Tropospheric Gradients of CO_2 Over the Southern Ocean

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1. BACKGROUND

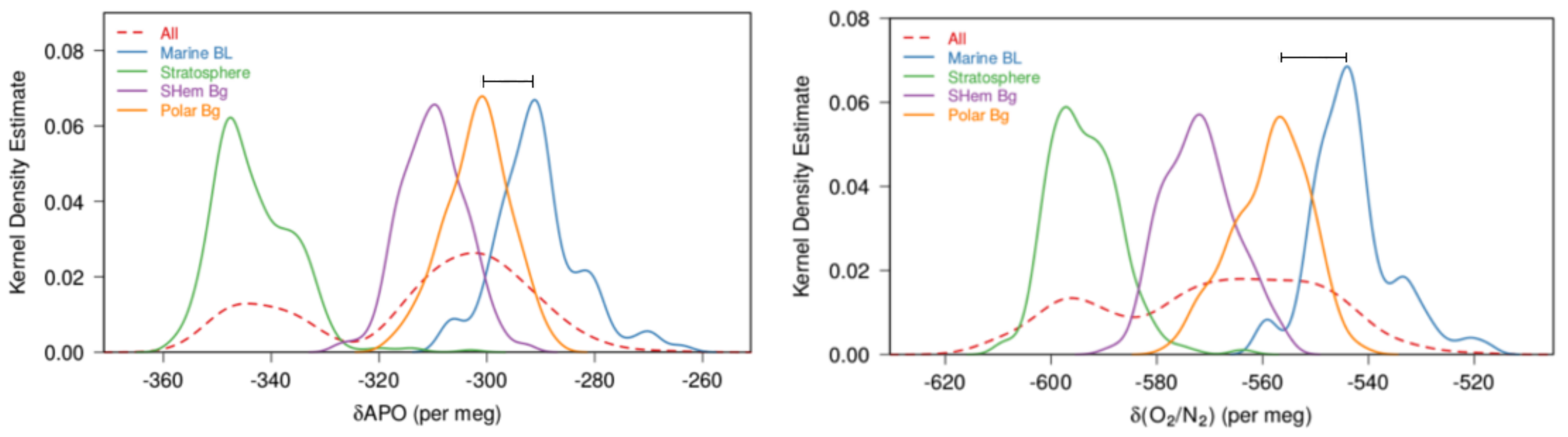
- While the Southern Ocean is a major sink for atmospheric CO_2 (Khatiwala et al., 2009), it remains fairly undersampled (Monteiro et al., 2015). The strength of this sink is zonally asymmetric, and shows considerable interannual and interdecadal variability. Currently the Southern Ocean is absorbing more atmospheric CO_2 than in previous decades, a trend that may continue in a warming climate (Ito et al. 2015, Landschutzer et al., 2015, Munro et al., 2015).

- Several major airborne campaigns have visited this region, and collected a number of vertical profiles both in the Atlantic and Pacific sectors of the Southern Ocean. Data used in this work are from: The HIAPER Pole-to-Pole Observations (HIPPO) 1-5, the O_2/N_2 Ratio and CO_2 Southern Ocean Study (ORCAS), and the Atmospheric Tomography Mission (ATom) 1-2.

- Dates: HIPPO1 (Jan '09), HIPPO2 (Nov '09), HIPPO3 (Apr '10), HIPPO4 (Jun '11), HIPPO5 (Aug '11), ORCAS (Jan '16), ATom1 (Aug '16), and ATom2 (Feb '17).

- The goal of this work is to understand the seasonality and stoichiometry of the vertical gradient of CO_2 and $\delta(O_2/N_2)$, specifically as it relates to marine surface fluxes.

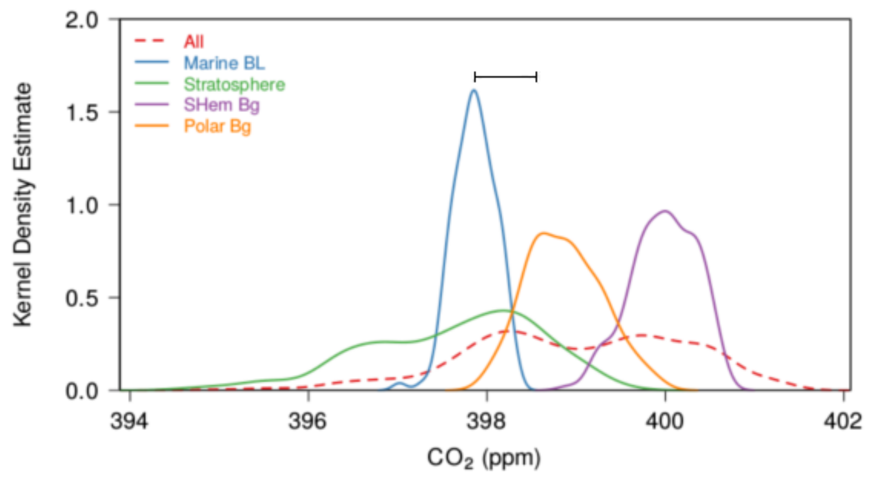
2. OBSERVATIONS: BINNING OF AIR MASSES



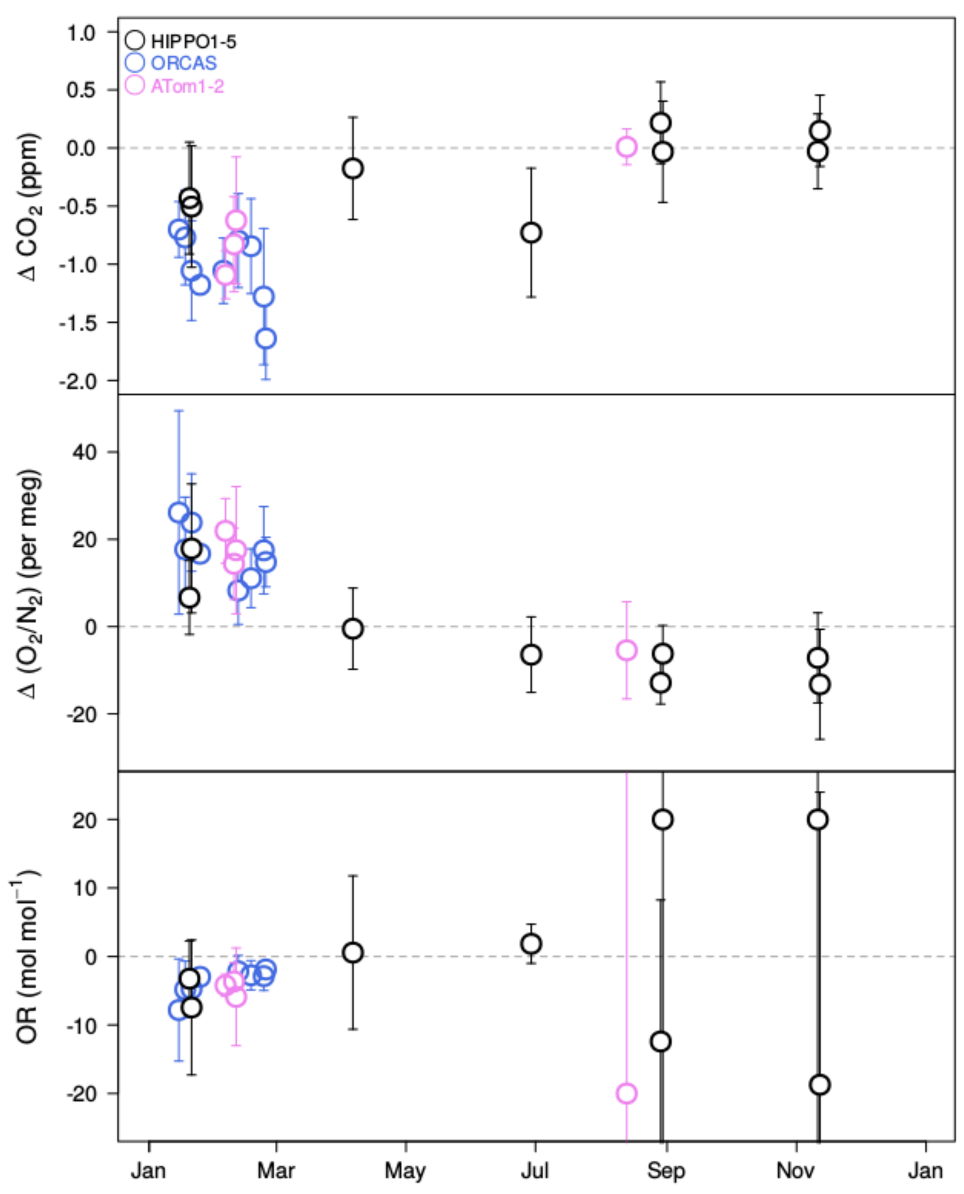
- Kernel density estimates of the distribution of selected airmasses during ORCAS in austral summer for δAPO, $\delta(O_2/N_2)$, and CO_2.

- Each air mass type was binned through seasonally varying criteria for different tracers: potential temperature, relative humidity, and carbon monoxide.

- Using air masses that are more southerly and have not seen air that was carrying influence from the northern hemisphere reduces the observed gradient between that airmass and air from the MBL. This was done as an attempt at an empricial correction for fossil fuel and terrestrial gradients. The horizontal bar illustrates how gradients are calculated between bins.



3. OBSERVED VERTICAL GRADIENTS



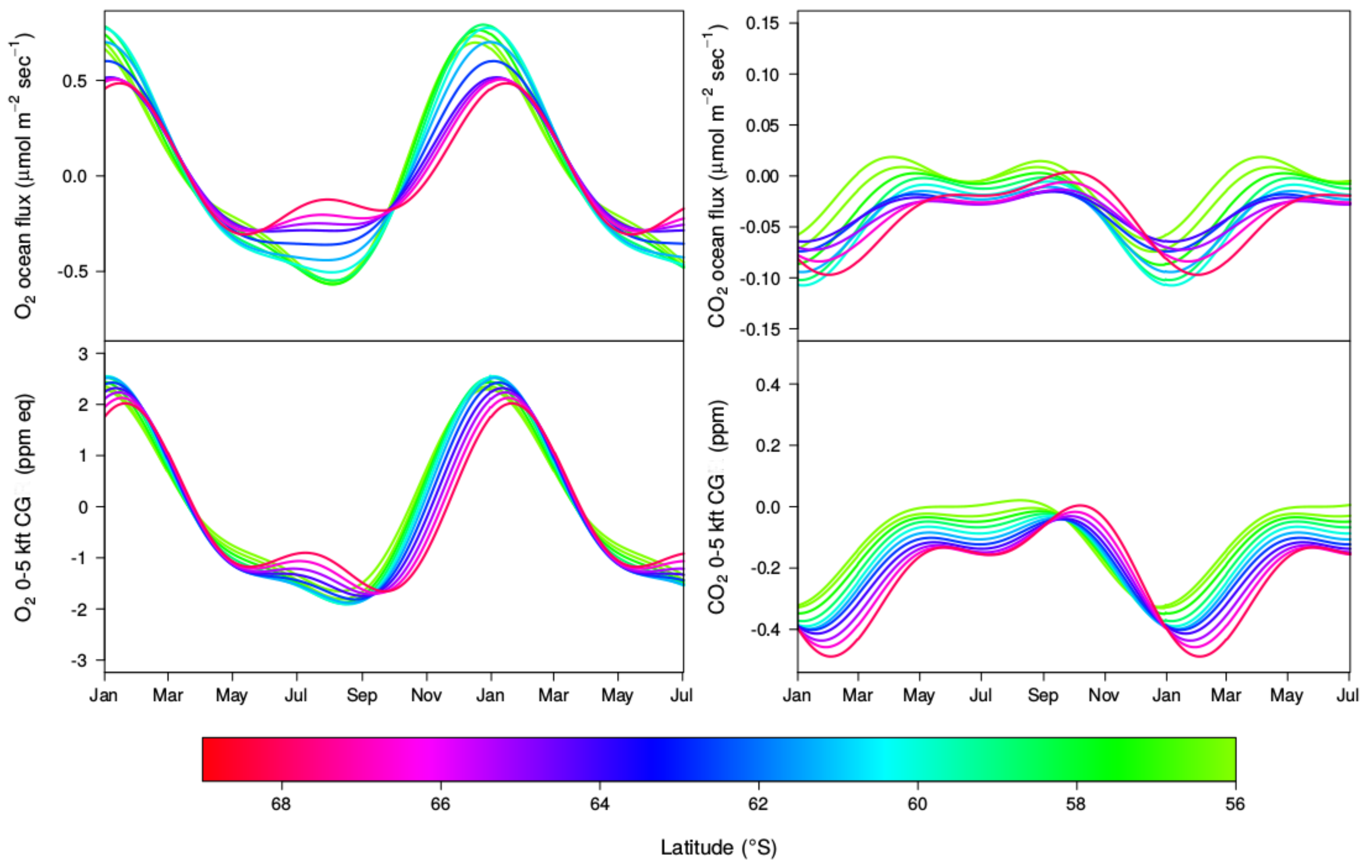
- Left, a climatology for the observed gradient between the "polar" bin and the "MBL" bin presented above, for all 7 airborne campaigns, for CO_2 and $\delta(O_2/N_2)$. Error bars are the standard deviation of each population.

- Also shown is the effective oxidative ratio (OR) between the gradients of the two species. Error bars are the propagated standard deviation of the two bins.

-The stoichiometry of oxygen and carbon dioxide informs on the process that created the gradient. A negative ratio is indicative of a dominant biological flux (either due to local productivity or ventilation of water masses with significant respiration effects, while a positive ratio is indicative of an air-sea flux governed by temperature changes that alter the solubility of both species.

- The OR can become ill-defined when the gradients are close to zero, and are less variable during austral summer when the signals are stronger, and hence the gradients are larger.

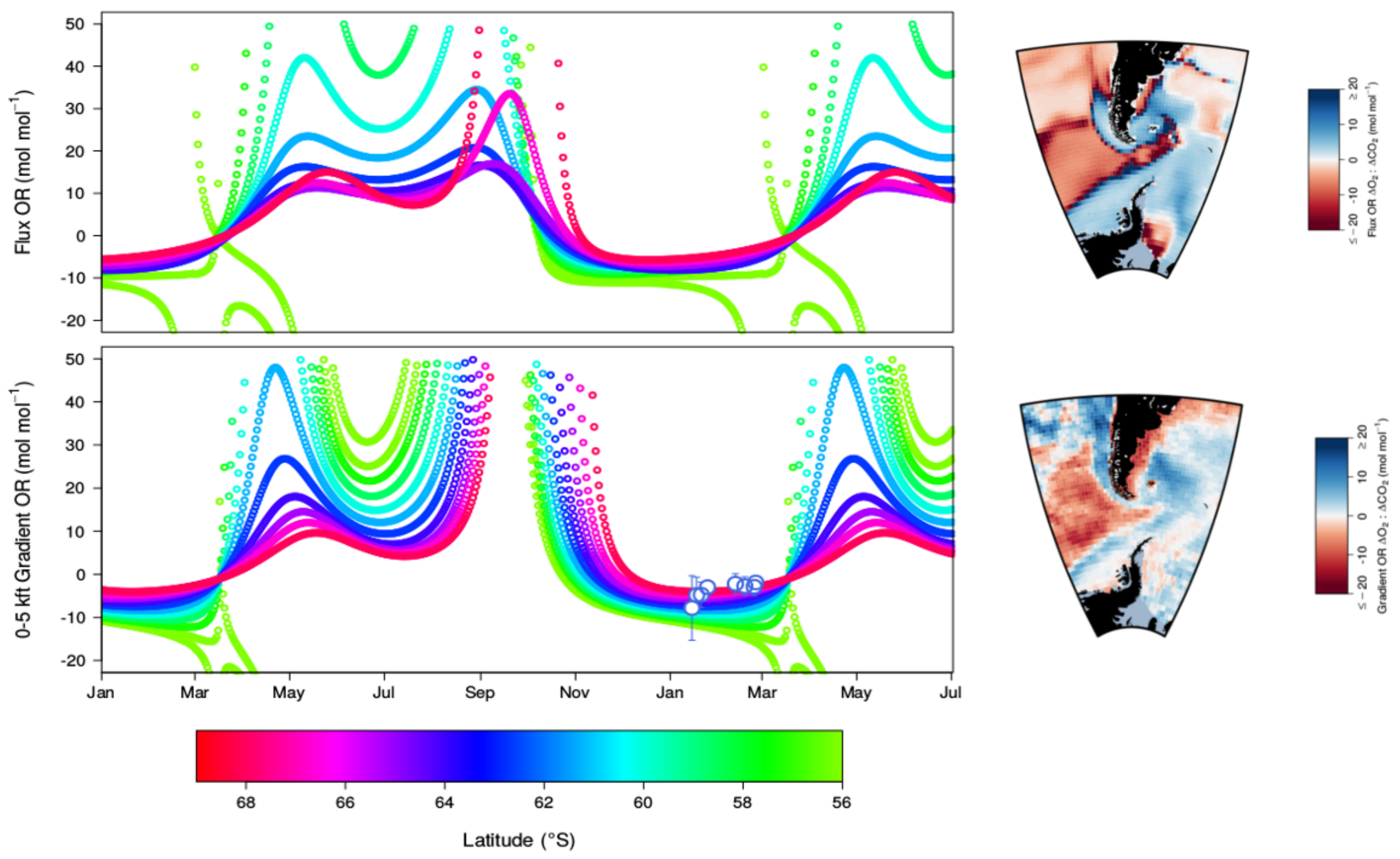
4. MODEL EXPERIMENTS IN CESM



- Data from a fully-coupled run of the Community Earth System Model (CESM), with nudging to GEOS-5, showing the average seasonal cycle of the CO_2 and O_2 ocean flux (positive into the atmosphere) for a domain centered around the Drake Passage, from 2007-2016 on top, and the average seasonal cycle of the vertical gradient between the surface and 5 kft for the same period.

- Phasing and latitudinal gradients are similar between fluxes and gradients, for both oxygen and carbon dioxide. There is a a small phase shift of less than 10 days between the flux and the gradient, with the surface flux peaking first.

5. CESM: GRADIENT RATIOS & FLUX RATIOS

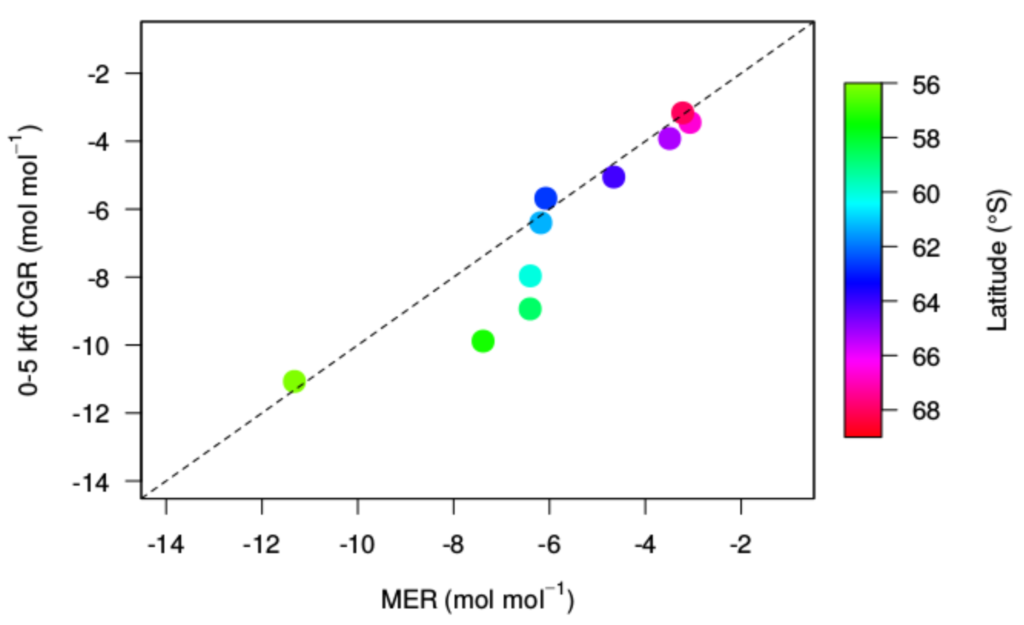


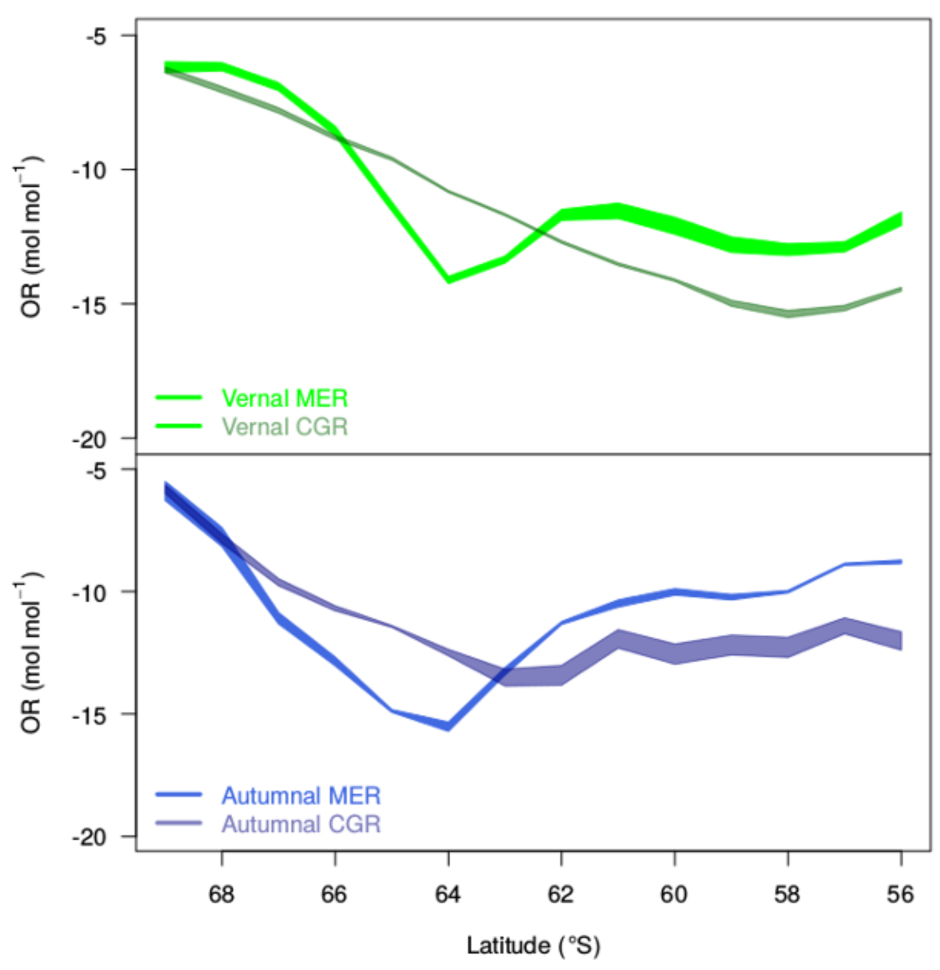
- Left, climatologies of stoichiometric ratios of oxygen and CO_2 from the CESM run. On the top row is the flux oxidative ratio (OR). On the bottom is the gradient oxidative ratio, with the observed ORCAS OR from the figure in section 3. Right, maps of the average flux and gradient ratios during ORCAS, for an arbitrarily selected domain. The scale on both maps is capped at -20 and +20.

- Ratios become very negative or very positive when the gradients or fluxes are very low. The spatial distribution of both ratios is quite similar over two months, despite atmospheric transport.

- Average concentration gradient ratio (CGR) and molar exchange ratio (MER; i.e. the flux ratio) in January from the climatology presented above, plotted against each other and colored by latittude. The dashed line is the 1:1 line.

- The gradient ratio (CGR) approximates the flux ratio (MER) during austral summer quite well south of about 62°S. The polar front is close to this latitude, and serves as an impediment to latitudinal mixing.





- Slope or stoichiometric ratio of the vernal (rising O_2 and falling CO_2) and autumnal (falling O_2 and rising CO_2) portions of the average seasonal cycle of the average flux and concentration gradient.

- There is fairly close correspondence between the MER and CGR, except for the latitudes centered around the Antarctic peninsula. This could be an effect of the selected domain, as it is a highly productive region, and the area of ocean is of course lower in this zonal band, while the atmosphere is still integrating the same volume.

6. SUMMARY & CONCLUSIONS

- Combining data from eight airborne campaigns, the gradients of CO_2 and $\delta(O_2/N_2)$ across the atmospheric boundary layer over the Southern Ocean were computed for a region that spanned most of the Pacific and the Drake Passage.

- Data were binned by air mass type, using serveral tracers, to compute the average gradient on a daily basis. Though these gradients were generally small, they exhibited a clear seasonality.

- Using data from CESM, it was shown that atmospheric gradients were mostly driven by marine surface fluxes of carbon dioxide and oxygen. In this model experiment, the seasonality and magnitude of the ratio of these gradients was compared to the seasonality and magnitude of the ratio of surface fluxes within a domain centered around the Drake Passage. The boundary layer gradient was found to be a reasonable proxy for the seasonal evolution of the surface flux ratio, and if care is taken to isolate additional influences, the surface flux ratio itself.

- To obtain a good empirical estimate of the flux ratio from atmospheric data, more work needs to be done to remove non-marine influences on the atmospheric gradient, and to investigate bias introduced by sparse sampling, as well as a footprint analysis to better match atmospheric gradients to surface fluxes..