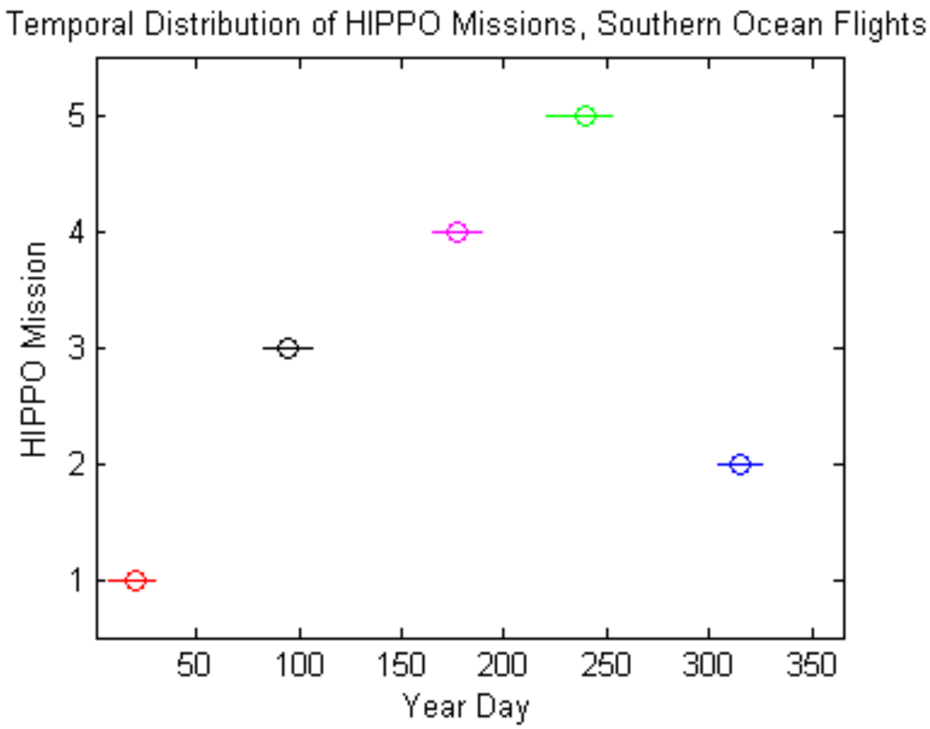
Establish which ATMs match HIPPO vertical structure when driven with retuned FFs and OBMs

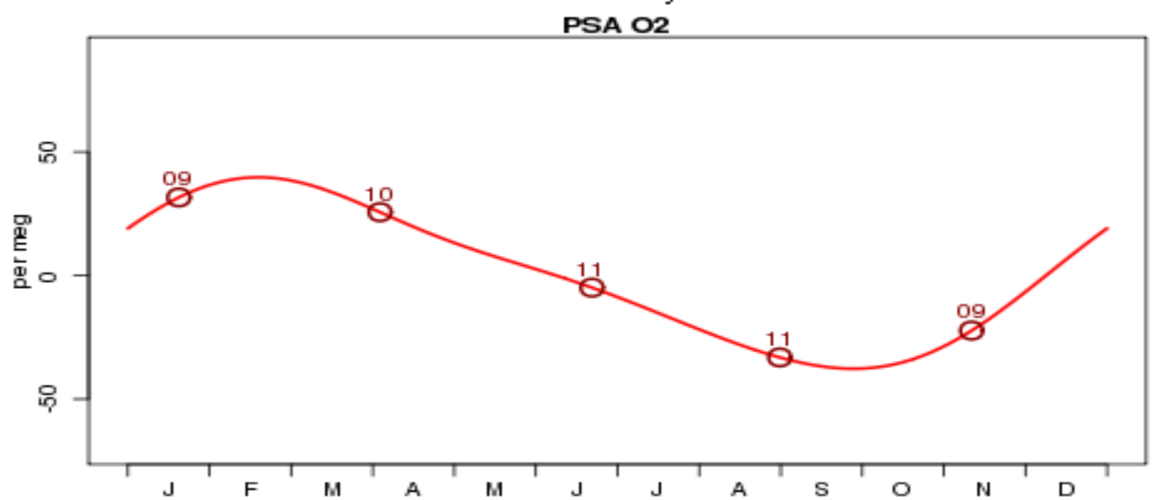
In the Meanwhile 2): 1-D APO Inversion Model

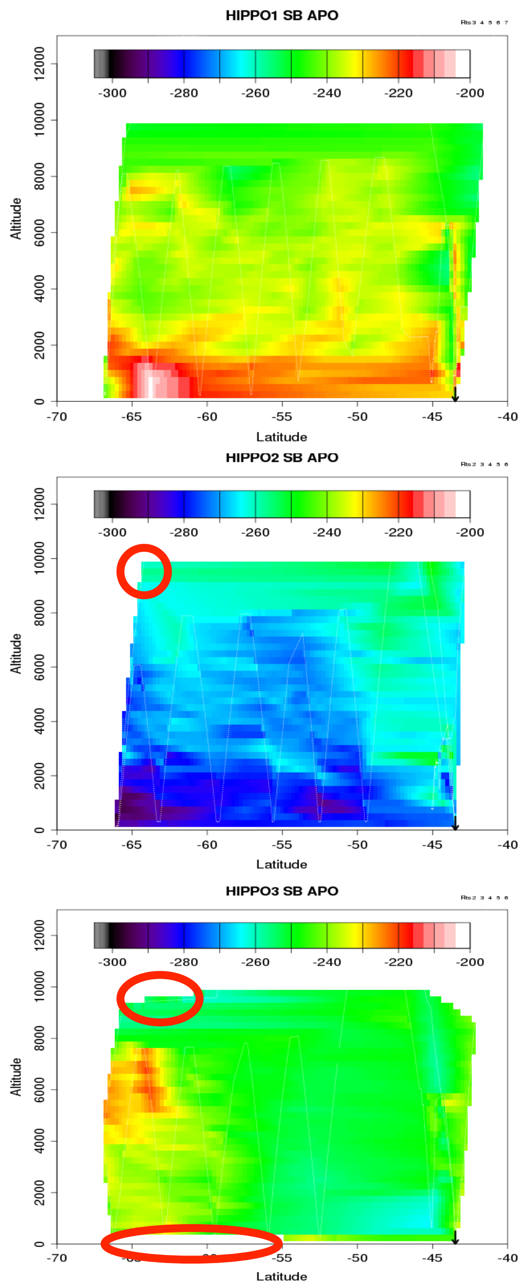


- Simple mathematical model of decaying harmonic function
- Driven by station data, optimized to fit airborne
- Potential to better resolve
  - d(Integral)/dt
  - d(phase)/dh
  - d(Amp)/dh

HIPPO Southern Ocean Coverage

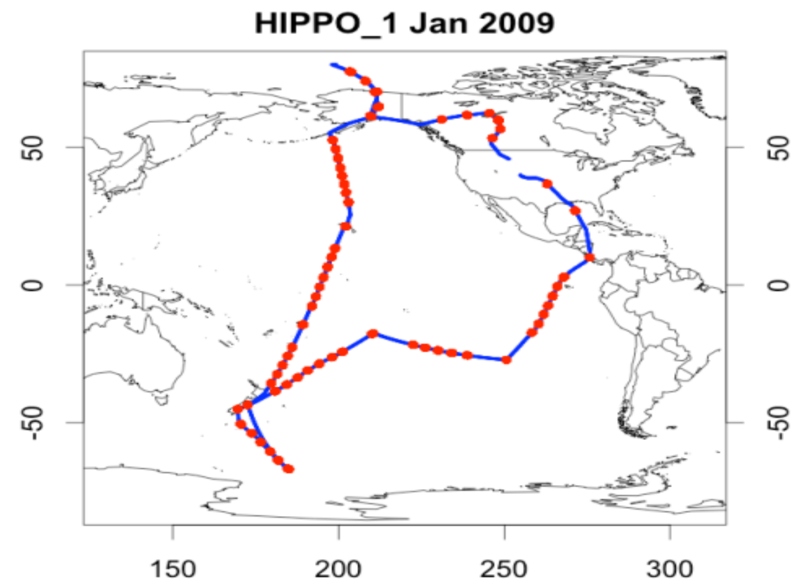


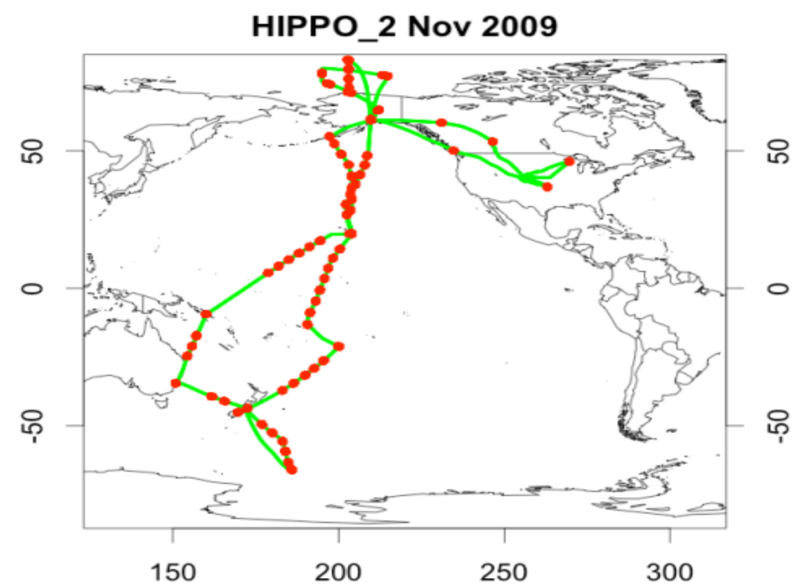



HIPPO1 SB APO
-300
-280
-260
-240
-220
-200
Altitude
Latitude
HIPPO2 SB APO
HIPPO3 SB APO

HIPPO Vertical and Geographic Coverage

- **Vertical Coverage**:
  Surface to 47,000ft
  Most of troposphere
  Some of lower stratosphere.
- **Latitude Coverage**:
  ~ 67S to 83N
- **Longitudinal Coverage**:
  Around 180°W meridian
  Typically between:
  Anchorage, AK (150°W)
  Christchurch, NZ (172°E)





The HIPPO Campaign: HIAPER Pole to Pole Observations

- A collaborative airborne campaign which attempts to understand the movement of tracers through the earth's atmosphere, and to ground-truth models.
- An attempt to establish an average climatology for the many transects sampled over three years.
- Researchers from NCAR, NOAA, Harvard, Princeton, RSMAS, SIO.

Mission	Dates	Research Flights	South. Hemi. Season
HIPPO1	08 Jan-30 Jan, 2009	11	Mid Summer
HIPPO2	31 Oct-22 Nov, 2009	11	Mid Spring
HIPPO3	24 Mar-16 Apr, 2010	11	Early Fall
HIPPO4	*14 Jun-08 Jul, 2011*	*11*	Early Winter
HIPPO5	*09 Aug-09 Sep, 2011*	*11-13*	Late Winter

Why measuring Atm. O_2 is Important

(Equations as per Keeling and Shertz, 1992)

O_2 varies inversely with CO_2 due to photosynthesis/respiration

But no "buffering" system regulating its concentration in oceans

You can resolve the oceanic sink of Anthropogenic CO2, and the terrestrial sink with:

And solve these two equations:

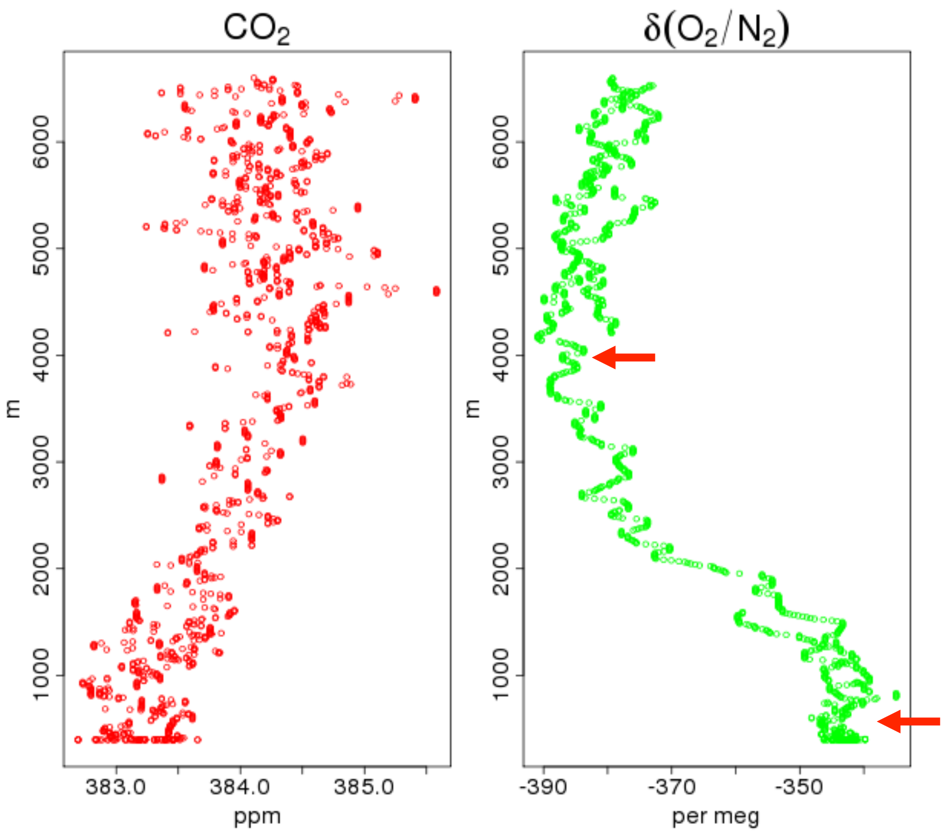
$$\Delta CO_2 = F - O + B$$

$$\Delta O_2 = -\alpha_F F + \alpha_B B$$

O: ocean sink of anthr. CO2
B: terrestrial sink of anthr. CO2
F: fossil fuel and cement CO2 sources (mol/year)
α **F:** 1.4, the exchange ratio for FF combustion (mol O2: mol CO2)
α **B**: 1.1, the terrestrial exchange ratio (mol O2: mol CO2)
ΔCO2, ΔO2: increase/decrease of atm CO2, O2 (mol/year)

In the meanwhile 1): Estimating Vertical Mixing

AO2 Profile at 65°S on 20 Jan 2009



- Vertical Profiles demonstrate a build up of O_2 at surface and concomitant (smaller) CO_2 deficit
- Mid way through SO summer, the vertical column is nowhere near mixed
- Profiles: B. Stephens 2009
- Jan-Mar Model APO 925-500mb gradient v. Amplitude (C. Nevison 2010)

- Δh=4000m (ΔO2=50 per meg)
- Δt=105 days
- **Δh/Δt= 38m/day**