Workshop Conservation Principles, Data and Uncertainty in Atmosphere-Ocean Modelling

April 2-4, 2019
Universität Potsdam, Campus Griebnitzsee

Organized by

CRC 1114

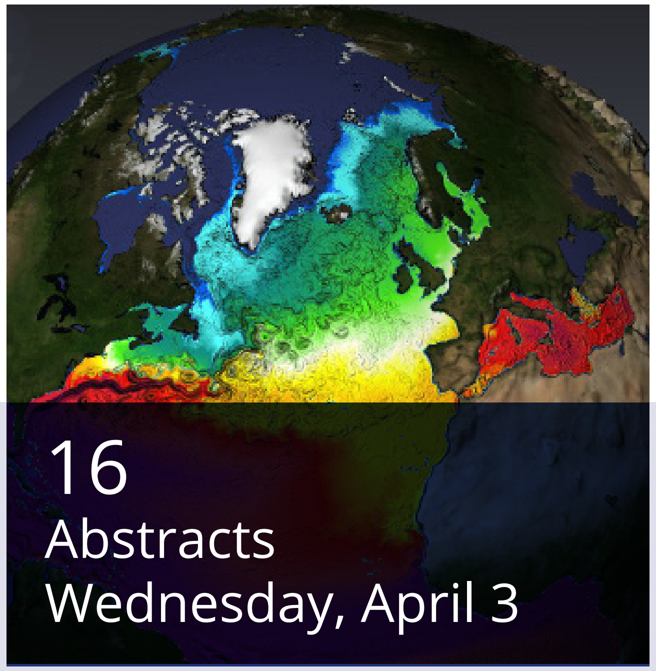
SFB 1294 Data Assimilation

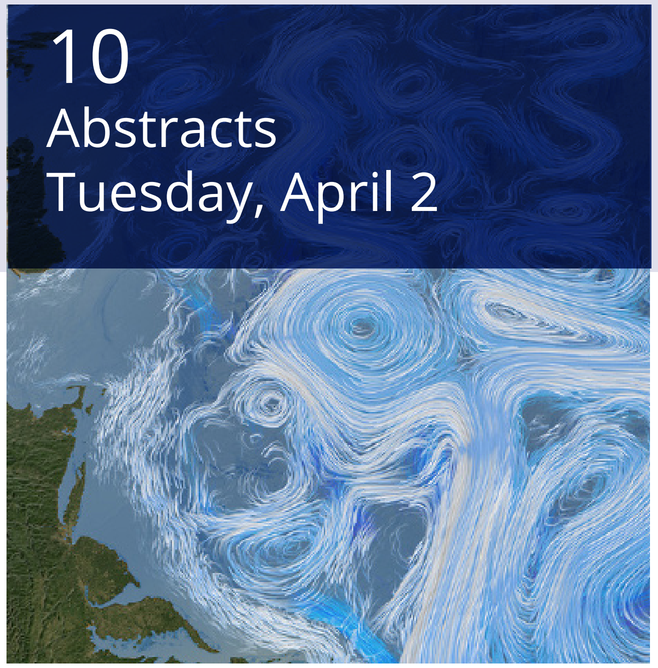
TRR181

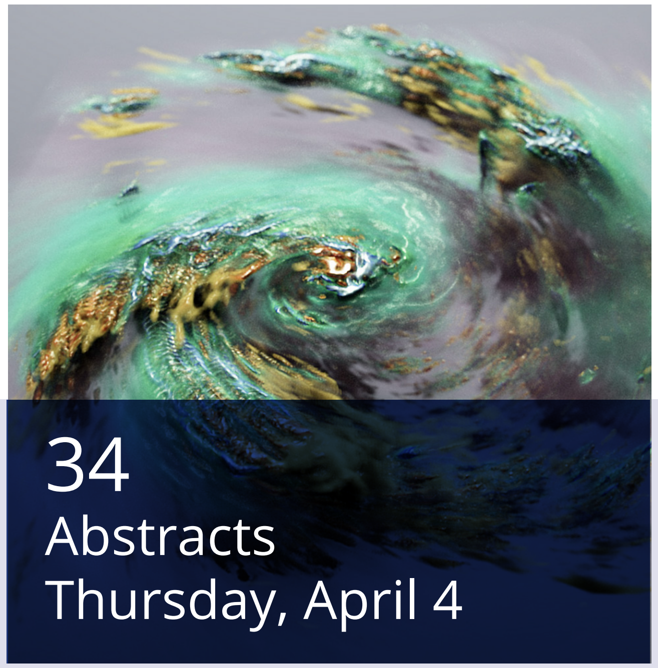
Funded by

DFG Deutsche Forschungsgemeinschaft

Content







Welcome

… to our workshop in Potsdam on

„Conservation Principles, Data, and Uncertainty in Atmosphere-Ocean Modelling“!

Developing complex climate and weather prediction models demand fundamental research in natural sciences. For example, understanding energy budgets and transfers in the climate system is a crucial challenge in order to evaluate the impact of human emissions in a changing climate.

Current models, however, show large biases in energy budgets which is reflected by a missing understanding of energy transfers between different dynamical regimes such as fast and slow modes, turbulence and mean flow. Increasingly complex weather and climate models require advanced tools for uncertainty quantification and, in combination with highly heterogeneous data sets, data assimilation. These are needed to calibrate and validate models as well as to quantify uncertainties in model-based predictions.

Furthermore, stochastic parameterizations are an emergent approach in weather and climate predictions. With their help model uncertainties are represented and subgrid-scale processes are parameterized. While stochastic schemes improve predictive skill and reduce many model biases, their implementation is still rather ad hoc and energetic consistency is rarely assessed.

This three-day workshop combines the expertise from three Collaborative Research Centers (SFB 1114, SFB 1294 and TRR 181) funded by the German Research Foundation (DFG) to assess our state of knowledge on energy budgets and energy transfers in the climate system and how they are represented in current computational models. The physical principles of these transfers and their numerical representation will be discussed. In addition, stochastic modelling and data assimilation schemes will receive particular attention in this context, as these are key to representing and controlling model uncertainties.

Program

Tuesday, April 2

Time	Title	Speaker
08:45	Welcoming	
SESSION 1: OBSERVATIONS AND RECONSTRUCTIONS		
09:00	Observing Earth's Energy Imbalance	Till Kuhlbrodt (Invited speaker)
09:40	Using Lagrangian transit time distributions to investigate eddy effects on carbon and heat uptake in the ocean	Manita Chouksey
10:00	Improved estimates of the coupled Arctic energy budget	Steffen Tietsche
10:20	Inverse modelling of the Earth's energy and water budgets using EO satellite and reanalysis data	Keith Haines
10:40	Coffee break	
SESSION 2: MODELS AND REANALYSES		
11:20	Earth's energy balance in global climate models	Doris Folini (Invited speaker)
12:00	Lunch break	
13:30	Principles of energy consistent atmospheric modelling	Almut Gassmann
13:50	Energy cascades in extreme convective events simulated by storm-resolving ICON-LEM and ICON-NWP models	Nikki Vercauteren
14:10	Oceanic overturning and heat transport: The role of background diffusivity	Jonas Nycander
14:30	Coffee break	
SESSION 3: DYNAMICAL PROCESSES		
15:10	On the linkage between atmospheric circulation and Arctic weather and climate	Rune Graversen (Invited speaker)
15:50	The role of synoptic and planetary scale interaction for the linkage between Arctic sea ice changes and mid-latitude atmospheric circulation	Dörthe Handorf
16:10	Stimulated Imbalance and the Enhancement of Eddy Kinetic Energy Dissipation by Internal Waves	Roy Barkan
16:30	Monsoon Response to Mid-Holocene Orbital Forcing and Greenhouse Gas-Induced Global Warming and its link with Net Energy Input in the Atmosphere	Roberta D'Agostino
Evening program		
16:50 - 18:00	Stand-up reception	

Wednesday, April 3

Time	Title	Speaker
SESSION 4: DA-APPROACHES SIDE-BY-SIDE		
09:00	Stabilizing unstable flows by coarse spatial scale observables and actuators - a pavement to data assimilation	Edriss Titi (Invited speaker)
09:40	Downscaling data assimilation techniques applied to low Froude number shallow water flows	Stefan Vater
10:00	Algorithms for non-linear filtering and smoothing problems	Sahani Patheraja
10:20	On the geometry of Stein variational gradient descent	Nikolas Nüsken
10:40	Coffee break	
SESSION 5: FLOW CONTROL: APPROACHES, ANALYSIS, APPLICATIONS		
11:20	Nonlinear Filtering and Particle Filters for high-dimensional Systems	Roland Potthast (Invited speaker)
12:00	Lunch break	
13:30	Assimilation of satellite sea surface temperature and profile observations into a coupled ocean-atmosphere model	Qi Tang
13:50	Coupled Data Assimilation and Ensemble Initialization with Application to Multiyear ENSO Prediction	Terence O'Kane
14:10	Reanalysis of radiation belt electron phase space density using four spacecraft and the VERB code	Sebastian Cervantes
14:30	Coffee break	
SESSION 6: DA AND UNCERTAINTY		
15:10	On the Development of an Ensemble Data Assimilation and Forecasting System for the Red Sea	Ibrahim Hoteit (Invited speaker)
15:50	Data assimilation for a quasi-geostrophic model with circulation-preserving stochastic transport noise	Igor Shevchenko
16:10	State and parameter estimation from observed signal increments	Paul Rozdeba
16:30	Parameter Estimation in Size-Structured Aerosol Populations using Bayesian State Estimation	Matthew Ozon
Evening program		
16:50 - 18:00	Poster session	

Thursday, April 4

Time	Title	Speaker
SESSION 7: STOCHASTIC REPRESENTATION OF MOIST PROCESSES		
09:00	Stochastic parameterisation of cumulus convection	Pier Siebesma (Invited speaker)
09:40	Constraining Stochastic Parametrisation Schemes using High-Resolution Model Simulations	Hannah Christensen
10:00	Uncertainty quantification for cloud simulation	Bettina Wiebe
10:20	Finite-time breakdown of chemical precipitation patterns	Marcel Oliver
10:40	Coffee break	
SESSION 8: STOCHASTIC TRANSPORT IN THE OCEANS		
11:20	A consistent framework for stochastic representation of large-scale geophysical flows	Etienne Mémin (Invited speaker)
12:00	Lunch break	
13:30	Stochastic modeling of oceanic dynamics for ensemble forecasting	Long Li
13:50	Data-driven augmentation of a low-resolution double-gyre flow	Eugene Ryzhov
14:10	On fluctuating air-sea-interaction in local models: linear theory	Achim Wirth
14:30	Coffee break	
SESSION 9: STOCHASTICS, ENERGETICS, THERMODYNAMICS, AND UNCERTAINTY		
15:10	Stochastic parameterization by transport	Darryl Holm (Invited speaker)
15:50	New derivation of Euler-α equations as a mean flow model for the motion of ideal fluid: stochastic approach	Sergiy Vasylkevych
16:10	Dynamics under location uncertainty and other energy-related stochastic subgrid schemes	Valentin Resseguir
16:30	Numerical development and evaluation of an energy conserving conceptual stochastic climate model	Federica Gugole

Tuesday April 2 - Abstracts

OBSERVING EARTH'S ENERGY IMBALANCE

Till Kuhlbrodt[1] - Invited Speaker

[1] NCAS, University of Reading

Human-induced atmospheric composition changes cause a radiative imbalance at the top of the atmosphere. This radiative imbalance, called Earth's Energy Imbalance (EEI), is driving global warming. It is a fundamental metric of climate change. Using in situ and remote sensing observations, EEI is estimated from changes in ocean, land and atmospheric heat storage, net radiation at the top of the atmosphere, and heat used for melting ice. The EEI at the top of the atmosphere can be inferred directly from satellite observations, but these observations need calibration from independent measurements. Because about 93% of the additional heat in the climate system are stored in the ocean, observations of ocean heat uptake play an important role. This talk will give an overview of the state of the art in determining EEI for the past forty years.

USING LAGRANGIAN TRANSIT TIME DISTRIBUTIONS TO INVESTIGATE EDDY EFFECTS ON CARBON AND HEAT UPTAKE IN THE OCEAN

Manita Chouksey[1], Alexa Griesel[1] and Carsten Eden[1]

[1] Universität Hamburg

The ocean transports heat, salt, and also other tracers across huge distances by the mean flow advection, along-isopycnal eddy mixing, and across-isopycnal small-scale mixing. Of particular importance is the anthropogenic Carbon which is taken up and stored on long time scales by these interior oceanic transports, which helps to reduce the greenhouse gas climate forcing. The distribution of such time scales at a single location is called the Transient Time Distribution (TTD) and is observed to reach decades at mid-depth to centuries in the deep ocean.

The accuracy of such TTD estimates and in particular the role of the isopycnal eddy mixing in the process, however, remains poorly understood. We aim to estimate the TTDs from tracer distributions, such as CFCs, and from Lagrangian particle trajectories in a high-resolution eddying model and compare it to observations. This will aid in assessing the storage potential and possible changes in intermediate, deep, and bottom water masses of the global ocean, in particular the Southern Ocean, and the effect on the oceanic anthropogenic Carbon uptake.

IMPROVED ESTIMATES OF THE COUPLED ARCTIC ENERGY BUDGET

Michael Mayer[1,2], Steffen Tietsche[1], Takamasa Tsubouchi[3], Leo Haimberger[2] and Joannes Mayer[2]

[1] European Centre for Medium-Range Weather Forecasts, [2] Department of Meteorology and Geophysics, University of Vienna, [3] Geophysical Institute, University of Bergen

The long-term average and mean annual cycle of the coupled atmosphere-ocean-sea-ice energy budget of the Arctic are of great scientific interest, but data paucity has hampered comprehensive quantitative assessments in the past. Here, we present an improved estimate of the Arctic energy budget, drawing on novel observational products like mooring-derived ocean heat transports through all Arctic gateways (ARCGATE), as well as the latest generation of atmospheric and oceanic reanalyses like ERA5 and ORAS5. We find that the long-term accumulation of energy fluxes into the Arctic is generally too small to balance the storage rate from the ocean reanalyses, but the discrepancy is relatively small at around 1 Wm^{-2}. Simulating the energy budget of the Arctic seasonal cycle remains challenging: residuals of monthly budget terms are of the order of 7 Wm^{-2}. Still, residuals and uncertainties in our analysis have improved upon previous estimates by at least a factor of two. While our results broadly confirm earlier estimates of atmospheric energy transports and top-of-the atmosphere radiation, they show that earlier estimates were wide off the mark for ocean heat transports and the seasonal cycle of heat storage in the Arctic ocean and sea ice. These results higlight recent advances in observing and modelling the Arctic ocean. However, it also implies that it is essential to maintain and expand the observational network in the region, in order to make progress in understanding and modelling the Arctic as a rapidly changing part of the
climate system.

INVERSE MODELLING OF THE EARTH'S ENERGY AND WATER BUDGETS USING EO SATELLITE AND REANALYSIS DATA

Keith Haines[1]

[1] University of Reading

We present an inverse analysis of the global energy and water budgets, extending the range of solutions based on the NASA NEWS studies of L'Ecuyer et al. (2015) and Rodell et al. (2015).

We have introduced two innovations in our study. The original NEWS analysis does not use prior estimates for energy exchange between regions. We use both atmospheric and oceanic reanalyses to introduce weak constraints on the inter-regional exchange fluxes for heat and freshwater within the inverse analysis. We show in particular that this can greatly improve the flux estimates over the N Atlantic and Arctic where strong ocean heat transport is known to be important. Over the Arctic the ocean transports are more tightly constrained than the atmospheric transports and therefore provide much more useful constraints. We contrast the surface fluxes with those obtained using atmospheric reanalyses and Top of Atmosphere energy fluxes alone following the methods of Trenberth and Caron (2002) and Allan et al (2015).

Horizontal transports do not alter the global solutions for the flux components (eg. radiative v turbulent fluxes). However we have also introduced non-diagonal spatial error covariances for individual EO flux products (especially ocean turbulent fluxes) and inter-component error covariances (eg. between upward and downward shortwave flux) within the NEWS solution. These changes are based on analysis of multiple flux products and assessment of radiative fluxes from CERES against the BSRN network. We show that even weak spatial error covariances strongly affect the inverse solutions and that solutions can be found which closely match those obtained with horizontal transport constraints.

The analyses have so far focussed on time mean, and mean seasonal cycles of fluxes, however work is ongoing to develop optimised solutions to include full interannual variability with uncertainties from the EO data, which could be used as evaluation targets for climate models.

EARTH'S ENERGY BALANCE IN GLOBAL CLIMATE MODELS

Doris Folini[1] - Invited Speaker

[1] ETH Zürich

The Sun's shortwave radiation constitutes the main energy input into Earth's climate system. The latter may be seen as a highly complex and interactive composite of numerous physical, chemical, and biological processes that not only thrive on this energy input but also modulate it, govern its system-internal partitioning, and regulate its re-emission via thermal radiation. Global Climate Models (GCMs) or Earth System Models (ESMs) attempt to capture this multifaceted system. Compared with the scales on which many relevant processes take place, associated computational grids are coarse, with typical grid box sizes on the order of tens to hundreds of kilometers. Consequently, to incorporate relevant sub-grid scale processes into a GCM or ESM, a range of different parameterizations are required that typically come with free parameters. ‚Model tuning', a compelling step in the development of any GCM or ESM, refers to the process of adjusting at least some of these free parameters such that the different parameterizations work well in concert and the model produces a ‚reasonably realistic' climate. A central aspect of the latter is a reasonable global energy balance.

In this talk I will give an overview on how different models, especially from CMIP5, perform with regard to different energy balance aspects and I will elaborate on the role of model tuning.

PRINCIPLES OF ENERGY CONSISTENT ATMOSPHERIC MODELLING

Almut Gassmann[1]

[1] Leibniz Institute for Atmospheric Physics

This talk gives and overview on modelling principles. It describes how energy conserving schemes for the reversible dynamics can be constructed via discretizing Poisson brackets. With regard to the irreversible processes, energy conservation and the second law of thermodynamics must be considered. Therefore, the tasks for a modeller are

- setting up the discrete version of the Poisson brackets in line with the envisioned numerical procedure (finite volume or finite elements etc.)
- providing an algebraic environment for the subgrid-scale fluxes such that only positive coefficients for the down-gradient fluxes can be found by the art of tuning

Some examples will be given where models were found to be error-prone with respect to conservation principles or the requirements by the second law of thermodynamics. For the atmosphere, the phase transitions are dominating energy exchanges. Therefore, care must be taken when approximating terms which are related to latent heating. This will be recapitulated with an example where the COSMO model was found to be inconsistent some years ago. Turbulence modelling in a dry atmosphere is sometimes problematic with regard to the conformance with the 2nd law of thermodynamics. Here, the turbulent heat flux at stable stratification is highlighted as a possible problematic parameterization.

ENERGY CASCADES IN EXTREME CONVECTIVE EVENTS SIMULATED BY STORM-RESOLVING ICON-LEM AND ICON-NWP MODELS

Davide Faranda[1,2], Valerio Lembo[3], Guido Cioni[4], Daisuke Sakurai[5], Francois Daviaud[6], Berengere Dubrulle[6] and Nikki Vercauteren[7]

[1] Laboratoire des Sciences du Climat et de l'Environnement, Université Paris-Saclay, [2] London Mathematical Laboratory, [3] Universität Hamburg, [4] Max Planck Institute for Meteorology, [5] Zuse Institute Berlin, [6] SPEC, CEA, CNRS, Université Paris-Saclay, [7] Freie Universität Berlin

The prediction of weather events leading to extreme convective precipitation and intense winds such as mesocyclones, Mediterranean Tropical-like Cyclones (MTLCs) or hurricanes is subject to parameterizations that largely impact their representation in NWP (Numerical Weather Prediction) models. Their dynamics is partly driven by energy exchange processes that happen at a multitude of scales. In moist convection, energy is injected at small scales by latent heat release, then transferred to clouds which aggregate on larger scale systems. The representation of the direct and inverse energy cascade is therefore crucial to correctly forecast the lifetime, trajectory and broader dynamics of extreme convective phenomena.

Storm-resolving simulations enable to study the energy exchange processes across the scale hierarchy. We apply a recently developed method relying on the analysis of the local and instantaneous energy balance. Applying a filter to the energy balance equation enables to quantify the amount of energy cascading through a given scale. We analyze a set of simulations of mesocyclones, MTLC and hurricanes simulated using the storm-resolving ICON-NWP or ICON-LEM (Large-Eddy Model) and present results for different filter scales and different resolutions of the simulations. In the mature phase, a stable dipole structure is present around the cyclone core, corresponding to a statistical equilibrium between direct and inverse cascades of energy. We use our method to explore the role of energy exchanges in modifying the dynamics of the cyclones when coarsening the resolution of the simulations.

OCEANIC OVERTURNING AND HEAT TRANSPORT: THE ROLE OF BACKGROUND DIFFUSIVITY

Magnus Hieronymus[1], Jonas Nycander[2], Joan Nilsson[2], Kristofer Döös[2] and Robert Hallberg[3]

[1] Swedish Meteorological and Hydrological Institute, [2] Stockholm University, [3] NOAA, Geophysical Fluid Dynamics Laboratory

The role of oceanic background diapycnal diffusion for the equilibrium climate state is investigated in the global coupled climate model CM2G. Special emphasis is put on the oceanic meridional overturning and heat transport. Six runs with the model, differing only by their value of the background diffusivity, are run to steady state and the statistically steady integrations are compared. The diffusivity changes have large-scale impacts on many aspects of the climate system. Two examples are the volume-mean potential temperature, which increases by 3.68°C between the least and most diffusive runs, and the Antarctic sea ice extent, which decreases rapidly as the diffusivity increases. The scaling of the overturning circulation with diffusivity is found to agree rather well with classical theoretical results for the upper overturning cell, but not for the lower one. An alternative empirical scaling with the mixing energy is found to give good results for both cells. The oceanic meridional heat transport increases strongly with the diffusivity, an increase that can only partly be explained by increases in the meridional overturning. The increasing poleward oceanic heat transport is accompanied by a decrease in its atmospheric counterpart, which keeps the increase in the planetary energy transport small compared to that in the
ocean.

ON THE LINKAGE BETWEEN ATMOSPHERIC CIRCULATION AND ARCTIC WEATHER AND CLIMATE

Rune Graversen[1] - Invited Speaker, Peter Langen[2] and M. Burtu[3]

[1] University of Tromsø, [2] Danish Meteorological Institute, [3] University of Stockholm

The atmospheric northward energy transport plays a crucial role for the Arctic climate; this transport brings to the Arctic an amount of energy comparable to that provided directly by the sun. In response to a forcing the local energy balance will change which may alter the energy transport, and the change of the transport may affect the climate response in a feedback loop. Hereby the meridional energy transport impacts for instance Arctic temperature amplification. In order to study the effect of the energy-transport change on Arctic climate, climate-model experiments are conducted: First the changes of the atmospheric energy transport due to a forcing from a doubling of the atmospheric CO2 content are computed. Then these transport changes are implemented as a forcing in a per-industrial climate. The results show that the energy-transport change due to a forcing plays a significant role in Arctic temperature amplification.

The meridional energy transport is mostly accomplished by atmospheric waves, for instance largescale planetary waves and synoptic-scale cyclones. These components of the energy transport impact the Arctic climate differently. A split of the transport into stationary and transient waves constitutes a traditional way of decomposing the transport. However this procedure does not take into account the transport accomplished separately by the planetary and synoptic-scale waves. Here a Fourier decomposition is applied, which decomposes the transport with respect to zonal wave numbers. Reanalysis and model data reveal that the planetary waves stand for by far the largest part of the atmospheric energy transport into the Arctic. Moreover planetary waves affect the Arctic temperatures much more than do synoptic-scale waves.

This presentation concerns the split of the meridional energy transport into zonal wave numbers. It also considers climate model experiments where the effect of the meridional energy-transport change due to a forcing is investigated.

THE ROLE OF SYNOPTIC AND PLANETARY SCALE INTERACTION FOR THE LINKAGE BETWEEN ARCTIC SEA ICE CHANGES AND MID-LATITUDE ATMOSPHERIC CIRCULATION

Dörthe Handorf[1], Ralf Kaiser[1], Klaus Dethloff[1], Tetsu Nakamura[2] and Jinro Ukita[3]

[1] Alfred Wegener Institute, Helmholtz Center for Polar- and Marine Research, Research Unit Potsdam, [2] Hokkaido University, [3] Niigata University

Observed global warming trends have their maximum in Arctic regions, a phenomenon referred to as Arctic Amplification. Consequently, Arctic sea ice shows a strong decreasing trend. These changes imprint modifications on atmospheric flow patterns not only in Arctic regions themselves. Changes of teleconnections and planetary scale waves (Rossby wave trains) affect mid-latitude climate as well. So far, most evidence has been found for a mechanism explaining how Arctic Amplification can lead to a negative Arctic Oscillation response via a stratospheric pathway.

Here we study the impact of sea-ice changes on changes in atmospheric synoptic and planetary waves and their interaction. Therefore, we analyse the atmospheric kinetic energy and enstrophy spectra based on ERA-Interim reanalysis data. Special emphasis has been put on synoptic and planetary scale interactions and subsequent changes in the planetary wave trains by examining the nonlinear kinetic energy and enstrophy interaction and subsequent redistribution of kinetic energy and enstrophy.

The results based on ERA-Interim reanalysis data do not allow to entirely dismiss other potential forcing factors leading to observed changes in the energy and enstrophy spectra. More importantly, properly designed Atmospheric General Circulation Model (AGCM) experiments with AFES (Atmosperic GCM for the Earth Simulator) are able to reproduce observed atmospheric circulation changes if only observed sea ice changes in the Arctic are prescribed. This includes the potential mechanism explaining how Arctic Amplification can lead to a negative Arctic Oscillation. The comparison of the analyses of the reanalysis data and the data of the model sensitivity experiments allow for an assessment of the impact of Arctic sea ice changes on changes in the nonlinear kinetic energy and enstrophy cascades.

STIMULATED IMBALANCE AND THE ENHANCEMENT OF EDDY KINETIC ENERGY DISSIPATION BY INTERNAL WAVES

Roy Barkan[1,2]

[1] Porter School of Environmental and Earth Sciences, [2] University of California

The effects of internal waves (IWs), externally forced by high-frequency wind, on energy pathways are studied in submesoscale-resolving numerical simulations of an idealized wind-driven channel flow. Two processes are examined: the direct extraction of mesoscale energy by externally forced IWs followed by an IW forward energy cascade to dissipation and stimulated imbalance, a mechanism through which externally forced IWs trigger a forward mesoscale to submesoscale energy cascade to dissipation. This study finds that the frequency and wavenumber spectral slopes are shallower in solutions with high-frequency forcing compared to solutions without and that the volume-averaged interior kinetic energy dissipation rate increases tenfold. The ratio between the enhanced dissipation rate and the added high-frequency wind work is 1.3, demonstrating the significance of the IW-mediated forward cascades. Temporal-scale analysis of energy exchanges between low- (mesoscale), intermediate- (submesoscale), and high-frequency (IW) bands shows a corresponding increase in kinetic energy E_k and available potential energy APE transfers from mesoscales to submesoscales (stimulated imbalance) and mesoscales to IWs (direct extraction). Two direct extraction routes are identied: a mesoscale to IW E_k transfer and a mesoscale to IW APE transfer followed by an IW APE to IW E_k conversion. Spatial-scale analysis of eddy-IW interaction in solutions with high-frequency forcing shows an equivalent increase in forward E_k and APE transfers inside both anticyclones and cyclones.

MONSOON RESPONSE TO MID-HOLOCENE ORBITAL FORCING AND GREENHOUSE GAS-INDUCED GLOBAL WARMING AND ITS LINK WITH NET ENERGY INPUT IN THE ATMOSPHERE

Roberta D'Agostino[1], Jürgen Bader[1,2], Simona Bordoni[3], David Ferreira[4] and Johann Jungclaus[1]

[1] Max Planck Institute for Meteorology, [2] Uni Research and the Bjerknes Centre for Climate Research, [3] California Institute for Technology, [4] University of Reading

Precipitation and circulation patterns of Northern Hemisphere monsoons are investigated in Coupled Model Intercomparison Project phase 5 simulations for mid-Holocene and future climate scenario rcp8.5. Although both climates exhibit Northern Hemisphere warming and enhanced interhemispheric thermal contrast in boreal summer, changes in the spatial extent and rainfall intensity in future climate are smaller than in mid-Holocene for all Northern Hemisphere monsoons except the Indian monsoon. A decomposition of the moisture budget in thermodynamic and dynamic contributions suggests that under future global warming, the weaker response of the African, Indian, and North American monsoons results from a compensation between both components. The dynamic component, primarily constrained by changes in net energy input over land, determines instead most of the mid-Holocene land monsoonal rainfall response.

Wednesday April 3 - Abstracts

STABILIZING UNSTABLE FLOWS BY COARSE SPATIAL SCALE OBSERVABLES AND ACTUATORS - A PAVEMENT TO DATA ASSIMILATION

Edriss Titi[1] - Invited Speaker

[1] University of Cambridge, Texas A&M University and Weizmann Institute of Science

One of the main characteristics of infinite-dimensional dissipative evolution equations, such as the Navier-Stokes equations and reaction-diffusion systems, is that their long-time dynamics are determined by finitely many parameters - finite number of determining modes, nodes, volume elements and other determining interpolants. In this talk I will show how to explore this finite-dimensional feature, of the long-time behavior of infinite-dimensional dissipative systems, to design finite-dimensional feedback control for stabilizing their solutions. Moreover, based on this approach I will also present a data assimilation (downscaling) algorithm for weather and climate predictions employing discrete coarse spatial scale measurements. Notably, numerical implementation of this algorithm yields errors that are bounded uniformly in time; consequently it can be reliably used for long-time integration and statistics. Finally, computational demonstrations implementing this algorithm will exhibit that its performance remarkably exceeds what is suggested by the theory.

DOWNSCALING DATA ASSIMILATION TECHNIQUES APPLIED TO LOW FROUDE NUMBER SHALLOW WATER FLOWS

Stefan Vater[1] , Edriss Titi[2] and Rupert Klein[1]

[1] Freie Universität Berlin, [2] University of Cambridge, Texas A&M University and Weizmann Institute of Science

In recent years, Titi and coworkers have presented theoretical results for special classes of downscaling data assimilation techniques applied to dissipative dynamical systems, in particular the incompressible Navier-Stokes equations. Under certain conditions, these algorithms can be shown to converge exponentially in time. Here we aim to assess these algorithms for practical situations. In a first step, the data assimilation is combined with a finite volume projection method applied to the zero Froude number shallow water equations (lake equations) with dissipation. The downscaling algorithms are either based on spatial nudging or on the classical technique of inserting new observational data directly into the discrete solution. We relate the numerical results to theory. Further, we investigate how the results hold for shallow water flows with small, but non-zero Froude numbers, which corresponds to the weakly-compressible Navier-Stoles equations.

ALGORITHMS FOR NON-LINEAR FILTERING AND SMOOTHING PROBLEMS

Jana de Wiljes[1], Sahani Pathiraja[1] and Sebastian Reich[1]

[1] Universität Potsdam

In many application areas there is a need to improve real-time predictions of the state of a dynamical system using partial observations that arrive sequentially in time. Such estimation problems are typically approached with so called filtering algorithms. It is also often required to using existing data sets to improve state estimates, known as performing a reanalysis or smoothing.

Filtering is particularly challenging in the context of non-linear evolution models with an extended state space. Smoothing can be viewed as a form of filtering where the state vector is time-augmented, thereby increasing the dimension of the estimation problem. Here we will present a series of tools for a class of different smoothers algorithms and explore techniques such as localisation (in time and space), hybrid formulations combining complementary smoothers and adaptive spread corrections that can be used to address the difficulties that arise in a high dimensional non-linear problem setting.

ON THE GEOMETRY OF STEIN VARIATIONAL GRADIENT DESCENT

Nikolas Nüsken[1]

[1] Universität Potsdam

Uncertainty quantication as well as sequential data assimilation requires sampling or approximating high-dimensional probability distributions. The focus of this talk is on the recently introduced Stein variational gradient descent methodology, a class of algorithms that rely on iterated steepest descent steps with respect to a reproducing kernel Hilbert space norm. This construction leads to interacting particle systems, the mean-eld limit of which is a gradient flow on the space of probability distributions equipped with a certain geometrical structure. We leverage this viewpoint to shed some light on the convergence properties of the algorithm, in particular addressing the problem of choosing a suitable positive denite kernel function.

NONLINEAR FILTERING AND PARTICLE FILTERS FOR HIGH-DIMENSIONAL SYSTEMS

Roland Potthast[1] - Invited Speaker
[1] Deutscher Wetterdienst

We discuss the development of non-linear filtering methods for very high-dimensional systems, in particular those operational for Numerical Weather Prediction. We show results for a Localized Adaptive Particle Filter (LAPF) for the global ICON model and for the convective-scale NWP model COSMO.

Non-linear filtering is developed in the framework of the operational ICON global+mesoscale model (two-way nested), 13km/6.5km resolution, with its hybrid ensemble variational data (assimilation (LETKF + EnVAR) run on a 3h cycle, and the ensemble prediction system ICON EPS.

This system drives the high-resolution ensemble data assimilation system COSMO-KENDA (Kilometer Scale Ensemble Data Assimilation) with 2.2km operational resolution at DWD and up to 1km resolu-tion at further members of the COSMO consortium (Germany, Switzerland, Italy, Russia, Poland, Ro-mania, Greece and Israel) to provide initial conditions for the high-resolution ensemble forecasting systems, e.g. the operational COSMO-D2-EPS or experimental ICON-LAM EPS. The system is also suc-cessfully run on GPU based supercomputers.

We show results on the tests of localized adaptive particle filter (LAPF) and several variants based on a Gaussian-Mixture approximation step for the prior (LMCPF), which are being tested for the global model setup, currently in the standard experimental global resolution of 40km, as well as the opera-tional resolution with and without European nest. We discuss how to overcome filter collapse or divergence by adaptive rejuvenation, mapping into ensemble space based on spread estimators. We also discuss how to keep balances intact when drawing from probability distributions in combination with localization. Here, we also employ incremental analysis update (IAU) for the ICON model sys-tem. Different further versions of particle-filters and hybrid ensemble-particle filters are under test both for ICON on the global scale as well as for COSMO or ICON-LAM on the convective scale in col-laboration with colleagues from ETH, Reading and Potsdam.

Finally, we have tested the above filters on the convective scale, and they are functional within the operational framework with a quality comparable to that of the LETKF.

ASSIMILATION OF SATELLITE SEA SURFACE TEMPERATURE AND PROFILE OBSERVATIONS INTO A COUPLED OCEAN-ATMOSPHERE MODEL

Qi Tang[1], Dmitry Sidorenko[1] and Lars Nerger[1]
[1] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research

Earth system models simulate different compartments like the ocean, atmosphere, or land surface in one coupled model framework like the AWI climate model AWI-CM. Data assimilation (DA) for such complex models is young and challenging. In this study, the parallel data assimilation framework (PDAF) is coupled with AWI-CM, which includes the ocean model FESOM and the atmospheric model ECHAM. A global domain with a varying horizontal resolution of 20km to 120km is used for FESOM and a resolution of 180km is for ECHAM. In this system, global satellite sea surface temperature (SST) and temperature and salinity profiles can be used for assimilation into the ocean, which is the so called 'weakly coupled DA'. The satellite SST observations used in this study are the Copernicus Level-3 product and were collected daily from multiple sensors covering almost the complete globe (80°N – 80°S) with a resolution of 0.1 degrees. The temperature and salinity profiles are from the EN4 data set from the UK MetOffice. They can reach down to a depth of 5000m and the average number of profiles is about 1000 per day. The ocean states are updated daily for the year 2016. The local Error-Subspace Transform Kalman Filter (LESTKF) is used for DA. Different simulation scenarios are carried out with different types of observations to investigate to which extent the DA leads to a better estimation of the ocean states in the coupled ocean-atmosphere model. The ocean water temperature error is reduced globally by up to 50% after 30 days for SST assimilation. The assimilation of either temperature or salinity observations, or the combined assimilation of both were tested for the same year using the same model configuration.

COUPLED DATA ASSIMILATION AND ENSEMBLE INITIALIZATION WITH APPLICATION TO MULTIYEAR ENSO PREDICTION

Terence O'Kane[1], Paul Sandery[1], Didier Monselesan[1], Pavel Sakov[2], Matthew Chamberlain[1], Richard Matear[1], Dougal Squire[1] and Lauren Stevens[1]
[1] CSIRO Oceans and Atmosphere, [2] Bureau of Meteorology, Docklands, Melbourne

We develop and compare variants of coupled data assimilation (DA) systems based on ensemble optimal interpolation (EnOI) and ensemble transform Kalman filter (ETKF) methods. The assimilation system is first tested on a small paradigm model of the coupled tropical–extratropical climate system, then implemented for a coupled general circulation model (GCM). Strongly coupled DA was employed specifically to assess the impact of assimilating ocean observations [sea surface temperature (SST), sea surface height (SSH), and sea surface salinity (SSS), Argo, XBT, CTD, moorings] on the atmospheric state analysis update via the cross-domain error covariances from the coupled-model background ensemble. Using the combined DA-EPS system, termed the Climate Analysis Forecast Ensemble (CAFÉ), we further examine the relationship between ensemble spread, analysis increments, and forecast skill in multiyear ENSO prediction experiments with a particular focus on the atmospheric response to tropical ocean perturbations. Initial forecast perturbations generated from bred vectors (BVs) project onto disturbances at and below the thermocline with similar structures to ETKF perturbations. BV error growth leads ENSO SST phasing by 6 months whereupon the dominant mechanism communicating tropical ocean variability to the extratropical atmosphere is via tropical convection modulating the Hadley circulation. We find that bred vectors specific to tropical Pacific thermocline variability were the most effective choices for ensemble initialization and ENSO forecasting. Multiyear ENSO forecasts from the system are then compared with those from operational systems comprising the North American Multi-Model Ensemble (NMME). Using CAFÉ we demonstrate improved skill in predicting ENSO at lead times longer than 6 months relative to the respective NMME models. Our results indicate that for multiscale systems there is utility in augmenting existing forecast systems with initial disturbances specific to particular climate teleconnections at targeted lead times.

REANALYSIS OF RADIATION BELT ELECTRON PHASE SPACE DENSITY USING FOUR SPACECRAFT AND THE VERB CODE

Sebastian Cervantes[1]
[1] German Research Centre for Geosciences

The dynamical evolution of the radiation belts has been a subject of extensive research since their discovery in 1959. After decades of study, it is now known that they experience significant changes due to acceleration, loss and transport of particles trapped in the Earth's magnetic field.

Nevertheless, analysis of radiation belt observations still presents major challenges. Satellite measurements are often restricted to a limited range of L-shells, pitch angles, and energies. Moreover, particle fluxes vary on short time scales, and observations from a single spacecraft do not allow for measuring the temporal variations on time scales shorter than the spacecraft orbital period. Analysis is further complicated by the fact that measurements are contaminated by errors, which are different for various instruments. As a consequence, to fill the spatiotemporal gaps and to understand the dominant physical processes in the radiation belts, observations can be combined with physics based dynamical models in an optimal way by means of data assimilation.

In this study we implement a data assimilation tool using a sequential Kalman filter approach. Reanalysis of the electron radiation belt fluxes is obtained over the period 2012 to 2016 by combining sparse observations from the Van Allen Probes spacecraft and the GOES 13 and 15 satellites with the 3D Versatile Electron Radiation Belt (VERB) code. At first, radial profiles of electron fluxes are reconstructed, and the innovation vector is analyzed to show how the data is correcting for physical mechanisms absent in the model. Such processes are then added in the reanalysis, and a validation against LANL GPS data is presented. Finally, major improvements with respect to the pure physics based model are discussed. It is demonstrated that the 3D data assimilative code provides a comprehensive picture of the radiation belts and is an important step toward performing reanalysis using observations from current and future missions.

ON THE DEVELOPMENT OF AN ENSEMBLE DATA ASSIMILATION AND FORECASTING SYSTEM FOR THE RED SEA

Ibrahim Hotteit[1] - Invited Speaker

[1] KAUST, Saudi Arabia

With a growing interest in exploiting the Red Sea resources and protecting its fragile ecosystem, there is more and more pressing demand for building an operational system to predict its circulation. This is a challenging task due to the dominant strong seasonal variability and short-living mesoscales in this basin. This talk will present our approach for building this system within an ensemble Kalman filtering (EnKF) framework, combining a (i) one-step-ahead smoothing formulation to enhance the ensembles sampling with the future observations, (ii) a hybrid formulation of the filter prior covariance for implementation with reasonable-size ensembles, and (iii) a second-order exact sampling of the observations perturbations for efficient implementation of (i) and (ii) with a stochastic EnKF. I will discuss the relevance of each of these schemes and demonstrate their performances with various applications.

DATA ASSIMILATION FOR A QUASI-GEOSTROPHIC MODEL WITH CIRCULATION-PRESERVING STOCHASTIC TRANSPORT NOISE

Colin Cotter[1], Dan Crisan[1], Darryl Holm[1], Wei Pan[1] and Igor Shevchenko[1]

[1] Imperial College London

This talk continues a series of studies on using the stochastic variational approach for geophysical fluid dynamics introduced by Holm (Proc Roy Soc A, 2015) as a framework for deriving stochastic parameterisations for unresolved scales. In this talk we present data assimilation results for a stochastic two-layer quasi-geostrophic model (derived from the stochastic variational approach) in a horizontally periodic channel with forcing and dissipation. We study how different data assimilation methods reduce the uncertainty of coarse-grid simulations.

STATE AND PARAMETER ESTIMATION FROM OBSERVED SIGNAL INCREMENTS

Paul Rozdeba[1]

[1] Universität Potsdam

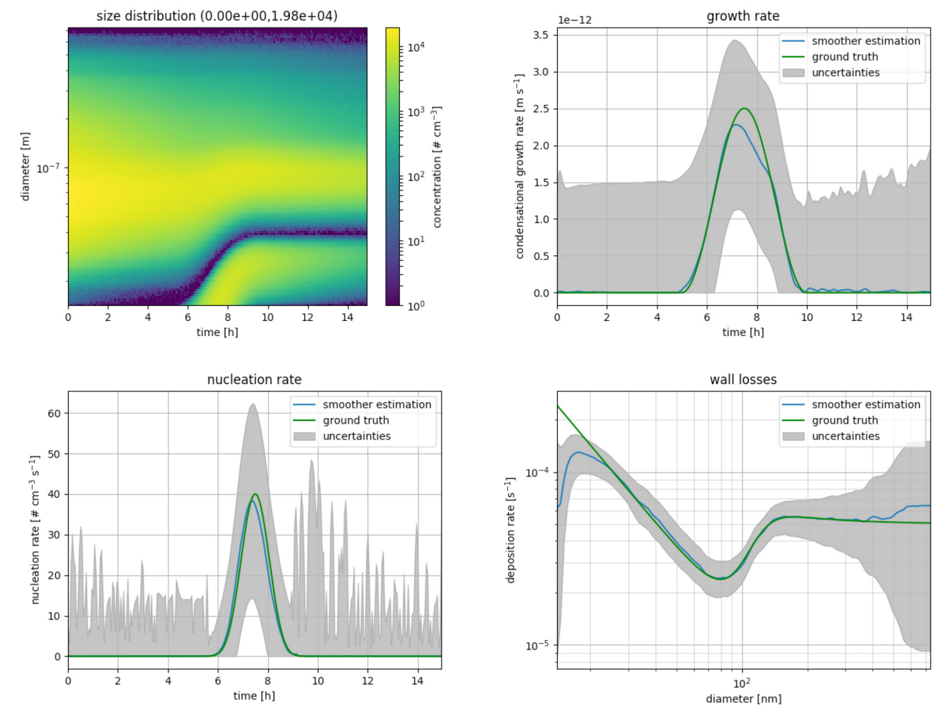
The success of the ensemble Kalman filter has triggered a strong interest in expanding its scope beyond classic state estimation problems. In a typical data assimilation setting, one has access to noisy and partial observations of Lagrangian particles which move under a stochastic velocity field. A partially unknown or mis-specified model of the system requires simultaneous state and parameter estimation. This talk will focus on continuous-time data assimilation in this setting where model and measurement errors are correlated. We take an appropriate class of McKean-Vlasov mean-field equations as the starting point to derive ensemble Kalman-Bucy filter algorithms for combined state-parameter estimation, and demonstrate their performance for a series of increasingly complex multi-scale model systems.

PARAMETER ESTIMATION IN SIZE-STRUCTURED AEROSOL POPULATIONS USING BAYESIAN STATE ESTIMATION

Matthew Ozon[1], Aku Seppänen[1], Jari Kaipio[1,2] and Kari Lehtinen[1,3]

[1] University of Eastern Finland, [2] University of Auckland, [3] Finnish Meteorological Institute

According to the Intergovernmental Panel on Climate Change reports, aerosols play a key role in the global radiative balance of the earth; it is the most important source of uncertainties in climate models. The number concentration, size distribution (SD) and chemical composition of aerosols affect their ability to scatter and absorb radiations, which controls cloud properties, e.g. lifetime. To quantify these effects, we need to be able to estimate, from time series of SD, the parameters describing the microphysical processes that are driving aerosol formation and growth. Despite the plentiful of papers dealing with the estimation of distributed parameters in population balance equations (PBE), the estimation of parameters, such as the growth rate, is still performed manually or via oversimplified methods, e.g. regression methods. The reason is twofold: 1) no method is specifically designed for the general dynamic equation (GDE) for aerosols, and 2) existing methods for related PBE rarely produce an estimation of the uncertainty. We propose to use a Bayesian approach, the Fixed Interval Kalman Smoother (FIKS), that gives time-dependent parameters along with their uncertainties in a proper theoretical framework. The FIKS needs evolution models for the SD (i.e. GDE) but also for the parameters being investigated. Therefore, stochastic processes substitute the unknown evolution equations. We successfully applied this method to several relevant experimental setups. In order to prove that the method performs well, we use simulated data such as those depicted in the figure. The simulated aerosol system evolves due to three mechanisms: 1) nucleation, 2) growth by vapor condensation, and 3) linear losses (e.g. wall deposition). The estimated parameters are plotted with their highest probability region (set to a probability of 0.7) and the reference values used for the simulation.



Poster session - Abstracts

REANALYSIS OF RING CURRENT ELECTRON PHASE SPACE DENSITIES USING VAN ALLEN PROBE OBSERVATIONS, CONVECTION MODEL, AND KALMAN FILTER

Nikita Aseev[1,2] and Yuri Shprits[1,2,3]

[1] GFZ German Research Centre for Geosciences, [2] University of Potsdam, [3] University of California

Models of ring current electron dynamics unavoidably contain uncertainties in boundary conditions, electric and magnetic fields, electron scattering rates, and plasmapause location. Model errors can accumulate with time and result in significant deviation of model predictions from observations. Data assimilation offers useful tools which can combine physics-based models and measurements to decrease model uncertainties. Data assimilation has been extensively used in radiation belt physics, but only a few studies have been devoted to its applications to the dynamics of the ring current. In this study, we perform a systematic analysis of the performance of the Kalman filter applied to a logtransformed convection model of the ring current electrons and Van Allen Probe data. By using synthetic data, we show that the Kalman filter is capable of correcting errors in electron lifetimes and boundary conditions. We demonstrate that the reanalysis retains features which cannot be fully reproduced by the convection model such as storm-time earthward propagation of the electrons down to 2.5 Earth's radii. The Kalman filter can adjust the model to satellite measurements even in the regions where data are not available. Inspecting the innovation vector, we show that model errors grow with increasing radial distance and enhanced geomagnetic activity. The results of this study demonstrate that data assimilation can improve performance of ring current models, better quantify model uncertainties, and help deeper understand the physics of the ring current particles.

IMPROVING THE OCEAN ENERGY CYCLE BY IMPLEMENTING PARAMETERIZATIONS FOR INTERNAL WAVE ENERGY

Nils Brüggemann[1], Johann Jungclaus[2], Oliver Gutjahr[2] and Carsten Eden[1]

[1] Universität Hamburg, [2] Max Planck Institute for Meteorology

We investigate the energy cycle in the ocean component of the Max Planck Climate model. A new parameterization for the internal wave field (IDEMIX) is used to increase the energetic consistency of this model. We will demonstrate how important a representation of the internal wave field is for the ocean circulation and diapycnal water mass transformation. Furthermore, we will discuss shortcomings in our current understanding of mesoscale energy dissipation and how this influences diapycnal mixing in the ocean.

SCALE INVARIANT DIFFUSION PARAMETERIZATION IN A MECHANISTIC GENERAL CIRCULATION MODEL

Serhat Can[1], Urs Schaefer-Rolffs[1] and Erich Becker[1]

[1] Leibniz Institute for Atmospheric Physics

Observations by Nastrom & Gage [1] in the upper troposphere showed the existence of continuous energy and enstrophy cascades of Kinetic Energy (KE) across the scales with regard to horizontal wavenumber, and as a result the well known spectral laws of -3 for synoptic [2] and -5/3 for mesoscales were found. Along with the observations, the concept of Lorenz Energy Cycle explains the continuous generation of KE from the conversion of Available Potential Energy (APE) [3] and provides a theoretical framework on how APE is converted into KE then KE is filling the Unavailable Potential Energy (UPE, i.e. TPE - APE) reservoir via irreversible dissipation and finally the generation of APE from UPE.

We use the high horizontal and vertical resolution Kühlungsborn Mechanistic general Circulation Model (KMCM) to obtain a realistic KE spectrum without employing any numerical filters or explicit hyperdiffusion [4]. Instead , we parameterize horizontal and vertical momentum diffusion with a newly-developed anisotropic version of the so-called Dynamic Smagorinsky Model (DSM)[5] . This scheme takes into consideration the hydrodynamic conservation laws and is also fully consistent with scale invariance. It should be noted that a macro turbulent inertial regime requires the scale invariance for the formulation of such a scheme.
In the present study, we completed the DSM with the horizontal diffusion of sensible heat, of which a similar cascade is also observed, see Figure 1. Our focus is on the spectra of the simulated KE and APE and their corresponding budgets. By looking at the contributing terms to these budgets, we aim to provide a picture of the irreversible branches of Lorenz Cycle in the free atmosphere.

References:
[1] G.D.Nastrom, K. S. Gage. A Climatology of Atmospheric Wavenumber Spectra of Wind and Temperature Observed by Commercial Aircraft. Journal of the Atmospheric Sciences 42: 950–960, 1984.
[2] G. J. Boer, T. G. Shepherd. Large-Scale Two-Dimensional Turbulence in the Atmosphere. Journal of the Atmospheric Sciences 40:164–184, 1982.
[3] E. N. Lorenz. Available Potential Energy and the Maintanence of the General Circulation. Tellus 7: 157–167, 1955.
[4] U. Schaefer-Rolffs, E. Becker. Scale-Invariant Formulation of Momentum Diffusion for High- Resolution Atmospheric Circulation Models. Monthly Weather Review 24: 1045–1062, 2018.
[5] M. Germano, U. Piomelli, P. Moin, W. H. Cabot. A Dynamic Subgrid-Scale Viscosity Model. Physics of Fluids A: Fluid Dynamics 3: 1760–1765, 1991.

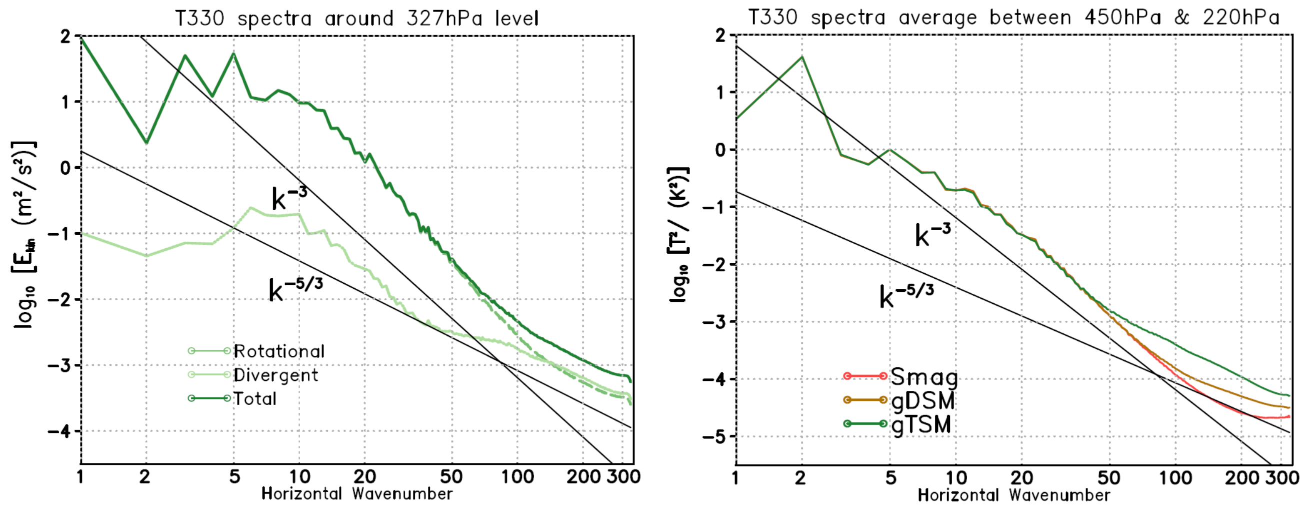


Figure 1: Left: KE Spectra with DSM applied to horizontal momentum and sensible heat diffusion. Right: Temperature power spectra compared between runs with classical Smagonrisky scheme (Smag), with DSM only for momentum diffusion (gDSM), with DSM for both heat and momentum diffusion (gTSM).

TWO-POINT VELOCITY AND MIGRATION STATISTICS FROM OCEAN SURFACE DRIFTER OBSERVATIONS AND FROM A HIGH RESOLUTION MODEL IN THE BENGUELA UPWELLING REGION

Julia Dräger-Dietel[1], Dhruv Balwada[2] and Alexa Griesel[1]

[1] Universität Hamburg, [2] New York University

Drifter velocity observations can be treated as scattered point Eulerian measurements, which can help in deducing the turbulent properties of the flow: e.g. the scale-dependent distribution of kinetic energy [1] and spectral fluxes [2]. Here we examine the probability distribution of relative longitudinal velocity, as a function of spatial separation, from surface drifters deployed in triplets at the boundary of a filament in the upwelling region off Namibia. For the drifters released at the northern boundary of the filament, close to the upwelling region, we find the PDF to be positively skewed (3rd order structure function) for relative separations of 10 km-80 km, supporting former findings of an inverse energy cascade (Richards scaling of pair separations) with an upward energy-transfer rate of

$\sim 10^{-8}$Wkg^{-1} [3].
For the drifters released at the southern boundary, we find the 2nd order structure function (variance) follows a 2=3 power law for relative separations of 1 km-800 km. This shallow power law, although reminiscent of Kolmogrov turbulence, points to potentially a few different possible underlying dynamics in the oceanographic context: mixed layer baroclinic instability [4], linear internal waves [5] or nonlinear internal waves/stratied turbulence [6]. We also perform a Helmholtz decomposition, to glean more into the dynamical origin of this scaling behavior. We contrast our findings with the corresponding analysis of model-trajectories from a high resolution model of the region.

[1] D. Balwada, J. H. LaCasce and K. G. Speer, 2016, Geophys. Res. Lett., 43, 10 856.
[2] A. Poje, T. M. Ozgokmen, D. J. Bogucki and A. D. Kirwan, 2017, Phys. Fluids. 29, 020 700.
[3] J. Dr□ager-Dietel, K. Jochumsen, A. Griesel and G. Badin, 2018, J. Phys. Oceanogr., 48, 2325-2341.
[4] Boccaletti, G., R. Ferrari and B. Fox-Kemper, 2007, J. Phys. Oceanogr., 37, 2228-2250.
[5] J. Callies, R. Ferrari and O. Buehler, 2014, Proc. Natl. Acad. Sci. (USA), 111, 17 033-17 038.
[6] E. Lindborg, 2006, J. Fluid Mech.,550, 207-242.

DIAPYCNAL DIFFUSIVITY INDUCED BY THE BREAKING OF LEE WAVES

Thomas Eriksen[1], Carsten Eden[1] and Dirk Olbers[2]
[1] Universität Hamburg, [2] University of Bremen

A key component in setting the large scale ocean circulation is the process of diapycnal mixing, since this provides energy required to increase the potential energy of the ocean and thereby to close the meridional overturning circulation. Diapycnal mixing in the interior ocean is most commonly associated with the breaking of internal waves. Traditionally diapycnal mixing has been represented in ocean models by a diapycnal diffusivity either constant or exponentially decreasing with depth. This approach, however, does not take into account the actual physics behind the breaking of internal waves. The energetically consistent internal wave model IDEMIX (Internal wave Dissipation, Energetics and MIXing) computes diffusivity rates directly on the basis of internal wave energetics. One such type of internal wave is leewaves. These are generated and subsequently dissipated when geostrophic currents interact with bottom topography and are therefore believed to be a source of energy for deep ocean mixing. Furthermore, leewaves extract from or provide momentum to the mean flow through wave drag. The amount of energy contained in leewaves are largely dependent on the strength of the bottom flow and on the roughness of the topography. This amount is believed to be especially high in the Southern Ocean due to exactly these factors. Using IDEMIX the energy flux into leewaves is integrated over wavenumber and in four directional compartments and is thereafter allowed to be used as a bottom forcing term in numerical simulations.

IMPACT OF STOCHASTIC PHYSICS IN COUPLED CLIMATE SIMULATIONS WITH EC-EARTH

Federico Fabiano[1], Virna Meccia[1] and Susanna Corti[1]
[1] ISAC-CNR

The inclusion of Stochastic Physics (SP) schemes in climate models has been found to produce improvements in the model performances with respect to the observations, partially filling the gap in the simulation of sub-grid scale processes.
Here we analyze two set of EC-Earth coupled climate simulations performed under the SPHINX project (Davini et al., 2017): one set of simulations is run with the Stochastically Perturbed Parametrization Tendencies (SPPT) and the Stochastic Kinetic Energy Backscatter (SKEB) schemes jointly applied to the atmospheric model, while the other set is run with the standard deterministic model, without SP. For both sets the RCP 8.5 scenario forcing is applied.

The experiments with SP show a significantly reduced climate sensitivity with respect to the standard experiments. Here we focus on the difference in the radiative feedbacks between the two sets of experiments (the largest being located in the tropics) and on the implications for the energy balance and meridional transport in the whole atmosphere.

On the other side we analyze the performance of the SP and non-SP ensembles in representing the wintertime (DJF) weather regimes in the North-Atlantic and North-Pacific sectors. The comparison is done in terms of the regime patterns, the associated frequencies and residence times and the transition probabilities between different regimes. The link of the different regimes with regional temperature/precipitation extremes is studied in both ensembles.

ENERGETICALLY CONSISTENT STOCHASTIC AND DETERMINISTIC KINETIC ENERGY BACKSCATTER SCHEMES FOR ATMOSPHERIC MODELS

Christian Franzke[1], Suneet Dwivedi[1,2] and Frank Lunkeit[1]
[1] Universität Hamburg, [2] University of Allahabad

Current climate models still suffer from many biases which are partly due to excessive subgrid-scale dissipation. Here we systematically develop energetically consistent stochastic energy backscatter (SEB) and deterministic energy backscatter (DEB) parameterization schemes. We implement our scheme in a spectral atmospheric Global Circulation Model (GCM). It is shown that the SEB scheme performs better than the DEB scheme at low horizontal resolutions (T21 and T31), whereas, the performance of both schemes becomes comparable as the resolution increases to T42 when comparing with our reference simulation at T127 resolution. The energy backscatter parameterization schemes improve eddy variability in low-resolution models and correctly capture the dominant mode of variability. The autocorrelation time scale of low-resolution models is also found to be more consistent with the reference simulation on applying the SEB and DEB parameterizations. Our schemes are also scale adaptive.

INVESTIGATING THE EDDY DIFFUSION MODEL IN THE BENGUELA UPWELLING REGION

Alexa Griesel[1], Julia Dräger-Dietel[1], Ria Oelerich[1] and Birte Gülk[1]
[1] Universität Hamburg

The Benguela upwelling system off the coast of Namibia is characterized by rich meso- and submesoscale features, such as eddies and filaments. We estimate eddy diffusivities from surface drifters deployed in the region during a cruise in Nov/Dec 2016 and investigate for what spatial scales the eddy-diffusion model is appropriate. We compare single- and pair particle statistics and discuss the relation of the diffusivities to the mean flow, the existing energy cascades and the presence of eddies. We find eddy diffusivities and their evolution with scale separation depend on the location of drifter release: diffusivities for the release in a filament are smaller and more anisotropic than the ones for the release close to the main upwelling cell. Diffusivities converge after time scales of > 50 days, corresponding to spatial scales of > 100km. Different methods of mean-flow subtraction are tested and results are compared to analyses of numerical trajectories in an eddying ocean model with a resolution of 9km in the region. We discuss to what extent the model reproduces the observed statistics and relate the results to what kind of energy cascade exists at what scale.

BALANCED DATA ASSIMILATION FOR ROTATIONAL SHALLOW WATER EQUATIONS

Gottfried Hastermann[1], Maria Reinhardt[2], Ray Chew[1], Sebastian Reich[2] and Rupert Klein[1]
[1] Freie Universität Berlin, [2] Universität Potsdam

In numerical weather prediction the inherent multi-scale nature of the underlying model equations poses several major challenges. One specific issue arises during the application of Bayesian data assimilation procedures, since they do not respect the balanced state of the atmosphere in general. This inconsistency leads to artificially triggered rapid internal waves although they should have only negligibly small amplitude. Since rapid waves also interact with the moist aerothermodynamics of the model, they can have negative impact on the forecast quality.

To improve the forecast skill in such situations, we therefore propose two different methods, each respecting the balances given by the model. The first directly modifies the posterior samples via a minimization problem and the second modifies the first steps of the subsequent forecast by pushing back the ensemble members to the slow evolution. For the latter we propose to use certain asymptotically consistent integrators which allow us to blend between a balanced and a unbalanced evolution model seamlessly.
In this talk we will present numerical results of the proposed methods, applied to the rotational shallow water equations.

ON THE UTILITY OF DATA ASSIMILATION FOR EXTREMES IN A CONCEPTUAL ATMOSPHERIC MODEL

Guannan Hu[1] and Christian Franzke[1]
[1] Universität Hamburg

An important research question is whether current data assimilation (DA) schemes can reproduce extreme events in analysis fields and how skillful they are in forecasting them. Here, we examine the utility of two widely used DA methods, the Ensemble Kalman Filter (EnKF) and the four-dimensional variational method (4DVar), for the estimation and prediction of extremes in a conceptual model of the atmosphere. We evaluate the DA performance by first examining whether the analysis captures the extreme value statistics of the control simulation. Second, we examine whether the forecasts generated from the analyses can well predict the extremes occurring in the verifying control simulation. Our results indicate that the two DA methods are beneficial for the prediction of extreme events, especially when compared with a rudimentary DA scheme which just imputes observations where they are available. Our results reveal that the EnKF is more accurate than the 4DVar in estimating the extreme, while the 4DVar produces better deterministic forecasts of extremes. However, we can take advantage of the EnKF and convert ensemble forecasts into probabilistic forecasts, which improve over the deterministic forecasts. Therefore, our results suggest the use of the EnKF for DA for extremes.

OCEAN KINETIC ENERGY BACKSCATTER PARAMETRIZATION ON UNSTRUCTURED GRIDS: IMPACTS ON MESOSCALE TURBULENCE IN A CHANNEL

Stephan Juricke[1,2], Sergey Danilov[1,2], Anton Kutsenko[1] and Marcel Oliver[1]
[1] Jacobs University, [2] Alfred Wegener Institute, Helmholtz Institute for Polar and Marine Research

At eddy-permitting ocean grid resolution, i.e. around 1/4° to 1/10°, classical viscosity closures tend to excessively dissipate kinetic energy. While some of the larger eddies may potentially be explicitly resolved, high viscosities lead to reduced eddy kinetic energy and a deteriorated simulation of the mean flow and of mean kinetic energy. Part of the motivation for such viscosity closures arises from considerations of numerical stability. To address this problem, the concept of kinetic energy backscatter in ocean models was recently proposed. It allows to reinject part of the excessively dissipated energy back into the flow using an additional negative viscosity term in the momentum equation. A prognostic equation for sub-grid kinetic energy keeps track of the dissipated energy that leaves the resolved flow. This sub-grid energy is then available for reinjection and defines the amplitude of the backscatter term. The backscatter is designed to act on larger scales than the viscosity, which guarantees that model stability is not compromised. We present results of a new backscatter parametrization in the finite volume model FESOM2 that supports unstructured grid configurations. Our setup is a periodic mid-latitude channel with northern and southern boundaries and 24 vertical layers. Resolution can be constant throughout the channel or it can be increased locally. We investigate the impact of different energy backscatterimplementations in combination with different viscosity parametrizations for structured grids of various resolutions. The new backscatter implementations lead to strongly increased eddy kinetic energy, corresponding to simulations with much higher, eddy-resolving resolution. Other flow statistics such as mean kinetic energy or variability in temperature are also considerably improved. Moreover, computational costs for the backscatter parametrization are substantially lower than a resolution increase. We also analyze an unstructured grid configuration with a mixed resolution channel. Part of the domain is eddy-resolving while the rest is only eddy-permitting, with narrow transition regions in between. The backscatter parametrization leads to much more uniform flow statistics across the channel. It substantially reduces negative impacts of the grid coarsening, both in the transition zones and in the coarse grid domain. We conclude with a discussion of future perspectives for global ocean grid configurations.

DYNAMICS OF OCEANIC ALTERNATING JETS FORMED OVER A TOPOGRAPHY

Hemant Khatri[1]
[1] Imperial College London

Multiple alternating jets have been seen in the oceans, which are formed due to an upscale transfer of energy by mesoscale eddies in the presence of Rossby waves. We study the jet dynamics in presence of a zonally sloped topography. The jets are tilted from the zonal direction and drift meridionally. In addition, it is found that the drifting jets are directly forced by the imposed vertical shear, whereas the eddies oppose the jets, which is opposite to the role of eddies in the classical zonal jets. This is because the buoyancy effects become more prominent with increasing the slope magnitude. Topography acts like a coupling between the jets and the background shear, and the jets are able to gain energy directly from the background flow. Also, the jet drift can be predicted with linear dynamics. Eddy heat and potential vorticity diffusivities are also computed, which are found to be positive everywhere; thus, confirming the down-gradient eddy fluxes.

A DIAGNOSTIC TOOL FOR THE ANALYSIS OF WATER, ENERGY AND ENTROPY BUDGET IN CLIMATE MODELS

Valerio Lembo[1], Frank Lunkeit[1] and Valerio Lucarini[1,2]
[1] Universität Hamburg, [2] University of Reading

We present here a collection of tools for the diagnosis of various aspects of the thermodynamics of the climate system in models and reanalyses. The collection has been implemented as part of the ESMValTool v. 2 community diagnostics. It consists of four independent modules: 1. the energy budgets and meridional energy transports, 2. the water mass and latent energy budgets and respective meridional transports, 3. the Lorenz Energy Cycle (LEC), 4. the material entropy production in climate models. If a land-sea mask is provided, the modules 1 and 2 provide results on land and oceans separately. As an example, we present here results from a subset of the CMIP5 multi-model ensemble, in which three scenarios are compared, one accounting for the pre-industrial conditions, one for nowadays conditions, and one for the business-as-usual greenhouse gas emissions at the end of the 21st Century. We notice that the metrics provided indicate a clear change
in the mean state of the climate in occurrence of increased GHG forcing. The hydrological cycle is stronger, and this is signaled by many features: the meridional water mass/latent energy convergence towards the Northern Hemisphere Tropics (about the ITCZ position) is increased, as well as the convergence of moisture from oceans towards the continents. The material entropy production is increased, mainly because of an increase in the component attributable to the hydrological cycle, especially tropical convection. Besides that, the LEC changes indicate a relatively sharp decrease in available potential energy and increase in kinetic energy reservoirs.

EFFECT OF GREEN HOUSE GASES, ANTHROPOGENIC AEROSOLS AND VOLCANISM ON THE HEMISPHERIC ENERGY BUDGETS AND CROSS-EQUATORIAL ENERGY TRANSPORT DURING THE 20TH CENTURY

Piero Lionello[1], Doris Folini[2], Martin Wild[2] and Valerio Lembo[3]
[1] Universita ́ del Salento, [2] ETH Zürich, [3] Universität Hamburg

Historical CMIP5 model simulations are here used to show that the response of the climate system to the ongoing forcing during the 20th century is significantly different from what would have been produced by an increase of Green House Gases (GHG) concentration alone. The GHG increase would have warmed the Northern Hemisphere (NH) more than the Southern Hemisphere (SH), with both hemispheres exhibiting similar and positive Energy Budget (EB) anomalies at the Top of Atmosphere (ToA) and no significant variation in time of the cross-equatorial energy transport (CET). On the contrary, the actual forcing (which includes the effect of anthropogenic and volcanic aerosols besides GHG) has produced a similar warming of both hemispheres, with a positive EB anomaly that is twice as large in the SH than in the NH, and an oceanic CET anomaly directed towards the NH. EB changes induced by GHG increase are found to be determined mainly by increasing shortwave absorption, which is homogeneous in the two hemispheres. The EB asymmetry determined by the full ongoing forcing is mainly due to a reduced long wave emission in the SH, which is explained by the different role of clouds in the two hemispheres. The positive CET anomaly produced by the full forcing is associated with the inter-hemispheric asymmetry in the aerosol forcing, which is stronger in the NH than in the SH.

LYAPUNOV EXPONENTS FOR STOCHASTIC LORENZ 63

Erwin Luesink[1]

[1] Imperial College London

Two different types of perturbations of the Lorenz 63 dynamical system for Rayleigh-Benard convection by multiplicative noise - called stochastic advection by Lie transport (SALT) noise and fluctuation-dissipation (FD) noise - are found to produce qualitatively different effects. For example, SALT noise preserves the sum of the deterministic Lyapunov exponents, while FD noise does not. In the process of making this comparison between effects of SALT and FD noise on the Lorenz 63 system, a stochastic version of a robust, reasonably accurate, deterministic numerical algorithm for obtaining the individual numerical Lyapunov exponents was developed. With this stochastic version of the algorithm, the value of the sum of the Lyapunov exponents differs from the deterministic value for the FD noise, whereas SALT noise retains this value with high accuracy.

ENERGY DECOMPOSITIONS FOR MOIST BOUSSINESQ AND ANELASTIC EQUATIONS WITH PHASE CHANGES

David Marsico[1]

[1] University of Wisconsin-Madison

To define a conserved energy for an atmosphere with phase changes of water (such as vapor and liquid), motivation in the past has come from generalizations of dry energie - in particular, from gravitational potential energy, ρgz. Here, another definition of moist energy is introduced, and it generalizes another form of dry potential energy, proportional to θ^2, which is valuable since it is manifestly quadratic and positive definite. This moist potential energy here is piecewise quadratic, and it is quadratic within each phase. The energy can be decomposed into three parts, proportional to $b^2_u H_u$, $b^2_s H_s$, and $M^2 H_u$, which represent, respectively, buoyant energies and a moist latent energy that is released upon a change of phase. The H_u and H_s are Heaviside functions that indicate unsaturated and saturated phases, respectively. The M^2 energy is also associated with an additional eigenmode that arises for a moist atmosphere but not a dry atmosphere. Both the Boussinesq and anelastic equations are considered, and similar energy decompositions are shown in both cases, although the anelastic energy is not quadratic. Extensions that include cloud microphysics are also discussed, such as the Kessler warm-rain scheme. As an application, empirical orthogonal function (EOF) analysis is considered, using the piecewise quadratic moist energy as a weighted energy in contrast to the standard L^2 energy. By incorporating information about phase changes into the energy, the leading EOF modes become fundamentally different and capture the variability of the cloud layer rather than the dry sub-cloud layer.

OPTIMAL BALANCE FOR GEOPHYSICAL FLOWS AND SPONTANEOUS WAVE EMISSION

Gökce Tuba Masur[1] *and Marcel Oliver*[1]

[1] Jacobs University

The method of optimal balance, in the context of rapidly rotating fluid flow first introduced by Viúdez and Dritschel (2004), is a computational strategy to decompose flows into balanced (slow) and imbalanced (fast) components, for example to provide balanced initializations for geophysical models. We investigate this numerical tool in the context of the rotating shallow water equations in primitive variables, which is different from the Lagrangian scheme used by Viúdez and Dritschel. The decomposition of slow-fast dynamics in the model is carried out through adiabatically deforming the nonlinear model into a linear one for which mode-splitting is exact. This procedure can be treated as a boundary value problem in time. We use the procedure first to initialize the shallow water equations to a nearly balanced state and to diagnose spontaneous excitation of imbalances are as the shallow water solution evolves.

INITIAL CONDITION ENSEMBLES AND THE CONTROL PARAMETERS FOR CLOUD PROPERTY VARIABILITY

Annette Miltenberger[1]*, Paul Field*[2,3] *and Adrian Hill*[3]

[1] Johannes-Gutenberg Universität Mainz, [2] University of Leeds, [3] MetOffice

Clouds are an important component of the atmospheric system and their properties vary over regional to global and hourly to centennial scales. Meteorological conditions as well as aerosol availability influence and dictate this variability. Of particular interest recently are anthropogenic modifications to the spatio-temporal aerosol distribution and their potential impact on the cloud property distribution. Quantifying the role of aerosol variability in controlling the cloud property distribution faces the challenge of co-varying meteorological and aerosol conditions, both in modelling and observational studies. Here we explore the implications of this co-variability for a robust quantification of aerosol-cloud interactions with the use of large initial condition ensembles for sea-breeze driven mixed-phase convective and orographic clouds.We also investigate the implications for observing aerosol-cloud interactions in the climate system in dedicated field campaigns and from a more climatological perspective. In particular, for mixed-phase convective clouds we find that for most cloud field variables, meteorological conditions are more important than aerosol perturbations making robust observations of cloud-aerosol interactions very challenging.

ASSIMILATING DATA INTO A SELF-EXCITING TEMPORAL POINT PROCESS MODEL FOR EARTHQUAKE OCCURRENCE

Christian Molkenthin[1]*, Gert Zöller*[1]*, Matthias Holschneider*[1] *and Sebastian Reich*[1]

[1] Jacobs University

Point process models are often employed in seismology to describe the occurrence of earthquakes in space and time. The most popular model in this context, representing a benchmark, is the Epidemic Type Aftershock Sequence (ETAS) model. The ETAS model is widely used for seismic forecasting and belongs to a particular class of self-exciting, linear, marked Hawkes processes. Model parameters are usually calibrated using earthquake data via maximum-likelihood estimation (MLE). Beyond MLE, Bayesian methods are becoming more and more popular, particularly as they enable the consideration of parameter uncertainties when generating forecasts. However, these methods are rarely applied to the ETAS model as the evaluation of the posterior distribution is not straightforward. Our aim is to investigate methods for improving seismic forecasts by (1) implementing a fully Bayesian analysis of posterior distributions of the ETAS model parameters using Markov Chain Monte Carlo methods, Hamiltonian Monte-Carlo methods and variational techniques; and (2) reformulating the ETAS model in such a way that it can be combined with sequential data assimilation techniques, e. g. sequential Monte Carlo methods and ensemble-based ltering methods. The overarching goal is to provide tools for combined state and parameter estimation. First results on a temporal ETAS model (one dimensional case) will be presented.

CONNECTION BETWEEN ARNOL'D STABILITY AND PHASE VELOCITY OF LINEAR WAVES

Jonas Nycander[1] *and Eyal Heifeitz*[2]

[1] Stockholm University, [2] Tel-Aviv University

Arnol'd proved a theorem for the nonlinear stability of incompressible two-dimensional shear flow. His result was subsequently extended to the quasigeostrophic vorticity equation, and to the shallow-water equations in "Ripa's theorem". The stability criteria in these theorems guarantee that the pseudo energy is positive definite in some reference frame. This proves stability, since the pseudo energy is both quadratic in the perturbation from the stationary background state, and conserved by the linearized evolution equations around the background state.

It is here demonstrated that such a nonlinear stability theorem can only exist if there is a gap in the spectrum of possible phase velocities of linear waves. Thus, there is a very simple connection between nonlinear stability and the spectrum of linear waves supported by the model. The reason for this is that stationary waves have zero pseudo energy, which means that the pseudo energy can only be positive definite (or negative definite) in a reference frame where no stationary linear waves exist. Such a reference frame can only be found if there is a gap in the spectrum of linear waves. The gap also precludes the instability mechanism with phase-

locking counter propagating waves. This gives a physical explanation for the stability criteria for the shallow-water equations in Ripa's theorem, and agrees with other known nonlinear stability theorems.
A key step in the analysis is to use variational calculus to show explicitly that the pseudo energy ΔE is the energy difference between the perturbed state and the isovortical background state (that unique background state which has the same value of all Casimir integrals as the perturbed state.) This is then used to show that the relation ΔE = cΔM holds for any steadily translating solution. Here ΔM is the pseudo momentum and c the phase velocity. This shows that ΔE = 0 for stationary waves.

NONLINEAR AUTOREGRESSIVE MODELS FOR THE NORTH ATLANTIC OSCILLATION

Thomas Önskog[1]
[1] *KTH Royal Institute of Technology*

In a previous paper (Önskog et al. J. Clim. 31, 537-554 (2018)), we studied the properties of time series of the daily NAO index, in particular the station-based time series published by Cropper and co-authors (Cropper et al. Geosci. Data J. 2, 12-24 (2015)). We found that the distribution of the NAO index has clear non-Gaussian features and long-range dependence. An autoregressive (AR) model with non-standardized t-distributed noise taking the values of the index during the last three days into account provided a good model for the daily NAO index on time scales up to two weeks. This model was, however, unable to replicate some features of the NAO including the long-range dependence on time scales of the order 20 days or more, the different time scales of the positive and negative phases of the NAO and the fact that the negative tail of the NAO distributions is fatter than the positive tail. Here, we model the NAO by means of nonlinear AR models, threshold AR models, and nonlinear ARMA models and nd that most of these features can be reproduced by some of these models. The performance of the models are evaluated by their forecasting skills and various statistical tests. The results are based on a joint project with Christian Franzke at University of Hamburg and Abdel Hannachi at Stockholm University.

VARIATIONAL MODEL REDUCTION FOR ROTATING GEOPHYSICAL FLOWS WITH FULL CORIOLIS FORCE

Gözde Özden[1]
[1] *Jacobs University*

We consider the motion of a rotating fluid governed by the Boussinesq equations with full Coriolis parameter. This is contrary to the so-called „traditional approximation“ in which the horizontal part of the Coriolis parameter is zero. We use a variational approach similar to Oliver and Vasylkevych (2016) to derive a balance model in the semigeostrophic limit which can be seen as the Boussinesq equation analog of the L1 model by R. Salmon (1996). At least formally, the resulting balance relation is valid for any latitude, also near the equator.

TOWARD A SPECTRAL BUDGET OF THE OCEAN'S INTERNAL GRAVITY WAVE FIELD

Friederike Pollmann[1], Carsten Eden[1] and Dirk Olbers[2]
[1] *Universität Hamburg,* [2] *University of Bremen*

Nonlinear interactions between internal gravity wave triads transfer energy through the spectrum from large scales, where internal waves are generated, to small scales, where the waves break and lose their energy to turbulence. Wave-induced turbulent mixing contributes to driving the large-scale overturning circulation and thus constitutes an important player of Earth's climate system.
Because it acts on scales too small to be resolved, it has to be parameterized in general circulation models. Consistent parameterizations of wave-induced mixing take internal wave energetics into account and hence require understanding of what shapes the spectral properties of the ocean's internal gravity wave field. We present new insights on this subject gained from the numerical evaluation of wave-wave interactions and the analysis of observed internal wave spectra obtained from finestructure profiles.

DATA-BASED LEARNING AND REDUCED MODELS FOR EFFICIENT SCALE COUPLING IN ATMOSPHERE SCIENCE

Robert Polzin[1]
[1] *Freie Universität Berlin*

Objective is the efficient modelling of large scales in atmosphere science. We develop a small scale stochastic model for convective activity and describe convective feedback on the large scale atmospheric flow using data-based learning and reduced models for efficient scale coupling. The aim is a hybrid model with a stochastic component for a conceptual description of convection embedded in a deterministic atmospheric flow model. From the meteorological perspective, we intend to use variants of the Dynamic State Index (DSI) on multiple scales and for multiple processes as new control variables for convective structures [4].

To analyse atmospheric processes on different scales, we need to consider the process as an embedded system as the restriction of an unknown larger dynamical system. Therefore, we extend the theory and algorithms for coherent sets for embedded domains and incomplete trajectory data and make towards unified transfer-operator approach for coherent sets and patterns [1, 2, 3]. The state of the art considering the work on transport-oriented methods and data-based analytics will be illustrated. In view of upward coupling the future work on a model for cloud characteristics with the help of the already obtained theory for coherent set analysis will be described. Perspectively, we try to combine machine learning with coherent sets in dynamical systems.

References

[1] Ralf Banisch and Péter Koltai. Understanding the geometry of transport: Diffusion maps for lagrangian trajectory data unravel coherent sets. Chaos: An Interdisciplinary Journal of Nonlinear Science, 27(3):035804, 2017.
[2] Gary Froyland. An analytic framework for identifying finite-time coherent sets in time-dependent dynamical systems. Physica D: Nonlinear Phenomena, 250:1–19, 2013.
[3] Gary Froyland and Oliver Junge. Robust fem-based extraction of finite-time coherent sets using scattered, sparse, and incomplete trajectories. SIAM Journal on Applied Dynamical Systems, 17(2):1891–1924, 2018.
[4] Peter Névir. Ertel's vorticity theorems, the particle relabelling symmetry and the energy-vorticity theory of fluid mechanics. Meteorologische Zeitschrift, 13(6):485–498, 2004.

A MODEL FOR WARM CLOUDS WITH IMPLICIT DROPLET ACTIVATION, AVOIDING SAUTRATION ADJUSTMENT

Nikolas Porz[1]
[1] *Johannes Gutenberg Universität Mainz*

The representation of cloud processes in weather and climate models is crucial for their feedback on atmospheric flows. Since there is no general macroscopic theory of clouds, the parameterization of clouds in corresponding simulation software depends fundamentally on the underlying modeling assumptions. We present a new model of intermediate complexity (a one-and-a-half moment scheme) for warm clouds, which is derived from physical principles. Our model consists of a system of differential-algebraic equations which allows for supersaturation and thus avoids the commonly used but somewhat outdated concept of so called ‚saturation adjustment'. This is achieved with an intrinsic automated droplet activation based on a coupling of the droplet mass- and number concentrations tailored to this problem. For the numerical solution of this system we have developed a semi-implicit integration scheme, with efficient solvers for the implicit parts. The model conserves air and water (if one accounts for the precipitation), and it comes with ten parameters that cannot be measured since they describe simplied processes, so they need to be fitted to the data. We have fitted the parameters with a trust region regularization to data which consist of precipitation measurements only. As a preliminary finding, our study shows the dependency of the parameters on the vertical spacial resolution inside a Lagrangian column moving uphill. For further studies we are implementing our cloud micro physics model into ICON, the weather forecast model operated by the German forecast center DWD.

SEQUENTIAL BAYESIAN INFERENCE AND MODEL SELECTION IN STOCHASTIC DIFFERENTIAL EQUATIONS

Paul Rozdeba[1]

[1] Universität Potsdam

Data assimilation (DA) is used to estimate a posterior probability distributions for dynamical model states and parameters conditioned on noisy data time series. The model itself must additionally be inferred from data if it is not fully specified. In this context, we investigate the use of nonparametric sequential Bayesian inference methods for drift estimation and model selection in nonlinear stochastic differential equation (SDE) systems observed in continuous and discrete time, with Gaussian process priors on drift functions. Challenges arising in the nonparametric setting include the computational complexity of the associated high-dimensional estimation problem, as well as issues of prior dependence and posterior non-Gaussianity in the presence of measurement noise and discrete-time observations. These are addressed through the use of tools and methods from DA such as ensemble approximations and localization, linking results in numerical examples to results from the statistics literature on prior impact and posterior contraction rates.

METRICS FOR HADLEY CIRCULATION WIDTH AND THEIR LINK TO ATMOSPHERIC ENERGY BUDGET

Ascanio Luigi Scambiati[1], Roberta D'Agostino[2] and Piero Lionello[1,3]

[1] University of Salento, [2] Max Planck Institute for Meteorology, [3] Euro-Mediterreanean Center for Climate Change

As key component of the climate system, the Hadley Circulation (HC) is one of the most studied atmospheric feature and changes in its width with global warming may affect the environment and the population of large part of the Earth. Giving a correct representation of its width is therefore fundamentally important. Here we investigate the relationship between the atmospheric energy budget (e.g. the outgoing longwave radiation field, OLR) and the HC width estimated by different methods (stream-function, total precipitation, precipitation minus evaporation, mean sea level pressure and vertical velocity) in ERA-20C reanalysis for the 20th century.

HC edges agree on their mean positions computed with OLR, mean sea level pressure and stream-function, but their mutual correlations are not significant at interannual time-scale. Furthermore, OLR-based HC edge does not show statistically significant trends during the 20th century in the northern hemisphere, as well as many other methods. Conversely, in the southern hemisphere, the OLRbased edge is the only one that shows significant contraction of HC, in contrast with the other significant trend signals. The lack of correlations and trends suggest that caution should be paid by drawing general conclusions about the HC behaviour from individual studies based on a single method.

INTRODUCING A SIMPLE STOCHASTIC FRAMEWORK TO ACCOUNT FOR TURBULENT INTERMITTECY IN ATMOSPHERIC BOUNDARY-LAYER PARAMETERIZATIONS

Metodija Shapkalijevski[1] and Nikki Vercauteren[1]

[1] Freie Universität Berlin

The predictability of atmospheric weather prediction and climate models depends on their limited resolution, which is induced by the discretization of the numerical scheme. This implies that subgrid-scale processes are not resolved, but parameterized. It has been shown that the parametrization of near-surface and boundary-layer turbulent transport processes are usual and important reasons of model error. The importance of an improved turbulence parameterization is even more dramatic in nocturnal and strongly-stratified flow, in which the scales of motion are smaller by an order or two magnitudes, compared to daytime and more turbulent (convective) flow. One of the difficulties in parameterization nocturnal (stable) boundary-layer turbulence is its intermittent character, and its random distribution in time and space. In this study an easy-to apply stochastic model that approximates and includes the effects of turbulence intermittency in atmospheric boundary-layer turbulence parameterizations is introduced. The model treats the turbulent intermittency as random stochastic forcing on background turbulent flow. Consequently, the model approximates the intermittent events as continuous function of their probability density distribution. To find the required intermittent properties in a turbulent flow (frequency of occurrence, duration, and magnitude of intermittent events), we have used a turbulent event detection (TED) method applied on time series of high-resolution measurement data. By constructing and running a simple one-dimensional prognostic model of the horizontal wind velocity and potential temperature, and adding the stochastic model for turbulence intermittence in the turbulent kinetic energy (TKE) closure, we have tried to demonstrate the applicability, ability, and the relevance of this model to introduce intermittency in the turbulence parameterization in atmospheric numerical models.

SEMI-LAGRANGIAN RECONSTRUCTION TECHNIQUES FOR TRANSIENT MULTISCALE PROBLEMS

Konrad Simon[1] and Jörn Behrens[1]

[1] Universität Hamburg

Long time scales in climate simulations, e.g., in simulations of paleo climate, require coarse grids due to computational constraints. Coarse grids, however, leave important smaller scales unresolved. Thus small scale processes that significantly influence the resolved scales need to be taken care of by different means. Such subgrid processes include (slowly) moving land-sea interfaces or ice shields as well as flow over urban areas or biogeochemistry. State-of-the-art dynamical cores represent the influence of subscale processes typically via subscale parametrizations and often employ a rather heuristic coupling of scales.

We aim to improve the mathematical consistency of the upscaling process that transfers information from the subgrid to the coarse prognostic and diagnostic quantities (and vice-versa). We investigate new bottom-up techniques for advection-dominated problems whose main motivation are climate simulations [3]. Our tools are based on ideas for multiscale finite element methods for elliptic problems that play a role, in oil reservoir modeling and porous media in general [1, 2]. These ideas, however, fail in advection-dominated scenarios (which are typical for flows encountered in climate models) since they are not based on a suitable decomposition of the computational domain.

We present new Garlerkin based ideas to account for the typical diffculties in climate simulations. Our idea is based on a previous work that employs a change of coordinates based on a coarse grid characteristic transform induced by the advection term to make its effect on coarse scales milder. This also accounts for appropriate subgrid boundary conditions for the multiscale basis functions. Boundary conditions are essential for such approaches. This is the starting point of a set of semi-Lagrangian techniques that locally in time reconstruct subgrid variability in a Galerkin basis through many local inverse problems. We discuss extensions and drawbacks of this approach and present examples with rapidly varying coefficients on several scales.

References

[1] Yalchin Efendiev and Thomas Y Hou. Multiscale finite element methods: theory and applications, volume 4. Springer Science & Business Media, 2009.

[2] Ivan G Graham, Thomas Y Hou, Omar Lakkis, and Robert Scheichl. Numerical analysis of multiscale problems, volume 83. Springer Science & Business Media, 2012.

[3] Peter H Lauritzen, Christiane Jablonowski, Mark A Taylor, and Ramachandran D Nair. Numerical techniques for global atmospheric models, volume 80. Springer Science & Business Media, 2011.

Thursday, April 4 - Abstracts

STOCHASTIC PARAMETERISATION OF CUMULUS CONVECTION

Pier Siebesma[1] - Invited Speaker

[1] Delft University of Technology

Traditional parameterisations of cumulus convection in weather and climate prediction models describe the intensity of the subgrid convective transport and precipitation in terms of a deterministic mass flux. Despite the success of this approach we will argue that is flawed for at least two reasons.

One reason is that a statistical deterministic relation between the resolved large scales and the unresolved subgrid scales as dictated by quasi-equilibrium breaks down at higher resolutions of weather and climate models. The second reason is that convective precipitation responds differently on changes of the large scale convergence than on changes of the vertical stability of the atmosphere. Traditional mass flux parameterisations are not able to take these different responses into account.

A new way of incorporating this behaviour of convective precipitation can be achieved through introducing a closure that independently estimates the convective vertical velocity and the convective area fraction at cloud base. This is realized through the use of Conditional Markov Chains (CMC) trained by observational data and conditioned on the large scale convergence. These CMS's allow to estimate the fractional convective area in a grid box of a numerical weather prediction or climate model in a stochastic and scale aware manner while the vertical convective velocity can still be estimated through a local updraft model. An additional advantage of this approach is that it can also incorporate the spatial organisation of cumulus convection on the subgrid scale.

References

J. Loriaux, G. Lenderink & A.P. Siebesma: "Large Scale Controls on extreme precipitation" Journal of Climate February 2017, Vol. 30, No. 3

J. Dorrestijn; Daan T. Crommelin, A.P. Siebesma, H.J.J. Jonker and F. Selten: "Stochastic Convection Parameterization with Markov Chains in an Intermediate-Complexity GCM". J. Atmos. Sci., 73, 1367-1382, (2016)

CONSTRAINING STOCHASTIC PARAMETRISATION SCHEMES USING HIGH-RESOLUTION MODEL SIMULATIONS

Hannah Christensen[1]

[1] University of Oxford

Stochastic parametrisations are used in weather and climate models to represent model error. Designing new stochastic schemes has been the target of much innovative research over the last decade, with a focus on developing physically motivated schemes. We present a technique for systematically deriving new stochastic parametrisations or for constraining existing stochastic approaches. We take a high-resolution model simulation and coarse-grain it to the desired forecast model resolution. This provides the initial conditions and forcing data needed to drive a Single Column Model (SCM). By comparing the SCM parametrised tendencies with the evolution of the high-resolution model, we can measure the 'error' in the SCM tendencies. As a case study, we use this approach to assess the physical basis of the widely used 'Stochastically Perturbed Parametrisation Tendencies' (SPPT) scheme. We provide justification for the multiplicative nature of SPPT, and for the large temporal and spatial scales used in the stochastic perturbations. However, we also identify issues with the SPPT scheme and motivate improvements. In particular, our results indicate that an alternative approach is needed to represent uncertainty in the convection scheme. It is hoped this new coarse-graining technique will improve both holistic and process-based approaches to stochastic parametrisation.

References:

Christensen, H. M., Constraining stochastic parametrisation schemes using high-resolution simulations. For submission to Q. J. Roy. Meteor. Soc.

Christensen, H. M., Dawson, A., and Holloway, C. E., 2018, Forcing Single-Column Models Using High-Resolution Model Simulations. JAMES, 10.

UNCERTAINTY QUANTICATION FOR CLOUD SIMULATION

Bettina Wiebe[1]

[1] University Mainz

Clouds constitute one of the most important component in the Earth-atmosphere system. They influence the hydrological cycle and by interacting with radiation they control the energy budget of the system. However, clouds are one of the most uncertain components, which, unlike the atmospheric flows, cannot be modeled using first principles of physics.

For investigations of the impact of uncertain cloud model parameters as well as the impact of variations in environmental conditions on atmospheric flows, we have developed a model consisting of the weakly compressible Navier-Stokes equations and random cloud evolution equations for water vapor, cloud water and rain, see [1]. We will present our recent results on uncertainty quantification of our cloud model, see [2, 3], by using a stochastic Galerkin method.

The results have been obtained in collaboration with A. Chertock (Raleigh), A. Kurganov (Shenzhen), M. Lukacova (Mainz) and P. Spichtinger (Mainz) and supported by the German Science Foundation under SFB/TRR 165 „Waves to Weather".

References

[1] Chertock, A., Kurganov, A., Lukacova-Medvid'ova, M., Spichtinger, P., Wiebe, B.: Stochastic galerkin method for cloud simulation. Math. Clim. Weather Forecast. (submitted) (2018)

[2] Lukacova-Medvid'ova, M., Rosemeier, J., Spichtinger, P., Wiebe, B.: IMEX finite volume methods for cloud simulation. In: Finite volumes for complex applications VIII|hyperbolic, elliptic and parabolic problems, Springer Proc. Math. Stat., vol. 200, pp. 179{187. Springer, Cham (2017)

[3] Porz, N., Hanke, M., Baumgartner, M., Spichtinger, P.: A consistent model for liquid clouds. Math. Clim. Weather Forecast. (submitted) (2018)

FINITE-TIME BREAKDOWN OF CHEMICAL PRECIPITATION PATTERNS

Marcel Oliver[1]

[1] Jacobs University

We discuss phenomena arising from a memory term with hysteresis in the context of chemical reaction kinetics - the Keller-Rubinow model for Liesegang precipitation patterns in the fast reaction limit. We present evidence that, in this model, the pattern of successive precipitation regions and precipitation-free interrings breaks down in finite time, either by rings accumulating at finite locus or by degeneration of the ignition condition. The results suggest that while the microscopic dynamics is complicated and only partially tractable analytically, a description via a macroscopic probability density function is possible and captures the long-time dynamics of the model well. While the example is a scalar reaction-diffusion equation, the results may provide a modeling paradigm for coarse-graining precipitation models in more complicated contexts such as atmospheric dynamics.

The proposed talk is joint work with Z. Darbenas and R. van der Hout.

A CONSISTENT FRAMEWORK FOR STOCHASTIC REPRESENTATION OF LARGE-SCALE GEOPHYSICAL FLOWS

Etienne Mémin[1] - Invited Speaker
[1] INRIA

In this talk, I will describe a formalism, called modelling under location uncertainty (LU), to derive in a systematic way large-scale stochastic representations of fluid flows dynamics that enables to take into account the inherent uncertainty attached to the flow evolution. The uncertainty introduced here is described through a random field and aims at representing principally the small-scale effects that are neglected in the large-scale evolution model. The resulting large-scale dynamics is built from a stochastic representation of the Reynolds transport theorem. This formalism enables, in the very same way as in the deterministic case, a physically relevant derivation (i.e. from the usual conservation laws) of the sought evolution laws. We will in particular show how to derive systematically stochastic representation of geophysical flow dynamics and how reduced order stochastic dynamical systems can be derived as well. We will give several examples of simulations obtained by such system and how they can be used in different contexts. In the quasi-geostrophic case, we will in particular focus on the quantities conserved by this modeling (total energy) and a modified potential vorticity that involves the effect of the unresolved scales.

Furthermore, this formalism brings into play very meaningful terms for turbulence modeling. As a matter of fact, it provides (i) a natural subgrid tensor expression figuring the mixing of the resolved components by the unresolved components; (ii) a multiplicative random term associated to an energy backscattering; and (iii) a modified advection that depicts a so-called turbophoresis phenomena that tends to drive fluid particles from regions of high turbulence toward areas of lower turbulent kinetic energy. We will in particular focus on this last term and show its relevance to describe several physical situations (such as wall-law velocity profiles or wave mean-current interaction and the apparition of the so-called vortex force). This will put an emphasis on the importance of the unresolved components inhomogeneity modeling.

STOCHASTIC MODELING OF OCEANIC DYNAMICS FOR ENSEMBLE FORECASTING

Long Li[1], Werner Bauer[2] and Etienne Mémin[2]
[1] University of Rennes, [2] INRIA

We propose to follow a recent stochastic quasi-geostrophic model [3, 4, 5] derived from a decomposition of the flow into a resolved component and a time-uncorrelated uncertainty. One important characteristic of this random model is that it conserves the total energy and a modified potential enstrophy along each realization. Numerically, we propose to keep the unstaggered Arakawa A-grid method [1] for the spatial discretization, and use an stabilized Euler-Heun's scheme [2] for the time integration, in which numerical viscosity is rigorously estimated at each time step according to the previous conservation properties. In the test case of a simplied Rossby wave, this random model displays a dichotomous pattern of linear-nonlocalized waves and nonlinear-localized vortices. Moreover, the proposed discretization preserves the magnitude and the propagation speed.

Once the structure-preserving scheme is validated, the performance on a coarse grid of a damped version of our random model will be assessed and analyzed for ensemble spread. This will be compared to the observations from a deterministic ne grid simulation. Some important criterion have been used to quantify accuracy of the ensemble forecasts prediction, such as Talagrand histogram, continuous ranked proper score, etc. The results show that the proposed random model, under both homogeneous and eterogeneous uncertainty, is more efficient compared to the randomized-initial-condition model. This may provide more benefits for data assimilation in future work.

References

[1] A. Arakawa, and V.R. Lamb, A Potential Enstrophy and Energy Conserving Scheme for the Shallow Water Equations, Monthly Weather Review, 109, 1, pp. 18-36 (1981).
[2] C. Colin, D. Crisan, D.D. Holm, P. Wei, and I. Shevchenko, Modelling uncertainty using circulation-preserving stochastic transport noise in a 2-layer quasi-geostrophic model, arXiv e-prints, Physics -Fluid Dynamics, Mathematical Physics, 1802.05711 (2018).
[3] E. Memin, Fluid flow dynamics under location uncertainty, Geophysical and Astrophysical Fluid Dynamics, 108, 2, pp. 119-146 (2014).
[4] V. Resseguier, E. Memin and B. Chapron, Geophysical flows under location uncertainty, Part I: random transport and general models, Geophysical and Astrophysical Fluid Dynamics, 111, 3, pp. 149-176 (2017).
[5] V. Resseguier, E. Memin and B. Chapron, Geophysical flows under location uncertainty, Part II: Quasi-geostrophy and ecient ensemble spreading, Geophysical and Astrophysical Fluid Dynamics, 111, 3, pp. 177-208 (2017).

DATA-DRIVEN AUGMENTATION OF A LOW-RESOLUTION DOUBLE-GYRE FLOW

Eugene Ryzhov[1], Dmitri Kondrashov[2] and Pavel Berloff[1]
[1] Imperial College London, [2] University of California

An approach to parameterise the effect of small-scale oceanic structures on the large-scale components in a low-resolution oceanic flow model is presented. The low-resolution model is augmented with features inferred statistically from the corresponding high-resolution model in order to reproduce the idiosyncratic geometrical structure of the high-resolution model.
The classic double-gyre flow is addressed as its dynamics is known to be heavily affected by the multi-scale interactions. Given a relatively short dataset produced by a high-resolution model that resolves all the necessary scales resulting in the correct coupling between the transient features and large-scale components, we extract information relating to the coupling from this dataset and augment the low-resolution model with this information. As a result,
the augmented low-resolution model demonstrates similar to the corresponding high-resolution model spectral characteristics. The geometric structure of the double-gyre flow in the augmented model becomes much more realistic. The large-scale structure of the double-gyre flow featuring a persistent eastward-jet barrier between the gyres, which is characteristic of the high-resolution model and absent in the low-resolution model, is satisfactory restored in the augmented model. The influence of the transient eddy-like features is then parameterised by a stochastic process in order to emulate the influence of the transient features. The stochastic process incorporates memory effects to produce reliable simulations.

ON FLUCTUATING AIR-SEA-INTERACTION IN LOCAL MODELS: LINEAR THEORY

Achim Wirth[1]
[1] LEGI/CNRS

The dynamics of three local linear models of air sea-interation commonly employed in climate or ocean simulations is compared. The models differ by whether or not the ocean velocity is included in the shear calculation applied to the ocean and the atmosphere. Analytic calculations for the models with deteministic and random forcing (white and colored) are presented. The short term behavior is similar in all models, which only small quantitative differences, while the longterm behavior differs qualitatively between the models.
The fluctuation-dissipation-relation, which connects the fast excitation to the slow dissipation, is establised for all models with random forcing.
The fluctuation-dissipation-theorem, which compares the response to an external forcing to internal fluctuations is established for a white-noise forcing and a colored forcing when the phase space is augmented by the forcing variable.
Using results from numerical integrations of stochastic differential equations shows that the fluctuation-theorem, which compares the probability of positive to negative fluxes of the same magnitude, averaged over time-intervals of varying length, holds for the energy gained by the ocean from the atmosphere.

STOCHASTIC PARAMETERIZATION BY TRANSPORT

Darryl Holm[1] - Invited Speaker

[1] Imperial College London

We discuss a data driven approach for parametrising the small fast scales of GFD flows by using temporal homogenization of Lagrangian paths. This approach leads to stochastic transport, instead of stochastic forcing or diffusion. The approach is called SALT (Stochastic Advection by Lie Transport). It is consistent with Newton's force law and Kelvin's circulation theorem. It can also be derived via a stochastic variational principle. The physics packages inherit stochasticity from the stochastically advected material properties. A methodology for calibrating the stochastic parameters using data analysis, quantifying the resulting uncertainty, and then reducing the uncertainty by using a further data assimilation step based on particle filtering will also be described.

NEW DERIVATION OF EULER-α EQUATIONS AS A MEAN FLOW MODEL FOR THE MOTION OF IDEAL FLUID: STOCHASTIC APPROACH

Sergiy Vasylkevych[1] and Marcel Oliver[2]

[1] Universität Hamburg, [2] Jacobs University

Euler-α equations were originally derived by D. Holm, J. Marsden, and T. Ratiu as abstract Euler-Poincare equations. Later they were re-derived by Holm, Marsden and Shkoller via a form of Lagrangian averaging as a turbulence model for the ideal fluid flow, where the small parameter α can be interpreted as a filtering length scale. The set of closure assumptions leading to this derivation consists of

- generalized Taylor hypothesis, stating that first order fluctuations are transported by the mean flow as vector fields;
- statistical near isotropy of fluctuations;
- second order fluctuations are parallel transported by the mean flow.

Importantly, the generalized Taylor hypothesis and isotropy are mutually consistent only over short O(α) time-intervals. We modify the Taylor hypothesis with strong damping and stochastic terms and proceed to re-derive Euler- equations using geometric generalized Lagrangian mean framework, recently proposed by D. Gilbert and J. Vanneste. The proposed stochastic Taylor hypothesis ensures that near isotropy persists over long time-scales of $O(\alpha^{-1+\delta})$. The second order closure assumption is also no longer needed, as it arises as a necessary consequence of the geometric notion of averaged map together with the stochastic Taylor hypothesis.

DYNAMICS UNDER LOCATION UNCERTAINTY AND OTHER ENERGY-RELATED STOCHASTIC SUBGRID SCHEMES

Valentin Resseguir[1], Long Li[2], Gabriel Jouan[1], Pierre Dérian[2], Etienne Mémin[2] and Bertrand Chapron[3]

[1] L@b, SCALIAN, [2] INRIA, [3] IFREMER

Subgrid processes induce strong errors in numerical simulations of geophysical flows. These effects can be quantified and possibly tempered through ensemble forecasts and stochastic subgrid parameterizations. Similar to the SALT method (Holm, 2015), the LU models (Mémin, 2014) are physically-based schemes which assume the stochastic transport of physical quantities by a combination of resolved and unresolved velocities. The latter is assumed to be random and uncorrelated in time but correlated in space. LU dynamics conserves energy. It also brings correlated additive and multiplicative noises and turbulent dissipations into transport equations. Several parametrizations (i.e. unresolved velocity covariance choices) with tuning (denoted "mu_spec", Resseguier et al., 2017) or without (denoted "mu_adsd", Fox-Kemper et al., in preparation) have already been proposed and successfully tested. Here, a new LU parametrization (denoted "mu_svd") -- based on spatial points random local switching -- is introduced. Moreover, we propose a new energy-budget-based stochastic subgrid tensor (denoted "mu_wavhv50"). It is built to stochastically backscatter a given ratio of the dissipation induced by the deterministic subgrid tensor.

For a Surface Quasi-Geostrophic flow, this talk will compare uncertainty skills of different ensemble forecast methods: two types of random perturbations of initials conditions (denoted "PIC"), three types of dynamics under location uncertainty (LU) and our new energy-budget-based stochastic subgrid tensor. Point-wise metrics (MSE, squared bias minus variance, CRPS) and multi-dimensional ones (energy score, variogram) are computed to quantify short-term ensemble forecasts skills of a free-decaying turbulence and a filament instability (see figure 1). In the longer term, ensembles are evaluated through their capabilities to encompass the different likely scenarios introduced by a bifurcation.

References:

- B. Fox-Kemper, D. D. Holm, W. Pan and V. Resseguier (in preparation). "Data-driven versus self-similar parameterizations for Stochastic Lie Transport and Location Uncertainty".
- D. D. Holm (2015). „Variational principles for stochastic fluid dynamics." Proc. R. Soc. A 471.2176: 20140963.
- E. Mémin (2014). "Fluid flow dynamics under location uncertainty". Geophys. Astrophys. Fluid Dyn., 108(2):119-146.
- V. Resseguier, E. Mémin, B. Chapron (2017). „Geophysical flows under location uncertainty, Part II Quasi-geostrophy and efficient ensemble spreading", Geophys. Astrophys. Fluid Dyn.

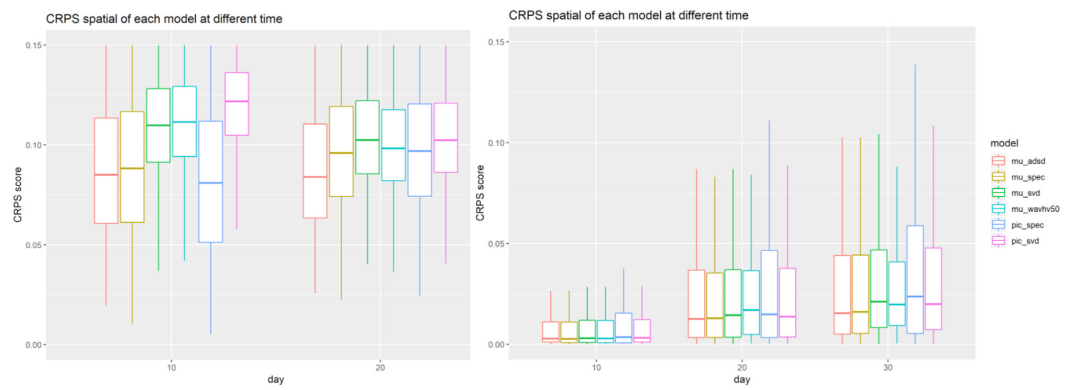


Figure 1 : Evolution over time of the box-plots of the distribution (in the sense of the values in different points) of the CRPS, computed on different ensembles, for free-decaying turbulence (left) and a filament instability (right).

NUMERICAL DEVELOPMENT AND EVALUATION OF AN ENERGY CONSERVING CONCEPTUAL STOCHASTIC CLIMATE MODEL

Federica Gugole[1] and Christian Franzke[1]

[1] Universität hamburg

We systematically derive an energy conserving conceptual stochastic climate model based on the inviscid 2-layer Quasi-Geostrophic (QG) equations. The stochastic terms have been introduced in such a way that the total energy is conserved. In this proof of concept study we give particular emphasis to the numerical aspects of energy conservation in a high-dimensional complex stochastic system. Our results show that the stochastic model conserves energy to an accuracy of about 0.5% of the total energy; this level of accuracy is mainly due to the level of accuracy of the deterministic discretization of the QG model. Furthermore, our results demonstrate that spatially correlated noise is necessary for the conservation of energy and the preservation of important statistical properties, while using spatially uncorrelated noise violates energy conservation and gives unphysical results. The spatial covariance structure is determined through Empirical Orthogonal Functions (EOFs). We find that only a small number of EOFs is needed to get good results with respect to energy conservation, autocorrelation functions, PDFs and eddy scale when comparing a 512x512 deterministic control to a 128x128 stochastic simulation. Our stochastic approach has the potential to seamlessly be implemented in comprehensive weather and climate prediction models.

Imprint

Publisher
TRR 181 „Energy transfers in Atmosphere and Ocean“
Center for Earth System Research and Sustainability
Universität Hamburg

SFB 1294 „Data Assimilation“
Universität Potsdam

SFB 1114 „Scaling Cascades in Complex Systems“
Freie Universität Berlin

Design
Herr Fritz Kommunikationsdesign
www.herr-fritz.de

Picture credits
NASA/Goddard Space Flight Center Scientific Visualization Studio (p. 1 (left)); Center for Earth System Research and Sustainability/German Climate Computing Center (p. 1 (right)); Thomas Wasilewski (p. 2 (left), 8); Alexander Kuhn/ Dept. Visual Data Analysis, Zuse Institute Berlin (p. 2 (right)); Universität Potsdam/ K. Fritze (p. 4)