Imperial College London

Ocean Day

18 April 2012

Participating authors: W. Ball, J. Craske, A. Czaja, J. Ingram, G. Messori, S. Mouradian, L. Sheldon., J. Tull, R. White, F. Zhang.

Grantham Institute for Climate Change

Contents

Executive Summary

The following document provides a summary of the talks, posters and discussions generated by the Ocean Day held at Imperial College on 18 April 2012. This event gathered more than a hundred academics from the main oceanographic centres in the UK. The range of topics addressed was enormous, despite solely addressing the physical aspects of the oceans. Three broad ideas came nevertheless frequently throughout the day:

(i) the two-way interactions between oceans and atmosphere are so prominent that it is difficult to study one fluid without the other.

(ii) Progresses in observations and numerical modelling of the ocean over the last decade have increased our knowledge of how it behaves, but they raise even more questions as to how it works.

(iii) The spatial and time scales accessible to numerical models of the oceans is truly fascinating, allowing the realistic study of its behaviour in present – day and in deep geological times.

Besides its scientific focus, the event also helped to raise the profile of Imperial College's oceanographic research and in developing a sense of community for UK physical oceanographers. There is a strong interest in the UK oceanographic community for a biannual repeat of the Ocean Day at Imperial College.

Background

Although the work on Oceans at imperial College involves more than 15 staff members and is spread across five departments (Mathematics, Physics, Earth Sciences, Aeronautics, Civil Engineering), there is the general feeling that the College is not known enough for its oceanographic research. To help in raising its profile within the UK community, it was decided to organize a one-day conference centred on the main themes covered by Imperial College's research ("Oceans and Climate" and "Ocean Modelling"). The "ocean Day" was held on the South Kensington Campus on 18 April 2012.

Summary of presentations

Keynote talk

Weighing the Ocean: Regional and Global Sea Level

Prof C. Hughes, National Oceanography Centre, Liverpool

Sea level rise has accelerated over the past two centuries, with global sea level currently rising at 30 ±4 cm/century. An understanding of this acceleration acts as a useful indicator of climate change, with a knowledge of the rate of rise allowing for an estimation of its volume.

Prof. Hughes mainly spoke of global sea levels, showing a 3mm yr^{-1} trend in sea level rise since 1992, but stressed such patterns cannot be analysed from just a global perspective. Although of the rate of acceleration is an important indicator of global mean sea level, the local scale changes in sea level are seen to cause the largest problems, for example flooding and coastal erosion, with such changes important even on the time scale of centuries. Such regional patterns are very important with sea levels showing a 3m range over the globe, reflecting ocean circulation patterns, e.g. the Gulf Stream.

Sea level (ocean volume) can change because of changes in ocean mass, or changes in density, whereas ocean bottom pressure is purely related to ocean mass changes. Bottom pressure has low dynamical variability and little power at long periods, showing mainly short period variability. Very little bottom pressure variability is seen in the Tropics compared to the high variability of the sea level in this region. Whereas global mean sea-level allows us to measure ocean volume, global ocean bottom pressure allows for measurement of ocean mass. With such low dynamical variability in the Tropics, can we use ocean bottom pressure in one location to measure change in ocean mass?

Results from the OCCAM model dynamical bottom pressure were presented, at varying degrees of resolution. Similar variability was seen at different resolutions, with regional patterns clearly seen between the Tropical and Extra-Tropical oceans and the 3mm/yr trend well above the dynamical variability in the tropical Pacific. Prof. Hughes talked about several problems inherent in this method, including each water source having a ‘fingerprint’. Yet, far from the source, e.g. middle of the Pacific Ocean, all fingerprints look very similar. Secondly, the sea floor has some vertical movement due to glacial isostatic adjustment. As an ice sheet melts, the change in location of mass affects land height and gravitational field due to Earth’s elasticity. Errors resulting from this effect are also small in the tropical Pacific. Also, large changes in the atmosphere have small effect on ocean bottom pressure, with the effect of atmosphere on annual cycle having an effect of a few mm on sea level.

Prof. Hughes concluded by determining the annual cycle of ocean mass using measurements from (effectively) a single measurement site, and showed that this measurement is as good as can be achieved using global satellite data. He suggested that, if bottom pressure recorders didn't suffer from drift problems, we could use this method to measure the ocean mass trend with accuracy probably better than 0.5mm/yr (with a 5-10yr record).

Oceans and Climate

Ocean chemistry: now and then

Dr T. van de Flierdt, Imperial College

The oceans play a significant role in the integrated climate system. The deep ocean contains ~60 times more carbon than the atmosphere and a large part of the exchange between them takes place in areas of deep water formation and upwelling. Therefore small changes in the rate of deep water formation are likely to have a large impact on the atmospheric carbon budget**.**

Reconstructions of past ocean circulation rely on proxy records based on chemical tracers preserved in ocean deposits. Dr. van de Flierdt showed that ocean circulation patterns in the Atlantic Ocean have changed since the last ice age. Deeper convection in the North Atlantic occurs in the warmer present day ocean, whereas the cooler oceans at the Last Glacial Maximum, some 20,000 year ago, seems to have been more stratified with deep and bottom waters formed around Antarctica occupying a larger volume in the Atlantic Ocean (see **Fig. 1**). Changes in water mass distributions in the Atlantic Ocean also occurred on shorter timescales. Chemical tracers, such as carbon isotopes in biogenic deposits and neodymium (Nd) isotopes in fossil fish teeth, seem to show that rapid climate changes during the last ice age were accompanied by rapid changes in deep water chemistry and circulation.

Neodymium isotopes are frequently used in studies of ocean changes as they show good correlation with water mass properties such as salinity in the modern ocean. To reconstruct the past requires reliable archives of seawater Nd isotopes such as marine sediments and fossilised shells. In particular, Dr. van de Flierdt showed that the Nd isotopic composition in the skeletons of modern deep-sea corals agrees very well with seawater Nd isotopes around the globe, with the caveat that observational data from seawater are still sparse.

Dr van de Flierdt then introduced the GEOTRACES program, an international effort to better understand the biogeochemical processes that affect trace metal distributions in the ocean. For example, a large effort within the UK GEOTRACES team is to understand palaeo-proxies such as Nd isotopes as well as micronutrients such as Fe, Co, Zn and Cd along a transect at 40^{o}S in the South Atlantic. While macronutrients are well-studied, micronutrients are equally essential to marine life (and hence the carbon cycle) in certain areas, but are not that well studied. Dr. van de Flierdt emphasised the potential of an improved understanding of such trace metal cycles by example of dissolved Cd isotopes, which can act as a tracer for the biological pump (i.e., transport of carbon from the surface ocean to the deeper ocean by biological uptake and regeneration, which plays a significant part in the Earth's carbon cycle).

A better understanding of the carbon cycle, today and in the past, will be greatly aided by an improved understanding of the processes driving the distribution of trace elements and their isotopes. The ongoing work presented here should lead to better insights into the ocean's role in climate change.

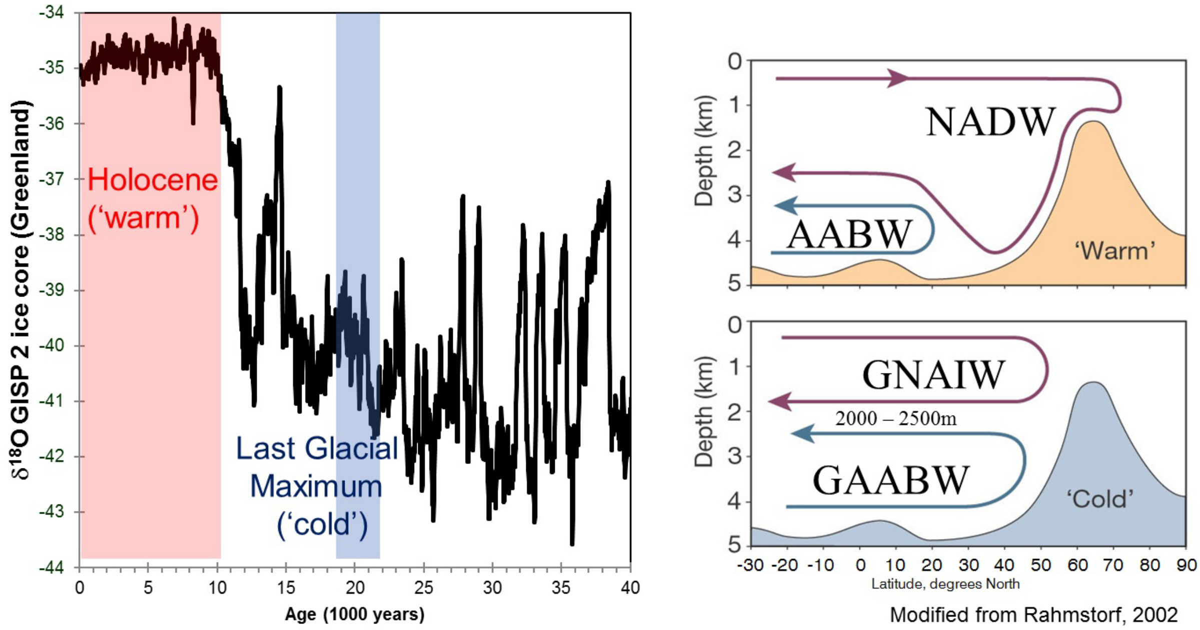

Figure 1: (**left**) Oxygen isotopic composition in the GISP 2 ice core over the past 40,000 years as a proxy record for air temperature over Greenland. Data from Grootes et al, 1993[1]. (**right**) Schematic of different modes of ocean circulation along the Atlantic Ocean. (**right, top**) Scenario during warm periods, such as the Holocene, where North Atlantic Deep Water (NADW) formation dominates the water column in the North Atlantic; Antarctic Bottom Water = AABW. (**right, bottom**) Scenario during cold periods, such as the Last Glacial Maximum, with a more stratified water column and shallower northern-sourced water (GNAIW = Glacial North Atlantic Intermediate Water) underlaid below 2000/2500m by Glacial Antarctic Bottom Waters (GAABW). Modified from Rahmstorf, 2002[2].

The Cooling Paradox in Ocean Energetics

Dr R. Tailleux, Reading University

An available potential energy (APE) framework provides a useful tool for understanding and predicting important aspects of the general circulation of the oceans. Such aspects include the relative strengths of wind and buoyancy forces in maintaining the Atlantic meridional overturning circulation (AMOC) and their response to anthropogenic forcing.

Dr Tailleux explained that an analysis of APE can account for the observation, known as the cooling paradox, that cooling applied locally to the top of a stably-stratified fluid can create kinetic energy. His general approach is applicable to the fully compressible Navier-Stokes equations[3], fitting comfortably with classical thermodynamics and the concept of a Carnot efficiency factor for the generation of APE.

A particularly simple implementation of this framework, applicable to atmosphere-ocean general circulation models (AOGCMs), can be used to decompose the creation of APE into mechanically-driven (adiabatic rearrangement by the wind) and buoyancy-driven (diabatic heating from surface fluxes) components. In collaboration with Professor Jonathan Gregory[4], Dr Tailleux demonstrated that the sign of the work of the pressure gradient provides a simple diagnostic that is able to discriminate between wind-driven and buoyancy-driven regions. Vertically averaged data from the AOGCM FAMOUS forms that buoyancy and wind provide the principle driving forces in regions of high latitude and over the Atlantic circumpolar current (ACC), respectively.

Importantly, this simple energy framework provided a means of inferring that the dominant cause of the predicted weakening of the AMOC under a $C0_2$-forced climate change is a reduction in the rate of APE production due to buoyancy in regions of high latitude. An accompanying increase in wind-driven APE production over the ACC under such conditions suggests that the wind over the ACC is not the dominant driving force of the AMOC (see **Fig. 2**).

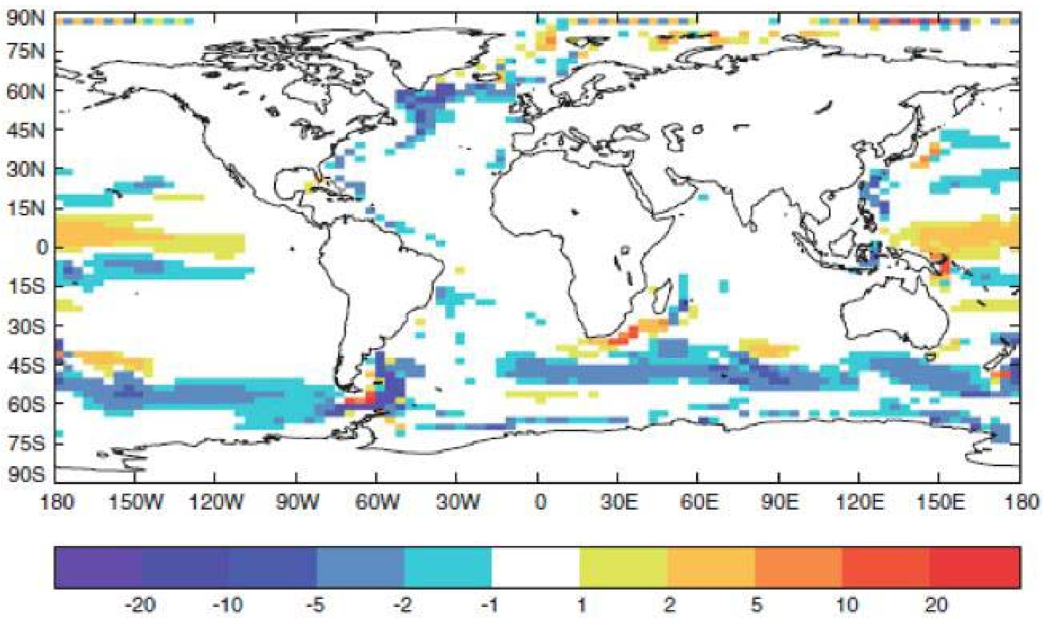

Figure 2: The difference between the rate of generation of depth integrated KE [mWm^{-2}] by the pressure gradient force between a CO_2 forced climate and a control climate using FAMOUS[4].

In response to a question at the end of his presentation, Dr Tailleux was able to clarify that his method does not rely on a linear equation of state. When asked about the role of wind-driven mixing, Dr Tailleux explained that this would affect the AMOC indirectly by modifying the reference state and modulating how much energy is created by the buoyancy forcing. In response to a concern that the topography of ocean basins might make it difficult to construct a reference state, Dr Tailleux emphasised that averages can be used to define an APE under the proposed framework.

Ocean Eddies at the Western Boundary

Dr Helen Johnson, Oxford University

Understanding how ocean eddies impact upon the mean circulation is a crucial component in understanding the ocean's dynamics. Ocean eddies impact upon the energy budget of the ocean and are everywhere throughout the ocean. As such it is important to understand where the eddy energies are lost and in this presentation Dr Johnson looked at eddies at the western boundary and whether it acts as a sink for eddy energy.

Dr Johnson began by considering the eddy energy budget in a simple reduced-gravity model. For an anticyclonic eddy incident on the western boundary only 7% of the initial eddy energy escapes equatorward; the rest is viscously dissipated close to the western boundary. For a random sea of eddies less than 2% of the energy escapes equatorward.

Dr Johnson then discussed the divergence of eddy energy in the first baroclinic mode throughout the ocean. Through a combination of altimetry and climatological hydrographic data this has been estimated (see **Fig. 3**). The total convergence of eddy energy near western boundaries (poleward of 10^{o} latitude) is 0.1-0.3 TW. The eddy energy sink is similar in each hemisphere (despite the fact that the majority of wind energy input to the large-scale circulation is found in the Southern Ocean) and it is likely that energy is scattered in high wavenumber vertical modes that rapidly dissipate. Some of the dissipating processes may lead to enhanced diapycnal mixing in western boundary regions.

Furthermore, variability in the reduced-gravity model with a random sea of eddies as initial state decays near the western boundary. Observations show that sea surface and dynamic height variability also decay within 100km of the western boundary. Dr Johnson then discussed how this reduction at the boundary is critical to understanding variability in the Meridional Overturning Circulation (MOC) and considered how eddies will impact upon estimates of its strength.

In summary, Dr Johnson concluded that western boundaries are a sink of (first baroclinic mode) eddy energy. This is consistent with predictions from linear wave theory and has been observed in both remote-sensing and in-situ ocean data. This removal of eddy energy may result in enhanced diapycnal mixing in the western boundary regions with important implications for ocean and climate. Furthermore, the reduction in variability on the western boundary is important for the success of current MOC monitoring efforts.

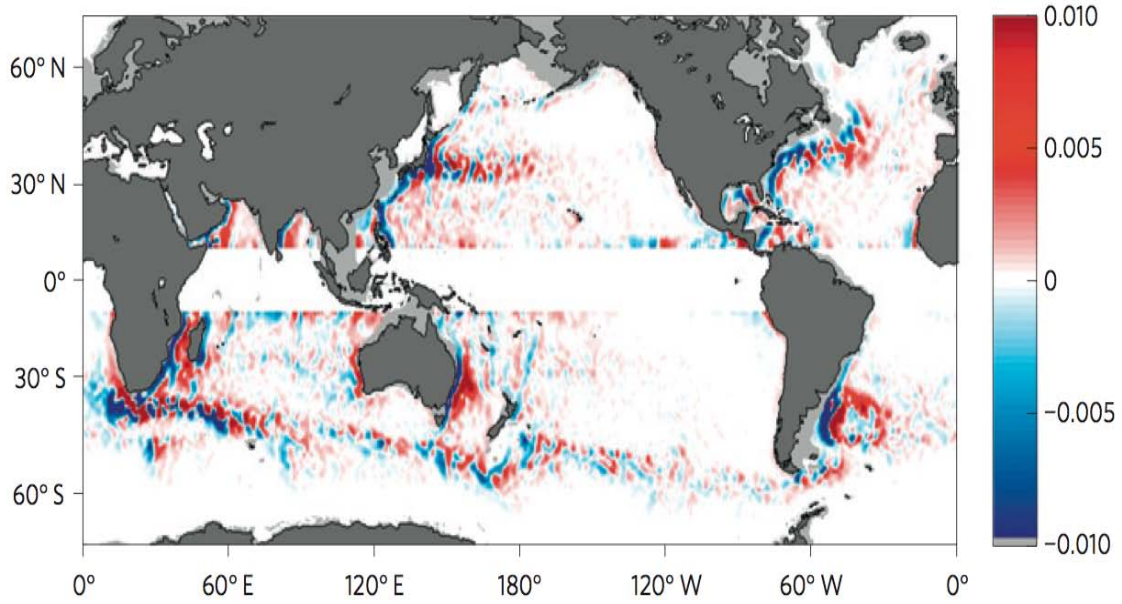

Figure 3: Eddy energy sink near western boundaries. Eddy energy source in ocean interior. Both expressed in Wm-2.

Frontal Ocean-Atmosphere coupling

Dr A. Czaja, Imperial College

The impact of the ocean circulation on climate variability has so far been mostly studied using coarse climate models. The latter resolve adequately the impact that ocean currents have on broad features of the sea surface temperature (SST) distribution, such as the equator-to-pole gradient, or the basin scale SST anomaly covarying with the North Atlantic Oscillation. However, ocean currents also impact strongly the SST distribution on smaller (~100km) scales which are not properly resolved yet by coarse climate models, but can be studied in observations. Dr Czaja introduced in his talk a new mechanism for ocean atmosphere coupling occurring precisely on those scales.

Specifically, the focus is on the interaction of oceanic and atmospheric temperature fronts. When the latter are aligned with each other (warm air over warm water on one side of the front and, conversely, cold air above cold water on the other side of the front), small heat air-sea heat exchange result and atmospheric frontogenesis is least damped. When the fronts are anti-aligned (cold air over warm water and warm air over cold water), large air-sea heat fluxes occur and a strong damping of the atmospheric front results. Dr Czaja showed that this simple picture is supported by an analysis of atmospheric front strength as a function of their relative positions with respect to the underlying ocean surface isotherms in the ERAinterim data set. He then went on to use this mechanism to explain some of the results obtained with high resolution atmospheric models[5].

Dr Taylor asked Dr Czaja to develop further his statement that frontal regions may be regions where active two-way interactions between the ocean and atmosphere take place in midlatitudes. Dr Czaja proposed that indeed aligned oceanic and atmospheric fronts support each other: on the atmospheric side, through the reduced thermal damping argument illustrated in the talk and, on the oceanic side, through a frontal spin up induced by wind driven Ekman currents.

Ocean modelling

Meridional coherence of western boundary currents

Dr J.Hirschi, National Oceanography Centre in Southampton

Dr Hirschi used an eddy resolving model to compare the coherence of the Florida, Agulhas and Kuroshio currents with their more poleward extensions. This is important as it allows us to understand the how local measurements can be put in a wider spatial context. The 1/12° ORCA12 model Dr Hirschi used was shown to be reliable as the boundary separations appeared accurate in the 10 year mean, although the simulated transport variability was lower than observed.

The model showed that for the Kuroshio and Gulf Stream there is large meridional coherence on a range of timescales, from sub-seasonal to inter-annual, and for both positive and negative transport anomalies (see **Fig. 4**). All the currents also had an equatorward shift in their zonal extension when the transport increased. In the North Atlantic, when the Florida Current transport increases and the Gulf Stream extension shifts southward it was found that there is also a cyclonic wind anomaly, with the opposite seen for a negative transport anomaly. Dr Hirschi proposed that the meridional shift in the Gulf Stream is due to the Ekman transport produced by the wind anomaly.

Dr Hirschi concluded by mentioning future research possibilities leading on from this work. This involves looking at the lagged relationships in the models and also by looking at composites in the observational data (for example cable data from the Florida Straits and satellite altimetry data).

In the discussion Claude Frankignoul commented how previous observational work by Terry Joyce saw the opposite response of the Gulf Stream extension to a change in the transport with increased transport producing a northward shift in the current.

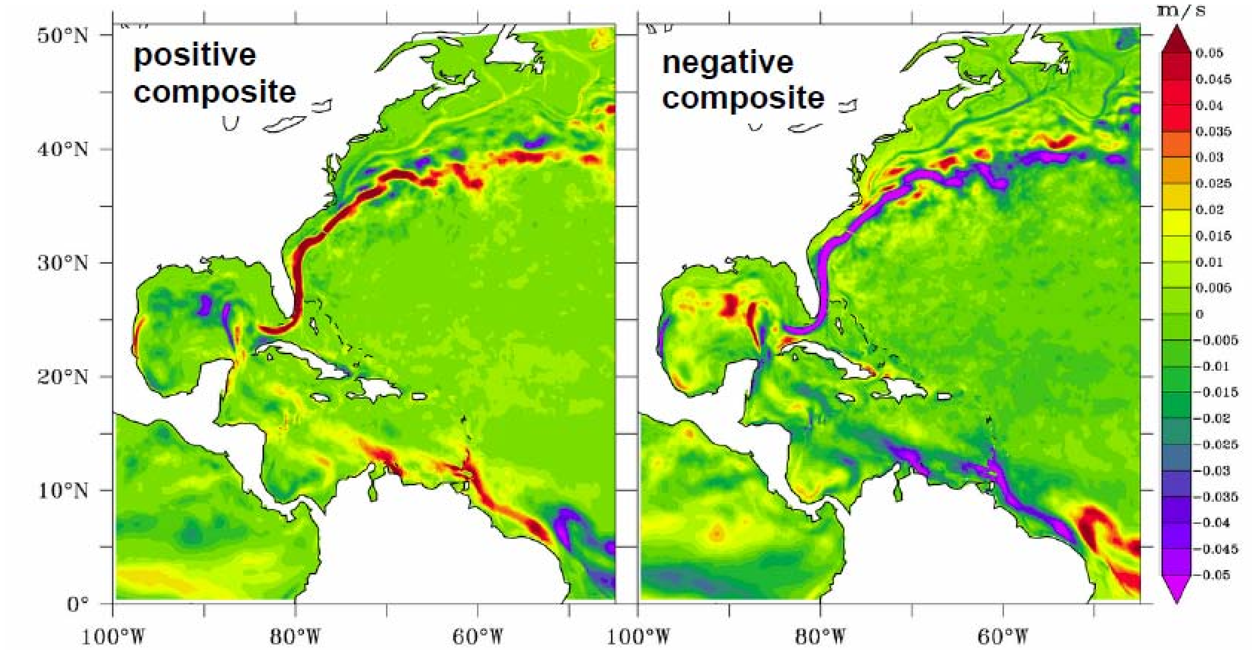

Figure 4: Composites of absolute velocity anomalies in the North Atlantic for positive (**left**) and negative (**right**) transport anomalies through the Florida Current.

Using flexible meshes to model the oceans

Dr M. Piggott, Imperial College

Dr. Matthew Piggott described the use of 'flexible' meshes and their potential advantages in solving large scale ocean modelling problems. He presented the finite element ocean model, Fluidity-ICOM, developed in the Applied Modelling and Computation Group and its validation and verification; through a series of applications ranging from laboratory scale lock-exchange type simulations to large-scale, global ocean simulations. He presents current development efforts, to include fluid-structure interaction and adjoint (optimisation) techniques and ends with the application to marine renewable energy generation.

The flexibility offered by the use of unstructured, adaptive meshes may be able to provide significant computational saving in problems consisting of multiple scales and complex geometries. Linking coastal and shelf scale processes to larger scales can be done explicitly through the use of unstructured meshes. Anisotropic elements may align with boundary layers to provide significant savings whilst capturing dynamics that would otherwise not be possible. In particular, Dr. Piggott shows the advantages of using techniques and experience obtained from challenging CFD type problems, such as the drag calculation of flow past a sphere, a problem for which significant literature is available. Particular emphasis is placed on the significant flexibility provided by Fluidity in terms of geometry and meshing, but also in terms of the discretisation options available. Both continuous and discontinuous Galerkin methods were discussed as well as control volume options for tracers, with various stabilisation options. Having presented the model, Dr. Piggott proceeds by showing a 3D high aspect ratio restratification problem and how this set-up was built upon to model more realistic problems, such as the UK west coast and the globe.

Conundrum of Geostrophic Turbulence in the Oceans: Multiple Alternating Jets, Waves and Vortices

Dr P. Berloff, Imperial College

Satellite and in-situ measurements provide solid evidence of the jet's existence but severe lack of more detailed information; and over the last 5-7 years ocean models started to resolve the jets by marginally resolving the mesoscale eddies. Dynamically similar multiple manifest jets in the atmospheres of giant gas planets, such as Jupiter and Saturn, have been known for a long time.

Dr Berloff started by present the idealised, two-layer, eddy-resolving, flat-bottom quasi-geostrophic model used for his research. Dr Berloff then discussed the extent that properties of very nonlinear, turbulent solutions are controlled by the underlying linear dynamics. Dr. Berloff showed two families of normal modes under uniform background flow and concluded that: effect of even weak (~1 cm/s) background flow on the eigenmodes properties is large; two families of the eigenmodes have very different structural and dynamical properties, although their dispersive properties may coincide locally; and most of the eigenmodes are mixed: i.e., neither barotropic nor baroclinic and therefore traditional interpretation of oceanic eddies as baroclinic and barotropic can be dynamically inconsistent.

Dr Berloff then presented the profiles of the normal modes under idealized non-uniform background flow and concluded that the strong zonal jets can affect the quantization and clustering of the dispersion curves, the stabilization of many dispersion curves, the range of phase velocities and the localization of normal modes on either eastward or westward jets.

Dr Berloff proceeded to discuss the effects of dynamically consistent background flow from the nonlinear model; Dr Berloff presented the dynamically consistent linear spectra and the $k-\omega$ spectra and concluded that patterns of $k-\omega$ -filtered eddies are similar to the underlying linear eigenmodes and the corresponding eddy flux divergences of potential vorticity, momentum, and heat (i.e., nonlinear eddy forcing) are similar to those of the underlying linear eigenmodes.

Finally Dr Berloff presented the final conclusions: wave-turbulence mechanism is correct framework for describing jets and eddies of anisotropic geostrophic turbulence; linear eigenmodes and their nonlinear interactions yield important predictions for (a) dynamic and kinematic properties of the eddies, and (b) for eddies/jets interactions; and roles of long-lived coherent isolated vortices remain unclear and require systematic studies.

In the Q&A section, Dr Remi Tailleux asked 'whether in the case of finite-amplitude jets individual dispersion curves correspond to specific meridional Fourier harmonics?' and Dr Berloff answered 'no, as most of the interesting the eigenmodes become meridionally localized on the jets'.

Note: the figures are available in Berloff *et al.*[6, 7, 8].

High resolution seasonal to decadal climate prediction

Prof D. Stevens, University of East Anglia

In his introduction Prof Stevens emphasized the need for more accurate climate predictions on a regional scale. A possible route towards this goal is the development of higher resolution climate models, such as is currently being done in the HiGEM project,

Prof Stevens first illustrated a few important improvements reached by using a higher spatial resolution (1/3^{o} horizontally in the ocean for example) compared to the standard HadGEM1 version of the Hadley Centre: reduced cold bias in sea surface temperature, better simulation of the Gulf Stream separation and better simulation of warm El Nino events in the tropical Pacific.

He then discussed the decadal prediction experiments conducted for the upcoming 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC). A particularly interesting result was the skill in predicting the large 1997/98 El Nino event. An ensemble of forecasts starting in December 1996 shows very good skill. More surprising is the apparent skill of an ensemble of forecasts starting in December 1994 (see **Fig. 5**). In addition, the results presented indicated that the assimilation system in HiGEM was able to capture the variability of the Atlantic meridional overturning circulation (AMOC) measured by RAPID at 26.5N, with some indication of predictive skill for this variable (AMOC minus Ekman transport) with a lead time of up to two years.

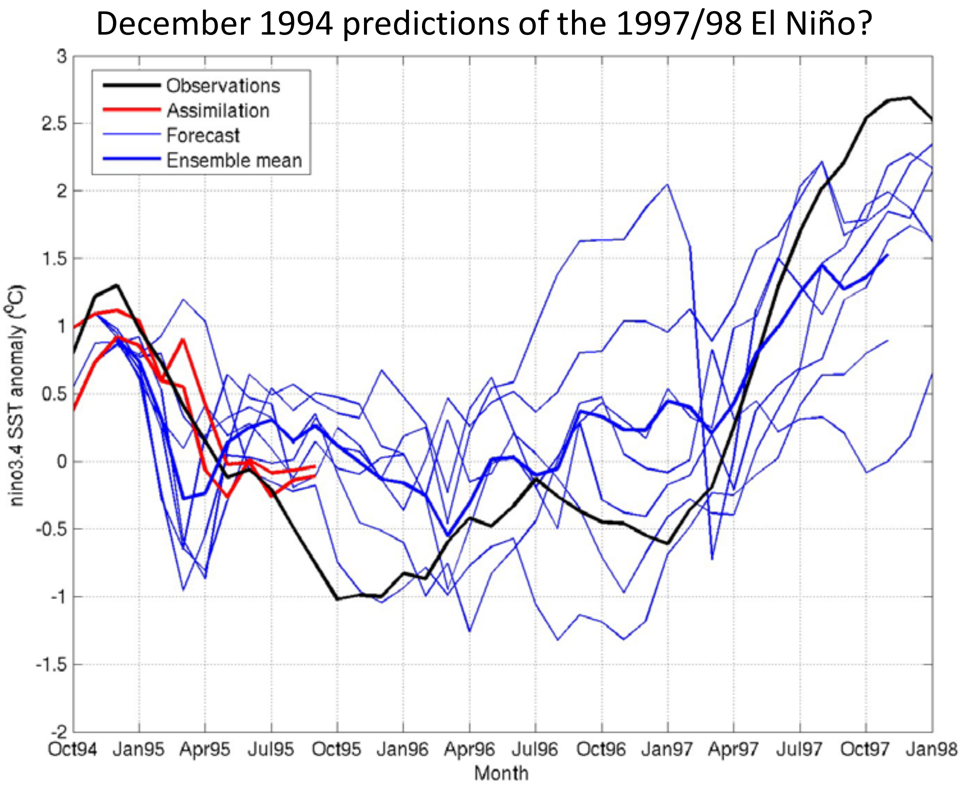

Figure 5: Timeries of the Nino 3.4 SST anomaly (in K) in the observations (black), the HiGEM assimilation run (red) and the HiGEM forecasts (blue).

Challenges and Future directions

"Interaction between Polar oceans and the Cryosphere"

Dr P. Holland, British Antarctic Survey

The cryosphere accounts for a relatively minor part of the world's surface, yet changes in its condition have the potential to severely affect large scale features of the global climate system. These include, among others, global mean sea level, and a host of atmospheric and oceanic feedbacks.

The cryosphere's largest component is the Antarctic Ice Sheet, which is thought to be a major contributor to the current 3mm/yr rise in global mean sea level. Using the MIT GCM in a circum-polar and a regional set up, Dr. Holland presented evidence for the role of the ocean in melting portions of the West Antarctic Ice Sheet. The bottom potential temperature in the Amundsen and Bellingshausen seas can be quite warm (up to 1 °C) due to a branch of the ACC flooding the continental shelf. *In situ* observations confirm that this warm water reaches and melts the base of ice shelves. As a specific example, Dr. Holland illustrated how basal melting has enlarged the cavity beneath Pine Island Glacier, where the ice was once resting on a sea bed ridge.

Dr. Holland then proceeded to discuss sea-ice extent trends. The Arctic sea-ice cover is rapidly declining, especially during the summer season, and this decline is captured, to a varying degree, by most climate models. In the Antarctic, on the opposite, a small but statistically significant increase in sea-ice cover is seen (see **Fig. 6**). This mean trend is not reproduced by models and is the average of a very broad spectrum of regional variations. It is therefore important to understand the mechanisms driving this growth. In particular, it is crucial to assess the role of dynamic (e.g. wind stress) versus thermodynamic (e.g. melting/freezing) factors. Dr. Holland showed that wind-driven export appears to be a dominant factor in large areas around the continent, with double-digit percent increases in meridional sea-ice export in many regions.

Dr. Holland then concluded by illustrating some plans for future research on the topic. These include further analysis of ice loss from ice sheets and sea-ice and including ice sheet changes in climate models.

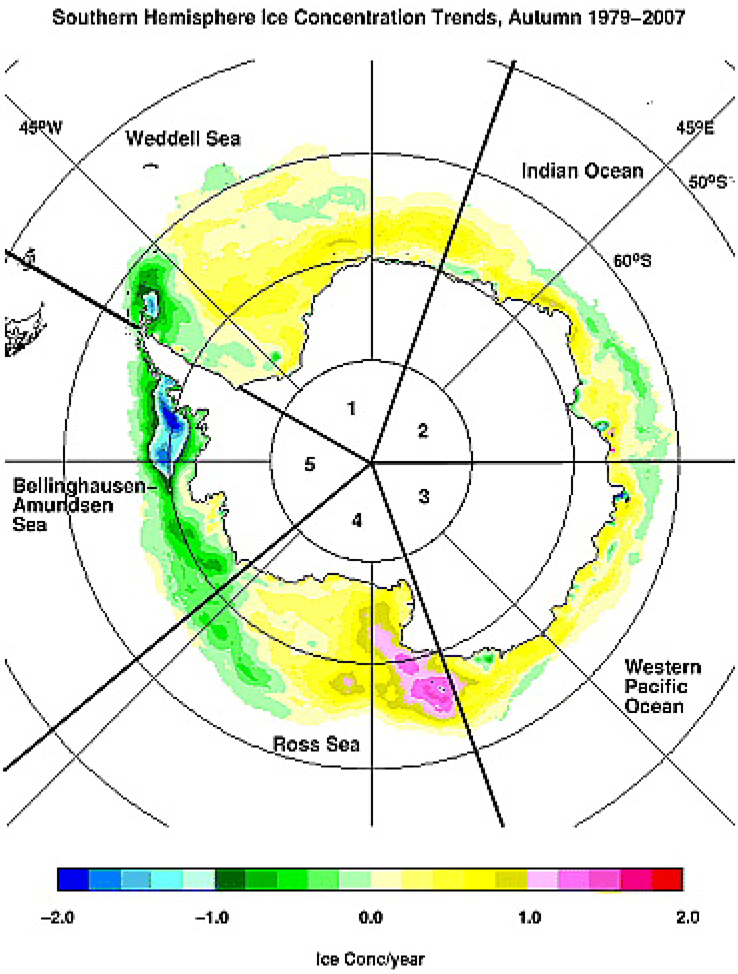

Figure 6: Autumn Antarctic sea-ice concentration trends over 1979-2007[9].

Influence of the extra-tropical ocean variability on the atmospheric circulation

Prof C. Frankignoul, University of Paris VI

Professor Frankignoul highlighted that much of the climate memory, and therefore predictability lies in the ocean but what we want to know is the resulting influence on the atmospheric circulation. This emphasizes the importance of understanding the role of the extra-tropical ocean in forcing the atmosphere.

Professor Frankignoul showed previous work demonstrating that a North Atlantic horseshoe sea surface temperature (SST) pattern preceded the North Atlantic Oscillation in the atmosphere by 4 months in early winter (see Figure 1). This atmospheric response may be due to anomalous diabatic heating driven by the SST or result from the variability in the oceanic front influencing a large scale atmospheric response.

Using the coupled IPSL-CM5 model Professor Frankignoul demonstrated that the Atlantic meridional overturning circulation (AMOC), through a similar horseshoe SST pattern (see

Fig. 7), modulates the surface heat flux and therefore produces a negative NAO and a southward shift in the storm tracks for an AMOC intensification. As this response was also seen at the seasonal scale, the seasonal and decadal responses are consistent. However the response to the AMOC was of opposite sign in the CCSM3 model, with a positive NAO and a storm track shifted northward following an AMOC intensification. Professor Frankignoul concluded that although in two different models the responses are opposite, it is clear that the ocean dynamics are determining the atmospheric response.

The horseshoe SST pattern resembles the Atlantic Multi-decadal Oscillation in both the observations and IPSL-CM5 (although the timescales are different) and in the model it was shown that this is partly due to the AMOC. This suggests that the AMOC may also play a role in the formulation of the horseshoe pattern in the observations and gives promise for decadal predictability in mid-latitudes. These results highlight the importance of testing air-sea interaction in coupled models for decadal prediction.

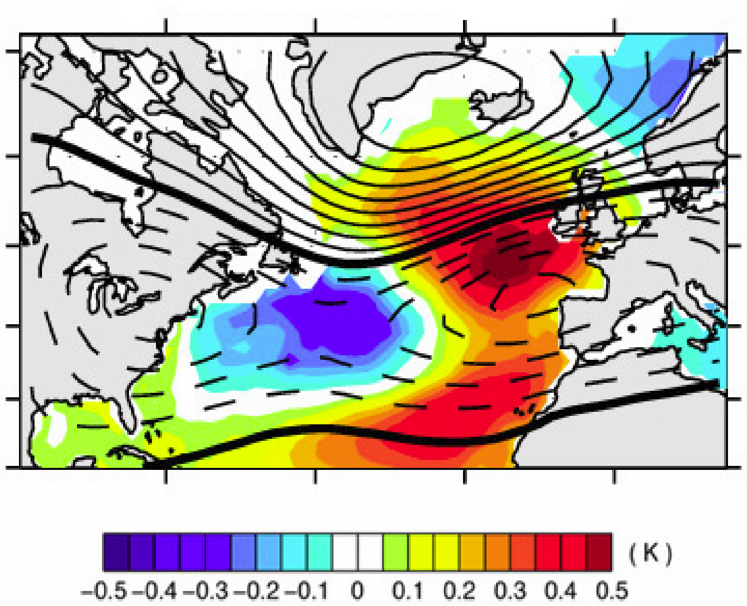

Figure 7: Covariance map of anomalies Z500 in NDJ lagging the SST by 4 months.

New model, old seas: using ICOM to understand geologically ancient seaways

Dr. P Allison, Imperial College

Dr. Allison began by explaining some of the working methodologies used by geologists to understand the conditions in which sedimentary rocks formed millions of years ago. Rocks are essentially the results of an ‘experiment’ and geologists seek to determine the boundary conditions of the experiment. One of the mainstays in the toolkit used by geologists is the principle of uniformitarianism - using modern counterparts to further our understanding of geologically ancient features. One of the problems inherent in this methodology arises if there are no modern counterparts to the ancient environment under investigation. Dr. Allison highlighted the fact that this is indeed the case with epicontinental seas. In the geological past, large swathes of continental crust were flooded by vast shallow seas. Modern coastal seas are several orders of magnitude smaller than some of these ancient counterparts and this limits the utility of the uniformitarian methodology.

Understanding the behaviour of ancient epicontinental seas is important. There are very little true palaeo-ocean sediments from the Jurassic period as much of the oceanic sedimentary rocks have since been subducted. As a result the whole of the marine climate and evolutionary record for pre-Jurassic times is from sedimentary rocks deposited in epicontinental seas deposits found on present day land. In addition, over 90% the world's hydrocarbons were deposited in epicontinental seas, and thus these seas were important carbon sinks. Dr. Allison described how he and his colleagues are using the Fluidity-ICOM (Imperial College Ocean Model) to study tides in epicontinental seaways. Tides are important sources of mixing in modern day coastal seas and have a profound and recognizable impact upon marine sediments. It has previously been argued that epicontinental seas experienced either very slight tides due to frictional damping or very large tides as a result of bathymetric funnelling and resonance.

Dr. Allison presented results showing that an ICOM simulation of the present day compares well to real-world data from the NW European Shelf (tidal gauge data on free-surface height, observed bed shear stresses and sediment transport pathways). He then described experiments performed to simulate the Lower Jurassic Laurasian Seaway – an epicontinental sea that covered much of NW Europe around 200 million years ago. The model results show a tidal range in the interior of the seaway that was less than 2m (micro-tidal). Further analysis of the model results showed that the ICOM bed shear stress predicted that there would be bed shear stress 'hotspots' in shallower straits between islands (see **Fig. 8**). These areas of enhanced tidal activity had bed shear stresses sufficient to transport fine sand and hence leave a tidal signature in the rocks. There are modern analogies to these strong tidal currents within narrow straits in the Gulf of Corinth and the Straits of Messina.

An additional benefit to the use of numerical models is the ability to perform experiments to determine what would have happened given slightly different conditions. Dr. Allison finished by presenting ICOM results of experiments which covered a 70m rise in sea-level. As the water-depth was deepened the tidal energy was able to penetrate deeper into the seaway but amplification in straits was eventually lost as the topography was progressively drowned. Dr. Allison concluded with a summary, noting that epicontinental seas had limited tidal activity, although with enhanced tidal currents in narrows strait. They were therefore perhaps more like variably salty lakes than true oceans. Further work will investigate the impact this had on carbon drawdown and the diversity of marine biota.

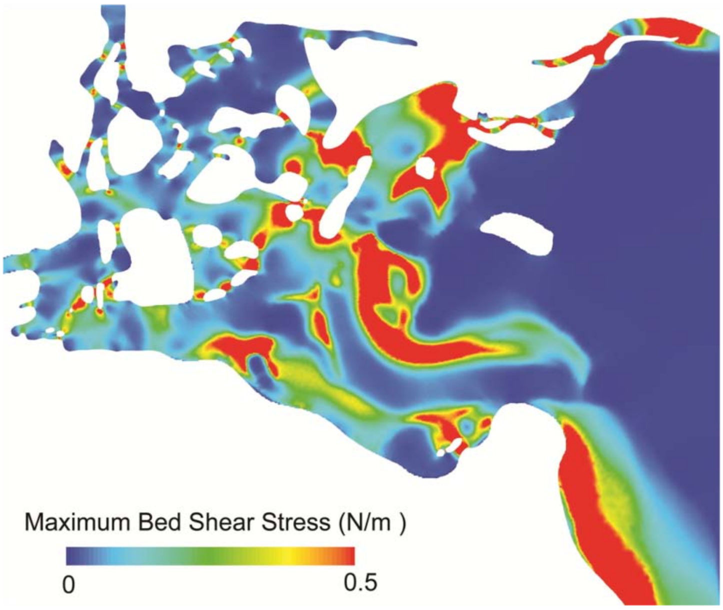

Figure 8: Bed Shear Stresses in N/m in the Laurasian Seaway of the Lower Jurassic. Hotspots can be seen in the straits between islands.

Concluding remarks and discussion

Prof C. Wunsch
MIT and Oxford University

“Would anybody have a Land Day?” asked Prof. Carl Wunsch. Such is the diversity of ocean research that we would probably need an Ocean Month. Several grand themes were covered in the Ocean Day Conference. Some of the common themes included discussions of noise in ocean data, and the problems of extracting signals, the dominant role sometimes of western boundary currents, and the issues in ocean modelling.

There are still a lot of basic processes that are not well understood, but although the modelling capabilities are getting better, they are becoming more complicated, with some contradictions among them. There is a tendency to play down the importance of observations – “you don’t get seasick when using models!” stated Prof. Wunsch. Yet the more we understand about oceans, the less we understand about the underlying processes.

The most unexpected subject raised during the day for some included the narrow technical issue of not being able to directly measure ocean bottom pressure. This stands out as a clear technical problem for future scientists and engineers and it may not have an affordable solution.

Prof. Wunsch concluded by stating that the talks covered a very diverse field with a lot of work still to be done. If a similar conference was to occur in 10 years time we would definitely see big progress in this large field of research.

Outlook for ocean research

Although the Ocean Day primarily focused on the physics of the oceans, only tackling ocean chemistry and biogeochemical cycles (and omitting entirely vast topics such as coastal oceanography), the range of topics discussed was vast. A few common themes can nevertheless be tentatively highlighted:

(i) *One cannot study the oceans in isolation from the atmosphere*. Interpreting the sea level record is a good example, with large regional changes reflecting temporal variations in major modes of atmospheric variability like the North Atlantic Oscillation. Conversely, the state of the ocean influences the state of the atmosphere, not only in the Tropics, as often emphasized, but in mid-latitudes as well.

(ii) *As one learns more about the oceans, one understands less*. For example, the sensitivity of ice shelves to ocean currents is now better established from an observational point of view, but the richness of plausible physical mechanisms involved is great (ranging from ice microphysics to thermodynamics to geophysical fluid dynamics) and the associated numerical modelling daunting. This certainly points to a need for process oriented studies helping to interpret observations, as opposed to “brute force” numerical modelling.

(iii) *The exciting new developments in numerical modelling*. The range of spatial and time scales that can be addressed in ocean models is truly enormous and fascinating. It allows to cope realistically with present – day ocean turbulence, with improved climate predictions, as well as with tidal mixing in deep time epicontinental seas!

By all measures, the event was a clear success. The lecture theatre was packed and there was a great dynamic during the talks and the subsequent question/answer sessions. Posters were well attended and discussions plentiful. All feedbacks received (formally or not) were extremely positive, and overall, the Ocean Day achieved its main goal of putting Imperial College “on the map”.

There is clearly the feeling that such gatherings of the UK oceanographic community are too rare. Indeed, besides targeted workshops (e.g., tied to a Research Council proposal), and the meetings of the Challenger Society, there are none. The one-day format of the Ocean Day was particularly appreciated, and central London seems to be the ideal location for this format.

The broad range of topics covered was a strength, allowing attendees to benefit from a large amount of background knowledge and associated networking. It is very clear that the Ocean Day should be held again the future, perhaps once every two years.

List of participants

Surname	First Name	Organisation
Abraham	Edo	Imperial College London
Allison	Peter	Imperial College London
Allison	Lesley	NCAS Climate, University of Reading
Arthun	Marius	British Antarctic Survey
Ball	William	Imperial College London
Berloff	Pavel	Imperial College London
Boland	Emma	University of Cambridge
Bouttes	Nathaelle	NCAS-Climate, University of Reading
Brannigan	Liam	University of Oxford
Broadbridge	Maria	Imperial College London
Candy	Adam	Imperial College London
Claus	Martin	GEOMAR | Helmholtz-Zentrum für Ozeanforschung Kiel
Clement	Louis	National Oceanography Centre, University of Southampton
Conneely	Sinead	Imperial College London
Craske	John	Imperial College London
Czaja	Arnaud	Imperial College London
Damzen	Michael	Imperial College London
Davis	Peter	University of Oxford
Day	John	n/a
de Boer	Agatha	University of East Anglia
De Rydt	Jan	British Antarctic Survey
Defriez	Emma	Imperial College London
Dong	Buwen	NCAS-Climate. University of Reading
Estella Perez	Victor	Imperial College London
Farley Nicholls	James	Imperial College London
Feltham	Daniel	UCL
Fox	Cathryn	Imperial College London
Frankignoul	Claude	Universite Pierre et Marie Curie
Funke	Simon	Imperial College London
Giles	Katharine	UCL
Goh	Chee Su	Imperial College London
Goldberg	Tatiana	Imperial College London
Gollan	Gereon	GEOMAR | Helmholtz-Zentrum für Ozeanforschung, Kiel
Gorman	Gerard	Imperial College London
Graham	Jennifer	University of East Anglia
Haigh	Jo	Imperial College London
Ham	David	Imperial College London
Hasa	Jokke	Imperial College London
Heaviside	Clare	Health Protection Agency
Heuze	Celine	University of East Anglia
Hide	Raymond	Imperial College London
Hiester	Hannah	Imperial College London
Hill	Jon	Imperial College London
Holland	Paul	British Antarctic Survey
Hoskins	Brian	Imperial College London
Hughes	Chris	National Oceanography Centre, Liverpool
Hung	Judy	Imperial College London
Ikenweiwe	Nafisat	Federal University of Agric.Abeokuta, Nigeria

Ingram	James	Imperial College London
Jackson	Laura	Met Office
Jacobs	Christian	Imperial College London
Joedan	Jim	Imperial College London / British Antarctic Survey
Johari	Mohd Aidy Faizal	Imperial College London
Johnson	Helen	University of Oxford
Karabasov	Sergey	University of Cambridge Department of Engineering
Keskin	Umit	Imperial College London
Kimura	Satoshi	Imperial College London
Klockmann	Marlene	University of Hamburg
Kramer	Stephan	Imperial College London
Kuhlbrodt	Till	NCAS-Climate, University of Reading
Kuklinski	Piotr	Institute of Oceanology PAS
Lim	Julien	Imperial College London
Maddison	James	University of Oxford
McIntyre	Michael	University of Cambridge
McIntyre	Michael	University of Cambridge
McVicar	Alistair	Imperial College London
Mecseki	Katalin	Imperial College London
Medhaug	Iselin	University of Bergen and Bjerkens Centre for Climate Research
Meijers	Andrew	British Antarctic Survey
Messori	Gabriele	Imperial College London
Morris	Rupert	n/a
Mouradian	Simon	Imperial College London
Mueller	Simon	University of Southampton
Munday	David	University of Oxford
Newinger	Christina	Imperial College London
Nurser	George	National Oceanographic Centre, Liverpool
O'Reilly	Christopher	Imperial College London
Pearson	David	Met Office Hadley Centre
Petto	Kelti	Imperial College London
Petto	Kelti	Imperial College London
Petty	Alek	UCL
Piggott	Matthew	Imperial College London
Piotrowski	Alex	University of Cambridge
Prentice	Katy	Imperial College London
Prince	Justin	Imperial College London
Rathgeber	Florian	Imperial College London
Roberts	Chris	Met Office Hadley Centre
Rye	Craig	National Oceanographic Centre, Liverpool
Sallée	Jean-Baptiste	British Antarctic Survey
Septham	Kamthon	Imperial College London
Sheldon	Luke	Imperial College London
Smith	Doug	Met Office
Srokosz	Meric	National Oceanographic Centre, Liverpool
Stevens	David	University of East Anglia
Tailleux	Remi	University of Reading
Tamura-Wicks	Helen	Imperial College London
Taylor	John	University of Cambridge
Teixeira	Rita	Imperial College London
Torri	Giuseppe	Imperial College London
Toumi	Ralf	Imperial College London

Tull	James	Imperial College London
Tymms	Vijay	Imperial College London
van De Flierdt	Tina	Imperial College London
Vire	Axelle	Imperial College London
Visram	Abeed	Imperial College London
Waeschenbach	Andrea	Natural History Museum
Watteaux	Romain	DAMTP-Cambridge University
Wei	Zhen	Imperial College London
White	Rachel	Imperial College London
Wilkinson	Laurie	UCL
Williams	Ric	Liverpool University
Williams	Paul	University of Reading
Willis	Gary	Imperial College London
Wilson	Chris	National Oceanography Centre, Liverpool
Wong	Benjamin	Imperial College London
Wunsch	Carl	University of Oxford
Zanacchi	Marcus	National Oceanographic Centre, Liverpool
Zhang	Fan	Imperial College London
Zheng	Yaxin	Imperial College London
Zika	Jan	University of Southampton

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