Not the SAM: Another form of large-scale variability in the Southern Hemisphere atmospheric circulation with potential implications for the Southern Ocean

David WJ Thompson

Presenter: **David WJ Thompson**

In this talk, I will provide novel evidence for a form of variability in the large-scale Southern Hemisphere atmospheric circulation that is very different from the SAM. In contrast to the SAM - which dominates variability in the atmospheric jet and exhibits variability on timescales from weeks to decades - the novel form of variability dominates the variance in atmospheric wave amplitudes and is characterized by periodic variability on timescales of 20-30 days. Implications for variations in the Southern Ocean will be discussed.

Drivers of Antarctic sea-ice expansion and Southern Ocean surface cooling over the past four decades

Matthew England and Ariaan Purich

Presenter: **Matthew England**

Despite global warming, total Antarctic sea-ice coverage has overall increased during the past four decades. In contrast, the majority of CMIP5 models simulate a decline. In addition, high-latitude Southern Ocean surface waters have largely cooled, in stark contrast to almost all historical CMIP5 simulations. Subantarctic Surface Waters have cooled and freshened while waters to the north of the Antarctic Circumpolar Current have warmed and increased in salinity. It remains unclear to what extent the cooling and Antarctic sea-ice expansion is due to natural variability versus anthropogenic forcing; due for example to changes in the Southern Annular Mode (SAM). It is also unclear what the respective role of surface buoyancy fluxes is compared to internal ocean circulation changes, and what the implications are for longer-term climate change in the region. In this presentation I will outline three distinct drivers of recent Southern Ocean surface trends that have each made a significant contribution to regional cooling: (1) wind-driven surface cooling and sea-ice expansion due to shifted westerly winds, (2) teleconnections of decadal variability from the tropical Pacific, and (3) surface cooling and ice expansion due to large-scale Southern Ocean freshening, most likely driven by SAM-related precipitation trends over the open ocean. We will also outline the main reasons why climate models for the most part miss these Southern Ocean cooling trends, despite capturing overall trends in the SAM.

Impact of SAM on the seasonal cycle of sea ice extent around Antarctica

Ed Doddridge, John Marshall (MIT), Max Kelley (GISS)

Presenter: **Ed Doddridge**

Through analysis of remotely-sensed sea surface temperature (SST) and sea ice concentration data we investigate the impact of the Southern Annular Mode (SAM) on sea-ice extent around Antarctica. The wintertime sea ice extent (SIE) maximum is not correlated with SAM from year to year, but we find a clear signal of SAM in the growth phase during Autumn. We show that positive SAM anomalies in the austral summer produce anomalously cold SSTs that persist and lead to anomalous ice growth in the following autumn. Negative SAM anomalies in summertime lead to anomalously warm SSTs and a reduction in the rate of sea ice growth. The anomalous patterns of sea-ice growth are not localised to one sector but evident all around Antarctica . The imprint of SAM appears to be seasonal: SST and ice extent anomalies do not persist from one year to the next, with the system resetting itself each winter. The signals we find in the data are also evident in the GISS coupled climate model, which we use to explore the underlying mechanisms. Finally we speculate about the effect of this mechanism may be having on Antarctic SIE in the current year.

Factors driving regional sea ice variability and trends

Marika Holland

Presenter: **Marika Holland**

Observed Southern hemisphere sea ice extent has increased since 1979 in contrast to results from most global climate models. The observed trend is made up of large regional changes that are partly compensating. While previous work has indicated that the observed increases in the total Antarctic sea ice extent are consistent with natural variability simulated by climate models, this is not the case if the regional and seasonal nature of the trends is considered. Here we explore factors that drive regional changes in Antarctic sea ice. This includes analysis of observed conditions over the historical record and how models simulate relevant processes that contribute to regional sea ice variations.

Why Did Antarctic Sea Ice Plummet in late 2016?

Cecilia M. Bitz and Malte F. Stuecker

Presenter: **Cecilia Bitz**

Near the end of 2016, Antarctic sea ice reversed course from its increasing trend since 1979. Only a few months earlier conditions were typical, but beginning in September, the ice began to rapidly decline. October 2016 was essentially tied with 1986 for the record of any October in the satellite era, and November and December obliterated the previous record lows in their respective months. While the extreme loss near the end of the year and carrying forward to the annual minimum in March made headlines, an explanation for the unusual conditions must begin months earlier. Very strong and unusual atmospheric circulation set up in September, with strong northerly winds in regions where major negative sea ice anomalies developed first. This circulation dominated by meridional anomalies gave way by November to strong easterly surface wind anomalies with a negative Southern Annular Mode. Using analysis of observations and models, I will discuss whether these unusual winds were sufficient to explain the remarkably low coverage, or whether the sea ice was likely anomalously thin or the ocean anomalously warm in advance as well. I will also discuss whether Antarctic sea ice may be on a new downward course.

The meandering and spiraling pathway of the Antarctic Circumpolar Current and climate variations

Lynne Talley, Matthew Mazloff, Veronica Tamsitt

Presenter: **Lynne Talley**

The Antarctic winter sea ice edge is closely associated with the southernmost Antarctic Circumpolar Current (ACC) fronts, which are guided northeastward, with their cold waters, by mid-ocean ridges in the Pacific and Atlantic, and Kerguelen Plateau in the Indian. In the Amundsen/Bellingshausen Seas and along Adelie Land, the southern ACC fronts are free from topographic control, and swing southwards towards Antarctica, carrying warmer waters. This suggests a planetary potential vorticity balance driven by wind-stress curl, distorted by deep upwelling along the major topographic ridges. Hydrographic observations show stronger penetration of full-depth ACC water into the Amundsen/ Bellingshausen Seas in 2011 compared with 1992, consistent with decreasing sea ice and increasing ice-shelf melt. Winter sea ice increased where the southern ACC is topographically locked into northeastward pathways. The standing eddy pattern of ACC poleward heat flux, strengthening winds, and decadal winter sea ice changes are consistent with strengthening circulation along the southern side of the ACC.

Transport and dynamics of the ACC in Drake Passage from observations made during cDrake

Teresa Chereskin, Kathy Donohue, Randy Watts, Yvonne Firing and Karen Tracey

Presenter: **Teresa Chereskin**

The cDrake program deployed a transport line and local dynamics array (LDA) of Current Meters and Pressure-recording Inverted Echo Sounders (CPIES) from 2007 to 2011 in Drake Passage to quantify the transport and dynamics of the Antarctic Circumpolar Current (ACC). The ACC was continuously monitored with a line of moored instrumentation with unprecedented horizontal and temporal resolution. Annual mean near-bottom currents are remarkably stable, yielding an estimated 45.6 Sv of barotropic transport with an uncertainty of 8.9 Sv. Together with the mean baroclinic transport relative to the seafloor of 127.7 Sv, the total mean ACC transport is 173.3 Sv. This transport is about 30% larger than the canonical value often used as a benchmark for numerical models, and the increase is entirely due to the contribution of the deep currents. The near-bottom currents are strongly topographically steered; however, they contribute to large bottom pressure torques where strong currents cross steep topography at small angles. The mean bottom pressure torque estimated for the cDrake line exceeds the wind stress curl by a factor of 15-20. The time-varying deep currents are found to be the prime agents in fluxing heat across the ACC in northern Drake Passage, when baroclinic instability results in barotropic geostrophic currents crossing the baroclinic Subantarctic and Polar Fronts. The average poleward mean-plus-transient eddy heat flux integrated vertically and horizontally across the 250-km length of the cDrake LDA is -0.013 +/- 0.005 PW. This 250-km LDA segment represents about 1.2% of the circumglobal path of the ACC and accounts for about 3.3% of the estimated total heat loss from ocean to atmosphere south of 60S. We estimate that the full Drake Passage would account for about 4-6 times the LDA estimate. About 6 hot spots like Drake Passage could account for the major portion of heat lost to the atmosphere south of 60S, with the balance coming from weaker eddy heat fluxes plus mean cross-front transport.

Is the Antarctic Circumpolar Current related to the Meridional Overturning Circulation?

Andy Hogg, Andrew Stewart, Paul Spence, Steph Downes & Oleg Saenko

Presenter: **Andy Hogg**

The Antarctic Circumpolar Current (ACC) is an expression of the forces that drive it, its eddy field and the topography which acts to brake the flow. Southern Ocean observations have revealed that, over the last few decades: - Wind stress forcing has increased; - The strength of the Southern Ocean eddy field has increased; and - ACC transport has not increased. However, the observing network is insufficient to diagnose changes in surface buoyancy fluxes; nor can it detect trends in the strength of the overturning circulation. Thus, we are left to models, theory and inference to understand Southern Ocean circulation. This presentation aims to use these three tools (models, theory and inference) to better understand the meridional overturning circulation (MOC) and its connection to the ACC. Models are used to highlight the sensitivity of the ACC and associated overturning to changes in forcing. The ACC is found to be strongly correlated with the strength of the lower overturning cell, but has a more complex relationship with the upper limb of the MOC. These relationships are placed into context using a simple, layer-wise momentum budget (which, coincidentally, helps to clarify the connection between eddy saturation and eddy compensation). This theoretical approach implies that the lower limb of the MOC contributes to the ACC momentum balance, and can be used to infer the possibility of detecting variations in Antarctic Bottom Water transport from Sea Surface Height measurements alone.

Eddy saturation of the Antarctic Circumpolar Current

David Marshall, Maarten Ambaum, Scott Bachman, James Maddison, Julian Mak, Dave Munday, Lenka Novak

Presenter: **David Marshall**

The Antarctic Circumpolar Current is the strongest current in the ocean and has a pivotal impact on ocean stratification, heat content, and carbon content. The circumpolar volume transport is relatively insensitive to surface wind forcing in models that resolve turbulent ocean eddies, a process termed "eddy saturation." A simple model is presented that explains the physics of eddy saturation with three ingredients: a momentum budget, a relation between the eddy form stress and eddy energy, and an eddy energy budget. The model explains both the insensitivity of circumpolar volume transport to surface wind stress and the increase of eddy energy with wind stress. The model further predicts that circumpolar transport increases with increased bottom friction, a counterintuitive result that is confirmed in eddy-permitting calculations. These results suggest an unexpected and important impact of eddy energy dissipation, through bottom drag or lee wave generation, on ocean stratification, ocean heat content, and potentially atmospheric CO_2. Finally, we show that the same physics suggests a simple modification of the Gent and McWilliams eddy parameterisation. The resultant eddy diffusivity agrees broadly with numerically-inferred values across four orders of magnitude and reproduces eddy saturation.

Could Cabbeling play a limiting role on the surface to interior pathway of Anthropogenic Carbon in the Southern Ocean?

Sjoerd Groeskamp

Presenter: **Sjoerd Groeskamp**

Changing ocean inventories of heat and tracers such as carbon are central to climate change. As the ocean is vertically layered in density, the surface to interior pathways of tracers depend on density changes, in order to penetrate through those layers. The study of density changes, or 'water mass transformation', is therefore essential to understand and quantify the tracer pathways in the ocean. In this talk I will show the surprising result that water mass transformation due to Cabbeling (densification upon mixing) is a first order contributor to Antarctic Intermediate Water (AAIW) formation. AAIW however, plays a key role for the surface to interior pathway of Anthropogenic Carbon. Using stream functions in Anthropogenic Carbon-density coordinates I will quantify the separate contribution from seasonality, advection, trend, surface fluxes, and mixing on for Anthropogenic Carbon pathways in an ocean model. This shows that currently, the accumulation of Anthropogenic Carbon is at the interface between SAMW and AAIW, a location influenced by Cabbeling. This raises a question, could Cabbeling play a limiting role on the surface to interior pathway of Anthropogenic Carbon, in the AAIW region?

Ocean-ice shelf interaction, polynya dynamics and bottom water change in East Antarctica

Steve Rintoul, Alessandro Silvano, Kate Snow and Esmee van Wijk

Presenter: **Steve Rintoul**

The largest (but most uncertain) contribution to future sea level rise will come from the Antarctic Ice Sheet. Recent studies suggest that the Antarctic Ice Sheet is more sensitive to ocean heat flux than previously thought, with ocean-initiated irreversible retreat of parts of the West Antarctic Ice Sheet underway and Antarctic mass loss set to double the sea level rise projected by the IPCC for 2100 under continued high emissions. Most attention to date has focused on West Antarctica, where observations show accelerating mass loss in recent decades and evidence of dynamic behaviour in the past. New observations show that East Antarctica is also an important part of the story. The first profiles collected from the front of the Totten Ice Shelf show that relatively warm water reaches the cavity and drives rapid basal melt, counter to the expectation that East Antarctica was isolated from warm ocean waters and therefore likely to be more stable than West Antarctica. Input of fresh water from basal melt of the ice shelf plays a key role in regulating ocean heat flux to the ice shelf cavity: buoyancy loss in the winter polynya is insufficient overcome the stratification, no dense shelf water is formed, and warm intrusions of modified Circumpolar Deep Water can persist throughout the year. The stratification and circulation at the Totten is therefore more similar to the rapidly melting glaciers in West Antarctica than to the cold-cavity ice shelves of its East Antarctic neighbours. The natural experiment resulting from calving of the Mertz Glacier Tongue in 2010 provides insight into polynya dynamics, dense shelf water formation and bottom water change. Changes in the regional icescape after calving reduced the size and activity of the polynya, leading to a sharp reduction in the salinity of dense shelf water. Mooring data from the sill through which dense water is exported to the deep ocean show that the increase in density from summer to winter is decreased by half after calving. This signal propagates to the deep ocean, where a twenty year time series of abyssal water properties confirms a sharp reduction in the density of the local variety of Antarctic Bottom Water. Freshening of the dense shelf water leads to warming of the Antarctic Bottom Water, a result explained by mixing of less dense overflows with the ambient fluid.

Effects of projected changes in wind, atmospheric temperature and freshwater inflow on the Ross Sea

J.M. Klinck, M.S. Dinniman, E.E. Hofmann, and W.O. Smith, Jr.

Presenter: **John Klinck**

A 5-km horizontal resolution regional ocean/sea ice/ice shelf model of the Ross Sea is used to examine the effects of changes in wind strength, air temperature and increased meltwater input on the formation of High Salinity Shelf Water (HSSW), on-shelf transport and vertical mixing of Circumpolar Deep Water (CDW) and its transformation into Modified CDW (MCDW), and basal melt of the Ross Ice Shelf (RIS). A 20% increase in wind speed, with no other atmospheric changes, reduces summer sea ice area by 11%, opposite the observed trend of the past three decades. Increased winds with spatially uniform decreased atmospheric temperatures increase sea ice concentrations, on-shelf transport of CDW, vertical mixing of MCDW, HSSW volume and (albeit small) RIS basal melt. Winds and atmospheric temperatures from the SRES A1B scenario forcing of the MPI ECHAM5 model produce decreased on-shelf transport of CDW and vertical mixing of MCDW for 2046-2050 relative to the end of the 20th century. The simulated MCDW concentrations for 2096-2100 are similar to those for the end of the 20th century. The RIS basal melt increased slightly by 2046-2050 (6%) and 2096-2100 (9%). Advection of lower salinity water into the model domain did not significantly affect sea ice extent or on-shelf CDW transport for the 2046-2050 or 2096-2100 simulations. However, freshening reduces vertical mixing of MCDW, enhances the RIS basal melt rate relative to the 20th century simulation for 2046-2050 (17%) and 2096-2100 (22%), and leads to a major reduction in the volume of HSSW produced

Water Mass Transformation Under Southern Ocean Sea Ice

Ryan Abernathey, Ivana Cerovecki, Paul Holland, Emily Newsom, Matt Mazloff, Lynne Talley

Presenter: **Ryan Abernathey**

This study quantifies the role of Antarctic sea ice in the transformations of water masses within the Southern Ocean State Estimate (SOSE). Winds drive a strong export of sea ice away from the continent towards the open ocean. The resulting freshwater fluxes at the ocean surface dominate the Southern Ocean freshwater budget (compared with direct precipitation and glacial melt), and these strong fluxes have a major impact on density, stratification, and circulation. Using Walins water mass transformation framework, we isolate the contributions of brine rejection, ice melt, and snow interception on the modification of seawater density. Together with direct atmospheric precipitation - evaporation, glacial melt, surface heat flux, and interior mixing, these processes provide the thermodynamic transformations necessary to sustain the meridional overturning circulation. The transformation analysis reveals that sea-ice freshwater fluxes are the main contributor to the transformation of upwelling Upper Circumpolar Deep Water, pushing it primarily towards lighter Antarctic Intermediate and Subantarctic Mode Water but also partly toward denser classes. We also examine the seasonal cycle in transformation, revealing a subtle interplay between brine rejection and upper ocean mixing. Overall these results indicate a tight coupling between Antarctic sea ice and the upper branch of the Southern Ocean overturning circulation.

Eddy/tidal mixing and transport at the Antarctic margins

Andrew L. Stewart, Andreas Klocker and Dimitris Menemenlis

Presenter: **Andrew L. Stewart**

Ocean processes occurring along the Antarctic continental slope admit shoreward transport of heat toward the continent's marine-terminating glaciers and export newly-formed dense waters from the continental shelf. Recent modeling studies indicate that both eddies and tides may modulate these processes in all sectors of the Antarctic margins. However, due the computational cost of resolving the small (20km) scales of Antarctic shelf/slope eddies, previous analyses have been limited to regional models and idealized process studies. In this study we analyze the contributions of both eddies and tides to shoreward heat transport around the entire Antarctic shelf break using output from recent global $ECCO_2$ simulations run at 1/24th and 1/48th degree horizontal resolutions. We show that both tides and eddies effect shoreward heat transport across the continental slope, whereas the heat transport associated with the time-mean flow tends to be directed offshore because it is associated with an Ekman overturning circulation driven by near-continental easterly winds. We discuss the localization of shoreward heat transport relative to troughs in the continental shelf, and variations of these heat transport processes between different sectors of Antarctica. To provide insight into the processes controlling cross-slope heat transport, we use energy and vorticity budgets to characterize the eddy/tidal-mean flow interaction in the Antarctic Slope Current (ASC). We show that tidal forcing produces a distinct dynamical regime in which the core of the ASC flows at almost exactly the same speed as the overlying sea ice, resulting in vanishing surface momentum input that is accommodated by lateral tidal momentum fluxes.

Observed mesoscale eddy signatures in Southern Ocean surface mixed-layer depth

U. Hausmann, D. McGillicuddy, J. Marshall

Presenter: **Ute Hausmann**

Combining satellite altimetry with Argo profile data a systematic observational estimate of mesoscale eddy signatures in surface mixed-layer depth (MLD) is provided across the Southern Ocean (SO). Eddy composite MLD anomalies are shallow in cyclones, deep in anticyclones, and increase in magnitude with eddy amplitude. Their magnitudes show a pronounced seasonal modulation roughly following the depth of the climatological mixed layer. Weak eddies of the relatively quiescent SO subtropics feature peak late-winter perturbations of +/-10 m. Much larger MLD perturbations occur over the vigorous eddies originating along the Antarctic Circumpolar Current (ACC) and SO western boundary current systems, with late-winter peaks of -30 m and +60 m in the average over cyclonic and anticyclonic eddy cores (a difference of 100 m). The asymmetry between modest shallow cyclonic and pronounced deep anticyclonic anomalies is systematic and not accompanied by corresponding asymmetries in eddy amplitude. Nonetheless, the net deepening of the climatological SO mixed layer by this asymmetry in eddy MLD perturbations is estimated to be small (few meters). Eddies are shown to enhance SO MLD variability with peaks in late winter and eddy-intense regions. Anomalously deep late-winter mixed layers occur disproportionately within the cores of anticyclonic eddies, suggesting the mesoscale heightens the frequency of deep winter surface-mixing events along the eddy-intense regions of the SO. The eddy modulation in MLD reported here provides a pathway via which the oceanic mesoscale can impact air-sea fluxes of heat and carbon, the ventilation of water masses, and biological productivity across the SO.

Mesoscale modulation of mixed layer depth and its impact on Southern Ocean chlorophyll

Hajoon Song, Matthew C. Long, Peter Gaube, Ivy Frenger, John Marshall and D.J. McGillicuddy Jr.

Presenter: **Hajoon Song**

Mesoscale eddies are ubiquitous in the World Ocean and more than 3000 eddies are usually found at any given moment. They leave detectable footprints on biogeochemistry reflected in significant cross-correlations between sea surface height (SSH) and chlorophyll (CHL) anomalies. Here we demonstrate that modulation of mixed layer depth by mesoscale eddies is a dominant driver of CHL, SSH correlations in the Southern Ocean along the path of the Antarctic Circumpolar Current, in contrast to the Gulf Stream or the Kuroshio Current where trapping and lateral transport in eddies prevail. We analyze satellite observations and an eddy-rich ocean model to show that mesoscale eddies strongly influence CHL concentrations, but drive CHL anomalies of opposite sign in winter versus summer. In austral summer deeper mixed layers in eddies with a positive SSH anomaly (or anticyclones) supply more iron, yielding higher CHL concentrations and a positive correlation between CHL and SSH. In austral winter, however, deeper mixed layers in anticyclones reduces light availability, leading to anomalously low CHL concentration and negative correlations between CHL and SSH. Eddies with a negative SSH anomaly (or cyclones) exhibit the opposite tendencies: lower CHL concentration in summer and higher in winter, contributing to positive correlations in summer and negative in winter. Our results suggest that modulation of vertical mixing by mesoscale eddies can cause systematic variations in primary productivity with implications for air-sea carbon exchange, a process that is currently not represented in coupled climate models.

The effect of resolving versus parameterizing the ocean mesoscale on ocean anthropogenic carbon storage

Frenger, I., Dufour, C. O., de Souza, G., Sarmiento, J., Griffies, S. M., and A. Gray

Presenter: **Ivy Frenger**

It is uncertain how the contemporary ocean carbon sink will develop in the future. One process contributing to this uncertainty is the ocean mesoscale, which we address here using three GFDL global climate models differing only in the resolution of their ocean component. The three models, which include an ocean biogeochemical component, were run under preindustrial atmospheric carbon dioxide levels and an idealized climate change scenario. We use this model suite to assess the effect of (i) better resolving the ocean mesoscale (comparison of a simulation with a 0.1° eddying ocean and one with a 0.25° ocean), and to (ii) assess the skill of the parameterization of the coarse resolution model for the mesoscale to capture this effect (comparison of 1° versus 0.1°). We find that (i) an improved representation of the ocean mesoscale results in close to 10% reduction in the uptake and storage of carbon by the ocean, due to a reduction of the volume of ventilated upper ocean waters including mode and intermediate waters, amplified by the tendency for longer ventilation time scales and only partially compensated for by a larger volume of newly formed deep waters; further, we find that (ii) if the mesoscale is parameterized, the decrease of volume of upper ocean waters is accentuated, yet that carbon uptake is increased instead of reduced. This increase is due to shorter ventilation time scales and a larger volume of newly formed deep waters, both compensating for the decreased volume of upper ocean waters. The relative fraction of the carbon uptake (44%) and storage (35%) accounted for by the Southern Ocean is very similar between the models, suggesting that the prominent contribution of the Southern Ocean to the global anthropogenic carbon sink is not primarily driven by mesoscale oceanic features. We contrast differences between ventilated waters originating in the Southern Ocean versus northern Atlantic and Pacific. These differences in carbon uptake between models with different ocean resolutions is substantial compared to the 25% structural uncertainty of preindustrial carbon uptake as represented by the CMIP5 model spread. Hence, we argue to pay enhanced attention to the effect of parameterizations for the mesoscale on upper ocean stratification and ventilation time scales in Earth system models to increase the robustness of projected ocean carbon uptake on decadal time scales.

Spatial Variations of Submesoscale Instabilities in Drake Passage

Giuliana A. Viglione, Andrew F. Thompson, Janet Sprintall, Mar Flexas, Sebastiaan Swart

Presenter: **Giuliana Viglione**

Submesoscale motions influence vertical velocities in the upper ocean and are thought to generate flows that penetrate the strong, persistent buoyancy gradients found at the base of the mixed layer. Despite the importance in setting ventilation, studies of submesoscale motions in the Antarctic Circumpolar Current (ACC) have been limited due to a lack of observations. The ChinStrAP (Changes in Stratification at the Antarctic Peninsula) field campaign consisted of a four-month summertime deployment of two gliders off the tip of the Antarctic Peninsula. The two gliders sampled on either side of Shackleton Fracture Zone (SFZ), a major bathymetric feature of the region, collecting over 2800 hydrographic profiles. These are used to examine the density structure and calculate potential vorticity in the region. The balanced Richardson angle (the ratio of the vertical to lateral buoyancy gradients) is used to classify submesoscale instabilities. Intermittent instances of symmetric instability are identified downstream of SFZ throughout the summer. Significant differences in the lateral buoyancy gradients and mixed layer depths up- and down-stream of SFZ suggest dissimilar dynamics between the two regions. We posit that the differences are due to the topographic steering of fronts upstream of SFZ and the injection of Weddell Sea waters downstream of SFZ. Comparisons are made between the observations, a 1-dimensional bulk mixed layer model, and a 1/48 GCM to determine the importance of the submesoscale. The results emphasize the significant role that submesoscale motions play in modulating the near-surface stratification at a key location for the ventilation of deep density classes.

Gradients of bio-optical properties within the Southern Ocean mixed layer

Magdalena M Carranza, Sarah T Gille and Peter JS Franks

Presenter: **Magdalena Carranza**

Turbulence levels can vary within the mixed-layer depth (MLD); thus, phytoplankton may not be fully homogenized within a mixed layer homogeneous in hydrographic properties. As phytoplankton are mixed through a light gradient, the competing effects of mixing and biological processes (i.e. photo acclimation and growth) determine whether gradients can form within a hydrographic mixed layer. Here, we exploit vertical profiles of bio-optical measurements from biogeochemical Argo floats and elephant seal tags in the Southern Ocean to assess biological structure within hydrographically defined mixed layers. Vertical profiles show significant variance in Chl-a fluorescence and particle backscattering within the mixed layer. We assess biological structure by fitting Chl-a fluorescence and particle backscattering profiles to typical functional forms (i.e. Gaussians, sigmoids, exponentials and their combinations), and select the best fit by means of a Chi-square goodness of fit test. Despite the Southern Ocean's deep mixed layers, only 40% of nighttime profiles showed homogenized bio-optical properties in the mixed layer. Of the remaining 60% that showed structure, 40% had a deep fluorescence maximum (DFM) below 20 m depth that correlated with particle backscattering. The depth of the DFM is compared to the MLD determined from density profiles based on several commonly used criteria. We find that a significant fraction of DFM are found within the MLD (20-80 %, depending on MLD definition). Our results suggest mixing timescales are often longer than biological timescales, thus, gradients can form within mixed layers more often than commonly thought. We hypothesize that periods of quiescence between synoptic storms are long enough ($>$ 3-4 days) to allow for phytoplankton growth and accumulation within layers that remain hydrographically well mixed.

The Outsized Role of the Southern Ocean in the Regulation of Carbon, Heat, and Biological Productivity

Presenter: **Jorge Sarmiento**

The Southern Ocean accounts for half the oceanic uptake of anthropogenic carbon, two-thirds of the oceanic uptake of heat from global warming, and supplies the nutrients that fertilize three-quarters of oceanic biological production in the rest of the world. Yet, because of its remoteness and the hostility of its environment, it is one of the poorest understood regions of the world. Recent major developments in observational and modeling capabilities are transforming our ability to study this region and the initial results from a fleet of new Argo floats equipped with biogeochemical sensors are stunning.

Seasonal cycle of nitrate observed with SOCCOM profiling floats and implications for carbon export

Ken Johnson

Presenter: **Ken Johnson**

Annual nitrate cycles have been measured throughout the pelagic waters of the Southern Ocean, including regions with seasonal ice cover and southern hemisphere subtropical zones. Vertically resolved nitrate measurements were made using in situ ultraviolet spectrophotometer (ISUS) and submersible ultraviolet nitrate analyzer (SUNA) optical nitrate sensors deployed on profiling floats. Thirty-one floats returned forty complete annual cycles. The mean nitrate profile from the month with the highest winter nitrate minus the mean profile from the month with the lowest nitrate yields the annual nitrate drawdown. This quantity was integrated to 200 m depth and converted to carbon using the Redfield Ratio to estimate Annual Net Community Production (ANCP) throughout the Southern Ocean south of 30 South. A well defined zonal mean distribution is found with highest values (3 to 4 mol C m-2 y 1) from 40 to 50 South. Lowest values are found in the subtropics and in the seasonal ice zone. The area weighted mean was 2.9 mol C m-2 y 1 for all regions south of 40 South. Cumulative ANCP from south to north is 1.3 Pg C y^{-1} at 50 South. This represents about 13% of global ANCP in about 14% of the global ocean area. Net Primary Production estimated from the ANCP is 3.7 Pg C y^{-1} south of 50 South, which is about two-fold larger than recent estimates based on ocean color remote sensing.

How the cryosphere may affect iron supply to Antarctic phytoplankton blooms

Mike Dinniman, Eileen Hofmann, John Klinck, Stefanie Mack, and Pierre St-Laurent

Presenter: **Mike Dinniman**

The enhanced biological productivity on the Antarctic continental shelf is primarily limited by light availability and micronutrient (iron) limitation. The cryosphere obviously affects light availability to the ocean in terms of sea ice cover, but the effect of the cryosphere on iron supply may be more subtle. Besides direct effects such as the input of meltwater with elevated iron concentrations from sea ice, floating ice shelves and icebergs, and grounded ice sheets, the physical interaction of the cryosphere with the ocean can lead to other pathways of iron to the euphotic zone. For example, in the Amundsen Sea, the "ice pump" overturning mechanism due to ice shelf basal melt may lead to a significant transport of deep iron into the surface waters. In the Ross Sea, intense sea ice formation leads to mixed layers that can extend throughout the entire water column and also supply benthic iron to the surface waters. We will show examples from regional ocean/sea-ice/ice shelf circulation models of the Amundsen Sea, Ross Sea and entire coastal Antarctic ocean to show how the ocean/ice physics can affect the supply of different simulated tracers representing iron into the Antarctic surface waters. Also, our regional Ross Sea model has been forced with projected atmospheric conditions for the end of the 21st century and results potentially relevant to micronutrient supply will be presented.

TBD

Presenter: **Curtis Deutsch**

TBD

Variability in the mechanisms controlling Southern Ocean phytoplankton bloom phenology in an ocean model and satellite observations

Tyler Rohr, Matt Long, Maria Kavanaugh, Keith Lindsay, Scott Doney

Presenter: **Tyler Rohr**

Understanding how physical processes –particularly vertical mixing- control biological productivity is critical to constraining Southern Ocean carbon storage. A coupled global numerical simulation (conducted with the Community Earth System Model) is used in conjunction with satellite remote sensing observations to examine the role of top-down (grazing pressure) and bottom-up (light, nutrients) controls on marine phytoplankton bloom dynamics in the Southern Ocean. Phytoplankton seasonal phenology is evaluated in the context of the recently proposed disturbance-recovery hypothesis relative to more traditional, exclusively bottom-up frameworks. All blooms occur when phytoplankton division rates exceed loss rates to permit sustained net biomass growth, however the nature of this decoupling period varies regionally. In particular, in the Subantarctic, southeast Pacific (55S - 45S) small spring blooms initiate early co-occurring with deep mixing and low division rates, consistent with dilution driven decoupling mechanisms outlined in the "disturbance-recovery" hypothesis. Similar systematics are present in the Subantarctic, southwest Atlantic (55S - 45S) during the spring, but are eclipsed by a subsequent, larger summer bloom that is coincident with shallow mixing and the annual maximum in division rates, consistent with a bottom-up, light limited framework. In the model simulation, increased iron stress prevents a similar summer bloom in the southeast Pacific. Satellite ocean color remote sensing and ocean physical reanalysis products do not precisely match model predicted phenology, but observed patterns do indicate regional variability in mechanism across the Atlantic and Pacific. Additionally, early work employing an eddy tracking algorithm in CESM to analyze eddies in a quasi-Lagrangian, eddy centric framework in order disentangle the variable mechanisms leading to observed eddy induced chlorophyll anomalies is previewed.

Atmospheric oxygen constraints on Southern Ocean air-sea CO_2 flux seasonality

Britton B. Stephens, Matthew C. Long, Ralph F. Keeling, Colm Sweeney, Eric A. Kort, Eric J. Morgan, Jonathan D. Bent, Kathryn McKain, Sara Mikaloff-Fletcher, Prabir Patra

Presenter: **Britton Stephens**

The seasonal exchange of CO_2 with the Southern Ocean (defined here as > 44 S) is driven by strong opposing thermal and biological forces. Climatological air-sea CO_2 flux estimates based on temporally and spatially sparse pCO_2 measurements in the region predict seasonal exchange in phase with biological forcing but relatively muted in amplitude. In contrast, many Earth system models predict large seasonal cycles in Southern Ocean air-sea CO_2 flux, in phase with biological forcing in some models but with opposite phase in others. Because air-sea O_2 exchanges are positively correlated for thermal and biological influences, and not affected by buffering chemistry, seasonal air-sea O_2 fluxes are considerably larger than their CO_2 counterparts. Consequently, atmospheric O_2 gradients are relatively unaffected by remote terrestrial and fossil influences and O_2 fluxes are more robustly constrained by atmospheric measurements. We use estimates of air-sea O_2 fluxes validated against atmospheric O_2, and O_2:CO_2 ratios in observed atmospheric gradients, to constrain the magnitude and drivers of seasonal CO_2 fluxes. We present results from the O_2/N_2 Ratio and CO_2 Airborne Southern Ocean (ORCAS) Study, which collected extensive measurements of atmospheric O_2, CO_2, and related species over the Southern Ocean, using the NSF/NCAR Gulfstream V aircraft based out of Punta Arenas, Chile, during January and February 2016. We use this intensive airborne campaign to leverage long-term in situ atmospheric O_2 and CO_2 measurements made over a latitudinal transect across the Drake Passage on the Antarctic Research and Support Vessel Laurence M. Gould (2012-2017), as well as flask based measurements from Palmer Station Antarctica (PSA) and South Pole (SPO) from the Scripps Oxygen Network (1997-2016). Collectively, these measurements show: 1) Consistently negative correlations between atmospheric O_2 and CO_2 gradients in both summer and winter, confirming the biological dominance of Southern Ocean seasonal CO_2 exchange and allowing rejection of Earth system models that predict air-sea CO_2 fluxes with opposite phase to biological forcing. 2) Strong atmospheric signals of O_2 outgassing and CO_2 ingassing during ORCAS, with a campaign mean ratio of -2.7 molO_2:molCO_2. These indicate large-scale O_2 efflux similar to observationally-based climatological estimates, and large-scale CO_2 uptake significantly larger than climatological summertime CO_2 flux estimates. 3) Summertime atmospheric O_2 and CO_2 differences between PSA and SPO with a long term mean ratio of -8.3 molO_2:molCO_2, which convolved with climatological air-sea O_2 flux estimates agree well with pCO_2-based flux climatologies, but also exhibit considerable interannual variability (1σ = 7.9 molO_2:molCO_2). 4) Wintertime latitudinal CO_2 gradients from the Gould that are flat and PSA-SPO differences that are small (+0.14 +/- 0.10 ppm). In comparison to O_2 observations (ratios -10 molO_2:molCO_2) convolved with O_2 flux estimates, these gradients are consistent with pCO_2-based climatologies showing weak wintertime outgassing.

Airborne constraints on Southern Ocean carbon and oxygen fluxes: implications for magnitude of exchange and the importance of intense exchange events

Eric Kort, Martin Hoecker-Martinez, Britt Stephens, Matt Long, Colm Sweeney, Ralph Keeling, Kathryn McKain, Eric Morgan, Jonathan Bent, ORCAS science team

Presenter: **Eric Kort**

Climatological representations of atmosphere-ocean carbon exchange with the Southern Ocean exhibit smooth, near-sinusoidal seasonal exchange with modest annual uptake. Model representations exhibit widely varying seasonality and net exchange, sometimes with strongly non-sinusoidal seasonality. Contrasting individual days between model representations (in this case CESM) and climatologies explains these differences in seasonal carbon exchange by illustrating the dominant summer role of localized biological activity and high-wind events in CESM ("high-flux events") not represented in a typical climatology. Here we will discuss using airborne observations of CO_2 and O_2 from the ORCAS (O_2/N_2 Ratio and CO_2 Airborne Southern Ocean Study) campaign to assess the importance of high-flux events and the accuracy of the CESM representation. We will contrast observed marine boundary layer variability in CO_2 and O_2 with that predicted by CESM and climatological representations, assessing the represented frequency and intensity of flux exchange. Further, we will leverage a Lagrangian atmospheric transport model to evaluate exchange on 4-48 hour time frames, producing fluxes of CO_2 and O_2 derived from atmospheric observations and compared with model and climatological representations. Combined, these results will provide insight into the role of intense exchange events in controlling Southern Ocean carbon exchange, potentially prioritizing mechanisms that drive these events for further study.

Modeling Atmospheric CO_2 in the Southern Ocean

Andrew R Jacobson[1,2], Kathryn McKain[1,2], and Colm Sweeney[1,2]

1. University of Colorado Boulder
2. NOAA Earth System Research Laboratory

Presenter: **Andrew R Jacobson**

Recent atmospheric profiles of CO_2 in the Southern Ocean are suggestive of stronger vertical gradients than are present in current CarbonTracker simulations. There are a number of potential explanations for this. One is that the paradigm of little atmospheric CO_2 variability in high southern latitudes is incorrect. This assumption is widely exploited in CO_2 analyses, for instance being explicitly used to determine empirical bias corrections for OCO-2 and TCCON retrievals, so if it is wrong there will be significant ramifications. It could also be due to faults in the atmospheric model: excessive vertical mixing for instance, or underestimation of Southern Ocean uptake. Modeling CO_2 in the deep southern hemisphere is challenging not only because there are relatively few in situ observations of atmospheric CO2 and oceanic pCO_2, but also because the meteorology itself is poorly constrained. We will explore the representation of atmospheric CO_2 by propagating multiple estimates of air-sea CO_2 exchange through two different atmospheric models: TM5 using ERA-interim winds, and GEOS-Chem with MERRA2 meteorology. These simulations will be compared with available atmospheric CO_2 observations from ORCAS and from the in situ CO_2 observing network, and will help to answer the question "Can you ever trust an atmospheric modeler?"

Geochemical evidence for the state of the ice-age Southern Ocean

Bob Anderson

Presenter: **Bob Anderson**

Geochemical tracers provide clues to the state of the Southern Ocean during the last ice age. Each tracer in isolation is subject to multiple interpretations. For example, the zone of maximum diatom productivity during the last ice age, inferred from sediment records of opal burial, was situated about 5 to the north of its present location. This displacement has been attributed either to inhibition of diatom growth in the south by northward expansion of sea ice, or to a northward displacement of the main axis of upwelling that supplies the Si to fuel diatom growth. The opal record alone cannot discriminate between these hypotheses, but adding N isotopes to the mix shifts the interpretation in favor of a northward displacement of upwelling. Further adding indicators of deep water ventilation (oxygen, carbonate ion) and of surface ocean pH (B isotopes) builds a picture of a poorly ventilated deep ocean during the ice age and a pulse of overturning during deglaciation, both at the termination of the last ice age and for each ice age of the last million years. This presentation will pull together evidence from published records to pose a challenge for ocean dynamicists to develop a physical context that is consistent with the geochemical evidence.

Deep-Sea Coral Evidence for the State of the Southern Ocean Biological Pump and Circulation During the Last Glacial Period and Deglaciation.

Adkins, J.F., Hines, S., Wong, T., Sigman, D., Burke, A., Robinson, L., Anagnostou, E., Sherrell, R., and Rae, J.

Presenter: **J.F. Adkins**

The Southern Ocean is thought to play a central role in governing glacial-interglacial pCO_2 in the atmosphere. This control arises from two features of the system. First, the efficiency of the biological pump in the surface waters determines the extent to which CO_2 is drawn down and exported to the interior of the ocean. Second, the rate of water mass renewal determines how long the water is isolated from the atmosphere. These two features can be combined into a single variable, the integrated pre-formed phosphate of the ocean, which has a first order ability to predict the steady-state pCO_2 of the atmosphere. Obtaining records of this crucial variable has been difficult. We will present four new records from deep-sea corals in the Southern Ocean that each track a different aspect of the combined biological and physical pieces of the system. This work is mostly focused on intermediate waters but does include some data that is monitoring the deepest circulation cell. Combined radiocarbon and clumped isotope data give us a sense of the circulation structure. P/Ca and d15N data confirm that the last glacial was a time of more efficient biological production and lower pre-formed phosphate in the Southern Ocean. Finally, d11B data show the direct signal of pH increase during times of pCO_2 rise in the deglaciation. This signal is the direct result of CO_2 degassing from the ocean?s deepest cell after prolonged storage during the last glacial. Together these new records are beginning to paint a coherent picture of a slower overturning circulation, in the lower cell, that accumulates the rain of organic matter from a more efficient biological pump during the last glacial that together help to keep pCO_2 low until the early deglaciation.

The ocean meridional overturning circulation at the LGM

Raffaele Ferrari

Presenter: **Raffaele Ferrari**

I will review recent work that on the role of the Southern Ocean in driving the observed changes in the ocean meridional overturning circulation. I will also discuss how these changes resulted in addition sequestration of carbon in the abyssal ocean.

Deciphering deep ocean circulation changes between the present and last glacial maximum

Malte Jansen, Alice Marzocchi, Louis-Philippe Nadeau

Presenter: **Malte Jansen**

The paleoclimate record indicates that the deep ocean circulation and water masses have undergone major rearrangements between glacial and interglacial climates, which have likely played an important role in the observed atmospheric carbon dioxide swings by affecting the partitioning of carbon between the atmosphere and ocean. The mechanisms by which the deep ocean circulation changed, however, are still unclear, which represents a major challenge to our understanding of past and future climates. We address this question using a hierarchy of models of varying complexity, from a highly idealized ocean-only model to coupled climate simulations from the Paleoclimate Modeling Intercomparison Project (PMIP). The results suggest that various inferred differences in the deep ocean circulation and stratification between glacial and interglacial climates can be attributed to increased Antarctic sea-ice formation in a colder world. Colder temperatures lead to thicker ice around Antarctica, which is exported by winds. The associated increased freshwater export leads to saltier and denser Antarctic Bottom Water, consistent with high abyssal salinities inferred for the Last Glacial Maximum (LGM). The enhanced deep ocean stratification moreover results in a shoaling of the inter-hemispheric overturning circulation, again consistent with proxy evidence for the LGM. The results also highlight the importance to distinguish between the equilibrium and transient response of the ocean circulation to climatic changes. The adjustment of the deep ocean circulation is shown to be highly non-monotonic, with the response on centennial time-scales differing qualitatively from the equilibrium results. This distinction is rarely observable in complex coupled climate models, which cannot be integrated for sufficiently long times.

Does Southern Ocean surface forcing shape the global ocean overturning circulation?

Shantong Sun, Ian Eisenman, and Andrew L. Stewart

Presenter: **Shantong Sun**

Paleo-proxy data suggests that the Atlantic Meridional Overturning Circulation (AMOC) was shallower at the Last Glacial Maximum (LGM) than its pre-industrial (PI) depth. Previous studies have suggested that this shoaling necessarily accompanies Antarctic sea ice expansion at the LGM. In this presentation, the influence of Southern Ocean surface forcing on the AMOC depth will be investigated using three ocean-only simulations of the Community Earth System Model (CESM) with surface forcing specified from the output of previous coupled PI and LGM simulations: one control simulation forced with PI surface conditions, a second control simulation forced with LGM surface conditions, and a test simulation forced with LGM surface conditions in the Southern Ocean and PI surface conditions elsewhere. In contrast to previous predictions, we find that the AMOC depth in the test run shoals only about half as much as in the LGM control simulation. We show that this occurs because diapycnal mixing renders the Southern Ocean overturning circulation more diabatic than previously assumed, which diminishes the influence of Southern Ocean surface buoyancy forcing on the depth of the AMOC.

The role of the Antarctic Ocean in glacial/interglacial CO_2 change as diagnosed from upper ocean biogeochemical conditions

Daniel M. Sigman

Presenter: **Daniel M. Sigman**

After a brief recap of the geochemical mechanisms by which the Southern Ocean can affect atmospheric CO_2 on glacial/interglacial time scales, I will summarize nitrogen isotopic and complementary data that argue for reduced nitrate supply to the Antarctic Zone surface during ice ages. This finding leads to a geochemically straightforward scenario for a significant portion (30-60 ppm) of the glacial/interglacial CO_2 change, which involves a flexible combination of (1) more complete nitrate consumption in the Antarctic surface water that subsequently flows into the deep ocean and (2) reduced flow of Antarctic surface water into the deep ocean. However, this scenario requires a physical mechanism; model simulations of ocean circulation under ice age conditions have not demonstrated this behavior. Moreover, an acceptable mechanism must be consistent with paleoceanographic data indicating that nitrate supply to the Subantarctic Zone continued during ice ages. To distinguish among alternatives, I will turn to a simple, isotope-focused geochemical box model of the Antarctic Zone as well as nitrogen isotope data from outside the Antarctic Zone. This exercise relies upon our understanding of, and thus has implications for, modern Southern Ocean processes, including mechanisms of deep ocean ventilation and nutrient transport by diapycnal mixing in the interior.

Linking Glacial-Interglacial cycles to multiple equilibria of climate

David Ferreira, John Marshall, Taka Ito, David McGee

Presenter: **Ferreira David**

Over the last 3 million years, Earth's climate has oscillated between cold and warm states with periods of 41,000 and 100,000 years, the glacial-interglacial cycles (GIC). Oscillations of Earth's orbital parameters are often identified as the ultimate driver of GIC but it is unclear how the associated rather small perturbations in top-of-the-atmosphere solar fluxes can be sufficiently amplified to drive such dramatic transitions. A potential solution to this long standing puzzle is that Earth's climate is endowed with multiple equilibrium states; the intransitivity of the climate system would permit large excursions in response to small variations of its forcing. A major obstacle to this theory is that global-scale multiple equilibria commensurate with the glacial-interglacial differences appeared to be the property of low-order models only. Here we report on two key advances. First we show that multiple stable states can be sustained in a complex coupled model of the ocean-atmosphere-sea ice system configured with an Earth-like geometry. In our model, two equilibrium states coexist for the same parameters and external forcings: a Warm climate with a small Northern hemisphere sea ice cap and a large southern one and a Cold climate with large ice caps at both poles. Second, we show that the warm and cold equilibrium climates of our system exhibit striking similarities to, respectively, present-day climate and what is known of the last glacial maximum (LGM), including biogeochemical signatures. Notably, the cold state supports an atmospheric pCO_2 drawdown of order 100 ppm, close to that seen in ice core records. Excess carbon is retained in the LGM deep waters primarily due to the inhibition of de-gassing over the upwelling regions in the southern hemisphere due to the expansion of the seaice cover, and the subduction of the excess carbon into the lower limb of the meridional overturning circulation. Solubility and biological effects and changes in the westerly winds may play secondary roles. Our results suggest that Glacial-Interglacial cycles could be a manifestation of multiple equilibrium states in the Earth's climate.

Carbon cycle responses to the multiple equilibria of climate

David Ferreira, John Marshall, Taka Ito, David McGee

Presenter: **Taka Ito**

Southern Ocean upwelling is a primary conduit through which the interior ocean carbon reservoir directly interacts with the atmosphere. Upwelled deep water releases its carbon into the atmosphere but it also brings up nutrients that support biological productivity and re-capture some of the upwelled carbon. The efficiency of the de-gassing is also regulated by seaice cover and relatively slow rate of air-sea carbon exchange. The total ocean-atmosphere carbon exchange results from the combined effects of these processes with implications to the future and past carbon cycle and global climate.

Here an idealized aquaplanet model based on the MITgcm is used to analyze the reorganization of the global carbon cycle associated with two (multiple) equilibrium climate states characterized by a large and small seaice area over the Southern Ocean. The two states differ by approximately 100 ppm in the atmospheric carbon dioxide similar to the contrast between the Last Glacial Maximum (LGM) and Holocene. Despite model biases and the absence of an iron cycle, it is able to reproduce the observed patterns of macronutrient (phosphate) distribution at the LGM with enriched abyssal phosphate relative to the modern climate. Furthermore, the model reproduces the mid-depth oxygenation in the cold state in agreement with the recent reconstructions of the oxygen levels during LGM.

A carbon budget analysis suggests that the carbon drawdown is predominantly controlled by the inhibition of de-gassing (-87.5ppm) which is partially compensated by the weakened biological pump (+36.4ppm). The weakened biological pump is reflected by the increase of preformed phosphate in the glacial AABW, which may be at odds against proxies of nutrient utilization in the polar Southern Ocean. Further study should assess the role of glacial iron fertilization in modulating the preformed nutrient level of the glacial AABW.

Insight into glacial interhemispheric ocean dynamics using a time-dependent box model with realistic ocean physics

Sophia K. Hines, Jess F. Adkins, Andrew F. Thompson

Presenter: **Sophia Hines**

One of the most striking discoveries from the first Greenland ice core records is the widespread presence of abrupt climate transitions during the last glacial period. These Dansgaard-Oeschger (DO) events are the manifestation of a climate system with multiple steady states and the ability to transition rapidly between them. High-resolution Southern Hemisphere ice cores have complementary oscillations known as Antarctic Isotope Maximum (AIM) events, and the anti-phase correspondence of these Northern and Southern Hemisphere oscillations is known as the bipolar seesaw. Dansgaard-Oeschger events have been linked to freshwater perturbations in the North Atlantic, which lead to changes in North Atlantic Deep Water (NADW) formation strength. We explore the ocean physics driving the bipolar seesaw using a time-dependent dynamical box model. This model consists of an ACC channel, an Atlantic basin, and a Pacific basin. There are multiple layers representing different density classes and the volume of the boxes responds to realistic residual-mean Southern Ocean dynamics. Our model has a surface buoyancy flux, wind forcing and transfer of mass between the basins in the ACC region, diffusive upwelling in the basins, and North Atlantic Deep Water formation. The model solves for the circulation and stratification in addition to the volumes of the boxes. In certain regimes, the model may undergo abrupt transitions linked to a transition between Southern Ocean surface outcropping in regions of positive and negative buoyancy forcing. Adjustment of the outcropping locations respond to changes in basin stratification following a perturbation in NADW formation. The transient dynamics of this adjustment introduce an advective timescale that closely matches the observed 200-year time lag between DO events and AIM events.

The dynamics of a multi-basin overturning circulation

Andrew Thompson, Andrew Stewart, Tobias Bischoff

Presenter: **Andrew Thompson**

The ventilation of deep and intermediate density classes at the surface of the Southern Ocean impacts water mass modification and the air-sea exchange of heat and trace gases, which influences the global overturning circulation and Earth's climate. Substantial zonal variability occurs along the Antarctic Circumpolar Current related to flow-topography interactions, variations in surface boundary conditions, and exchange with the northern basins. These zonal variations influence the interpretation of the overturning circulation, typically represented by a two-dimensional (depth-latitude), two-cell streamfunction that suppresses information about zonal mass and tracer transport. This study extends zonally-averaged overturning theories to explore a three-dimensional, or figure-eight circulation that cycles through multiple basins. The dynamics that influence the closure of the overturning in both steady-state and transient situations will be addressed. Our analysis is based on the derivation of a three-dimensional model of the overturning circulation that is simplified to a multi-basin isopycnal box model. The model determines the stratification and diabatic water mass transformations in each basin. The idealization to multiple, two-dimensional basins permits zonal mass transport along isopycnals in a Southern Ocean–like channel, while retaining the dynamical framework of residual-mean theory. The sensitivity of the overturning to basin widths and and other external forcing will be discussed. A solution for the full isopycnal structure in the Southern Ocean reproduces observed stratification differences between Atlantic and Pacific Basins and provides a scaling for the diffusive boundary layer in which the zonal mass transport occurs. Mechanisms that support transitions between different overturning states as well as links between the idealized model and observations will also be presented.

The Atlantic-Pacific Buoyancy Dipole: a Global Context for Southern Ocean Zonal Asymmetry

Emily R. Newsom and Cecilia M. Bitz

Presenter: **Emily R. Newsom**

The Southern Ocean's essential role in the climate system stems, in part, from the differences in continental geometry between the northern and southern extra-tropics. Studies of ocean dynamics traditionally focus on the unique zonal *symmetry* of the Southern Ocean system, instead highlighting the meridional asymmetry in the global circulation. In doing so, these studies reinforce a two-dimensional, two-celled model of the Global Overturning Circulation (GOC). Recent studies have cautioned that this two-celled model severely limits our understanding of the GOC, which is better described by a 'figure-of-eight' loop through the full global ocean. Here, we argue that this traditional two-celled conception of the GOC further obscures a fundamental feature of the global scale thermodynamic coupling between the ocean and atmosphere, and the essential function of the Southern Ocean therein.

A global-scale analysis of a preindustrial control simulation in CCSM 4 reveals that the Indo-Pacific Oceans receive a significant surplus of buoyancy flux, when fluxes are integrated over their Equatorial and Northern Hemisphere surfaces; in contrast, the Atlantic constantly loses buoyancy to the atmosphere over the same latitudes. This asymmetric surface forcing is countered by an interior ocean buoyancy transport, accomplished by the predominately counterclockwise isopycnal circulation emanating from the Southern Ocean into the Indo-Pacific Basins, and the predominately clockwise circulation extending towards the Atlantic. This figure-of-eight circulation structure, integrated across all depths, provides a global conduit of buoyancy from the Northern Hemisphere Indo-Pacific and into the Northern Hemisphere Atlantic, which persists only through zonal asymmetries in the structure of the Southern Ocean circulation.

While the global pattern of surface buoyancy flux and the structure of the GOC are deeply coupled, it is further argued that the distribution of surface buoyancy gains and losses is geometrically constrained by the significant differences in ocean basin width at each latitude. We present a new model for understanding the structure of the GOC from a thermodynamic perspective: the overturning circulation is a means of redistributing broadly persistent, zonally asymmetrical features in oceanic heat and uptake over the global scale. This model provides a new context in which to consider zonal asymmetries in Southern Ocean dynamics, which are essential in maintaining a steady global climate.

Southern Ocean upwelling timescales

Adele Morrison, Henri Drake, Stephen Griffies, Jorge Sarmiento, Wilbert Weijer, Alison Gray

Presenter: **Adele Morrison**

The timescale for deep water to upwell in the Southern Ocean significantly impacts air-sea fluxes of heat and CO_2, as well as the transient climate response. However, upwelling timescales are particularly difficult to measure from observations and have been largely unexplored by modelling studies. Using a suite of global coupled models with ocean resolution varying from 1 to 0.1, we investigate the advective transit times for Lagrangian particles to upwell from the deep ocean at 30S to the high-latitude surface ocean. Lagrangian timescales for Southern Ocean upwelling shorten from 88 years to 32 years to 17 years as the model ocean resolution is refined from 1 to 0.25 to 0.1. Stronger eddy fields lead to faster upwelling timescales, as demonstrated by an experiment where we degrade the temporal resolution of the 0.1 model velocity field. Consistent with the pattern in upwelling timescales, we find that a Lagrangian particle completes on average 3.2 circumpolar loops in the 1 model, but only 0.9 loops in the 0.1 model. These differences suggest that coarse resolution models may overestimate upwelling transit times and inter-basin merging of deep waters in the Southern Ocean.

Pathways of upwelling deep waters to the surface of the Southern Ocean

Veronica Tamsitt, Henri Drake, Adele Morrison, Lynne Talley, Carolina Dufour, Alison Gray, Stephen Griffies, Matthew Mazloff, Jorge Sarmiento, Jinbo Wang, Wilbert Weijer

Presenter: **Veronica Tamsitt**

We investigate Southern Ocean deep water upwelling pathways in three dimensions, using hydrographic observations and Lagrangian particle tracking in three high-resolution ocean and climate models. The northern deep waters enter the Antarctic Circumpolar Current (ACC) via narrow southward currents along the boundaries of the three ocean basins, before spiraling southeastward and upward through the ACC. Upwelling is greatly enhanced at five major topographic features, associated with vigorous mesoscale eddy activity. Deep water reaches the upper ocean predominantly south of the southern ACC boundary, with a spatially nonuniform distribution, regionalizing warm water supply to Antarctic ice shelves and the delivery of nutrient and carbon-rich water to the sea surface. In addition, we quantify water mass transformation along Lagrangian trajectories, to identify where diabatic processes are important along the upwelling pathways.

Observations of the Southern Ocean Meridional Overturning Circulation from Argo Data

Alison R. Gray, Stephen C. Riser

Presenter: **Alison Gray**

The southern limb of the global meridional overturning circulation has a critical impact on the climate system by regulating the air-sea balance of carbon dioxide and shaping biological production throughout the tropics and subtropics. However, observations of this region have historically been limited in both space and time. Here we present a direct circumpolar estimate of the overturning circulation in the upper 2000 dbar of the Southern Ocean, produced using absolute geostrophic velocities and eddy thickness fluxes estimated from observations from the Argo array of profiling floats. The spatial variability of the overturning and the relative contributions of the mean and eddy components of the flow are both analyzed. Eddies are found to generate significant cross-stream transport of Upper Circumpolar Deep Water, primarily localized to regions just downstream of major topographic features, consistent with predictions based on analytic and numerical models. In addition, our analysis suggests that the eddy component is associated with the restratification of deep winter mixed layers and the export of mode and intermediate waters.

Localized rapid warming of West Antarctic subsurface waters by remote winds

P. Spence, R. Holmes, A. Hogg, S. Griffies, K. Stewart, M. England

Presenter: **Paul Spence**

The largest rates of Antarctic glacial ice mass 15 loss are occurring to the west of the Antarctica Peninsula in regions where warming of subsurface continental shelf waters is also largest. However, the physical mechanisms responsible for this warming remain unknown. Here we show how localized changes in coastal winds off East Antarctica can produce significant subsurface temperature anomalies (>2C) around much of the continent. We demonstrate how coastal-trapped Kelvin waves communicate the wind disturbance around the Antarctic coastline. The warming is focused on the western flank of the Antarctic Peninsula because the anomalous circulation induced by the coastal-trapped waves is intensified by the steep continental slope there, and because of the presence of pre-existing warm subsurface water. The coastal-trapped waves lead to an adjustment of the flow that shoals isotherms and brings warm deep water upwards onto the continental shelf and closer to the coast. This result demonstrates the unique vulnerability of the West Antarctic region to a changing climate.

Overturning Compensation in an Eddy-Resolving Climate Simulation

Stuart Bishop, Peter Gent, Frank Bryan, Andrew Thompson, Matthew Long and Ryan Abernathey

Presenter: **Peter Gent**

The Southern Ocean's Antarctic Circumpolar Current and meridional overturning circulation response to increasing zonal wind stress is analyzed in a high-resolution (0.1 ocean and 0.25 atmosphere), fully coupled global climate simulation using the Community Earth System Model. Results from a 20-year wind perturbation experiment, where the Southern Hemisphere zonal wind stress is increased by 50% south of 30S, show only marginal changes in the mean ACC transport through Drake Passagean increase of 6% [136–144 Sverdrups] in the perturbation experiment compared with the control. However, the upper and lower circulation cells of the MOC do change. The lower cell is more affected than the upper cell with a maximum increase of 64% versus 39%, respectively. Changes in the MOC are directly linked to changes in water mass transformation from shifting surface isopycnals and sea ice melt, giving rise to changes in surface buoyancy forcing. The increase in transport of the lower cell leads to upwelling of warm and salty Circumpolar Deep Water and subsequent melting of sea ice surrounding Antarctica.

Why the ventilation-defined ocean surface layer is isolated from the adiabatic interior

Todd Ringler, Juan Saenz, Phillip Wolfram and Luke Van Roekel

Presenter: **Todd Ringler**

Within a strongly eddying, zonally symmetric, idealized configuration of the Antarctic Circumpolar Current (ACC), we study the force and mass balance within buoyancy coordinates using the Thickness-Weighted Averaged (TWA) equations. By adopting the TWA analysis framework, a concise dynamical explanation for the climatological momentum and buoyancy budget is readily obtained. Of particular note is the isolation of the ventilation-defined ocean surface from the adiabatic interior. Here we defined the "surface layer" not based on an Eulerian boundary layer depth, but rather in buoyancy space as the range of buoyancy coordinates that ever reach the ocean surface at any given horizontal position. This ventilation-based definition of the surface layer allows us to separate, by construction, the diabatic and adiabatic regions of the ocean at any given horizontal position, this interface is the densest isopycnal to ever make it to the ocean surface. At the base of the ventilation-defined surface layer, we show that the continuity equation forces the meridional velocity to be zero which, in turn, leads to the surface layer being materially isolated from the adiabatic interior across the meridional extent of the idealized ACC. An equally complete and concise description of momentum balance is obtained; at the bottom of the surface layer, the eddy-driven vertical flux of zonal momentum is both non-divergent and exactly equal to the input wind stress. While these relationships are developed in an idealized setting, we argue that the basic findings will hold true in the realistic setting of the Southern Ocean.

Timescales of mesoscale eddy equilibration in the Southern Ocean

Anirban Sinha and Ryan P. Abernathey

Presenter: **Anirban Sinha**

Stratification in the Southern Ocean is determined by a competition primarily between westerly wind driven upwelling and baroclinic eddy transport. The presence of multiple timescales in the forcing over the SO, and the complicated relationship between forcing frequency and eddy response frequency calls for a better understanding of the underlying mechanisms of ocean eddy response to variable dynamic forcing. This study investigates the time scales of equilibration of the Southern Ocean in response to variable winds through an idealized channel model. An analytical framework describing the energetic pathways between wind input, available potential energy (APE), eddy kinetic energy (EKE), and dissipation provides a simple theory of the phase and amplitude response to oscillating wind stress. The transient ocean response to variable winds lies between the two limits of Ekman response (high frequency), characterized by the isopycnal slope responding directly to wind stress, and eddy saturation (low frequency), wherein a large fraction of the anomalous wind work goes into mesoscale eddies. The crossover time scale is essentially the time scale of meridional eddy diffusive transport across the Antarctic Circumpolar Current (ACC) front. For wind variability with a period of 3 months (high-frequency forcing), the relative conversion of wind work to APE/EKE is 11, while for a period of 16 years (low-frequency forcing), the relative conversion to APE/EKE reduces to 3. The systems frequency response is characterized by a complex transfer function. Both the phase and amplitude response of EKE and APE predicted by the linear analytic framework are verified using multiple ensemble experiments in an eddy-resolving (4-km horizontal resolution) isopycnal coordinate model and the role of eddy feedback on the mixing rate is investigated in the context of this model. The results from the numerical experiments show agreement with the linear theory and can be used to explain certain features observed in previous modeling studies and observations. The implications of these results for baroclinic instability, eddy mixing and heat transport in the Southern ocean are discussed.

Topographic closure of the overturning circulation in the Southern Ocean

Xiaozhou Ruan (Caltech), Andrew F. Thompson (Caltech), Mar M. Flexas (Caltech) & Janet Sprintall (Scripps)

Presenter: **Xiaozhou Ruan**

Waters upwelling across the Southern Ocean's Antarctic Circumpolar Current (ACC) and into the mixed layer has been highlighted as a key process in the closure of the overturning's upper branch. Surface buoyancy forcing is the primary mechanism for water mass modification along this pathway. Here, using twelve high-resolution hydrographic sections in southern Drake Passage, collected with autonomous ocean gliders, we show that Lower Circumpolar Deep Water, originating from the North Atlantic, outcrops not in the mixed layer, but on the continental slope in narrow and strong boundary currents. The hydrographic data reveal strong geostrophic currents exceeding 30 cm/s near the bottom (Rossby number 0.5), enhanced bottom mixing (low Richardson numbers) and thick bottom mixed layers (O(100)m). Modified water masses over the continental slope are collocated with regions susceptible to near-bottom, submesoscale instabilities. Similar flow-topography interactions are shown to occur elsewhere along the southern boundary of the ACC based on output from a high-resolution global simulation. We propose that, in addition to the existing water mass modification pathways, topographic boundary layers host a significant closure of the overturning in the Southern Ocean.