

# Atmospheric CO<sub>2</sub> and the Southern Ocean: A master control of global climate?

Jon Baker (supervisors: Andy Watson and Geoff Vallis)

Presenter: **Jon Baker**

Over the past one million years, atmospheric CO<sub>2</sub> and Antarctic temperatures covaried over several glacial cycles. The overall aim of this study is to investigate the importance of variations in the oceans global overturning circulation during the glacial cycles, in causing the associated changes in climate. Thus far, an energy balance model has been coupled to a semi-analytical single basin ocean model, SAMBUCA, to investigate the effects of changes in solar irradiance on the overturning circulation. It has been shown that the consequent direct changes in temperature, neglecting climate feedbacks, cannot explain the reduction in the NADW cell during glacial times as suggested by proxy evidence. Thus, climate feedbacks must play an essential role. In particular, changes in salinity caused by changes in sea-ice extent and export must be crucial in the variation of the overturning circulation. The impact of variations in brine fluxes at high latitudes has been modelled using SAMBUCA and has been shown to cause large changes in the overturning circulation, with a weakening and shoaling of the mid-depth cell when the fluxes are increased in the Southern Ocean. However, the single basin representation of the ocean does not account for the inter-basin exchanges and thus may not be able to model the changes in the overturning circulation realistically. The impact of changes in high latitude ocean surface buoyancy fluxes on the circulation and consequently atmospheric CO<sub>2</sub> in a single basin, multi-basin and realistic geometrical setup will be modelled using a general circulation model. The variation of the circulation and atmospheric CO<sub>2</sub> within these three ocean model setups will be inferred for varying initial parameters, and thus the significance of inter-basin exchanges will be determined.

# Agreement of simulated and observed ocean CO<sub>2</sub> uptake

Ben Bronselaer, Michael Winton, Joellen Russell

Presenter: **Ben Bronselaer**

Previous studies have found large global and spatial biases between individual observational and model estimates of historical ocean anthropogenic carbon uptake. We show that the global bias between CMIP5 and between the Sabine et. al. 2004 and Khatiwala et. al. 2009 observational estimates of 1995 ocean anthropogenic carbon is due to a difference in start date. We adjust the CMIP5 and observational estimates to the 1800-1995 period and show that all three global carbon uptake estimates agree to within 3 Pg of C. Adjusting for the temporal bias allows us to better constrain the spatial biases between models and observations. We therefore show that the CMIP5 model spatial bias compared to the observations is smaller than the observational error in the majority of the ocean, apart from a negative bias in the Southern Ocean, and a positive bias in the Southern Indian and Pacific Oceans. This dipole pattern is likely due to a bias in the position of Southern Hemisphere westerlies. However, the dipole pattern does not affect global carbon uptake as of yet, but may do so in the future as winds intensify poleward.

# CO<sub>2</sub> fluxes in the Southern Ocean: a model-data comparison

Carolina Dufour, Ivy Frenger, Alison Gray, Jorge Sarmiento, Stephen Griffies

Presenter: **Carolina Dufour**

The Southern Ocean plays an important role in the global carbon cycle and as such in the climate system. Climate models generally disagree the most in the Southern Ocean, with one of the reasons being the lack of observational data in providing some constraints to the modelled fields. The recent deployment of numerous autonomous biogeochemical floats under the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project offers an unprecedented opportunity to examine model-observation agreement and to revisit the models' spread in representing air-sea CO<sub>2</sub> fluxes. To do so, we compare annual averages of CO<sub>2</sub> fluxes between estimates from SOCCOM floats measurements and a set of climate models run under an idealized climate change scenario. The set of climate models comprises a subset of eight CMIP5 models and a GFDL climate model run with coarse-resolution (1) and high-resolution (0.1) in the ocean. We investigate the spatial pattern and intensity of the CO<sub>2</sub> fluxes in different regions of the Southern Ocean from the observational and model dataset and conclude on the ability of the current generation of climate models to simulate Southern Ocean CO<sub>2</sub> fluxes.

# Present and projected variability of biogeochemical fronts in the Southern Ocean

Natalie M. Freeman, Nicole S. Lovenduski, Kristen K. Krumhardt, Keith Lindsay, Matthew C. Long

Presenter: **Natalie M. Freeman**

The Antarctic Polar Front (PF) is an important biogeochemical divide in the Southern Ocean, marking the boundary between silicate-rich and silicate-poor waters and therefore distinct phytoplankton communities of diatoms (silicifiers) and coccolithophores (calcifiers). Variability in the PF and its associated silicate front (SF) has the potential to influence Southern Ocean biogeochemistry and biological productivity both locally and at the basin scale. Previous work has shown that the PF, defined as a thermal front, has shifted northward (southward) in the Pacific (Indian) sector and intensified across the basin from 2002 to 2014. Here, we employ output from the Community Earth System Model Large Ensemble (CESM-LE) simulations to elucidate the (1) relationship between the PF, SF, and biogeochemistry and (2) mechanisms of forced trends and variability. Under this modeling framework, we can separate natural (internal) climate variability from long-term, forced trends. We quantify spatial and temporal variability in biogeochemical fronts and further investigate co-variance between fronts and local biogeochemistry and phytoplankton community structure. We find that the SF shifts poleward over the historical record and under the RCP 8.5 forcing scenario, likely due to changes in wind, circulation, and stratification. Characterizing frontal variability is important for contextualizing recent biogeochemical observations in the Southern Ocean as well as for understanding how anthropogenic change is influencing biogeochemistry here.

# On the relationship between Southern Ocean eddies and phytoplankton

Frenger, I., Münnich, M., and N. Gruber

Presenter: **Ivy Frenger**

Effects on phytoplankton in the Southern Ocean are crucial for the global ocean nutrient and carbon cycles. Such effects potentially arise from mesoscale eddies which are omnipresent in the region. Eddies are known to affect phytoplankton through either advection and mixing, or the stimulation/suppression of growth. Yet, the climatological relationship between Southern Ocean eddies and phytoplankton has not been quantified in detail. To provide an estimate of this relationship, we identified more than 100,000 eddies in the Southern Ocean and determined associated phytoplankton anomalies using satellite-based chlorophyll-a (CHL) measurements. The eddies have a substantial impact on the CHL levels, with eddy associated CHL differing by more than 10% from the background over wide areas. The structure of these anomalies is largely zonal, with positive anomalies north of the Antarctic Circumpolar Current (ACC) and negative anomalies within the circumpolar belt of the ACC for cyclonic eddies. The pattern is similar but of opposite sign for anticyclonic eddies. The seasonality of this signal is weak north to the ACC, but pronounced in the vicinity of the ACC. The spatial structure and seasonality of the signal can be explained largely by advection, i.e., the eddy-circulation driven lateral transport of anomalies across large-scale gradients. We conclude this based on the shape of local CHL anomalies of eddies and ambient CHL gradients. In contrast, ACC winter anomalies are consistent with an effect of eddies on the light exposure of phytoplankton. The clear impact of eddies on CHL implies a downstream effect on Southern Ocean biogeochemical properties and air-sea fluxes.

# Eddies and the Antarctic Circumpolar Current

Sarah T. Gille, Tianyu Wang, Uriel Zajaczkovski, Matthew Mazloff, Nathalie Zilberman

Presenter: **Sarah Gille**

The Southern Ocean supports high levels of eddy kinetic energy, with eddy variability concentrated along the path of the Antarctic Circumpolar Current (ACC). Eddies serve two roles. First, they provide a pathway to transport heat and other properties meridionally, across the mean streamlines defined by the ACC. In most of the world's oceans anticyclonic (warm core) eddies transport heat equatorward and cyclonic eddies (cold core) transport water poleward, supporting upgradient heat transport. This process is reversed in the ACC, where anticyclonic eddies move poleward, and cyclonic eddies move equatorward, supporting a downgradient, or poleward cross-ACC, heat transport. Second, eddies play a role in the momentum balance. A 1/6 degree-resolution model shows that eddies tend to converge momentum into the core of jet, thus driving the mean ACC. Numerical Argo floats, released in the model at 1000 m depth, accelerate over the course of 5-10 day trajectories, as they converge towards the ACC jets. This has implications, both for understanding the Southern Ocean momentum balance and for inferring ACC velocities from Argo positions.

# Modeling Water Mass Production and Basal Melt in the Weddell Sea

Julia Hazel, Andrew Stewart Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA

Presenter: **Julia Hazel**

Strong westerly winds of the Southern Hemisphere (SH) mid-latitudes drive the Antarctic Circumpolar Current (ACC), which connects the major ocean basins and allows for a global overturning circulation. Further south, however, easterly winds force the ocean in a narrower band around the Antarctic coast. This near-Antarctic circulation has a pronounced impact on the global ocean and climate system. One such impact includes closing the global meridional overturning circulation (MOC) via formation of dense Antarctic Bottom Water (AABW), which ventilates a large fraction of the subsurface ocean. AABW is also partially composed of modified Circumpolar Deep Water (CDW), a warm, mid-depth water mass whose transport towards the continent has the potential to induce rapid retreat of marine-terminating glaciers. Previous studies suggest that these water mass exchanges may be strongly influenced by high-frequency processes such as downslope gravity currents, tidal flows, and mesoscale/submesoscale eddy transport. Due to the regions relatively small scales of motion and the logistical difficulties in taking measurements beneath sea ice, an assessment of the relative contributions of these processes to near-Antarctic water mass transports has been hindered. In this study we develop a regional model of the Weddell Sea, which is the largest established source of AABW, and whose inflow is dependent on the near-Antarctic easterly winds. The model is forced by a daily atmospheric state constructed from the Antarctic Mesoscale Prediction System data (AMPS) and by annually repeating monthly climatological lateral boundary conditions constructed from the Southern Ocean State Estimate (SOSE). The model incorporates the full Filchner-Ronne cavity and simulates the thermodynamics and dynamics of sea ice. To analyze the role of high-frequency processes in the transport and transformation of water masses, we compute the models overturning circulation, water mass transformations, and ice sheet basal melt across a range of model horizontal grid resolutions. We discuss the relative roles of tides and eddies in transporting surface heat and freshwater fluxes between the atmosphere, ocean, and ice.

# Partitioning of Southern Ocean heat transport between transient and standing eddies: Insight from an idealized multi-resolution study

Matthew W. Hecht, Wilbert Weijer, Geoffrey Vallis, Christopher Dawson

Presenter: **Matthew W. Hecht**

Here, we explore the balance between standing and transient eddy heat transports within a simple ocean model configuration. We compare a strongly eddying version of the model with a lower resolution configuration in which the effect of transient eddies is parameterized, as in most ocean climate models. We also consider a suite of cases that include two additional resolutions, together spanning the range from strongly eddying to non-eddying, all four of which are configured without use of the eddy parameterization.

The standing eddy heat transport dominates in all cases run without the eddy parameterization. In contrast, the low resolution case with parameterized eddies has a standing eddy heat transport that is weak by around a factor of two. While eddy parameterizations have proven of great value to climate modeling, our findings highlight the unintended consequences of their impact on the strength and character of the mean flow, and provide support for the use of eddying simulations for the study of problems in which the details of cross-ACC heat transport may be important.



# Flux Estimates from Lagrangian Flights over Drake Passage and the Patagonian Shelf

Martín Hoecker-Martínez, Eric A. Kort, Matthew C. Long, Britton B. Stephens, Eric Apel, Colm Sweeney, Rebecca Hornbrook, Kathryn McKain, Alan Hills

Presenter: **Martín Hoecker-Martínez**

The ORCAS ( $O_2/N_2$  Ratio and  $CO_2$  Airborne Southern Ocean Study) was designed to add new observational constraints on summertime fluxes and controlling processes for carbon dioxide and oxygen with unprecedented spatial coverage over the Southern Ocean. One approach unique to these air-sea gas exchange studies involved using Lagrangian modeling to determine flight paths for sampling different biogeochemical regions in the Southern Ocean and defined Lagrangian flights to sample the same air mass. We will discuss the Stochastic Time-Inverted Lagrangian Transport (STILT) modeling system as used in planning and analyzing flights. We will show results from two Lagrangian experiments that constrain short-term air-sea gas exchange over the Palmer Antarctic Long Term Ecological Research Network (PALTER) grid and the Argentine Basin. In addition to  $CO_2$  and  $O_2$  we will present estimates of exchanges of short lived biogenic species like  $(CH_3)_2S$  and more inert species to discriminate between processes driving the observed fluxes.

# Antarctic density stratification and the strength of the circumpolar current during the Last Glacial Maximum

Jean Lynch-Stieglitz, Taka Ito and Elizabeth Michel

Presenter: **Taka Ito**

The interaction between ocean circulation and biological processes in the Southern Ocean is thought to be a major control on atmospheric carbon dioxide content over glacial cycles. A better understanding of stratification and circulation in the Southern Ocean during the Last Glacial Maximum (LGM) provides information that will help us to assess these scenarios. First we evaluate the link between Southern Ocean stratification and circulation states in a suite of climate model simulations. While simulated Antarctic Circumpolar Current (ACC) transport varies widely (80-350Sv), it co-varies with horizontal and vertical stratification and the formation of the southern deep water. We then test the LGM simulations against available data from paleoceanographic proxies, which can be used to assess the density stratification and ACC transport south of Australia. The paleoceanographic data suggests a moderate increase in the Southern Ocean stratification and the ACC strength during the LGM. Even with the relatively large uncertainty in the proxy-based estimates, extreme scenarios exhibited by some climate models with ACC transports of greater than 250Sv and highly saline Antarctic Bottom Water are highly unlikely.

# Biogeochemical sensor performance in the SOCCOM profiling float array

Ken Johnson

Presenter: **Ken Johnson**

The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program has begun deploying a large array of biogeochemical sensors on profiling floats in the Southern Ocean. As of February 2016, 86 floats have been deployed. Here the focus is on 56 floats with quality controlled and adjusted data that have been in the water at least 6 months. The floats carry oxygen, nitrate, pH, chlorophyll fluorescence, and optical backscatter sensors. The raw data generated by these sensors can suffer from inaccurate initial calibrations and from sensor drift over time. Procedures to correct the data are defined. The initial accuracy of the adjusted concentrations is assessed by comparing the corrected data to laboratory measurements made on samples collected by a hydrographic cast with a rosette sampler at the float deployment station. The long-term accuracy of the corrected data is compared to the GLODAPv2 data set whenever a float made a profile within 20 km of a GLODAPv2 station. Based on these assessments, the fleet average oxygen data is accurate to 11%, nitrate to within 0.50.5 mol kg<sup>-1</sup>, and pH to 0.0050.01, where the error limit is 1 standard deviation of the fleet data. The bio-optical measurements of chlorophyll fluorescence and optical backscatter are used to estimate chlorophyll a and particulate organic carbon concentration. The particulate organic carbon concentrations inferred from optical backscatter appear accurate to within 35 mg C m<sup>-3</sup> or 20%, whichever is larger. Factors affecting the accuracy of the estimated chlorophyll a concentrations are evaluated.

# Variable Southern Ocean sea-to-air fluxes of CO<sub>2</sub> tagged by deep ocean <sup>14</sup>C

Colin Lindsay<sup>1</sup>, Scott Lehman<sup>1</sup>, John Miller<sup>2</sup>, Colm Sweeney<sup>2</sup>, Nicole Lovenduski<sup>3</sup> <sup>1</sup>University of Colorado/INSTAAR <sup>2</sup>NOAA/ESRL and University of Colorado/CIRES <sup>3</sup>Atmospheric and Oceanic Sciences, University of Colorado/INSTAAR

Presenter: **Colin Lindsay**

The net CO<sub>2</sub> sink of the Southern Ocean (SO) is the relatively small residual of the invading air-sea CO<sub>2</sub> flux and the large sea-air flux of outgassing ocean carbon that opposes it. Several studies suggest that ongoing global warming and/or regional changes in stratospheric ozone may strengthen and shift the westerly winds poleward, provoking increased upwelling of carbon-rich, radiocarbon-depleted water from the deep ocean while impeding the uptake of excess anthropogenic carbon from the atmosphere. Here we evaluate the use of precise measurements of radiocarbon in carbon dioxide from Drake Passage air ( $\Delta^{14}\text{C}$  of CO<sub>2</sub>) to detect short-term fluctuations in the Southern Ocean gross sea-to-air carbon flux. Drake Passage (DRP) boundary layer air has been sampled since 2006 at roughly 2-week intervals, resulting in an 8-year high-resolution <sup>14</sup>CO<sub>2</sub> time-series with accompanying same-flask CO<sub>2</sub> concentration measurements. We compare detrended and deseasonalized CO<sub>2</sub> concentration and  $\Delta^{14}\text{C}$  anomalies to indices of atmospheric and SO variability. CO<sub>2</sub> anomalies are correlated with the Southern Annular Mode (SAM), an index of SO westerly wind strength, while  $\Delta^{14}\text{C}$  anomalies appear to be anti-correlated with both the CO<sub>2</sub> anomalies and the SAM. This is preliminary evidence for enhanced outgassing of low- $\Delta^{14}\text{C}$  deep ocean carbon during positive SAM/stronger westerly wind conditions. Similar relationships are also observed to the Southern Oscillation Index (SOI), an index of atmospheric conditions associated with tropical sea surface temperature variability. This may be caused by a teleconnection that promotes greater upwelling in the Pacific sector of the SO during La Nia conditions.

# Uncertainty in projections of Southern Ocean acidification

Nicole Lovenduski, Claudine Hauri

Presenter: **Nikki Lovenduski**

We investigate projections of carbon uptake and the associated acidification of the Southern Ocean over 2006-2080 using output from two ensembles of the Community Earth System Model run under business as usual (RCP8.5) and mitigation (RCP4.5) emission scenarios. On basin-wide and regional scales we observe a rapid onset of aragonite undersaturation in surface waters by mid-century that may be detrimental to calcareous organisms. An analysis of variance reveals that the speed of transition from supersaturation to undersaturation is driven almost entirely by emission scenario, as internal variability in saturation depth across ensemble members is small. Regional differences are observed in the timing and magnitude of aragonite saturation state changes. In the Patagonian Shelf region, undersaturation of the top 200m of the water column is observed by 2080 regardless of emission scenario. Whereas, in the Weddell Sea, saturation state is significantly different between the two emission scenarios by 2080, and undersaturation of the surface waters is “avoidable” if we follow RCP4.5, rather than RCP8.5.

# Variability and change in Southern Ocean carbon: The Drake Passage bellwether

Amanda Fay, Nicole Lovenduski, Galen McKinley, David Munro, Colm Sweeney, Nancy Williams, Alison Gray

Presenter: **Nikki Lovenduski**

The Southern Ocean is highly under-sampled with respect to variables needed to assess trends in air-sea carbon dioxide fluxes and total carbon uptake. Since this region is dominant to the mean global ocean sink for anthropogenic carbon, understanding temporal change is critical. Underway measurements of the partial pressure of carbon dioxide ( $p\text{CO}_2$ ) collected as part of the Drake Passage Time-series (DPT) program beginning in 2002, can inform our understanding of changing air-sea carbon fluxes in the Southern Ocean. Here, we use underway  $p\text{CO}_2$  data from the Drake Passage to investigate  $p\text{CO}_2$  seasonality, variability, and long-term trends in Drake Passage and in the broader subpolar Southern Ocean region. Further comparisons with the entire SOCATv4 dataset (Bakker et al. 2016) are used to assess how representative these are of the larger Southern Ocean. Additionally, we analyze SOCCOM estimates of surface  $p\text{CO}_2$  in the Drake Passage region.

We find that the high temporal density of sampling by the DPT is critical for capturing the full seasonal cycle of surface  $p\text{CO}_2$  in this region. Although more data are needed to reduce uncertainties, trend analyses with available data both within the Drake Passage and the broader Southern Ocean show that overall trends are indistinguishable from one another when using only underway DPT observations versus non-DPT data included in SOCATv4 and with the entire SOCATv4 dataset for years 2002-2015. Additionally, seasonal trends show no statistical difference. Further investigations into regional differences within the Southern Ocean and specific years with intriguing signals will also be discussed. We also demonstrate the utility of the DPT as a calibration point for SOCCOM floats, finding that two recent float estimates of surface  $p\text{CO}_2$  align with that estimated by our underway system in the Drake Passage.

# Interfacial form stress in the Southern Ocean State Estimate

Jessica Masich, Matthew R. Mazloff, Teresa K. Chereskin

Presenter: **Jessica Masich**

The wind stress that drives the Antarctic Circumpolar Current (ACC) exits the fluid largely via topographic form stress (TFS) at the sea floor in the Southern Ocean State Estimate (SOSE); interfacial form stress (IFS) carries this momentum from source to sink. These two momentum fluxes combine to set the strength of the geostrophic component of the meridional overturning circulation (MOC). We separate the contributions of TFS and IFS to the residual overturning circulation by segmenting the geostrophic transport in an isopycnal layer according to where the layer is bound zonally by land or by fluid in the Southern Ocean State Estimate. This method allows us to construct three-dimensional maps of the IFS field.

These maps show that IFS compensates wind stress at the surface, carries this momentum through the ocean interior to the seafloor, and compensates TFS where the momentum exits the fluid and enters the solid earth. IFS helps set the structure of the residual MOC by compensating wind stress in the thermocline and intermediate waters, and by balancing deep southward transport and bottom northward transport across the Drake Passage latitudes. Eddy and mean IFS balance each other when integrated from surface to seafloor, but eddy IFS appears to dwarf mean IFS when calculated separately over each of the water masses that comprise the MOC. The strongest eddy IFS signals appear to concentrate over topographically steered currents whose transport variability is enhanced by the presence of adjacent mesoscale eddies.

# Large-scale vertical gradients of atmospheric trace gases to constrain air-sea CO<sub>2</sub> fluxes in the Southern Ocean

Kathryn McKain, Colm Sweeney, Matt Long, Britt Stephens, Elliot Atlas, Prabir Patra, David Munroe, Eric Kort, Ralph Keeling

Presenter: **Kathryn McKain**

Traditional ocean-based estimates of the air-sea flux of CO<sub>2</sub> imply that the Southern Ocean is significantly increasing, but the delicate balance between the seasonal cycle in sea surface temperatures and biological uptake make estimation of the CO<sub>2</sub> flux climatology and trends challenging to diagnose. In this study, we use vertical gradients of multiple trace gases measured throughout the free troposphere to constrain the large-scale air-sea flux of CO<sub>2</sub> using data from the O<sub>2</sub>/N<sub>2</sub> Ratio and CO<sub>2</sub> Airborne Southern Ocean Study (ORCAS), HIAPER Pole-to-Pole Observations (HIPPO) and Atmospheric Tomography Mission (AToM) campaigns. This study leverages the vertical distribution of methane and several shorter-lived species in the atmosphere over the Southern Ocean to constrain the input of CO<sub>2</sub> from the northern latitudes, the vertical mixing, and the air-sea flux of CO<sub>2</sub>. The resulting air-sea fluxes are compared with flux estimates made from the 16 years of measurements made in the Drake Passage Time Series, climatological estimates, as well as forward and inverse model estimates of Southern Ocean Fluxes. The results of this study demonstrate the advantage of aircraft profiles to provide a strong constraint on large-scale air-sea fluxes, and avoid the uncertainties associated with extrapolation of sparse ocean measurement in space and time and air-sea flux parameterizations.



# Inter-annual Variability in the Seasonal Cycle of Nutrients, Dissolved O<sub>2</sub>, Dissolved Inorganic Carbon, and Surface Ocean pCO<sub>2</sub> from the Drake Passage Time-series

David R. Munro, Nicole S. Lovenduski, Cynthia D. Nevison, Colm Sweeney

Presenter: **David R. Munro**

The Drake Passage Time-series (DPT) represents the most densely sampled time series of ocean biogeochemical measurements in the Southern Ocean. Over the last decade, an increase in uptake of carbon dioxide (CO<sub>2</sub>) has been observed both within the Drake Passage and across the Southern Ocean. However, mechanisms driving observed inter-annual variability in CO<sub>2</sub> uptake remain unclear. We examined seasonal cycles in macronutrients, dissolved oxygen (O<sub>2</sub>), dissolved inorganic carbon (DIC), and the surface ocean partial pressure of carbon dioxide (pCO<sub>2</sub>) from 15 years (2002-2016) of ship-based observations with the aim of understanding how the shifting balance of physical and biological processes influences inter-annual variability in uptake of CO<sub>2</sub>. Observations from the DPT are compared with time-series of atmospheric potential oxygen and satellite-based estimates of biological productivity to understand how changes in the Drake Passage are related to changes throughout the Southern Ocean.

# A nonlinear equivalent barotropic model of the ocean

Dave Munday, Chris Hughes and Helen Johnson

Presenter: **Dave Munday**

The Antarctic Circumpolar Current is often described as being “equivalent barotropic” (or even just “barotropic”). The expression is frequently used in the loose sense that currents at different depths tend to resemble each other, e.g. an exponential decay from the surface values. But there is also a strict definition of the term that has dynamical consequences, and which differs from the similarly strict definition of barotropic. After examining evidence for equivalent barotropic structure in the ACC, we will look at the equations that govern equivalent barotropic fluids. These equations will be used to construct a few simple wave solutions, which illustrate how the system differs from baroclinic and barotropic ones. The equations are also amenable to numerical methods, allowing us to see a nonlinear, equivalent barotropic fluid in motion.

# Constraining Satellite Ocean Color-Derived Export Fluxes in the Southern Ocean Using Atmospheric Potential Oxygen (APO) Data

Dave Munro, Ralph Keeling, Mati Kahru, Manfredi Manizza, Nicole Lovenduski

Presenter: **Cynthia Nevison**

The ability to constrain and detect changes in oceanic export flux (EF) is critical to accurately predicting the impact of ocean biota on atmospheric CO<sub>2</sub>. However, current estimates of the magnitude of carbon export from the oceanic surface layer range from 5 to 20 Pg C yr<sup>-1</sup> at the global scale, with even larger uncertainties at the regional scale. Past work has shown that remotely sensed ocean color and atmospheric potential oxygen (APO) data are valuable complementary metrics for evaluating the carbon cycle in the Southern Ocean. APO data provide a broad-scale, regionally-integrated constraint on the absolute magnitude of EF and also offer insight into subsurface ventilation processes that are not captured by ocean color measurements. In this presentation, the observed APO mean annual cycle will be used to evaluate satellite ocean color EF products derived from a range of NPP algorithms (VGPM, CbPM, QAA) and associated ef-ratio formulae (Laws, Dunne). This exercise involves decomposing the observed APO cycle into thermal, ventilation and net community production (NCP) components:  $APO_{obs} = APO_{thermal} + APO_{vent} + APO_{NCP}$ . The APO<sub>NCP</sub> component can be compared directly to the satellite EF products, after making two conversions. First, the EF product must be converted into an air-sea O<sub>2</sub> flux, based on the relationships among EF, NCP and the associated air-sea O<sub>2</sub> flux,  $fgO_{2,NCP}$ . These relationships have been evaluated recently using the CESM ocean biogeochemistry model, which suggests that a large fraction of spring and summertime O<sub>2</sub> outgassing is associated with seasonal production and storage of DOC, most of which does not leave the mixed layer. This needs to be taken into account when translating satellite-based EF fluxes into  $fgO_{2,NCP}$ . Second, the satellite-based  $fgO_{2,NCP}$  fluxes must be converted to an atmospheric oxygen tracer using an atmospheric tracer transport model. The relative uncertainties in these two conversions and the resulting constraints on satellite-based EF will be discussed. We will also report on trends in the seasonal cycle of APO detected in the Southern Ocean from the early 1990s to present, and will examine their consistency with trends in satellite ocean color data.

# Synoptic cyclones and sea ice in CESM: Their interactions in historical and projected climates

Ana Ordonez, Cecilia Bitz

Presenter: **Ana Ordonez**

Synoptic cyclones can change sea ice through both dynamic and thermodynamic processes. For example, winds can induce anomalous ice drift, which tends to be divergent at the storm center. Ice melt can be supported by warm air advection and the entrainment of warm ocean water into the surface from lower depths. The presence strong, year-round storms in the Southern Ocean make it an optimal location to assess the effects of synoptic cyclones on sea ice. This study uses the Community Earth System Model (CESM) to compare these interactions in the late twentieth and twenty-first centuries. Results are broken down by season and era (late 20th century vs. late 21st century). Storm composite analysis shows that there are clear spatial patterns of anomalies in ice concentration and growth rates around a low pressure center, and these anomalies appear to be related to the cyclone structure. In all seasons, dynamic forcings on the sea ice are larger than thermodynamic forcings. Storm-related bottom melt is notable only in austral summer. It was anticipated that a less compact, thinner ice pack in the late 20th century would be more susceptible to both dynamic and thermodynamic processes resulting from storm passages. There are slight increases in ice area and volume responses to storm forcings but with many exceptions in different seasons, offering weak evidence to support this hypothesis.

# Lagrangian analysis of Kerguelen’s naturally iron-fertilised phytoplankton bloom

A.Della Penna, S. De Monte, M. Grenier, S. Blain, S. Wotherspoon, C. Johnson, T. Trull and F. d’Ovidio

Presenter: **Alice Della Penna**

The role of iron as a limiting micro-nutrient for primary production in High Nutrient Low Chlorophyll regions has been highlighted by paleoceanography, artificial fertilisation experiments and observed naturally fertilised systems. Examples of natural fertilisation have suggested that (sub-)mesoscale (1-100 km, days-months) horizontal transport modulates and structures spatial and temporal extent of iron enrichment, phytoplankton production and biogeography. Here we combine different satellite products (altimetry, ocean color, PHYSAT), drifting floats and autonomous profilers to analyse the role of mesoscale dynamics on the naturally iron-fertilised phytoplankton bloom of the Kerguelen region (Southern Ocean). Considering the Kerguelen Plateau as the main source of iron in the region, we compute two Lagrangian diagnostics: the “age” -how long before a water parcel has touched the plateau- and the “origin” -latitude where a water parcel has left the plateau. First, we verify that these altimetry-defined diagnostics’ spatial patterns -computed using geostrophic and Ekman corrected velocity fields- are coherent with the ones structuring the trajectories of more than 100 drifters and that surface Chlorophyll (Chl) presents an overall agreement with total column contents. Second, assuming a first-order removal, we fit “age” with dissolved iron measurements and we estimate removal rates for bloom and abiotic conditions. Then, we relate “age” and “origin” with in-situ iron measurements, locations of high Chl concentrations and diatom-dominance. We find out that locations of high Chl concentration correspond to water parcels that have recently left the Kerguelen Plateau. Furthermore, general additive models reveal that recently enriched waters are more likely to present a diatom dominance. However, the expected exponential fit varies within the geographic domain suggesting that other mechanisms may influence diatom dominance. Finally, we evaluate the role of differences in Mixed Layer Depth at the time of enrichment, complex ecological dynamics and injections of iron caused by strong vertical velocities.

# Antarctic Bottom Water variability in the Southeast Pacific Basin along 103W

Sarah G. Purkey and Gregory C. Johnson

Presenter: **Sarah Purkey**

Antarctic Bottom Water (AABW) forms in the marginal seas around Antarctica and spreads to fill much of the abyssal global ocean. It has shown significant decadal variability, making contributions to both global heat energy and sea level rise budgets. We use 1994, 2008, and 2017 occupations of a meridional oceanographic transect along 103 W across the Southeast Pacific Basin to evaluate three decades of regional changes in AABW, down-stream from one of its major formation sites in the Ross Sea . The data reveal a statistically significant steady warming rate of 0.024 C per decade below 4000 m. The warming is accompanied by freshening, even on isotherms or isopycnals (reflecting water-mass changes). These changes are likely linked to the strong freshening of the Ross Sea shelf waters, one of the end-members of AABW. A slight decrease in the deep oxygen concentration provides supporting evidence that the AABW ventilation rate is declining.

# Fine-scale Southern Ocean dynamics from space: Preliminary results

Cesar B. Rocha, Sarah T. Gille, Teresa K. Chereskin

Presenter: **Cesar B. Rocha**

Existing numerical simulations and observations suggest that the Southern Ocean is host to a vigorous submesoscale ( $< 10$  km) field with striking geographic variability. Submesoscale flows are a route to dissipation of mesoscale energy and have an extraordinary impact on oceans biogeochemistry. The goal of this project is to investigate whether the geographic variability of submesoscales is linked to finescales ( $< 100$  km) and mesoscales, which can be observed from space. Traditional Ku-band and C-band nadir-looking altimeters have a footprint of 20 km, resulting in along-track resolutions that barely resolve finescales. Hence, we analyze recently released Ka-band altimeter data from the SARAL/AltiKa and Sentinel-3 satellite missions these altimeters have a footprint of about 8 km. To assess whether these data resolve fine-scale flows, and their geographic variability, we compare altimetric wavenumber spectra of SSH variance with a 1/48 MITgcm numerical simulation and observations near Drake Passage.

# High-Resolution Simulation of Sea Ice, Ocean Circulation and Marine Biogeochemistry in the West Antarctic Peninsula (WAP)

Cristina Schultz, Scott Doney

Presenter: **Cristina Schultz**

Over the past several decades, the West Antarctic Peninsula (WAP) has undergone physical and ecological changes at a rapid pace, with winter air temperatures warming up to 4.8 times the global average rate. The effects of this warming are felt by the ecosystem, with substantial decadal changes in the phytoplankton chlorophyll patterns and a poleward shift of ice-dependent species. These fluctuations are associated with the changing sea-ice cover in the region, which influences the upper ocean mixed layer depth, heat exchanges and local circulation. Recent research has found a consistent trend of shortening in the sea-ice season along the WAP, associated with changes in the wind pattern. The mechanisms behind these drastic climate changes are not fully understood and have been investigated by the Palmer-LTER (Long Term Ecological Research) program over the past two and a half decades. In this context, numerical modeling is a powerful tool, given the weather and sea ice constraints on data acquisition in the region. A high-resolution ocean circulation model, coupled to sea-ice and biogeochemistry modules, was implemented for the WAP to simulate the decadal trends and seasonal cycles of sea-ice advance, mixed layer depth and bloom formation as marked by chlorophyll and other biogeochemical tracers. The model used is MITgem (general circulation model) coupled with REcoM-2 (Regulated Ecosystem Model, version 2). The model results were compared to the data collected by the Palmer-LTER data. General seasonal pattern of chlorophyll, nutrients and inorganic carbon variables simulated (DIC and Alkalinity) are consistent with the observations, with onshore-offshore and north-south gradients well represented. Further sensitivity analyses on the biogeochemical model are still required, though, before we can make interpretations on the mechanisms behind changes in the ocean chemistry and ecosystem.



# Low-frequency and high-frequency oscillatory winds synergistically enhance phytoplankton at fronts

Dan Whitt, Marina Levy and John Taylor

Presenter: **Dan Whitt**

When phytoplankton growth is limited by low nutrient concentrations, full-depth-integrated phytoplankton biomass increases in response to intermittent mixing events that bring nutrient-rich waters into the sunlit surface layer. Here it is shown how oscillatory winds can induce intermittent nutrient entrainment events and thereby sustain more phytoplankton at fronts in nutrient-limited oceans. Low-frequency (i.e., synoptic to planetary scale) along-front wind drives oscillatory cross-front Ekman transport, which induces intermittent deeper mixing layers on the less dense side of fronts. High-frequency wind with variance near the Coriolis frequency resonantly excites inertial oscillations, which also induce deeper mixing layers on the less dense side of fronts. Moreover, we show that low-frequency and high-frequency winds have a synergistic effect and larger impact on the deepest mixing layers, nutrient entrainment, and phytoplankton growth on the less dense side of fronts than either high-frequency winds or low-frequency winds acting alone. These theoretical results are supported by two-dimensional numerical simulations of fronts in an idealized nutrient-limited open-ocean region forced by low-frequency and high-frequency along-front winds. In these model experiments, higher-amplitude low-frequency wind strongly modulates and enhances the impact of the lower-amplitude high-frequency wind on phytoplankton at a front. Moreover, sensitivity studies emphasize that the synergistic phytoplankton response to low-frequency and high-frequency wind relies on the high-frequency wind just below the Coriolis frequency.

# Novel use of profiling floats to estimate sea ice production on the Antarctic continental shelf

Esmee van Wijk, Steve Rintoul and Breck Owens

Presenter: **Esmee van Wijk**

Ocean and sea ice observations of the Antarctic continental shelf are sparse and consequently the physical processes and dynamics of this region are not well understood. Most historical observations are from hydrographic surveys during ice-free summers, with very few observations from under the ice during winter. The Argo program has successfully used profiling floats to observe the global ice-free oceans to a depth of 2000 m over the past 15 years. Advances in float design now give us the capability to deploy profiling floats in the seasonal ice zone. In this study, we describe the first results from polar profiling floats deployed on the Antarctic continental shelf in the Mertz polynya, Adlie Land. We use the floats in a novel way, deliberately grounding floats between profiles, in order to obtain full-depth water column profiles and to increase their residence time in a poorly observed region. The seasonal cycle of salinity reflects the formation and melt of sea ice and water mass formation. Using a salinity budget, sea-ice production is estimated monthly and seasonally over two full annual cycles (2012-2013). Sea ice production peaks in March in both years. The mean winter (March to October) ice formation rate was 2.4 cm/day in 2012 and 1.5 cm/day in 2013. These rates are lower than some previously published estimates for the Mertz Polynya, likely reflecting the decrease in polynya area and ice formation following the calving of the Mertz Glacier Tongue in 2010. The float provided the first full water column sampling in an Antarctic coastal polynya through the complete annual cycle, increasing our understanding of sea ice production and water masses and circulation in the Mertz polynya. Widespread deployment of similar floats would allow further insights into ocean ice interaction, circulation and seasonality of the Antarctic continental shelf.

# Investigating the observed relationships between variability in Agulhas sea surface temperatures and the atmospheric circulation

Samantha Wills, Dave Thompson

Presenter: **Samantha Wills**

There is a growing body of evidence which suggests that variations in sea surface temperatures (SST) in the midlatitude oceans are capable of significantly influencing the large-scale atmospheric circulation, especially near the major western boundary currents (WBC). In the Northern Hemisphere, observational analyses based on daily-mean data suggest that variations in the SST fields over the Kuroshio-Oyashio extension and Gulf Stream extension are associated with two distinct and robust patterns of atmospheric variability: 1) a pattern which peaks in amplitude approximately 2-3 weeks prior to the largest SST anomalies and is consistent with atmospheric forcing of the ocean and 2) a different pattern which lags the largest SST anomalies by approximately a few weeks to a month. The results suggest that the latter pattern is dependent on the anomalies in the SST field, indicating a potential response of the atmospheric circulation to SST variability in the WBC extension regions. In this study, the authors examine the observational support for (or against) a robust atmospheric response to midlatitude SST variability in the Agulhas current located along the southern tip of South Africa. Lead-lag analysis based on daily-mean data is used to assess the evidence for two-way coupling between SST anomalies and the atmospheric circulation on transient time scales. The results are compared against those for the Kuroshio-Oyashio and Gulf Stream extensions to assess the similarities and differences in midlatitude air-sea interaction between the Northern and Southern Hemispheres.

# Basin-Width Dependence of Northern Deep Convection

Madeleine K. Youngs, Raffaele Ferrari

Presenter: **Madeleine K. Youngs**

In the current climate there is deep convection in the North Atlantic but not the North Pacific. This has been suggested to be because of zonal asymmetries in freshwater forcing or inter-basin exchange. This study examines the role of basin width in convection shut-off. As the magnitude of freshwater forcing is increased in single basin experiments with a re-entrant Southern Ocean, the convection shuts off at a weaker forcing for the wider basin. Salt-advection feedback and the relative strengths of diffusive upwelling and Southern Ocean upwelling are examined as potential causes for the width dependence.