Atmosphere and Ocean Dynamics 2024

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Book of Abstracts

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Conference

Cold anticyclonic eddies and warm cyclonic eddies in the ocean

Autor Xiaoming Zhai[None]

Korrespondenzautor: xiaoming.zhai@uea.ac.uk

Anticyclonic and cyclonic ocean eddies are traditionally thought to be associated with positive and negative temperature anomalies, respectively. Our recent study found that about one-fifth of the eddies identified from altimeter data are surface cold-core anticyclonic eddies (CAEs) and warm-core cyclonic eddies (WCEs). Idealized numerical model experiments highlight the role of relative wind-stress-induced Ekman pumping, surface mixed layer depth, and vertical entrainment in the formation and seasonal cycle of these unconventional eddies in the tropical oceans. The abundance of CAEs and WCEs in the global ocean calls for further research on this topic.

Conference

Observations of near-inertial wave interactions within coherent mesoscale eddies

Autoren Florian Schütte[1]; Marco Schulz[1]; Marcus Dengler[2]; Tim Fischer[2]

[1] *FB1 - Physikalische Ozeanographie*

[2] *GEOMAR*

Korrespondenzautor: fschuette@geomar.de

Based on an extensive dataset obtained from multiple individual ship-based samplings of mesoscale eddies (2006-2023), interactions between mesoscale eddies and internal waves are analyzed. Theory predicts that anticyclonic mesoscale eddies shift the effective Coriolis frequency for near-inertial waves (NIW) locally in regions of strong relative vorticity towards subinertial frequencies, leading to trapping of NIW in their core and accelerated downward propagation to a critical layer at the eddy base where mixing is eventually enhanced. In contrast, cyclones might expel NIW through the same but reverse effect. In both cases, and independent of their relative vorticity, increased mixing is expected in regions of strong vertical geostrophic shear at the rims due to critical layer processes. We are able to confirm these theoretical predictions in the observed dataset in composites of several eddies in the subtropics of the southern and northern Hemisphere. Velocity measurements in coherent anticyclonic eddies repeatedly show pronounced alternating current bands with amplitudes up to 15 cm/s, likely associated with convergence of downward propagated NIW. Increased vertical shear at the eddy base of anticyclones indicates energy accumulation in a critical layer. Low (< 1) Richardson numbers and dissipation rates from microstructure measurements, complemented by fine-scale parameterizations, indicate enhanced dissipation rates at the base of anticyclones. For cyclones, slightly increased dissipation rates are more likely to be observed at the eddy rim where geostrophic shear is strong. In all computed frequency spectra, it is evident that the NIW frequency band undergoes modification based on the relative strength of the mesoscale eddies. There is a notable high variability in the internal wave field overall, with the effects of mesoscale eddies particularly pronounced in anticyclones. These eddies serve as conduits for energy into the deeper ocean and play a pivotal role in local mixing processes.

Conference

Vertical fluxes in subpolar eddies from a high-resolution, multi-platform experiment in the Labrador Sea

Autor Fehmi Dilmahamod[1]

Co-Autoren: Johannes Karstensen [1]; Jochen Horstmann [2]; Gerd Krahmann [1]

[1] *GEOMAR Helmholtz Centre for Ocean Research Kiel*

[2] *Helmholtz-Zentrum Hereon*

Korrespondenzautor: fdilmahamod@geomar.de

Mesoscale structures are key dynamical features of the ocean. They are associated with a variety of short lived and small-scale dynamics linked to physical, biological, and chemical processes at the submesoscale, such as cascading energy, impacting ocean stratification, and guiding ocean carbon and oxygen uptake. In the high latitudes, the spatial extent of the mesoscale is only tens of kilometres, making it challenging to observe the submesoscale processes. In August-September 2022, an extensive submesoscale-resolving multiplatform experiment was conducted across an Irminger Ring in the Labrador Sea. The experiment leveraged two underwater electric gliders equipped with nitrate, microstructure shear, chlorophyll fluorescence, oxygen, and turbidity sensors, operated in concert with a variety of ship operated instruments including underway-CTD's, a moving vessel profiler, Thermosalinograph, ADCPs and a X-band radar system. Observations were acquired both, along the peripheries and within the core of the eddy, and offered insight into submesoscale dynamics of the ring. Making use of nearly concurrent turbulence and nutrients observations, we estimated the vertical flux pattern across the eddy's frontal and interior regions. From the recorded and expected glider vehicle motion a vertical water velocity could be inferred and compared with the nutrient flux pattern. The stability of the ring was tracked with surface drifters, for weeks after the ship and glider survey ended, and a link between the disintegration of the ring and an atmospheric event was investigated.

Conference

Vertical coupling and dynamical source for the intraseasonal variability in the deep Kuroshio Extension

Autor Yang Yang[1]

Co-Autoren: X. San Liang [2]; Hideharu Sasaki [3]

[1] *Xiamen University*

[2] *Fudan University*

[3] *Japan Agency for Marine-Earth Science and Technology*

Korrespondenzautor: yyang2@xmu.edu.cn

In the power spectrum, the upper and deep parts of the Kuroshio Extension have distinctly different peaks. The former peaks around 200 days, while the latter is mainly at the intraseasonal band. How the upper meandering jet links the deep intraseasonal eddy current then makes an issue. In this study, it is investigated using the outputs from a 1/10° ocean general circulation model. The theoretical framework is the theory of canonical transfer that gives a faithful representation of the energy transfers among distinct scales in the light of energy conservation, and a space-time-dependent energetics formalism with three-scale windows, namely, a slowly varying background flow window, an intraseasonal eddy window, and a high-frequency synoptic eddy window. The vertical pressure work is found to be the primary driver of the deep intraseasonal variability; it transports intraseasonal kinetic energy (IKE) to the deep layer (below 3000 m) from the interior layer (~ 200–3000 m) where the intraseasonal variability is generated through baroclinic instabilities. Besides the downward IKE fluxes, significant upward fluxes also exist in the surface mixed layer of the upstream Kuroshio Extension (above ~ 200 m, west of 146°E) as a comparable IKE source as baroclinic instability. The accumulated upstream IKE is advected eastward, forming the primary KE source of the intraseasonal variability in the surface layer of the downstream Kuroshio Extension (east of 146°E). Regarding the IKE sinks, the deep layer IKE is damped by bottom drag, while in the surface (interior) layer, IKE is damped by the wind stress and may also be given back to the background flow (the up/downward IKE fluxes via pressure work).

Conference

The ocean flows downhill near the seafloor and recirculates uphill above

Autor René Schubert[1]

Co-Autoren: Jonathan Gula [1]; Esther Capo [2]; Pierre Damien [2]; Maarten Molemaker [2]; Clément Vic [1]; James McWilliams [2]

[1] *UBO, CNRS, IRD, Ifremer, LOPS, IUEM, Plouzané, France*

[2] *UCLA, Los Angeles, USA*

Korrespondenzautor: rene.schubert@univ-brest.fr

The oceans circulation redistributes heat, salt, biota, dissolved gases, microplastics, and sediments on Earth. The interior ocean, 100 - 1000 m above the sloping seafloor, moves on average mainly with the deeper seafloor to its left in the Northern Hemisphere and to its right in the Southern Hemisphere. It has not been addressed how bottom friction and the steepness of the seafloor affect this widespread interior flow and what the consequences are for the vertical circulation. Here we show, using current meter measurements and numerical simulations, that the interior flow is deflected by bottom friction into a widespread near-bottom downhill flow, which is stronger the steeper the seafloor. Typical local changes in seafloor steepness lead to a shallow divergence and a deep convergence of this downhill flow that are connected by an overlaying uphill re-circulation to closed overturning cells that reach far up into the water column. As oceanic overturning is climate-relevant, our study highlights the need to better understand the associated dynamics, to identify its climate and Earth system impacts, and to implement these impacts into climate and Earth system simulations. Furthermore, the effects of widespread near-bottom downwelling on sediments, microplastics, and biota need to be investigated in the future. (The abstract is taken from this preprint: www.researchsquare.com/article/rs-3872319/v1)

Conference

Parameterizing ocean eddies: Kinetic energy injection via stochastic and deterministic approaches

Autoren Stephan Juricke[None]; Sergey Danilov[1]; Ekaterina Bagaeva[2]

[1] *Alfred Wegener Institute for Polar and Marine Research*

[2] *Constructor University Bremen*

Korrespondenzautor: sjuricke@geomar.de

Correctly representing the ocean mesoscale in ocean models at eddy-permitting resolution is a challenging task. Due to overdissipation and insufficient resolution, eddy energy tends to be significantly underestimated, which has implications for the overall representation of the ocean circulation. In this study, both stochastic and deterministic ocean eddy parameterizations are introduced that aim at an improved representation of mesoscale ocean turbulence. They reduce the overdissipation at eddy-permitting resolutions by utilizing the inverse energy cascade and energy conversions between potential and kinetic energy.
Mesoscale eddies cascade energy across scales, transport tracers and heat, and interact with the mean currents and the atmosphere. At eddy-permitting resolutions which are close to the Rossby radius of deformation, eddies are barely resolved but such grids are still commonly applied for decadal climate simulations. They will also remain state-of-the-art at high latitudes for years to come. Due to their excessive dissipation of kinetic energy, these simulations feature reduced eddy variability, eddy formation and eddy-mean flow interactions.
One option to reduce overdissipation is the optimization of viscous closures. An alternative is the reinjection of parts of the overdissipated energy back into the resolved flow via so called kinetic energy backscatter parameterizations. In our study, we will introduce different viscous and backscatter schemes and how to complement them with stochastic components, to account for unresolved chaotic variations of dissipative processes and for scale interactions across the resolution limit. For this purpose, we use both data informed and theoretical approaches to drive the development of both stochastic and deterministic backscatter parameterizaions. Our results show that incorporation of such schemes can help to substantially improve the kinetic energy and mean flow characteristics. When tuned with caution, these schemes provide a means to incorporate model uncertainty and to reduce systematic biases in ocean models, both in idealized configurations as well as global ocean simulations.

Conference

Relaxation, teleconnection and storylines

Autor Thomas Jung[1]

[1] *AWI*

Korrespondenzautor: thomas.jung@awi.de

This paper commemorates the 70th birthday of a distinguished colleague and friend, Richard Greatbatch, celebrating a fruitful collaboration that has spanned over two decades. As part of our joint journey in the early 2000s, we set out to unravel the complexities of teleconnections within the Earth's climate system. Utilizing the relaxation approach, we went to explore the intricate relationships that govern atmospheric interactions across vast distances – so-called teleconnections.

In recent years, the scope of our research has expanded, employing the relaxation approach to craft compelling storylines that encapsulate recent extreme weather events and their manifestation in various climatic contexts. This narrative technique has proven instrumental in rendering the abstract concept of climate change into a more concrete and relatable language, thereby enhancing understanding what climate change means to people.

Beyond these applications, the relaxation approach has also demonstrated its versatility in other pivotal areas of climate science. Notably, it has been applied to the evaluation of climate models, leveraging data from field campaigns such as the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC). Furthermore, it has shown promise in the initialization of coupled predictions, offering potential improvements in the accuracy and reliability of climate forecasts.

Conference

Vertical momentum advection enhances the tropical Rossby wave source

Autor Wolfgang Wicker[1]

[1] *University of Lausanne, Lausanne, Switzerland*

Korrespondenzautor: wolfgang.wicker@unil.ch

Tropical precipitation and organized convection have a global influence in the form of extratropical teleconnections. The main source for these stationary Rossby wave trains is believed to be vortex stretching by the divergent outflow of convection. We present the tropical zonal-mean momentum budget from reanalysis data and use a Helmholtz decomposition as a diagnostic tool. In contrast to common scaling arguments, vertical advection is an important source of westerly momentum in the tropical upper troposphere, possibly connected to the Madden-Julian Oscillation. The curl of vertical momentum advection, namely vortex tilting and vertical vorticity advection, enhances the tropical Rossby wave source for extratropical teleconnections. The results can inform modeling choices in seasonal prediction and climate models.

Conference

Disentangling North Atlantic ocean-atmosphere coupling using circulation analogues

Autoren Chris O'Reilly[1]; Jon Robson[1]; Matthew Patterson[2]; Tim Woollings[2]

[1] *University of Reading*

[2] *University of Oxford*

Korrespondenzautor: matthew.patterson@physics.ox.ac.uk

The coupled nature of the ocean-atmosphere system frequently makes understanding the direction of causality difficult in ocean-atmosphere interactions. This study presents a method to decompose turbulent heat fluxes into a component which is directly forced by atmospheric circulation, and a residual which is assumed to be primarily 'ocean-forced'. This method is applied to the North Atlantic in a 500-year pre-industrial control run using the Met Office's HadGEM3-GC3.1-MM model. The method shows that atmospheric circulation dominates interannual to multidecadal heat flux variability in the Labrador Sea, in contrast to the Gulf Stream where the Ocean primarily drives the variability. An empirical orthogonal function analysis identifies several residual heat flux modes associated with variations in ocean circulation. The first of these modes is characterised by the ocean warming the atmosphere along the Gulf Stream and North Atlantic Current and the second by a dipole of cooling in the western subtropical North Atlantic and warming in the sub-polar North Atlantic. Lead-lag regression analysis suggests that atmospheric circulation anomalies in prior years partly drive the ocean heat flux modes, however there is only a weak atmospheric circulation response in years following the peaks of the modes. Overall, the heat flux dynamical decomposition method provides a useful way to separate the effects of the ocean and atmosphere on heat flux and could be applied to other ocean basins and to either models or reanalysis datasets.

Conference

The interannual wintertime climate modes over mid-high latitude Eurasia and their climate impacts

Autor Xuguang Sun[1]

Co-Autoren: Xinyou Zhang [1]; Shuai Yuan [1]; Zhiqi Zhang [2]; Xiu-Qun Yang [1]; Jiabei Fang [1]

[1] *School of Atmospheric Sciences, Nanjing University*

[2] *Shanghai Regional Climate Center, China Meteorological Administration*

Korrespondenzautor: xgsun@nju.edu.cn

Eurasian teleconnection pattern (EU) and its two variants (EU1 and EU2) are the representative wintertime atmospheric teleconnections over Eurasian continent. They are mainly indicative of the local features and closely related to other teleconnection patterns. What are the major interannual climate modes over mid-high latitude Eurasia in boreal winter is still an open question. With the ERA5 reanalysis datasets after removing the linear impact of El Niño-Southern Oscillation (ENSO), three wintertime climate modes over mid-high latitude Eurasia are identified by the first three empirical orthogonal function (EOF) modes of the anomalous relative tendency (ART) of 500 hPa geopotential height. They approximately explain 75% of the interannual variance in total. The three climate modes have combined features of EU-like patterns with Arctic Oscillation (AO), North Atlantic Oscillation (NAO) and West Atlantic (WA) teleconnections, respectively, and they are named EU-AO, EU-NAO and EU-WA climate modes accordingly. All the three climate modes originate mainly from the North Atlantic and demonstrate clear Rossby wave trains downstream to East Asia along the great circle route, and they can be primarily stimulated and maintained by positive air-sea feedback over North Atlantic regarding to the obvious North Atlantic tripole-like (NAT-like) sea surface temperature (SST) patterns. Interannual climate variations over the most Eurasian continent are strongly linked to and well reproduced by the three ENSO-independent climate modes, which can be applied as the important signals for monitoring and predicting winter interannual climate variabilities over mid-high latitude Eurasia.

Conference

Numerical Study of Seasonal and Interannual Variability of Freshwater Fluxes over the Eastern Canadian Shelf

Autor Jinyu Sheng[1]

Co-Autoren: Bo Yang [1]; Bruce Hatcher [2]

[1] *Department of Oceanography, Dalhousie University, Canada*

[2] *Bras d'Or Institute for Ecosystem Research, Cape Breton University, Canada*

Korrespondenzautor: jinyu.sheng@dal.ca

The three-dimensional (3D) currents and hydrography over the eastern Canadian shelf (ECS) are affected significantly by atmospheric forcing and freshwater discharges from rivers and low salinity waters associated with ice/snow melting at high latitudes. A significantly large knowledge gap exists in our understanding of temporal and spatial variability in the 3D circulation and temperature/salinity distributions over the region. A newly developed Coupled Circulation-Ice Modelling System for the northwest Atlantic (CCIMS-NWA) is used in this study to examine the seasonal and interannual variability of freshwater fluxes over the ECS. This coupled modelling system is based on the Regional Ocean Modeling System (ROMS, Haidvogel et al., 2008) and Los Alamos Sea Ice Model (CICE, Hunke et al., 2015). The semi-prognostic method (Sheng et al., 2001; Greatbatch et al., 2004) and the spectral nudging method (Thompson et al., 2007) are used to reduce the systematic errors of the circulation model. The CCIMS is forced by hourly ERA5 atmospheric reanalysis fields produced by ECMWF and boundary forcing based on the daily GLORYS ocean reanalysis data. The performance of the CCIMS-NWA is assessed using the satellite remote sensing data and in-situ oceanographic observations. Analysis of 3D model results for the 5-year period (2014-2018) shows that the freshwater in the top 100 m over the ECS flows equatorward, with significant seasonal variability. Freshwater flux over the northwestern Gulf of St. Lawrence is correlated strongly with the river discharge of St. Lawrence River. Wind forcing plays an important role in affecting interannual variability of cross-slope freshwater flux over the Labrador Shelf, northern Newfoundland Shelf and Scotian Shelf. The cross-slope freshwater transport over Grand Banks is affected significantly by eddies over the continental slope.

Conference

Sea level variations in shelf waters off the coast of British Columbia: from sub-synoptic to interannual time scales

Autor Youyu Lu[1]

Co-Autor: Li Zhai [1]

[1] *Bedford Institute of Oceanography*

Korrespondenzautor: youyu.lu@dfo-mpo.gc.ca

This study examines sea level variations beyond monthly time scales during 2008-2016 in the north-east Pacific, using the solution of the 1/36-deg NE Pacific regional model combined with tide gauge and gridded altimeter data, and surface atmospheric forcing. Main results are:
(1) Along a zonal section extending westward from the Tofino tide gauge on Vancouver Island, sea level variations are mostly accounted for by the steric height calculated using density variations from surface to 1000 m depth in deep waters, and using the "bottom density"method (Helland-Hansen 1934) in regions shallower than 1000 m.
(2) Sea level variations on the shelf, represented by that at Tofino, are dominated by the halosteric height, with the seasonal maxima occurring in winter that can be explained by the downwelling wind driving the downward transport of low salinity water.
(3) The de-seasonalized anomalies of both the halosteric and thermosteric heights are correlated with winds over a zone stretching from offshore at mid-latitude to the coast at time scales of less than 20 months, and in the tropical Pacific Ocean at time scales of 5-20 months.
(4) Over the continental slope, the sea levels show minimum seasonal amplitude and standard deviation of de-seasonalized anomalies due to weaker salinity variations at depths of 100-200 m.

Conference

On the role of canyons on pathways of Atlantic Water towards the glaciers of Northwest Greenland

Autor Julie Pietrzak[1]

Co-Autoren: Miren Vizcaino [1]; Marije van Hell [1]; Claudia Wekerle [2]; Stef Lhermitte [1]

[1] *Delft University of Technology*

[2] *Alfred Wegener Institute*

Korrespondenzautor: j.d.pietrzak@tudelft.nl

Warm Atlantic Water is resulting in significant retreat of marine terminating glaciers in Northwest Greenland. We use the FESOM ocean model, together with observations of salinity, temperature, and bathymetry from NASA's Ocean Melting Greenland mission, and Mankoff's discharge estimates to understand the pathways of Atlantic Water towards these glaciers. Using the model we explore the role of the southern and northern canyons of Melville Bay on the pathways of Atlantic Water. We find these pathways are crucial for understanding the increase in discharge of certain glaciers over the 'ocean warming period'. We explore how the susceptibility of a marine terminating glacier in Northwest Greenland to Atlantic Water depends on the location of the channel entrance of the fjord with respect to head of the Southern or Northern canyon. It also depends on whether the fjord channel is deep enough to be a pathway for Baffin Bay Intermediate Water. The Upernavik N and C glaciers are in the most vulnerable location. They contribute 10% to the total discharge change of Northwest Greenland. Moreover, the glaciers that exhibited the largest normalised discharge change, showed a correspondence between their discharge estimates and the observed changes in fjord geometry, during the retreat of the glacier calving front. Warming of deep Atlantic Water during the warming period impacted the normalised discharge estimates, but the sensitivity to the fjord geometry also controlled large parts of the observed trends too.

Conference

Role of equatorial basin modes for equatorial Atlantic productivity

Autor Peter Brandt[1]

Co-Autoren: Ajit Subramaniam [2]; Gerd Krahmann [1]; James N. Moum [3]; Marcus Dengler [1]; Mareike Körner [1]; Marisa Roch [1]; Rainer Kiko [1]; Rena Czeschel [1]

[1] *GEOMAR Helmholtz Centre for Ocean Research Kiel*

[2] *Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA*

[3] *College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA*

Korrespondenzautor: pbrandt@geomar.de

The eastern equatorial Atlantic hosts a productive marine ecosystem that relies on upward supply of nitrate, the main limiting nutrient in this region. The annual peak in surface chlorophyll occurs in boreal summer, roughly coincident with increased easterly winds. Enhanced turbulence is expected with increased winds. However, upward nitrate supply by mixing requires this turbulence to act on adequate nitrate gradients. Here, we show the combination of independent wind-forced processes that seasonally elevates the nitracline into the turbulent layer above the core of the Equatorial Undercurrent (EUC). Detailed measurements from two trans-Atlantic surveys plus extended time series from equatorial moorings show how the nitracline responds in quasi-equilibrium to strengthening easterly winds. The vertical migration of the EUC core is independently determined by an annual oscillation caused by the presence of a resonant equatorial basin mode. When both processes cause the nitracline to be raised above the EUC core, local and instantaneous winds force an enhanced diffusive nitrate flux. This interplay of mechanisms synchronizes to create the seasonal cycle of nutrient supply and productivity unique to the equatorial Atlantic but not present in the mainly iron-limited equatorial Pacific, highlighting fundamental biogeochemical and dynamical distinctions between the two basins.

Conference

Generation of the Equatorial Intermediate Current in the eastern Pacific Ocean

Autor Yusuke Terada[1]

Co-Autor: Yukio Masumoto [1]

[1] *The University of Tokyo*

Korrespondenzautor: terada@eps.s.u-tokyo.ac.jp

It has been shown that the Equatorial Intermediate Current (EIC) in the Pacific Ocean, which is a westward current along the equator at intermediated depth (from 500m to at least 2000 m), has a basin-wide zonally uniform structure. In addition to the EIC, intraseasonal variability (ISV) has also been observed near the equator at 1000 m depth with significant amplitude in the eastern Pacific Ocean. Although this intermediate ISV in the eastern basin is considered as an energy source for the EIC, the origin of the intermediate ISV and its relation to the EIC in the Pacific Ocean are still open questions. In this study, we use the observed data and idealized simulations to investigate the relationship among the EIC, the ISV at the depth of 1000 m, and the ISV in the upper layer.
The observed meridional component of eddy kinetic energy (V-EKE) at 1000 m depth depicts large intraseasonal variability with a period of about 30 days in the equatorial eastern Pacific, showing a significant seasonality and interannual amplitude modulation. The upper-layer ISV signal also indicates significant seasonal and interannual variation in its magnitude, which has the highest correlation with the ISV at 1000 m depth at a time lag of 3 months. These results suggest that the ISV at a depth of 1000 m is provided by the upper layer ISV through a downward propagating Yanai wave, which takes about 3 months to reach 1000 m depth from the upper layer.
Argo-based zonal velocity in the equatorial Pacific Ocean is found to be westward during most of the high V-EKE season, and its magnitude varies on semiannual to interannual time scales. This suggests that intermittent Yanai wave propagation generates a westward flow at 1000 m depth, which could contribute to the generation of the EIC. Furthermore, a comparison of results from two numerical simulations of idealized box ocean with or without eastern basin ISV indicates that the downward propagating Yanai wave in the eastern Pacific Ocean generates westward flow locally at the intermediate depth. This may explain the observed basin-scale zonal extent of the EIC, which is unique to the Pacific Ocean. Influences of the realistic topography on the ISV and EIC at the intermediate depth will also be discussed.

Conference

A Great Batch of Beers: The Social Value of Beer with Historical reference to the Ouseburn district of Newcastle-upon-Tyne

Autor Mike Greatbatch[None]

The lower Ouseburn has long been famous for its brewing and beer outlets, and today's scene is in many respects not that much different from its past, as this short presentation will illustrate.

The most important factor in attracting beer outlets to the lower Ouseburn was its industrial character and density of population.

In an age when the water supply came directly from the River Tyne, to be distributed through lead pipes to public fountains or communal stand-pipes, it was generally healthier to drink water in the form of beer because the process of fermenting malted barley removed many of the more unpleasant bacteria. Communities generally were aware that you were less likely to suffer from a bad stomach if you drank beer, and this was particularly important for those employed as labourers and other factory workers where hot, dry, and physically demanding work required regular rehydration.

To meet this demand, public houses and small breweries produced what was called 'small beer'–a form of low alcohol ale –and consequently pubs and beer houses became a widespread feature of the Ouseburn industrial landscape.

A number of the area's most famous public houses began life as beer houses, including the Cumberland Arms off Byker Bank. Like many of the local pubs, beer houses were set up to brew beer on the premises and these small-scale outlets are the predecessor of today's micro-breweries.

Mike Greatbatch is a historian who specializes in the history of working people. He has been teaching the history of the Ouseburn district since 1998.

Conference

Strong Eastern Pacific El Niños dominate amplitude variations and asymmetry in observations and climate models

Autoren Joke Lübbecke[1]; Tobias Bayr[None]

Co-Autor: Mojib Latif

[1] *GEOMAR*

Korrespondenzautor: jluebbecke@geomar.de

The amplitude of El Niño/Southern Oscillation (ENSO) varied considerably over the last 140 years. We find that the difference between high and low ENSO-amplitude periods results mainly from the number of strong Eastern Pacific (EP) El Niños, while Central Pacific (CP) El Niños and La Niña events do not contribute much. Further, the asymmetry of ENSO, i.e. SST anomalies during El Niño being stronger and located further to the east than during La Niña events, is closely linked to ENSO amplitude as well as the number of strong EP El Niño events in observations.

We find similar relations in the 40 historical runs of the Large Ensemble with CESM1 that simulates the ENSO asymmetry realistically. Further, there is a strong relation between the ENSO amplitude and the tropical Pacific mean state, indicating that a warmer eastern equatorial Pacific favors more EP El Niños due to a lower convective threshold in that area.

Consistent with these findings, CMIP6 models that suffer from a strong cold tongue bias underestimate the fraction of strong EP El Niños with implications for their representation of ENSO asymmetry.

Conference

Seasonality of Feedback Mechanisms Involved in Pacific Coastal Niño Events

Autor Daniel Rudloff[None]

Co-Autoren: Joke Lübbecke [1]; Sebastian Wahl [1]

[1] *GEOMAR*

Korrespondenzautor: drudloff@geomar.de

The very strong warming off the Peruvian coast in 2017 marked the strongest Pacific Coastal Niño Event so far. Due to its catastrophic socioeconomic consequences, it rapidly caught the attention of the scientific community. Since then numerous studies have been conducted analysing the causes and consequences of this event. While the strong connection between SST anomalies and local rainfall, especially during boreal spring, is well established, the causes of the extreme warming are still a subject of discussion. In this study, we focus on the seasonality of the effectiveness of mechanisms and feedbacks involved in coastal Niño Events, utilising reanalysis products and historical model simulations from the Flexible Ocean and Climate Infrastructure (FOCI).
The 2017 event was stronger than other comparable events found in the record. It also occurred earlier in the year, during a season when atmospheric convection is present and the wind-driven upwelling is strongest. This was crucial for the forcing of a short but very intense event. To further analyse the underlying mechanisms model sensitivity experiments were performed, applying the same local wind stress forcing in different seasons. The strongest impacts are found during the months of strongest entrainment. Events forced by atmospheric forcing such as local heat fluxes and wind stress forcing, do not lead to any subsurface warming, which is shown to be responsible for the rapid decay of those events. The atmospheric response to a coastal warming shows strong seasonal differences, but the atmospheric feedbacks are at no season strong enough to sustain the warming. For longer-lasting events or ones which spread along the equator into the central Pacific.

Conference

Anticyclonic and Cyclonic Circulations of Wave Energy in the Western and Eastern Tropical-Subtropical Pacific Ocean: a Reevaluation of the Zonal Interactions

Autoren Borui Wu[1]; Hidenori Aiki[2]; Takahiro Toyoda[3]; Tomomichi Ogata[4]; Motoki Nagura[4]

[1] *Nagoya Univ.*

[2] *Institute for Space-Earth Environmental Research, Nagoya University*

[3] *JMA*

[4] *JAMSTEC*

Korrespondenzautor: aiki@nagoya-u.jp

The present study has determined the anticyclonic and cyclonic circulations of wave energy in the western and eastern parts, respectively, of the tropical-subtropical Pacific Ocean in each hemisphere. In terms of directionality, these wave energy circulation patterns contrast sharply with those in the Indian and Atlantic Oceans where wave energy circulation is cyclonic in the western part of each basin. A key feature of the present study lies in our quantification of the wave energy circulation in the absence of a smooth transition between the equatorial and off-equatorial regions. This may provide a new perspective for understanding the development and demise of the El Niño–Southern Oscillation. The study highlights an important application of the time series of the regional extrema of the energy-flux streamfunction and the energy-flux potential to investigate the zonal interaction between the western, central, and eastern parts of the basin. It is shown that the time series of these wave energy quantities should be compared with the absolute value of the Niño-3 index owing to the fact that the wave energy quantities do not differentiate between upwelling and downwelling waves. For example, the peak value of the energy-flux potential associated with the wind input in the central Pacific Ocean may be regressed as 1.13 ΔT^2 + 0.80 (in gigawatts), where ΔT is the sea surface temperature anomaly (in degrees Celsius) associated with the Niño-3 index.

Conference

ENSO from the perspective of linear, shallow water models

Autor Richard John Greatbatch[1]

[1] *GEOMAR*

Korrespondenzautor: rgreatbatch@geomar.de

co-authors: Martin Claus, Jufen Lai and Xiaoting Zhu

In the 1970's and 80's, Jim O'Brien's group at Florida State University showed that linear, reduced-gravity shallow water models have skill at capturing and interpreting ENSO events. At that time, the models were driven by estimates of the surface wind stress derived from ship measurements and were verified using sea level measured at sparsely distributed tide gauge stations. We revisit and extend this approach in the context of modern datasets such as the AVISO satellite altimeter data and wind stress derived from reanalysis products. Aside from demonstrating considerable skill, this approach also motivates using residual sea level as a diagnostic in which the influence of local vertical movements of the thermocline are removed from sea level data using linear regression. We show that residual sea level is a useful diagnostic for capturing and understanding Central Pacific ENSO and suggests a role for Rossby waves in the dynamics of CP ENSO.

Conference

The formation and ventilation of an Oxygen Minimum Zone in a simple model for latitudinally alternating zonal jets

Autor Eike Köhn[1]

Co-Autoren: Martin Claus [2]; Peter Brandt [2]; Richard John Greatbatch [3]

[1] *ETH Zürich*

[2] *GEOMAR Helmholtz Centre for Ocean Research Kiel*

[3] *GEOMAR*

Korrespondenzautor: eike.koehn@usys.ethz.ch

The eastern tropical North Atlantic (ETNA) features strongly deoxygenated waters between approximately 100-1000 meters depth, commonly referred to as oxygen minimum zone (OMZ). While observations suggest a prolonged intensification of this OMZ, it remains a challenge to discern to which degree this imbalance in oxygen consumption and ventilation is a forced trend or due to natural variability. As latitudinally alternating zonal jets (LAZJs) play an important role in ventilating the OMZ, changes in their intensity have been hypothesized to contribute to the observed long-term oxygen changes. In this study, we therefore investigate the role of LAZJs in driving the natural variability of OMZs on interannual to interdecadal time scales. To this end, we employ an advection-diffusion model coupled with a non-linear shallow water model, set up for ETNA. The advection-diffusion model carries a tracer mimicking oxygen, and the simple dynamical model is forced by an annually oscillating zonal mass flux confined to the near-equatorial band. The forcing generates mesoscale eddies at higher latitudes that lead to the formation of LAZJs. Although the model is forced only at the annual period, the model nevertheless exhibits decadal and multi-decadal variability in the ETNA OMZ in its spun-up state. The associated trends are sufficient to explain the observed trends in oxygen within the OMZ. Notable exceptions are the observed multi-decadal decrease in oxygen in the lower OMZ, and the sharp decrease in oxygen in the upper OMZ between 2006 and 2013.

Conference

Spectrally resolved Lorenz Energy Cycle in the Ocean

Autoren Carsten Eden[None]; Jan Dettmer[None]

Korrespondenzautor: carsten.eden@uni-hamburg.de

The inverse eddy kinetic energy (EKE) cascade from small to larger scales appears to be a robust observed feature of ocean dynamics. It follows the traditional paradigm of an inverse eddy energy cascade from the scales of baroclinic eddy production L to dissipation at larger scales. Challenging this paradigm, however, we present a scale-dependent sign of the baroclinic EKE production term which is a source of EKE at L, but can become a sink at larger scales of the same magnitude in a variety of realistic and idealised ocean models. The Lorenz energy cycle is spectrally resolved to understand the energy cascades and to resolve our missing understanding of the eddy energy route to dissipation.

Conference

The Balance Conundrum

Autor Manita Chouksey[1]

[1] *Leibniz Institut for Ostseeforschung Warnemünde (IOW)*

Korrespondenzautor: manita.chouksey@io-warnemuende.de

Atmosphere and ocean dynamics are dictated by balanced flows, such as mesoscale eddies, but determining a precise balanced state remains challenging in the presence of its nonlinear coupling with the unbalanced flows, such as internal gravity waves. This results in nonlinear internal wave generation by spontaneous loss of balance, that challenges the conundrum of the existence of an invariant balanced state from a mathematical perspective, and at the same time has physical implications for the energy cycle of the atmosphere and ocean.

In this talk, I will discuss the recent progress in deriving and quantifying the balanced state in geophysical flows from nonlinear flow decomposition. This is applied to varied oceanic regimes to quantify wave generation from spontaneous loss of balance and assess its role in the energy cycle and in the balance conundrum. Further, to diagnose these processes in complex flows, a new flow decomposition approach is presented for realistic applications, such as flows with boundaries. These developments provide new avenues to determine the balanced state and offer fresh insights into the atmosphere and ocean dynamics, that are central to understand the dynamics of the climate.

Conference

Do we need non-Boussinesq effects in an ocean general circulation model for climate simulations?

Autor Martin Losch[1]

Co-Autor: Jean-Michel Campin [2]

[1] *Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung*

[2] *MIT, Cambridge, MA*

Korrespondenzautor: martin.losch@awi.de

The Boussinesq approximation is commonly made in ocean general circulation models (OGCMs). As a consequence, the model ocean is incompressible and conserves volume, but not mass. It has been argued that these consequence introduce errors at the noise level of coarse OGCMs, but that non-Boussinesq modeling is preferable simply for tidiness. Here, we use the height-pressure coordinate isomorphism implemented in the MITgcm to construct a non-Boussinesq OGCM and revisit the differences between Boussinesq and non-Boussinesq models at a resolution comparable to IPCC climate models. Subtleties such as the choice of a proper equation of state that includes the effect of pressure on heat capacity, but also the use of mass as a convenient alternative to pressure coordinates are discussed.

Conference

Ocean Boundary Pressure: Insights and generalizations from Stommel and Munk models.

Autor Chris Hughes[1]

Co-Autor: Anthony Wise [2]

[1] *University of Liverpool/NOC*

[2] *NOC-Liverpool*

Korrespondenzautor: cwh@liverpool.ac.uk

The difference between eastern and western boundary pressures is strongly constrained by the zonal wind stress via the balance of angular momentum, and the meridional derivative of boundary pressure represents the bottom pressure torque, closely related to boundary current transport. Here, we use the analytical solutions available due to the Stommel and Munk models to investigate the behaviour of these boundary pressures in the case of a frictionally closed barotropic vorticity balance. We find a number of interesting results. 1) The eastern pressure torque is locally determined, whereas the western torque "mops up" what remains of the angular momentum balance. 2) with longshore winds included, the torque becomes decoupled from the boundary current, and can even occur at the opposite side of the ocean. 3) The nature of the boundary currents is sensitive to the form of friction considered, and can even produces an offshore jet maximum in the Stommel case with variable friction. 4) Even for the general case with topography, a relationship can be found between boundary pressure, longshore wind stress, and interior ocean pressure, which shows the boundary pressure relaxing towards the interior pressure as the equator is approached, but the wind stress counteracting this. This last result generalizes a result found for sea level in 2D models due to Minobe et al. (2017).

Conference

Enhance Ocean Reanalysis in Regions with Limited Observations using a Time-Guided Physics-Informed Machine Learning Approach

Autoren Christopher Kadow[1]; Simon Lentz[2]

Co-Autoren: Johanna Baehr [2]; Sebastian Brune [2]

[1] *German Climate Computing Center (DKRZ)*

[2] *UHH*

Korrespondenzautor: kadow@dkrz.de

Observing subsurface temperatures in the ocean can be challenging due to their natural sparsity, leading to considerable uncertainties in model-based estimates. As a result, historical assessments of ocean heat content (OHC) often suffer from distortions and biases. In this research, we explore the feasibility of employing physics-informed neural networks (PINNs) to reconstruct subsurface temperature data, with a specific focus on the North Atlantic Subpolar Gyre.

We train our neural network using a time period abundant in observations to capture authentic physical patterns. Subsequently, we assess the network's ability to apply these learned patterns to time periods characterized by significantly fewer observations within a consistent data assimilation framework. Our goal is to enhance historical OHC estimates in such scenarios. Our findings demonstrate the efficacy of this PINN approach in both learning and transferring realistic physical patterns from its training data. Consequently, when dealing with limited observational input, the PINN-generated reconstructions display more faithful representations of physical structures compared to current state-of-the-art data assimilation methods.

This improvement is particularly evident in the enhanced estimation of the North Atlantic Current's flow. Our technique is able to represent the North West Corner even in the early days with very sparse observational information, where pure Ensemble Kalman Filter fails to show this physical pattern. Thus, we provide evidence that time-guided physics-informed machine learning has the potential to significantly improve monthly reanalyses, especially in regions and time periods where observations are sparse. Furthermore, by rectifying historical biases and misrepresentations, these techniques offer the prospect of greatly impacting the initialization and assessment of forecast models.

Conference

Quantification of Constrained Scales with an Ensemble Ocean Analysis

Autor Andrew Peterson[1]

Co-Autoren: Chikhar Kamel [1]; Gregory C. Smith [1]; Andrea Storto [2]

[1] *Environment and Climate Change Canada*

[2] *Consiglio Nazionale delle Ricerche Italy*

Korrespondenzautor: kandrewpeterson@yahoo.ca

Ocean models have unresolved processes and scales, normally associated with processes that model resolution or model physics cannot account for. For systems initialized to observations, one also has unconstrained scales, scales that cannot be constrained by the observational network. Ensemble systems, through accessing the full parameter space with Monte Carlo methods, are one method to remove these unconstrained scales – or at least represent the uncertainty related to these scales. For an ensemble consistent with the truth, or observed state, the spread of the ensemble is a proxy for model uncertainty – and it is important that model uncertainty match as best as possible, the model error with respect to observation in the system. The ultimate goal being that uncertainty between observation and system should match uncertainty within the system: The observations should be as suitable an outcome as any member of the ensemble. Using analyzed outcomes for sea surface height and velocities from an ensemble version of the Environment and Climate Change (ECCC) Global Ice Ocean Prediction (GIOPS) system, we show that the ensemble spread is a good representation of error in the system, and that the ensemble is capable of removing scales associated with unconstrained mesoscale activity not suitably constrained by the observations.

Conference

Improving Atmospheric Processes in Earth System Models with Deep Learning Ensembles and Stochastic Parameterizations

Autor Gunnar Behrens[1]

Co-Autoren: Tom Beucler [2]; Fernando Iglesias-Suarez [3]; Sungduk Yu [4]; Pierre Gentine [5]; Michael Pritchard [6]; Mierk Schwabe [3]; Veronika Eyring [1]

[1] *Universität Bremen, IUP ; DLR, IPA*

[2] *Faculty of Geosciences and Environment, University of Lausanne ; Expertise Center for Climate Extremes, University of Lausanne*

[3] *DLR, IPA*

[4] *Department of Earth System Science, University of California Irvine*

[5] *Department of Earth and Environmental Engineering, Columbia University ; Earth Institute and Data Science Institute, Columbia University*

[6] *Department of Earth System Science, University of California Irvine ; NVIDIA*

Korrespondenzautor: gbehrens@uni-bremen.de

Deep learning has proven to be a valuable tool to represent subgrid processes in climate models, but most application cases have so far used idealized settings and deterministic approaches. Here, we develop ensemble and stochastic parameterizations with calibrated uncertainty quantification to learn subgrid convective and turbulent processes and surface radiative fluxes of a superparameterization embedded in an Earth System Model (ESM). We explore three methods to construct stochastic parameterizations: 1) a single Deep Neural Network (DNN) with Monte Carlo Dropout; 2) a multi-network ensemble; and 3) a Variational Encoder Decoder with latent space perturbation. We show that the multi-network ensembles improve the representation of convective processes in the planetary boundary layer compared to individual DNNs. The respective uncertainty quantification illustrates that the two latter methods are advantageous compared to a dropout-based DNN ensemble regarding the spread of convective processes. We develop a novel partial coupling strategy to sidestep issues in condensate emulation to evaluate the multi-network parameterizations in online runs coupled to the ESM. We can conduct Earth-like stable runs over more than 5 months with the ensemble approach, while such simulations using individual DNNs fail within days. Moreover, we show that our novel ensemble parameterizations improve the representation of extreme precipitation and the underlying diurnal cycle compared to a traditional parameterization, although faithfully representing the mean precipitation pattern remains challenging. Our results pave the way towards a new generation of parameterizations using machine learning with realistic uncertainty quantification that significantly improve the representation of subgrid effects.

Conference

Uncertainty evolution and its estimation with respect to the atmosphere-ocean system

Autor X. San Liang[1]

[1] *Dept. of Atmos. & Oceanic Sci., Fudan University, Shanghai, China, and the Artificial Intelligence Dept., Southern Marine Laboratory, Zhuhai, China*

Korrespondenzautor: xsliang@fudan.edu.cn

Understanding the uncertainty of a state is not only important in assessing the forecast of that state, but also of interest in its own right from a physical point of view. Within the information theoretic framework, uncertainty is conveniently measured in terms of Shannon entropy, which we denote by H henceforth. For the atmosphere-ocean system, however, H is in general computationally intractable due to its huge dimensionality. Liang (2011) argued that this actually can be circumvented by studying *dH/dt*, rather than H itself, on the basis of a side finding in Liang and Kleeman (2005). The finding is best expressed as a formula: *dH/dt = E(gradF)*, where E stands for the operator of mathematical expectation, and **F** for the vector field of the dynamical system under consideration, which in this context can be viewed as the atmosphere/ocean model. A comprehensive and systematic derivation with both deterministic and stochastic systems has been made (Liang, 2014), bringing connections between the two physical notions, namely, uncertainty and instability. It is interesting to note that the Lorenz system and stochastic flow system are both examples of self-organization in the light of uncertainty reduction. The latter particularly shows that, sometimes stochasticity may actually enhance the self-organization process.

More often than not, we are more interested in, for a forecast, its local performance, rather than its overall performance. In this case, the above law does not help much; what we need to know is the local marginal entropy evolution. This requires a solution of the entailed probability density equation, which is in general computationally intractable. Here we show that, from a data science point of view, it actually can be estimated through maximum likelihood estimation. The resulting formulas are rather concise in form, stating that the marginal entropy evolution of a variable at a point is equal to the rate of the local uncertainty generation, plus the transference of the uncertainties from all other locations. This has also been connected to another systematic work of the author, i.e., quantitative causality analysis ab initio (e.g., Liang 2016; a recent short review is referred to Liang et al., 2023).

As a demonstration, shown in Fig. 1 are the uncertainty evolutions of the 2015 "monster"El Niño and South China Sea surface circulation based on the ECCO SST data. Since only positive entropy implies uncertainty, the negative values are not contoured here. For the El Niño case (Fig. 1a), uncertainty is maximized in spring. This is the well-known spring predictability barrier. Something overlooked before is the second maximum in the fall of 2015, though much weaker than its spring counterpart. For the South China Sea case (Fig. 1b), one easily sees the maximum in fall south of Vietnam, a fall predictability barrier which has been identified before in operational forecasts.

Keywords: uncertainty; entropy; second law of thermodynamics; information flow; ensemble prediction; quasi-geostrophic flow; Fisher information matrix; self-organization; El Niño; spring predictability barrier; South China Sea

Fig. 1. Uncertainty evolution of (a) the 2015 "Monster"El Niño and (b) South China Sea surface circulation

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Conference

Extracting spatial spectra using coarse-graining based on implicit filters

Autoren Sergey Danilov[1]; Stephan Jurické[None]; Kacper Nowak[1]; Dmitry Sidorenko[1]; Qiang Wang[1]

[1] *Alfred Wegener Institute for Polar and Marine Research*

Korrespondenzautor: sergey.danilov@awi.de

Scale analysis based on coarse-graining has recently been proposed as an alternative to Fourier analysis for the analysis of eddy-rich ocean simulation data. It requires interpolation to a regular grid for data on general meshes, especially for the output of unstructured-mesh models. We propose an alternative coarse-graining method based on implicit filters using powers of discrete Laplacians. Since discrete Laplacians can be provided for any mesh, this method can work with data on arbitrary (structured or unstructured) meshes and is directly applicable to both scalar and vector data in spherical geometry. We explain the mathematical side of the method and give illustrations of filtering and power spectrum computation using FESOM output on native triangular meshes. A fast Python-based implementation is available for FESOM data, and support for other meshes will be provided in the future.

Conference

Exploring AMOC Dynamics: density vs. traditional z frameworks

Autor Dmitry Sidorenko[1]

[1] *Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research*

Korrespondenzautor: dmitry.sidorenko@awi.de

This study investigates the variability of Atlantic Meridional Overturning Circulation (AMOC) using both density and traditional z frameworks in the AWI-CM climate model. By prioritizing the density framework, we aim to understand which water mass transformations cause the AMOC change. These transformations are seen as diapycnal velocities through given isopycnal surfaces, and their geographical distribution provides a clearer understanding of AMOC dynamics. Our findings demonstrate that the AMOC responds to fast (annual or faster) fluctuations in atmospheric forcing associated with the NAO. In contrast, the connection between AMOC and deep water production south of Greenland is identified for slower fluctuations and remains consistent across both frameworks.

Conference

Dynamics of circumpolar volume transport and global ocean heat content

Autoren David Marshall[1]; Xiaoming Zhai[2]; James Maddison[3]; Julian Mak[4]

[1] *University of Oxford*

[2] *University of East Anglia*

[3] *Univeristy of Edinburgh*

[4] *Hong Kong University of Science and Technology*

Korrespondenzautor: david.marshall@physics.ox.ac.uk

The volume transport of the Antarctic Circumpolar Current is typically described in textbooks as set by a combination of wind and buoyancy forcing. However, results of eddy-permitting numerical ocean models contradict this statement, instead indicating minimal sensitivity of circumpolar volume transport to the magnitude of the surface wind stress. A simple theoretical model is developed, building on the GEOMETRIC parameterisation of ocean eddies, which relates circumpolar volume transport to three length scales divided by the residence time of Southern Ocean eddy energy and an eddy efficiency parameter, but not to surface wind stress. These parameters are estimated from a mix of observations, showing that the predicted circumpolar transport is of the correct order of magnitude. Due to the close coupling between circumpolar volume transport and global ocean heat content through thermal wind balance, it is argued that Southern Ocean eddies play a fundamental role in controlling global ocean heat content and the strength of other global currents. The latter statement is supported by calculations with a global ocean circulation model incorporating the GEOMETRIC parameterisation of ocean eddies.

Conference

Asymmetries in heat and carbon uptake by the Southern and northern oceans

Autor Ric Williams[1]

[1] *University of Liverpool*

Korrespondenzautor: ric@liverpool.ac.uk

The Southern Ocean provides dominant contributions to global ocean heat and carbon uptake, which is widely interpreted as resulting from its unique upwelling and circulation. Here we show a large asymmetry in these contributions, with the Southern Ocean accounting for 83%±33% of global heat uptake versus 43%±3% of global ocean carbon uptake over the historical period in state-of-the-art climate models. Using single-radiative forcing experiments, we explore why there is this asymmetry in heat and carbon uptake. In future projections, such as the shared socio-economic pathway SSP2-4.5, the Southern Ocean contributions to global heat and carbon uptake become more comparable, 52%±5% and 47%±4% respectively. Hence, the past is not a reliable indicator of the future, with the northern oceans becoming important for heat uptake while the Southern Ocean remains important for both heat and carbon uptake.

Conference

Role of ocean memory in driving decadal thermal variability in the subpolar North Atlantic Ocean

Autor Hemant Khatri[1]

Co-Autoren: Ric Williams [1]; Tim Woollings [2]; Doug Smith [3]

[1] *University of Liverpool*

[2] *University of Oxford*

[3] *UK Met Office*

Korrespondenzautor: hkhatri@liverpool.ac.uk

Decadal variability in subpolar North Atlantic Ocean heat content is strongly influenced by the atmosphere. Seasonal and annual atmospheric disturbances leave a lasting impact on the ocean for several years due to the ocean's substantial thermal inertia. These atmospheric perturbations first generate anomalous air-sea heat fluxes and wind patterns, rapidly modifying upper ocean temperatures (a short-term, local response). Subsequently, these modifications can alter meridional heat transport rates, leading to persistent anomalous heat convergence (long-term, far-field response) in the subpolar ocean (Khatri et al., 2022, Geophys Res Lett).

We propose a novel approach that incorporates both short-term and long-term ocean responses to evaluate ocean memory and its role in driving decadal ocean variability. This approach combines heat budget analysis with linear response theory to investigate how the North Atlantic Oscillation (NAO) influences the decadal variability of upper ocean temperatures and quantifies the associated ocean memory. Using CMIP6 climate model outputs and observations, we find that ocean memory in the subpolar North Atlantic ranges from 10 to 20 years. Furthermore, we find that the NAO significantly influences long-term ocean variability, explaining 20%-30% of subpolar ocean heat content variability on decadal timescales. This implies that the impact of seasonal atmospheric events on the ocean persists for over a decade through a combination of local and far-field ocean responses.

The proposed framework, built upon the concept of ocean memory, integrates local and far-field ocean effects into a single metric. This framework can be used to analyse how relatively short-lived atmospheric variations drive changes in the ocean state over decadal timescales.

Conference

On the Strength of the Atlantic Meridional Overturning Circulation

Autor markus jochum[1]

[1] *nbi*

Korrespondenzautor: mjochum@nbi.ku.dk

Following Straub (1996) and Greatbatch and Lu (2003) we try to understand the AMOC strength in a simple box model with a channel. Rather than starting with a set of assumptions that allow a solution to the Navier-Stokes equations, we will empirically (with numerical models) determine the impact of various parameters and boundary conditions like Southern Ocean windstress, density gradients, details of the convective parameterization and friction. So far we were not able to bring the results in the form of a simple equation, but we hope that they will inform lively discussions during the meeting.

Poster

Mixing processes in the upper tropical Atlantic: An event data base for evaluating vertical mixing parameterizations in Earth System Models

Autor Marcus Dengler[1]

Co-Autoren: Tim Fischer [1]; Markus Jochum [2]; Vera Stockmayer [1]; Hannah Melzer [1]; Johann Jungclaus [3]

[1] *GEOMAR*

[2] *University of Copenhagen*

[3] *Max Planck Institute for Meteorology*

Korrespondenzautor: mdengler@geomar.de

Observational and modelling studies of the tropical ocean mixed layer have shown a dominate role of the vertical diffusive heat flux due to turbulent mixing for maintaining sea surface temperature in the tropical Atlantic. Progress has been made in identifying ocean processes responsible for enhancing turbulent mixing in the upper stratified ocean including near-inertial waves and Tropical Instability Waves. Additionally, the vertically sheared large-scale equatorial circulation provides an energy source that can overcome stratification and drive turbulence known as deep cycle turbulence. In this contribution we exploit a large observational data base of turbulence and hydrographic measurements to construct average mixing events by near-inertial waves, Tropical Instability Waves and deep cycle turbulence that can be used to evaluate high-resolution earth system models.

Poster

Observed variability of AMOC transport components at 11°S

Autor Anna Hans[1]

Co-Autoren: Rebecca Hummels [2]; Peter Brandt [3]; Rodrigue Imbol [4]

[1] *GEOMAR - FB1 - Physikalische Ozeanographie*

[2] *FB1 - Physikalische Ozeanographie*

[3] *GEOMAR Helmholtz Centre for Ocean Research Kiel*

[4] *GEOMAR*

Korrespondenzautor: ahans@geomar.de

The Atlantic meridional overturning circulation (AMOC) is a key feature of the oceanic circulation and has a big impact on regional weather and global climate. As the characteristics of the northward return flow of the AMOC crossing the equator are crucial for deep water formation at high latitudes in the North Atlantic, the AMOC variability in the South Atlantic is of particular interest. Here, we present observations of several components of the upper branch of the AMOC at 11°S taken from the Tropical Atlantic Circulation and Overturning at 11°S (TRACOS) array. We focus on the transport time series and seasonal to interannual variability of the North Brazil Undercurrent at the western boundary, the Angola Current at the eastern boundary and the upper layer AMOC transport composed of the geostrophic interior and the Ekman transports. The two boundary currents are derived from 10 years of direct moored current measurements. For the geostrophic interior transport, transport anomalies are derived from 10 years of bottom pressure measurements at the eastern and western continental margin at 300 m and 500 m depth and from sea level anomaly data. In all three analysed time series, no long-term trend is visible, and seasonal to interannual variability dominates. Water mass characteristics of the NBUC show a salinification in the central water range.

Poster

How Has the Ferrel Cell Contributed to the Maintenance of Antarctic Sea Ice at Low Levels from 2016 to 2022?

Autor Shaoyin Wang[1]

Co-Autoren: Dongxia Yang [2]; Fengming Hui [3]; Hua Li [4]; Jiping Liu [3]; Shuoyi Ding [5]; Xiao Cheng [3]; Zixin Wei [1]

[1] *Sun Yat-sen University*

[2] *Analycia Pty. Ltd*

[3] *Sun Yat-Sen University*

[4] *Nanjing University of Information Science and Technology*

[5] *Fudan University*

Korrespondenzautor: wangshy96@mail.sysu.edu.cn

This study investigates the specific circulation anomalies that have sustained the low Antarctic sea ice state since 2016. Firstly, we find a significant strengthening and southward shift in the Ferrel Cell (FC) during 2016–2022, resulting in a marked increase in southward transport of heat and moisture. Secondly, this enhanced FC is closely associated with a stronger circumpolar wave pattern over the same period. This pattern is zonally asymmetric and greatly amplifies the poleward advections of heat and moisture, leading to the increased downward longwave radiation, more liquid precipitation and sea ice retreat in specific regions, including the western Pacific and Indian Ocean sectors, eastern Ross and northern Weddell Seas. The mechanism deduced from the short-term period is further supported by the results of 40 ensemble members of simulations. The southward expansion of the FC is closely linked to La Niña-like conditions but may also be influenced by anthropogenic global warming.

Poster

Importance of ocean observations in ECCC's Global Ocean Analysis GIOPS: The SynObs Project

Autor Andrew Peterson[1]

Co-Autoren: Gregory C. Smith ; Chikhar Kamel ; Dorina Surcel-Colan [2]; Brayden Zheng [2]

[1] *Environment and Climate Change Canada*

[2] *ECCC*

The Synergistic Observing Network for Ocean Prediction (SynObs) project (https://oceanpredict.org/synobs) seeks to find synergies between ocean observations and ocean prediction through a multi-system approach to an Observing System Experiment (OSE). Best estimates and predictions of the location of eddies, ocean sound speed profiles, ocean currents and ocean water masses are important ocean diagnostics for a variety of ocean and/or coupled NWP applications. Skillful estimates of these diagnostics is presumably determined by the quantity and quality of ocean observations used in the ocean state estimation, but the exact value of the observations, and in particular, which observations are most crucial is unknown. Through OSE experiments performed by Environment and Climate Change Canada's (ECCC's) system the Global Ice Ocean Prediction System (GIOPS) for the SynObs project, we will investigate the effect of observation withholding experiments on these diagnostics. Particular attention is paid experiments withholding ARGO observations,
but other experiments withholding altimeter, or only assimilating SST observations also prove interesting.

Poster

Mixed layer modes of the two-gyre system

Autor Arnaud Czaja[1]

[1] *Imperial College London*

Korrespondenzautor: a.czaja@imperial.ac.uk

The coupling of the upper mixed layer with the thermocline is investigated in a planetary geostrophic model. Assuming that submesoscale instabilities lead to a rectified effect of geostrophic eddies on the (late winter) mixed layer depth D, and that the mesoscale eddy field is stronger where the thermocline (depth G) is larger, a parameter (r) coupling D to G is identified. Inclusion of this parameter in the Pedlosky and Young (1983) model leads, given an idealised wind forcing, to two modes, each valid over both subtropical and subpolar gyres. One has a mixed layer of uniform depth, the other a mixed layer deepening westward with a maximum in the subpolar gyre. The latter mode is particularly interesting as it displays an "overlapping" between the surface and subsurface gyres (i.e., an expanded subpolar gyre at the surface and an expanded subtropical gyre at depth), cross-gyre exchange, asymmetry between subduction and obduction, as well as Eastern boundary jets. It is suggested that this mode is relevant to the structure of the North Pacific thermocline.

Poster

Impact of Intraseasonal Waves on Angolan Warm and Cold Events

Autor Rodrigue Anicet Imbol Koungue[1]

Co-Autor: Peter Brandt [1]

[1] *GEOMAR Helmholtz Centre for Ocean Research Kiel*

Korrespondenzautor: rimbol@geomar.de

The intraseasonal variability of the tropical eastern boundary upwelling region in the Atlantic Ocean is investigated using multiyear mooring and satellite data. Pronounced oscillations of alongshore velocity and sea level off Angola at periods of about 90 and 120 days are observed. Similar spectral peaks are detected along the equator suggesting an equatorial forcing via equatorial and coastally trapped waves. Equatorial variability at 90 days is enhanced only in the eastern Atlantic likely forced by local zonal wind fluctuations. Variability at 120 days is generally stronger and linked to a second equatorial basin mode covering the whole equatorial basin. Besides forcing of the 120-day variability by equatorial zonal winds, additional forcing of the resonant basin mode likely originates in the central and western tropical North Atlantic. The coastally trapped waves generated at the eastern boundary by the impinging equatorial Kelvin waves that are detected through their variations in sea level anomaly are associated with corresponding sea surface temperature anomalies delayed by about 14 days. Off Angola, those intraseasonal waves interfere with major coastal warm and cold events that occur every few years by either enhancing them as for the Benguela Niño in 1995 or damping them as for the warm event in 2001.