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Dear Colleague,

Welcome to the fifth annual meeting of the CliMathNet network! For the first time the meeting is being held at the campus of the University of Reading.

This network was set up four years ago with the intention of linking mathematicians, climate scientists and policy makers. Since then it has run a wide range of activities, with the annual meetings as the centrepiece. We are happy to acknowledge funding from EPSRC, under the auspices of ReCoVER, for the continuation for this and next year. Note that several of the contributions are from projects that have been supported by ReCoVER.

We hope that you find the plenary and contributed talk on these topics informative, as well as taking advantage of the opportunity to meet others and to learn from each other. This year, we will have on Tuesday afternoon a session specifically dedicated to young scientists, with the goal of showcasing some examples of high quality research being performed by graduate students in UK universities. We also hope that you will have a chance to join us for the conference dinner on the same day. On Thursday afternoon, we shall have a discussion session aimed at receiving feedback and ideas from the meeting’s participants. The purpose of CliMathNet has always been to bring people together in this area, and we hope that you will all contribute to make this a success. We hope you enjoy the meeting and that it will spark collaborations, both new and old.

Your sincerely,

Peter Ashwin and Valerio Lucarini
On behalf of the scientific committee
Scientific Programme

The conference addresses emerging mathematical, computational and statistical techniques for understanding weather and climate. Areas of interest include:

- Stochastic and deterministic modelling
- Data/model fusion and assimilation
- Prediction and predictability
- Climate variability and climate change
- Understanding future from past climatic conditions
- Extreme events and critical transitions
- Model reduction techniques and parameterisation
- Downscaling and post-processing
- Geophysical turbulence
- Statistical Mechanics of Climate
- Numerical Models
- High Performance Computing

The Conference Programme is being organised by Prof Valerio Lucarini, University of Reading with the help of the scientific committee:

**The Scientific Committee:**

Valerio Lucarini, University of Reading, Chair
Peter Ashwin, University of Exeter
Tamas Bodai, University of Reading
Jochen Broecher, University of Reading
Hayley Fowler, University of Newcastle
Melina Freitag, University of Bath
Darryl Holm, Imperial College, London
Tobias Kuna, University of Reading
Claudia Neves, University of Reading
Jennifer Scott, University of Reading
Ted Shepherd, University of Reading
Paul Williams, University of Reading

**Also with thanks to:**

Emily Paremain, ReCoVER
Lea Oljaca, University of Reading
Plenary Speakers

<table>
<thead>
<tr>
<th>Freddy Bouchet</th>
<th>Andrey Gritsun</th>
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<tr>
<td>Gualtiero Badin</td>
<td>Wilco Hazeleger</td>
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<tr>
<td>Mickael Checkroun</td>
<td>Christian Kuehn</td>
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<tr>
<td>Davide Faranda</td>
<td>Philippe Naveau</td>
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<tr>
<td>Ulrike Feudel</td>
<td>Peter Read</td>
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<td>Jeroen Wouters</td>
<td>Stéphane Vannitsem</td>
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## Programme

**Tuesday 29th August**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>10.00</td>
<td>Registration</td>
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<tr>
<td>10.30</td>
<td>Arrival tea and coffee</td>
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<tr>
<td>11.45</td>
<td>Welcome and Introduction</td>
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<tr>
<td>12.00</td>
<td>Invited Talk: <strong>Peter Read</strong>, University of Oxford</td>
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<tr>
<td></td>
<td>Macroturbulent cascades of energy and enstrophy in observations and models of planetary atmospheres</td>
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<tr>
<td>12.45</td>
<td>Lunch</td>
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<td><strong>Early Career Researcher Session</strong></td>
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<tr>
<td>13.40</td>
<td><strong>Lea Oljaca</strong>, University of Reading</td>
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<tr>
<td></td>
<td>Asymptotic accuracy of data assimilation with unbounded stochastic noise</td>
</tr>
<tr>
<td>14.00</td>
<td><strong>Elizabeth Cooper</strong>, University of Reading</td>
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<td>A new observation operator for ensemble Kalman filter data assimilation in fluvial flood forecasting</td>
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<tr>
<td>14.20</td>
<td><strong>Victor Estella-Perez</strong>, National Oceanography Centre Southampton</td>
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<td>Impacts of initial SSS errors on the AMOC decadal predictability problem</td>
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### Tuesday 29th August - continued

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker/Title</th>
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| 14.40 | **Marco Gorelli**, University of Reading  
Regularity structures, controlled rough paths and snowflakes |
| 15.00 | Tea and Coffee |
| 15.30 | **Andrea Gabrielski**, University of Reading  
A 2.5-Layer Diabatic Long-wave Balance Model for the Equatorial $\beta$-plane |
| 15.50 | **Joakim Kjellsson**, University of Oxford  
The impact of horizontal resolution on energy transfers in ocean models |
| 16.10 | **Marco Cucchi**, Amigo Climate  
The Extreme Climate Index: a novel and multi-hazard index for extreme weather events |
| 16.30 | **Daniel Green**, University of Bath  
A low-rank approach to the solution of weak constraint variational data assimilation problems |
| 16.50 | **Vera Melinda Galfi**, International Max Planck Research School on Earth System Modelling  
Extreme value statistics in a two-layer quasi-geostrophic atmospheric model |
| 17.10 | **Poster Introductions**  
All of those presenting posters are asked to be available to introduce their poster and to answer questions |
| 17.30 | Poster Session |
| 19.00 | Conference Dinner, Meadow Suite Park House |
### Wednesday 30th August

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>08.45</td>
<td>Arrival Tea and Coffee</td>
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<tr>
<td>09.30</td>
<td>Invited Talk: <strong>Christian Kuehn</strong>, Technical University of Munich</td>
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<tr>
<td></td>
<td>Stochastic PDEs in Climate: Tipping and Numerical Continuation</td>
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<tr>
<td>10.15</td>
<td>Invited Talk: <strong>Mickael Checkroun</strong>, UCLA</td>
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<td>To be confirmed</td>
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<tr>
<td>11.00</td>
<td>Tea, Coffee and Posters</td>
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<tr>
<td>11.30</td>
<td>Invited Talk: <strong>Ulrike Feudel</strong>, Carl von Ossietzky University Oldenburg</td>
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<td></td>
<td>Harmful algal blooms: combining excitability, competition and hydrodynamic flows</td>
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<tr>
<td>12.15</td>
<td>Invited Talk: <strong>Andrey Gritsun</strong>, Russian Academy of Sciences, Moscow</td>
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<td></td>
<td>Instability characteristics of blocking regimes in a simple quasigeostrophic atmospheric model</td>
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<td>13.00</td>
<td>Lunch</td>
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**Contributed Talks in Parallel Sessions**

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<thead>
<tr>
<th>Session 1</th>
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<tr>
<td>14.00  <strong>Peter Watson</strong>, University of Oxford</td>
<td><strong>Anna von der Heydt</strong>, Utrecht University</td>
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<tr>
<td>The impact of stochastic physics on tropical rainfall variability in global climate models on daily to weekly timescales</td>
<td>The Eocene-Oligocene transition - observations, mechanisms, cascading tipping?</td>
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<td>Time</td>
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<tr>
<td>14.20</td>
<td><strong>Katherina Schlinagl</strong>, University of Bonn</td>
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<td>Bayesian inverse modeling for quantitative precipitation estimation</td>
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<tr>
<td>14.40</td>
<td><strong>Henning Rust</strong>, Freie Universität Berlin</td>
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<td>Re-calibration of decadal ensemble predictions</td>
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<td>15.00</td>
<td><strong>Mark Williamson</strong>, University of Exeter</td>
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<td>Towards an emergent constraint on equilibrium climate sensitivity</td>
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<tr>
<td>15.20</td>
<td>Tea, Coffee and Posters</td>
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<tr>
<td>16.00</td>
<td><strong>Frank Kwasniok</strong>, University of Exeter</td>
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<td></td>
<td>Data-driven stochastic subgrid modelling: a pattern-based approach</td>
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<tr>
<td>16.20</td>
<td><strong>John Bruun</strong>, Independent Researcher</td>
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<td>Heartbeat of the Southern Oscillation explains ENSO climatic resonances</td>
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<tr>
<td>16.40</td>
<td><strong>Jochen Broecker</strong>, University of Reading</td>
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<td></td>
<td>What is the correct cost functional for variational data assimilation?</td>
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<tr>
<td>17.00</td>
<td><strong>Tobias Kuna</strong>, University of Reading</td>
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<td>Extreme values for dynamical systems and linear response</td>
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<td>17.20</td>
<td>End of Day</td>
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### Thursday 31st August

<table>
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<tr>
<th>Time</th>
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<tr>
<td>08.45</td>
<td>Arrival Tea and Coffee</td>
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<tr>
<td>09.30</td>
<td>To be confirmed</td>
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<tr>
<td>10.15</td>
<td>Invited Talk: Wilco Hazeleger, Netherlands eScience Centre</td>
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<td>Future Weather Extremes</td>
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<tr>
<td>11.00</td>
<td>Tea, Coffee and Posters</td>
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<tr>
<td>11.30</td>
<td>Invited Talk: Freddy Bouchet, ENS de Lyon and CNRS</td>
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<td>Title: To be confirmed</td>
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<tr>
<td>12.15</td>
<td>Invited Talk: Gualtiero Badin, University of Hamburg</td>
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<td></td>
<td>A study of surface semi-geostrophic turbulence: freely decaying dynamics</td>
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<tr>
<td>13.00</td>
<td>Lunch</td>
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Thursday 31st August - continued

<table>
<thead>
<tr>
<th>Time</th>
<th>Session 1</th>
<th>Session 2</th>
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<tbody>
<tr>
<td>14.00</td>
<td><strong>Zahari Zlatev</strong>, Aarhus University</td>
<td><strong>Valerio Lembo</strong>, University of Hamburg</td>
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<td>Studying the Impact of Climate Changes on Pollution Levels</td>
<td>A new software for diagnosing water, energy and entropy budgets in climate models</td>
</tr>
<tr>
<td>14.20</td>
<td><strong>Paul Williams</strong>, University of Reading</td>
<td><strong>Jill Johnson</strong>, University of Leeds</td>
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<td>Optimising flight routes through an atmospheric wind field: the effects of climate change</td>
<td>Confronting the Uncertainty in Regional Aerosol Forcing with Comprehensive Observational Data</td>
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<tr>
<td>14.40</td>
<td><strong>Peter Dueben</strong>, ECMWF</td>
<td>To be confirmed</td>
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<tr>
<td></td>
<td>To link precision to predictability to optimise ensemble predictions</td>
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<tr>
<td>15.00</td>
<td><strong>Tamas Bodai</strong>, University of Reading</td>
<td><strong>Alemtsehai Turasie</strong>, University of Witwatersrand</td>
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<td></td>
<td>Linear response theory applied to geoengineering</td>
<td>Exceedance and return period of high temperatures in the African region</td>
</tr>
<tr>
<td>15.20</td>
<td>Tea, Coffee and Poster</td>
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<tr>
<td>16.00</td>
<td>Discussion session</td>
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<tr>
<td>17.00</td>
<td>End of Day</td>
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## Friday 1st September

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Details</th>
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<tbody>
<tr>
<td>08.45</td>
<td>Arrival Tea and Coffee</td>
</tr>
</tbody>
</table>
| 09.30 | Invited Talk: **Jeroen Wouters**, University of Reading  
Beyond the limit of infinite time-scale separation: Edgeworth approximations and homogenisation |
| 09.45 | Invited Talk: **Davide Faranda**, Laboratoire des Sciences du Climat et l'Environnement (LSCE) CNRS  
Stochastic Chaos in a Turbulent Swirling Flow |
| 11.00 | Tea, Coffee and announcement of the winner of the poster competition |
| 11.30 | Invited Talk: **Stéphane Vannitsem**, Royal Meteorological Institute of Belgium  
A dynamical systems approach to investigating the low-frequency variability of the ocean-atmosphere coupled system |
| 12.15 | Invited Talk: **Philippe Naveau**, Laboratoire des Sciences du Climat et l'Environnement (LSCE) CNRS  
An entropy-based test for multivariate extreme value models |
| 13.00 | Lunch |
| 14.00 | End of Conference |
Invited Speaker Abstracts

Gualtiero Badin, University of Hamburg

Title: A study of surface semi-geostrophic turbulence: freely decaying dynamics

Abstract:
In this study we give a characterization of semi-geostrophic turbulence by performing freely decaying simulations for the case of constant uniform potential vorticity, a set of equations known as the surface semi-geostrophic approximation. The equations are formulated as conservation laws for potential temperature and potential vorticity, with a nonlinear Monge-Ampère type inversion equation for the streamfunction, expressed in a transformed coordinate system that follows the geostrophic flow. We perform model studies of turbulent surface semi-geostrophic flows in a domain doubly periodic in the horizontal and limited in the vertical by two rigid lids, allowing for variations of potential temperature at one of the boundaries, and we compare the results with those obtained in the corresponding surface quasi-geostrophic case. The results show that, while the surface quasi-geostrophic dynamics is dominated by a symmetric population of cyclones and anticyclones, the surface semi-geostrophic dynamics features a more prominent role of fronts and filaments. The resulting distribution of potential temperature is strongly skewed and peaked at non-zero values at and close to the active boundary, while symmetry is restored in the interior of the domain, where small-scale frontal structures do not penetrate. In surface semi-geostrophic turbulence, energy spectra are less steep than in the surface quasi-geostrophic case, with more energy concentrated at small scales for increasing Rossby number. The energy related to frontal structures, the lateral strain rate and the vertical velocities are largest close to the active boundary. These results show that the semi-geostrophic model could be of interest for studying the lateral mixing of properties in geophysical flows. Work in collaboration with F. Ragone.

Freddy Bouchet, ENS de Lyon and CNRS

Title and Abstract
To be confirmed

Mickael Checkroun, UCLA

Title and Abstract
To be confirmed
Davide Faranda, French National Centre for Scientific Research

Title: Stochastic Chaos in a Turbulent Swirling Flow

Authors: D. Faranda, Y. Sato, B. Saint-Michel, C. Wiertel, V. Padilla, B. Dubrulle, and F. Daviaud

Abstract:
We report the experimental evidence of the existence of a random attractor in a fully developed turbulent swirling flow. By defining a global observable which tracks the asymmetry in the flux of angular momentum imparted to the flow, we can first reconstruct the associated turbulent attractor and then follow its route towards chaos. We further show that the experimental attractor can be modeled by stochastic Duffing equations, that match the quantitative properties of the experimental flow, namely, the number of quasistationary states and transition rates among them, the effective dimensions, and the continuity of the first Lyapunov exponents. Such properties can be recovered neither using deterministic models nor using stochastic differential equations based on effective potentials obtained by inverting the probability distributions of the experimental global observables. Our findings open the way to low-dimensional modeling of systems featuring a large number of degrees of freedom and multiple quasistationary states.

Ulrike Feudel, Carl von Ossietzky University Oldenburg

Title: Harmful algal blooms: combining excitability, competition and hydrodynamic flows

Abstract:
Harmful algal blooms (HABs) are rare events which are characterized by a sudden large abundance of potentially toxic plankton species which can alter the dynamics of the whole ecosystem. Since as a consequence of climate change, the frequency of HABs is increasing, there is a strong need in understanding the possible causes for such bloom events.

We discuss a model, which is based on the idea of an excitable activator-inhibitor system in which two activators (toxic and non-toxic phytoplankton) compete with each other and the inhibitor (zooplankton) has a certain preference for a specific activator. We show how the interplay of the competition and environmental factors like increasing nutrient input due to upwelling result in a sudden growth of toxic species.

Hydrodynamic flows are also important determinants for the emergence and the spread of HABs in the real ocean. Analyzing data from observations in the Southern California Bight we demonstrate, that particularly mesoscale hydrodynamic vortices are of crucial importance for the spread of HABs. Moreover, such vortices can lead to heterogeneous dominance patterns of different plankton species in the ocean. We illustrate the mechanism of the emergence of spatially localized HABs using a simplified kinematic flow. Furthermore we demonstrate the importance of the interplay between biological and hydrodynamic time scales for the formation of blooms.
Andrey Gritsun, Russian Academy of Sciences, Moscow

Title: Instability characteristics of blocking regimes in a simple quasigeostrophic atmospheric model

Abstract:
In this paper we study statistics and instability characteristics of blocking events in the three layer quasi-geostrophic model of atmosphere by Marshall and Molteni. It is shown that the model is able to reproduce reasonable longitudinal distribution of blocking events as well as simulate blocking events with lifetime of up to 40 days. Using Lyapunov exponents and covariant Lyapunov vectors we analyze predictability of onset, duration and decay of blockings. It is shown that on the average blockings are less predictable than the system trajectory with the blocking onset and decay being the most unstable and unpredictable. We verify our findings by looking at unstable periodic orbits (UPOs) of the system representing blocking and nonblocking events. It was found that blocking UPOs have 20% more positive (unstable) Lyapunov exponents than the system trajectory, and 50% larger leading exponent.

Wilco Hazelheger, Wageningen University

Title: Future Weather Extremes

Abstract:
Extreme weather events expose society’s vulnerability to weather. Recent extreme events are placed more and more in the context of climate change. Event attribution can indicate whether the risk of extreme events changes due to climate change. Information on future climate, however, is often based on projections with relatively coarse resolution climate models that may not resolve such extremes well. Downscaling can remedy this partly since the driving of extremes are often of large scale nature, such as blocking, and events are often compounded. We place recent extremes in a future context. We use EC-Earth simulations to generate plausible simulations of future weather events, similar to those experienced in current climate. We enrich the model information with knowledge on the physics and on vulnerability and impacts of the events. Different cases will be presented, such as the wet winter of 2013/14 in the UK and extreme rainfall in the city of Amsterdam last summer. Finally, some technological and methodological challenges will be addressed which will help the climate research community to generate high resolution simulations.
Christian Kuehn, Technical University of Munich

Title: Stochastic PDEs in Climate: Tipping and Numerical Continuation

Abstract:
In my talk, I am going to give an introduction to several aspects of stochastic partial differential equations (SPDEs) in climate modelling with a view towards practical applications. First, I am going to show that the theory of early-warning signs for critical transitions (or tipping points) can be extended to cover spatially extended systems, i.e., it is possible to extract warning signs from spatial data in certain cases. Secondly, I am going to illustrate, how one can compute bifurcation diagrams - and hence locate certain tipping points - effectively using numerical continuation in models. I shall demonstrate a major extension of these methods to SPDEs. The numerical methods will be illustrated with an SPDE model for the AMOC. The talk is also intended as a showcase, how flexible and broad the applications of SPDEs could be in climate science in the future.

Philippe Naveau, Laboratoire des Sciences du Climat et l’Environnement

Title: An entropy-based test for multivariate extreme value models

Sebastian Engelke Ecole Polytechnique Fédérale de Lausanne (Switzerland)
Philippe Naveau Laboratoire des Sciences du Climat et l’Environnement (France)
Chen Zhou Erasmus Universiteit Rotterdam & De Nederlandsche Bank (The Netherlands)

Abstract:
Many effects of climate change seem to be reflected in the frequency and severity of the extreme events in the distributional tails. Detecting such changes requires a statistical methodology that efficiently uses the large observations in the sample. We propose a simple, non-parametric test that decides whether two multivariate distributions exhibit the same tail behaviour. The test is based on the entropy, namely Kullback-Leibler divergence, between exceedances over a high threshold of the two multivariate random vectors. We show that such a type of divergence is closely related to the divergence between Bernoulli random variables. We study the properties of the test and further explore its effectiveness for finite sample sizes. As an application we apply the method to precipitation data where we test whether the marginal tails and/or the extreme value dependence structure have changed over time.

Key Words: multivariate extreme value dependence, Kullback-Leibler divergence, asymptotics.
Peter Read, University of Oxford

Title: Macroturbulent cascades of energy and enstrophy in observations and models of planetary atmospheres

P. L. Read, F. Tabataba-Vakili, A. Valeanu, Y. Wang & R. M. B. Young
Atmospheric, Oceanic & Planetary Physics, Department of Physics, University of Oxford, UK.

Abstract:
Many features of the structure and evolution of the large-scale flows in the atmospheres (and oceans) of the Earth and other planets can be regarded as resulting from the nonlinear exchanges of energy (kinetic and potential) and vorticity (enstrophy) across widely varying length and time scales in processes described as “macroturbulent cascades”. The influence of planetary rotation can be very substantial on some scales, for example, leading to quasi-two-dimensional flows accompanied by upscale transfers of kinetic energy, the dominance of anisotropically propagating waves and the formation of zonal jets. The theory behind these processes is far from complete, however, and it is important, therefore, to explore the quantitative character of such macroturbulent cascades in models and (where possible) in observations over a wide range of conditions. We will present diagnostics of such cascades of kinetic (and, in some cases, potential) energy and enstrophy in new analyses of observations of the atmospheres of Jupiter and Mars, based on structure functions and spectral flux computations for comparison with the Earth’s atmosphere and oceans. These reveal some clear similarities and differences, with evidence of upscale cascades at large scales and downscale transfers at small and mesoscales, though the precise nature of these downscale cascades is still uncertain. Similar trends are found in a set of simplified global circulation model simulations of Earth-like planetary atmospheres across a wide range of planetary parameters. These results will be discussed in the context of an over-arching theoretical framework for planetary and mesoscale turbulence.
Stéphane Vannitsem, Royal Meteorological Institute of Belgium

Title: A dynamical systems approach to investigating the low-frequency variability of the ocean-atmosphere coupled system.

Abstract:
The low-frequency variability (LFV) of the atmosphere at mid-latitudes develops on a wide range of time scales. One particularly interesting indicator of this variability is the North Atlantic Oscillation index measuring the fluctuations of predominant weather patterns in the course of the years over the Atlantic and Western Europe. The source of variability is, however, controversial and several possibilities have been envisaged, including oceanic and coupled ocean-atmosphere variability and stratospheric warming, possibly related to ENSO in the tropical Pacific.

Recently we have demonstrated that genuinely coupled LFV can emerge in a very simple low-order, nonlinear, coupled ocean-atmosphere model. This LFV concentrates on and near a long-periodic, attracting orbit. This orbit combines atmospheric and oceanic modes, and it arises for large values of the meridional gradient of radiative input and of the frictional coupling. Chaotic behavior develops around this orbit as it loses its stability. This behavior is still dominated by the LFV on decadal and multi-decadal time scales that is typical of oceanic processes. Furthermore, this natural coupled mode is still present as the number of variables is increased in the model. This dynamics will be discussed in the first part of the talk.

In the second part, we will discuss the relevance of these results for the realistic coupled ocean-atmosphere dynamics emerging from reanalysis datasets, using advanced tools from nonlinear time series analysis. It is shown in particular that LFV is present in the real coupled dynamics over the Atlantic, bearing some resemblances with the one that could be emulated in the low-order system.

Jeroen Wouters, University of Reading

Title: Beyond the limit of infinite time-scale separation: Edgeworth approximations and homogenisation

Abstract:
Homogenization has been widely used in stochastic model reduction of slow-fast systems, including geophysical and climate systems.

The theory relies on an infinite time scale separation. In this talk we present results for the realistic case of finite time scale separation. In particular, we employ Edgeworth expansions as finite size corrections to the central limit theorem and show improved performance of the reduced stochastic models in numerical simulations.
David Armstrong McKay
Agent-based models for the analysis of early warning signals of ecosystem tipping points

University of Southampton

David L Armstrong McKay*, James G. Dyke¹, John A. Dearing¹, C. Patrick Doncaster², Rong Wang³
¹Geography and Environment, University of Southampton
²Biological Sciences, University of Southampton
³Nanjing Institute of Geography and Limnology Chinese Academy of Sciences
*D.Armstrong-McKay@noc.soton.ac.uk

Rather than respond gradually to stressors, ecosystems can suddenly undergo a critical transition to a new regime state after reaching a tipping point, such as a lake shifting from a clear to turbid state as a result of eutrophication. Much effort has been employed in developing robust early warning signals (EWS) of impending tipping points by monitoring certain ecosystem properties for statistically observable changes such as increasing autocorrelation and variance. However, these ‘classical’ EWS techniques have not always been found to be reliable in predicting critical transitions in a wide range of systems. More recently novel methodologies focusing on the changing structural composition of an ecosystem, including compositional disorder (Doncaster et al, 2016) and food web stability (Kuiper et al, 2015), have been developed that offer an alternative means of assessing ecosystem stability and potentially providing robust EWS. Here we present preliminary results of the further development of these structure-based EWS methods, using lake eutrophication as a test-bed. In particular we seek to establish whether the dynamics of diatom populations can be used as an easily monitored sub-system informing on the stability of the wider lake biogeochemical system. To this end an agent-based model of Lotka-Volterra competition dynamics for a community of diatoms responding to phosphorus loading is under development, which will be driven across critical transitions while monitoring for changes in both structure-based and classical EWS metrics. Convergent cross mapping (CCM) is used to trace causality through lake biogeochemical systems in order to confirm the structure of this modelling. The same EWS metrics are also applied to an extensive dataset of Chinese lakes, ranging from pristine and clear to polluted and turbid, in order to further assess the real-world potential of these methods. Further work will also include assessing the use of a Generalised Modelling (GM) approach, which allows stability to be monitored based on only a simplified representation of the system’s core relationships, and loop analysis to identify key feedback loops for monitoring.

Linked to ReCoVER Pilot Study Project RFFLP021: “Agent-based models for the analysis of early warning signals of ecosystem tipping points”
We investigate in an intermediate-complexity climate model the applicability of linear response theory to a geoengineering problem. Global climate change with respect to an appropriate ensemble average of the surface air temperature $[T]$ due to a given rise in carbon dioxide concentration [CO$_2$] is attempted to be cancelled out or modulated by an appropriately chosen modulation of the solar forcing. The latter is predicted by linear response theory in frequency-domain as: 

$$
\Delta f_s(\omega) = (\Delta<T>(\omega) - \chi_{CO2}(\omega)\Delta f_{CO2}(\omega)) / \chi_s(\omega),
$$

where the $\chi$'s are linear susceptibilities.

With a doubling of [CO$_2$] the response is nonlinear to a certain degree, but a significant cancellation with respect to (wrt.) $[T]$ is achieved, the asymptotic total response to combined forcing being only 10% of that with [CO$_2$]-doubling alone.

We investigate in this geoengineering scenario the response wrt. uncontrolled variables such as zonal or regional averages of $T$ too. The nonlinearities have a more severe effect wrt. the predictability of the spatial total response pattern, but in actual fact a significant cancellation is achieved even locally. Similar conclusions can be drawn wrt. the model variable of large scale precipitation.

We are able to reduce the asymptotic total response to combined forcing five-fold with an improved estimation of the linear susceptibility.
Heartbeat of the Southern Oscillation explains ENSO climatic resonances

Independent Researcher

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The El Niño–Southern Oscillation (ENSO) non-linear oscillator phenomenon has a far reaching influence on the climate and human activities. The up to 10 year quasi-period cycle of the El Niño and subsequent La Niña is known to be dominated in the tropics by non-linear physical interaction of wind with the equatorial wave-guide in the Pacific. Long term cyclic phenomena do not feature in the current theory of the ENSO process. We update the theory by assessing low (> 10 years) and high (< 10 years) frequency coupling using evidence across tropical, extratropical and Pacific basin scales. We analyse observations and model simulations with a highly accurate method called Dominant Frequency State Analysis (DFSA) to provide evidence of stable ENSO features. The observational datasets of the Southern Oscillation Index (SOI), North Pacific Index Anomaly and ENSO Sea Surface Temperature Anomaly, as well as a theoretical model all confirm the existence of long and short term climatic cycles of the ENSO process with resonance frequencies of \{2.5, 3.8, 5, 12 to 14, 61 to 75, 180\} years. This fundamental result shows long and short term signal coupling with mode locking across the dominant ENSO dynamics. These dominant oscillation frequency dynamics, defined as ENSO frequency states, contain a stable attractor with three frequencies in resonance allowing us to coin the term Heartbeat of the Southern Oscillation due to its characteristic shape. We predict future ENSO states based on a stable hysteresis scenario of short and long term ENSO oscillations over the next century.
During a fluvial flood, future water levels and flood extents can be forecast with a numerical hydrodynamic model. Such predictions can be inaccurate; data assimilation is a powerful tool that can be used for state and parameter estimation to improve forecast skill. In data assimilation, model predictions are updated using observational information, taking into account the uncertainties in both the observations and the model forecast. This process requires a suitable observation operator. The observation operator maps model predictions into observation space so that the difference between the observations and the model forecast can be calculated. In this paper we demonstrate a novel observation operator for inundation forecasting using observations from synthetic aperture radar (SAR) satellite instruments. We compare its performance with that of two more conventional approaches in which image processing techniques are used to differentiate between dry and wet areas to locate flood extents. Flood extent information is then intersected with a digital terrain map to calculate water elevation at suitable, usually sparse flood edge locations; the observation operators compute the model water level at corresponding locations. Our new approach directly uses SAR backscatter values as observations and simulates backscatter values for wet and dry model pixels using a statistical model; such an approach has not been used before in an ensemble Kalman filtering framework. This new approach potentially allows for the use of many more observations per SAR image than the flood edge observation approach, but the observations do not contain any water height information. We compare the performance of the three operators in synthetic twin experiments in an idealised domain and discuss the strengths and weaknesses of the three approaches. We test how well the operators can predict true water levels and how well they can retrieve the correct value of an initially misspecified channel friction parameter, given SAR-like synthetic observations. We find that using a large number of observations in the new approach can lead to variance collapse in the channel friction parameter distribution and show that none of the observation operators works well when the river is not in flood. We find that our novel backscatter observation operator is able to produce good results in most situations and is therefore a promising new development in the field of data assimilation for inundation forecasting.
In this presentation we introduce the Extreme Climate Index (ECI): an objective, multi-hazard index capable of tracking changes in the frequency or magnitude of extreme weather events in African countries, thus indicating that a shift to a new climate regime is underway in a particular area. This index has been developed in the context of XCF (eXtreme Climate Facilities) project lead by ARC (African Risk Capacity, specialised agency of the African Union), and will be used in the payouts triggering mechanism of an insurance program against risks related to the increase of frequency and magnitude of extreme weather events due to climate regimes’ changes.

The main hazards covered by ECI will be extreme dry, wet and heat events, with the possibility of adding region-specific risk events such as tropical cyclones for the most vulnerable areas. It will be based on data coming from consistent, sufficiently long, high quality historical records and will be standardized across broad geographical regions, so that extreme events occurring under different climatic regimes in Africa can be comparable.

The first step to construct such an index is to define single hazard indicators. In this first study we focused on extreme dry/wet and heat events, using for their description respectively the well-known SPI (Standardized Precipitation Index) and an index developed by us, called SHI (Standardized Heat-waves Index). The second step consists in the development of a computational strategy to combine these, and possibly other indices, so that the ECI can describe, by means of a single indicator, different types of climatic extremes.

According to the methodology proposed in this paper, the ECI is defined by two statistical components: the ECI intensity, which indicates whether an event is extreme or not; the angular component, which represent the contribution of each hazard to the overall intensity of the index. The ECI can thus be used to identify “extremes” after defining a suitable threshold above which the events can be held as extremes.

In this presentation, after describing the methodology we used for the construction of the ECI, we present results obtained on different African regions, using NCEP Reanalysis dataset for air temperature at sig995 level and CHIRP dataset for precipitations. Particular attention will be devoted to 2015/2016 Malawi drought, which received media attention due to the failure of the risk assessment model used to trigger insurance payouts: it will be shown how, on the contrary, combination of hydrological and temperature data used in ECI succeed in evaluating the extremeness of this event.
Predictability study of the coupled ocean-atmosphere system with maooam

Lesley De Cruz, Sebastian Schubert, Jonathan Demaeyer and Stephanie Vannitsem

Royal Meteorological Institute of Belgium, Brussels

The Modular Arbitrary-Order Ocean-Atmosphere Model (maooam) [1] was developed as free software at the Royal Meteorological Institute of Belgium (RMIB). It addresses the need for a flexible, fast and open tool to effectively study the dynamics of the coupled ocean-atmosphere system. Maooam uses a tensorial representation of the system of nonlinear ordinary differential equations, and is implemented in different languages: Fortran, Lua, and Python (since v1.2).

Maooam re-implements and extends earlier versions of a nonlinear coupled ocean-atmosphere model: OA-WS-QG v1 [2], OA-WS-QG v2 [3] and VDDG [4], based on the quasigeostrophic equations for a two-layer atmosphere, coupled to a shallow-water ocean layer through friction and an energy balance scheme. Maooam was shown to capture essential dynamical features such as the low-frequency variability (LFV) observed at mid-latitudes. This feature was shown to persist for higher model resolutions [1]. The modular design of maooam allows one to easily add physical processes, a feature that we exploit to investigate the impact of a scale-dependent dissipation, associated with turbulent diffusion.

We study the predictability of different configurations of maooam, and the impact of the model resolution, by computing the Lyapunov spectra. As in the 36-variable model [5], different groups of exponents can be discerned: next to the positive and negative exponents, there is a group of negative near-zero exponents, associated with the presence of a large time-scale separation. Finally, the impact of the scale-dependent dissipation and the ocean-atmosphere coupling strength on the Lyapunov spectra is investigated.

References
In operational weather forecasts ensemble methods gain more and more popularity since the spread of ensemble forecasts provides an estimate for the uncertainty of predictions (large spread -> large uncertainty; small spread -> low uncertainty). However, the evaluation of ensemble forecasts can only provide an approximation of local probability density functions of forecast variables at a given time and gridpoint. The quality of this approximation depends on the number of ensemble members in the forecast. A different approach would propagate probability density functions solving Liouville or Fokker-Planck equations. However, this could not yet be realised successfully for a system as complex as the Earth System.

We suggest a new approach to optimise ensemble simulations propagating approximations of probability density functions through existing Earth System models by calculating many ensemble members within a single model simulation. In general, this approach would increase computing time and memory requirements linearly with the number of ensemble members with limited benefit. However, we counteract this criticism suggesting a new storage format to represent prognostic variables in combined ensemble simulations. The new format is normalising ensemble data by both ensemble mean and ensemble spread for each model variable. Individual ensemble members are then stored using low precision integer numbers such that efficiency can be increased significantly in ensemble simulations. This format exploits similarities between ensemble members to reduce data volume and memory requirements significantly. The new format relates numerical precision to predictability such that precision will be high for predictable weather situations while it is low for uncertain weather regimes such that resources are optimised for reliable predictions. The suggested method can be realised on existing high performance computing architectures and within model code of the complexity of an Earth System model. The knowledge of ensemble spread within simulations opens new opportunities to adjust stochastic parametrisation schemes within model simulations and fellow ensemble members can be used to pre-condition elliptic solvers.

We demonstrate the usefulness of the new approach in simulations with a toy model for atmospheric dynamics (Lorenz’95) and we prove that the method works well for data of real Earth System models by testing it in model output of operational weather forecasts at ECMWF. We show that the suggested data format can also be used to improve data compression in data storage for ensemble simulations.
The Atlantic Meridional Overturning Circulation (AMOC) is one of the principal regulators of the climate system in the North Atlantic on decadal to multi-decadal time scales. The impact of initial errors in these time scales are still not yet completely understood, errors due to model forcing start to impact the predictability of the climate system as time scale increases. This work aims to look at the effects of initial errors on the AMOC variability and predictability on a decadal time scale, particularly in the initialization of the sea surface salinity field (SSS). We performed a set of experiments perturbing the initial surface salinity field in the North Atlantic. The perturbations considered are Gaussian perturbations that depend on two variables: intensity and horizontal extension. The results show a similar qualitative AMOC response but not quantitatively, nonlinear processes limit the intensity of the response. The anomalies imposed induce a propagation mechanism based on baroclinic Thermal Rossby waves affecting the convection sites in the Labrador Sea. They induce an oscillatory response of the AMOC that varies up to $0.14 \text{ Sv per psu}$ of the perturbation distributions maxima introduced. With the additional goal of understanding possible precursors of AMOC variability such as the observed Great Salinity Anomalies, current work is focused on reproduce the experiments in a higher resolution ocean model.
Some of the most serious effects of climate change are expected to be felt in the tropics. Yet climate models exhibit a wide divergence of predicted responses to climate change in the tropics, especially in terms of atmospheric circulation, and also struggle with accurately representing tropical variability. It is widely believed that the two problems are related, and that both stem from systematic model errors in diabatic heating associated with convection. Unfortunately, observational estimates of diabatic heating are highly uncertain, and there is no accepted framework for relating circulation and diabatic heating on large scales. Both factors limit progress in this area. An asymptotic expansion is used to derive a diabatic balance model for the Boussinesq equations on the equatorial β-plane. The approach is based on the anisotropy of planetary-scale flows and implies a semi-geostrophic balance between the zonal wind and the meridional pressure gradient at leading order. The balance model is a fully non-linear vertically layered model including a boundary layer, which will be extended to include a moisture budget. It provides a complete description of the low frequency planetary-scale structures in the tropics and thereby offers a theoretical framework to study the coupling between diabatic heating and the tropical circulation, including the relationship between different model errors. The balance relations can be used to calculate the wind field directly from temperature observations and to obtain better constrained observational estimates of diabatic heating. A number of numerical examples are presented to demonstrate the performance of the balance model.
**Vera Melinda Galfi**

**Extreme value statistics in a two-layer quasi-geostrophic atmospheric model**

Meteorological Institute, University of Hamburg

Vera Melinda Galfi (1,2), Tamas Bodai (3), Valerio Lucarini (1; 3; 4)

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We search for the signature of universal properties of extreme events, theoretically predicted for Axiom A flows, in a chaotic and high dimensional dynamical system by studying the convergence of GEV (Generalized Extreme Value) and GP (Generalized Pareto) shape parameter estimates to a theoretical value, expressed in terms of partial dimensions on the attractor. We consider a two layer quasi-geostrophic (QG) atmospheric model using two forcing levels, and analyse extremes of different types of physical observables. We find good agreement in the shape parameter estimates with the theoretical value only in the case of strong forcing, corresponding to a strongly chaotic behaviour, for some observables. In the case of weak forcing, inducing a less pronounced chaotic ow with regime behaviour, we find, unsurprisingly, worse agreement with the theory developed for Axiom A flows.

**Marco Gorelli**

**Regularity structures, controlled rough paths and snowflakes**

University of Reading

Marco Gorelli

Regularity structures are a relatively new theory, which build on elements of the theory of rough paths. They allow to make sense of ill-posed SPDEs (such as the KPZ equation) which arise in some physical models. I will give a quick introduction to the theory, and show how it applies to controlled rough paths. I will conclude with a section on the KPZ equation and snowflake growth.

**Daniel Green**

**A low-rank approach to the solution of weak constraint variational data assimilation problems**

University of Bath

Dan Green and Melina Freitag, University of Bath

Weak constraint four-dimensional variational data assimilation is an important method for incorporating data (typically observations) into a model. The linearised system arising within the minimisation process can be formulated as a saddle point problem. A disadvantage of this formulation is the large storage requirements involved in the linear system. In this talk, we present a low-rank approach which exploits the structure of the saddle point system using techniques and theory from solving large scale matrix equations. Numerical experiments with the linear advection-diffusion equation, and the non-linear Lorenz-95 model demonstrate the effectiveness of a low-rank Krylov subspace solver when compared to a traditional solver.
In [Holm, Proc. Roy. Soc. A 471 (2015)] stochastic fluid equations were derived by employing a variational principle with an assumed stochastic Lagrangian particle dynamics. Here we show that the same stochastic Lagrangian dynamics naturally arises in a multi-scale decomposition of the deterministic Lagrangian ow map into a slow large-scale mean and a rapidly uctuating small scale map. We employ homogenization theory to derive eective slow stochastic particle dynamics for the resolved mean part, thereby justifying stochastic uid partial equations in the Eulerian formulation. To justify the application of rigorous homogenization theory, we assume mildly chaotic fast small-scale dynamics, as well as a centering condition. The latter requires that the mean of the uctuating deviations is small, when pulled back to the mean flow.

Joint work with Colin J Cotter (Imperial college London) Georg A Gottwald (University of Sydney).
Confronting the Uncertainty in Regional Aerosol Forcing with Comprehensive Observational Data

University of Leeds

Jill S Johnson¹, Leighton Regayre¹, Masaru Yoshioka¹, Kirsty Pringle¹, David Sexton², Lindsay Lee¹ and Ken Carslaw¹

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The effect of aerosols on cloud droplet concentrations and radiative properties is the largest uncertainty in the overall radiative forcing of climate over the industrial period. This forcing cannot be quantified through observations because aerosol concentrations were not measured in the pre-industrial period. As such, aerosol forcing can only be estimated through model simulations. Simulating the global distribution and composition of aerosols in the atmosphere, and its effects on the climate, is highly complex and contains many sources of uncertainty.

In this study, we take advantage of a large perturbed parameter ensemble of model runs from the UK Met Office HadGEM-UKCA model (the aerosol component of UKESM1) and apply advanced statistical techniques to comprehensively sample the parametric model uncertainty in climatically important regions caused by uncertain aerosol and dynamical parameters. We find that the magnitude of model outputs (radiative forcing, aerosol concentrations and cloud amounts) and the uncertainty in those outputs is regionally dependent. We also identify the key sources of parametric uncertainty and find significant differences in which parameters drive the uncertainty both regionally and seasonally.

As the aerosol radiative forcing itself is unobservable, we investigate the potential for observations of aerosol and radiative properties (and changes in these properties over recent decades) to act as constraints on the large forcing uncertainty. We test how eight different theoretically ‘perfect’ aerosol and radiation observations can constrain our simulated forcing uncertainty over Europe. We find that the complex relationships between model output responses and the multiple interacting uncertainties in the model mean that the achievable constraint is weak unless many diverse observations are used simultaneously. We show that the aerosol forcing uncertainty can potentially be reduced by around 50% when we reduce a large sample of model variants (~1 million) that covers the full parametric uncertainty to around 1% that are observationally plausible.

This research has been supported by the UK-China Research & Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund, and by the NERC funded GASSP project.
The world ocean is a turbulent fluid with processes acting on a variety of spatial and temporal scales. Quantifying the flux of energy between different length scales helps us understand how the mean flow is maintained as well as the formation and breakdown of mesoscale eddies. To be able to simulate oceanic flows in a realistic manner, representing these fluxes of energy in ocean models is of vital importance.

We investigate the impact of horizontal resolution on the kinetic energy budget in a suite of realistic global ocean models. The set of ocean-only simulations have different horizontal resolution and horizontal viscosity, but with identical forcing. Similarly to results in idealised ocean models, we show that eddy-permitting ocean models have weaker kinetic energy cascades and thus weaker currents than eddy-resolving models. We further find discrepancies in the effect of wind forcing, horizontal viscosity, potential to kinetic energy conversion, and non-linear interactions. We also explore fluxes of kinetic energy within the barotropic and first baroclinic mode, as well as the partitioning of kinetic energy between them. We find that the mechanism by which baroclinic flows organise into barotropic flows is weaker at lower resolution, thus making the flow more baroclinic. Hence, the horizontal resolution of the model impacts the vertical structure, e.g. vertical shear of the simulated flow.

Our results suggest that the effect of mesoscale eddies can be parameterised by enhancing the potential to kinetic energy conversion, i.e. the horizontal pressure gradients, or enhancing the inverse cascade of kinetic energy.
Tobias Kuna

**Extreme values for dynamical systems and linear response**

University of Reading

Tobias Kuna\(^1\), Joint work with Valerio Lucarini\(^3\), Davide Faranda\(^2\), Jeroen Wouters\(^1\) and Viviane Baladi\(^3\)

1 University of Reading
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In this talk I discuss the distribution of extreme events for dynamical systems for different classes of observables.

In the last fifteen years the classical extreme value theory for stochastic processes has been extended to dynamical systems. Extreme value theory is concerned with either the asymptotical distribution of running maxima or the asymptotic of over threshold events for large thresholds and the relation between these two. We will review the relation between the parameters of the extreme distributions and invariants of the underlying dynamical system. Furthermore, we consider a conjecture what linear response theory can give us for the perturbation of this relation under forcing.

This is based on a joint work with Valerio Lucarini, Davide Faranda and Jeroen Wouters. In particular, I present what one can prove using transfer operator techniques. The latter is a joint work with Viviane Baladi and Valerio Lucarini.

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Frank Kwasniok

**Data-driven stochastic subgrid modelling: a pattern-based approach**

University of Exeter

Frank Kwasniok

In this contribution a methodology for data-driven stochastic modelling of unresolved scales and processes in weather and climate models is discussed. It has been shown that a stochastic subgrid model should be conditional on the state of the resolved variables. Here patterns in the space of resolved scales are identified and linked predictively to patterns in the space of subgrid forcing. On top of this deterministic subgrid scheme the subgrid patterns are forced stochastically. The method is explored in the Lorenz 1996 model and then applied to parametrisation of meso-scale eddies in ocean models. Ensemble prediction and long-term simulations are evaluated. Also an attempt on scale-invariant parametrisation is made.
We have developed a new flexible software for studying the hydrological cycle, the internal energy budget and the material entropy production in a wide range of gridded datasets, including climate models and Reanalyses. The program receives as input NetCDF files containing radiative, latent and sensible heat energy fluxes for the computation of energy budgets at Top-of-Atmosphere (TOA), at the surface and in the atmosphere as a residual. Annual mean climatological maps, meridional sections, global and hemispheric time series are provided as outputs. Meridional heat transports are also computed from the divergence of the zonal mean energy budget fluxes and location and intensity of peaks in the two hemispheres are provided as outputs. Rainfall, snowfall precipitation and evaporation fluxes (or alternatively latent heat fluxes) are received as inputs for computation of the water mass and latent energy budgets. If a land-sea mask is provided, the software also computes the required quantities separately over continents and oceans. Two methods have been implemented for the computation of the material entropy production, one relying on the convergence of radiative heat fluxes at TOA and at the surface (indirect method), one combining the irreversible processes occurring in the climate system, particularly heat fluxes in the boundary layer, the hydrological cycles and the kinetic energy dissipation. Currently, diagnostics for the energy budget, hydrological cycle and material entropy production with the indirect method have been implemented in the Earth System Model Evaluation Tool (ESMValTool) community diagnostics, in order to assess the performances of soon available CMIP6 model simulations. The aim is to provide a comprehensive picture of the thermodynamics of the climate system as reproduced in the most updated coupled general circulation models.
Valerio Lucarini

**Edge states in the climate system: exploring global instabilities and critical transitions**

University of Reading

Valerio Lucarini

Multistability is a ubiquitous feature in systems of geophysical relevance and provides key challenges for our ability to predict a system’s response to perturbations. Near critical transitions small causes can lead to large effects and—for all practical purposes—irreversible changes in the properties of the system. As is well known, the Earth climate is multistable: present astronomical and astrophysical conditions support two stable regimes, the warm climate we live in, and a snowball climate characterized by global glaciation. We first provide an overview of methods and ideas relevant for studying the climate response to forcings and focus on the properties of critical transitions in the context of both stochastic and deterministic dynamics, and assess strengths and weaknesses of simplified approaches to the problem. Following an idea developed by Eckhardt and collaborators for the investigation of multistable turbulent fluid dynamical systems, we study the global instability giving rise to the snowball/warm multistability in the climate system by identifying the climatic edge state, a saddle embedded in the boundary between the two basins of attraction of the stable climates. The edge state attracts initial conditions belonging to such a boundary and, while being defined by the deterministic dynamics, is the gate facilitating noise-induced transitions between competing attractors. We use a simplified yet Earth-like intermediate complexity climate model constructed by coupling a primitive equations model of the atmosphere with a simple diffusive ocean. We refer to the climatic edge states as Melancholia states and provide an extensive analysis of their features. We study their dynamics, their symmetry properties, and we follow a complex set of bifurcations. We find situations where the Melancholia state has chaotic dynamics. In these cases, we have that the basin boundary between the two basins of attraction is a strange geometric set with a nearly zero codimension, and relate this feature to the time scale separation between instabilities occurring on weather and climatic time scales. We also discover a new stable climatic state that is similar to a Melancholia state and is characterized by non-trivial symmetry properties.

Reference
Valerio Lucarini and Tamás Bodai, Edge states in the climate system: exploring global instabilities and critical transitions, Nonlinearity 30 R32 (2017)

Lea Oljaca

**Asymptotic accuracy of data assimilation with unbounded stochastic noise**

University of Reading

Lea Oljaca

Due to the high dimensionality of the weather problem, various ad-hoc methods are used in data assimilation. Despite widespread usage, the mathematical properties of these methods are still relatively poorly understood.

We build on recent work on the Lorenz 96, Lorenz '63 and the 2D compressible NS equations as toy models. A remarkable fact of the 2D incompressible Navier Stokes equations is that the projection of the solution onto a suitable finite dimensional subspace will eventually determine the whole infinite dimensional solution. This 'synchronisation' is a key property of the dynamics which has allowed for asymptotic accuracy of the data assimilation to be shown analytically, under the assumption that the noise is bounded. For the more realistic case of unbounded noise (e.g. Gaussian) however, it has only been shown that we can control the expected value of the error in the estimation of the initial state. We look to analyse and show that the overall distribution of the data assimilation error is nicely behaved.
There are two main types of uncertainty in the prediction of weather and its variability. The first is the transport uncertainty of where the flow takes the thermodynamics. The second is the uncertainty in what the thermodynamics does when it gets there. We address the first type of uncertainty in our models, due to what we call "stochastic Lie transport". The framework for introducing cylindrical stochastic noise is based on the well known Hamilton's variational principle. This was first developed in D. Holm's 2015 paper. The result is the Eulerian representation of ideal fluid dynamics in the form of stochastic partial differential equations, or SPDEs for short, where the stochastic perturbation is in the form of Stratonovich stochastic integrals of vector fields that depend on the gradients of the solution. This previously unseen form of noise is what we call transport noise.

For application purposes, e.g. data assimilation, the spatial correlation structure (SCS) of the transport noise is crucial and must be specified apriori. This leads to many important theoretical and practical questions regarding the determination of SCS as it is not possible to directly observe such quantity in practise. Thus, determining SCS would introduce its own uncertainty, but not even trying to determine them will mean neglecting the effects of transport uncertainty on weather prediction. As this form of noise is new, we propose the SCS components are to be supplied as spatial correlation EOFs of the data. We describe our estimation methodology, and how we benchmark the validity of the estimation. We aim to answer important questions such as the interpretation of SCS, the choice on the number of SCS and the implications of these choices on the Eulerian distributional properties of the velocity and vorticity, and the impact on practical computations. This is the first step of a larger data assimilation project which we are embarking on.

This is joint work with C. Cotter, D. Crisan, D. Holm and I. Shevchenko. Paper in preparation.
Decadal climate predictions are of great socio-economic value, because typical planning horizons of political and economic decision makers coincide with that time scale. Due to the uncertainties in initial conditions of weather and climate, forecasts should be and are increasingly issued in a probabilistic way. One problem frequently observed for probabilistic ensemble forecasts is that they tend to be not reliable, i.e. the ensemble spread does not represent the forecast uncertainty. They thus need to be re-calibrated to be useful. Moreover, decadal prediction systems typically exhibit systematic errors like lead-time dependent unconditional and conditional biases.

We propose a decadal forecast recalibration strategy (DeFoReSt) which simultaneously adjusts unconditional and conditional bias, as well as the ensemble spread while considering the typical setting of decadal predictions, i.e. model drift and a climate trend. The resulting parametric correction terms for bias, conditional bias and ensemble spread are functions of time and lead time and can be used to localize causes of non-calibrated forecasts. Applying DeFoReSt to the MiKlip system (Germany's initiative for decadal prediction) reveals that the forecast system's ensemble spread needs only minor adjustment if bias and conditional bias are properly adjusted.
Polarimetric radars provide us with a richness of precipitation related measurements. Especially the high spatial and temporal resolution make the data an important information, e.g. for hydrological modeling. However, uncertainties in the precipitation estimates are large. Their systematic assessment and quantification is thus of great importance.

Polarimetric radar observables like horizontal and vertical reflectivity $Z_H$ and $Z_V$, cross-correlation coefficient $\rho_{HV}$ and specific differential phase $K_{DP}$ are related to the drop size distribution (DSD) in the scan. This relation is described by forward operators which are integrals over the DSD and scattering terms. Given the polarimetric observables, the respective forward operators and assumptions about the measurement errors, we investigate the uncertainty in the DSD parameter estimation and based on it the uncertainty of precipitation estimates.

We assume that the DSD follows a Gamma model, $N(D) = N_0 D^\mu \exp(-\Lambda D)$, where all three parameters are variable. This model allows us to account for the high variability of the DSD. We employ the framework of Bayesian inverse methods to derive the posterior distribution of the DSD parameters. The inverse problem is investigated in a simulated environment (SE) using the COSMO-DE numerical weather prediction model. The advantage of the SE is that - unlike in a real world application - we know the parameters we want to estimate. Thus, building the inverse model into the SE gives us the opportunity of verifying our results against the COSMO-simulated DSD-values.
One of the most relevant weather regimes in the mid-latitudes atmosphere is the persistent deviation from the approximately zonally symmetric jet stream to the emergence of so-called blocking patterns. Such configurations are usually connected to exceptional local stability properties of the flow which come along with an improved local forecast skills during the phenomenon. It is instead extremely hard to predict onset and decay of blockings.

Covariant Lyapunov Vectors (CLVs) offer a suitable characterization of the linear stability of a chaotic flow, since they represent the full tangent linear dynamics by a covariant basis which explores linear perturbations at all time scales. Therefore, we assess whether CLVs feature a signature of the blockings. As a first step, we examine the CLVs for a quasi-geostrophic beta-plane two-layer model in a periodic channel baroclinically driven by a meridional temperature gradient $\Delta T$. An orographic forcing enhances the emergence of localized blocked regimes. We detect the blocking events using a Tibaldi-Molteni index adapted to the periodic channel. When blocking occurs, the global growth rates of the fastest growing CLVs are significantly higher. Hence, against intuition, the circulation is globally more unstable in blocked phases.

Such an increase in the finite-time Lyapunov exponents with respect to the long term average is attributed to stronger barotropic and baroclinic conversion in the case of high temperature gradients, while for low values of $\Delta T$, the effect is only due to stronger barotropic instability.

In order to determine the localization of the CLVs, we compare the meridionally averaged variance of the CLVs during blocked and unblocked phases. We find that on average the variance of all CLVs is clustered around the center of blocking. These results show that blocking is a collective phenomenon acting on all time scales and processes captured by the CLVs.

References
High-dimensional climate models may undergo abrupt changes with parameters due to chaotic attractor crises. Contrary to local bifurcations, such crises cannot be characterized by the eigenvalues of the linearization of the system, nor by the Lyapunov exponents. Instead, the stability of chaotic invariant sets may be characterized by the rate of convergence of ensembles, or probability densities to the statistical steady-state, or invariant measure associated with this set. This rate is given by the real part of the eigenvalues of the generator of the semigroup of transfer operators governing the evolution of densities. Some of these eigenvalues are thus expected to approach the imaginary axis during a crisis and to result in the slowing down of the recovery of the system to perturbations and/or of the decay of correlations associated with the break-down of response theory.

This is shown to be the case during a chaotic attractor crisis of the Lorenz '63 system. However, we find that the eigenvalues affected by the crisis are associated with the contraction of densities to the attractor, rather than with the decay of correlations due to mixing on the attractor. This shows that some crises may not be predicted from long time series and that early-warning indicators based on the lag-1 auto-correlation do not always allow for the prediction of a crisis.

We then use a reduction method of approximation of the transfer operators to study a warm-to-snowball transition associated with a chaotic attractor crisis in a climate model of intermediate complexity. The generator eigenvalues of the reduced transfer operators are also found to approach the imaginary axis. In this case, however, these eigenvalues affect the decay of correlations, so that lag-1 auto-correlation based indicators may signal the crisis.

The spectral theory of chaotic and stochastic systems thus provides a particularly interesting framework to study the stability and the variability of such systems.
Alemtsehai Turasie

Exceedance and return period of high temperatures in the African region

University of the Witwatersrand, South Africa

Alemtsehai Turasie

Several studies have suggested that the social, economic and other costs associated with global warming can be measured in terms of changes in the frequency and intensity of extreme weather/climate events. Developing countries, particularly the African region, are highly affected by extreme events such as high temperature usually followed by drought. Therefore, studying the chance of occurrence and return periods of extreme events is highly important for policy making and mitigation works in the region. This study aims to address this issue by assessing probability of exceedance and the return period of extreme (the 90th percentile of the distribution in this case) temperatures.

Anna von der Heydt

The Eocene-Oligocene transition - observations, mechanisms, cascading tipping?

Utrecht University

Anna von der Heydt, Institute for Marine and Atmospheric research Utrecht and Center for Extreme Matter and Emergent Phenomena, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands

Over the last 65 million years, the Earth’s climate has undergone a large transition from a warm and ice-free greenhouse climate to an icehouse climate with extensive ice sheets on both hemispheres. The gradual cooling may be seen as response to the overall slowly decreasing atmospheric CO$_2$-concentration due to weathering processes in the Earth System, however, continental geometry has changed considerably over this period and the long-term gradual trend was interrupted, by several rapid transitions and periods where temperature and greenhouse gas concentrations seem to be decoupled. The Eocene-Oligocene boundary (34 Ma) reflects a first major phase of Antarctic ice sheet build-up and global climate cooling. In detail, the transition consists of two distinct steps in the oxygen isotope record, where the first reflects mostly ocean cooling, while during the second a large ice sheet has built up. Here we consider the possibility of two coupled critical transitions in explaining the two-step nature of the Eocene-Oligocene climate change. In this view, a leading bistable system undergoes a transition thereby changing the background conditions for a second following bistable system, which under the altered background conditions undergoes a critical transition. For the Eocene-Oligocene transition, the leading system could be a bistable ocean meridional overturning circulation, while the second following system reflects the bistable land-ice system coupled by the atmospheric CO$_2$ concentration. We investigate the possibility of cascading systems in a simple conceptual climate model. Moreover, the necessary condition of the existence of bistability in the ocean circulation is tested in an ocean general circulation model under Eocene continental boundary conditions.
### Peter Watson

**The impact of stochastic physics on tropical rainfall variability in global climate models on daily to weekly timescales**

University of Oxford

Peter Watson

Many global atmospheric models have too little precipitation variability in the tropics on daily to weekly time scales, and also poor representation of tropical precipitation extremes associated with intense convection. Stochastic parameterisations of subgrid processes have the potential to mitigate this problem by representing unpredictable subgrid variability that is left out of deterministic models. We evaluate the impact on the statistics of tropical rainfall of two stochastic schemes, the stochastically perturbed parameterization tendency scheme (SPPT) and stochastic kinetic energy backscatter scheme (SKEBS), in three climate models. The schemes generally improve the statistics of simulated tropical rainfall variability, particularly by increasing the frequency of heavy rainfall events, reducing its persistence and increasing the high-frequency component of its variability. There is a large range in the size of the impact between models, however. The improvements are greater than those obtained by increasing horizontal resolution to ~20km. Using stochastic parameterisations is therefore likely to be important for producing good simulations of tropical variability and extremes in the present day and future.

### Paul Williams

**Optimising flight routes through an atmospheric wind field: the effects of climate change**

University of Reading

Paul Williams

For an aircraft flying between two airports, the best route is the one that minimises the journey time in a given atmospheric wind field. This is a classical optimisation problem that was first studied by Zermelo in the 1930s. The solution to the problem is now implemented in flight routing algorithms, which are used daily in aircraft operations.

But how will climate change affect the optimised flight routes and journey times? Here we feed synthetic atmospheric wind fields generated from climate model simulations into a routing algorithm of the type used operationally by flight planners. We focus on transatlantic flights between London and New York, and how they change when the atmospheric concentration of carbon dioxide is doubled. We find that a strengthening of the prevailing jet-stream winds causes eastbound flights to significantly shorten and westbound flights to significantly lengthen in all seasons. Eastbound and westbound crossings in winter become approximately twice as likely to take under 5 h 20 min and over 7 h 00 min, respectively. For reasons that are explained using a conceptual model, the eastbound shortening and westbound lengthening do not cancel out, causing round-trip journey times to increase. Even assuming no future growth in aviation, the extrapolation of our results to all transatlantic traffic suggests that aircraft will collectively be airborne for an extra 2000 h each year, burning an extra 7.2 million gallons of jet fuel at a cost of US$ 22 million, and emitting an extra 70 million kg of carbon dioxide, which is equivalent to the annual emissions of 7100 average British homes. Our results provide further evidence of the two-way interaction between aviation and climate change.
Mark Williamson

Towards an emergent constraint on equilibrium climate sensitivity

University of Exeter

Mark Williamson, Peter Cox, University of Exeter

Fluctuation dissipation theorems (FDTs) provide a way to relate the statistics of the variability of a system to the sensitivity of the same system to external forcing. A FDT for the climate system would be very useful as it could provide a means to estimate the Equilibrium Climate Sensitivity (ECS) simply by measuring statistics of the Earth system’s natural variability, a number that is still uncertain within a factor of three (1.5-4.5K). The aim is to estimate the climate sensitivity by using an FDT-inspired relationship with climate variability for the CMIP5 models, to find an Emergent Constraint (EC) on the climate sensitivity.
Zahari Zlatev

Studying the Impact of Climate Changes on Pollution Levels

Aarhus University

Zahari Zlatevᵃ, Ivan Dimovᵇ and Krassimir Georgievᵇ

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Fourteen scenarios ([3], [5] – [7]) were used to study the impact of climatic changes on some pollution levels in different European countries during a period of sixteen consecutive years. The mathematical tool used in the simulations ([1], [2] and [4]) is a large-scale environmental model described by a system of non-linear partial differential equations (PDEs). The space domain of the model covers the whole of Europe together with some of its surroundings and the direct discretization of the system of PDEs leads to huge systems of several hundred millions linear algebraic equations, which have to be solved during many thousands of time-steps for each scenario and for each year. It is possible to resolve the enormous computational difficulties only if several requirement are simultaneously satisfied. More precisely, one should (1) select efficient, fast and sufficiently accurate numerical methods, (2) implement some suitable splitting procedure, (3) parallelize the code (4) apply high-speed computers and (5) find out how to exploit in the best possible way the cache memories of the available computer architecture. It will be shown how these five requirements can simultaneously be satisfied. Some numerical results, which will illustrate (A) the computational efficiency of the code and (B) the fact that the climatic changes will result in an increase of some potentially dangerous ozone pollution levels, will be presented and discussed. Results obtained at several English sites will also be given.

AMS Subject Classification: Primary: 86A10, Secondary: 65N22, 65Z05, 65Y05

Key words: Large-scale mathematical models, Systems of PDEs, Numerical methods, Splitting, Parallel codes, Cache memory, Ozone levels

References

Several past episodes of rapid carbon cycle and climate change are hypothesised to be the result of the Earth system reaching a tipping point beyond which an abrupt transition to a new state occurs. At the Palaeocene-Eocene Thermal Maximum (PETM) ~55.5 Ma hypothesised tipping points involve the abrupt transfer of carbon from surface reservoirs to the atmosphere. Theory suggests that tipping points in complex dynamical systems should be preceded by early warning signals (EWS) due to critical slowing down of their dynamics, including increasing temporal autocorrelation and variability. However, detecting EWS in palaeorecords is challenging, with issues of data quality, false positives, and parameter selection potentially affecting reliability. Here we show that in the highest-resolution palaeorecord currently available, there is evidence of destabilisation of the carbon cycle prior to the PETM, elevated carbon cycle instability after the PETM in the lead up to Eocene Thermal Maximum 2 (ETM2), and further instability thereafter. This may reflect gradual forcing of the carbon cycle due to the North Atlantic Volcanic Province eruptions. Whilst our results do not prove the existence of a tipping point, they do indicate a loss of ‘resilience’ in the carbon-climate system with weakened stabilising negative feedbacks. We also present preliminary results of resilience analysis across other Cenozoic palaeoclimate perturbations, including the Cretaceous-Palaeogene boundary and the Eocene-Oligocene Transition.

Linked to ReCoVER Early Career Research Project RFFECR002: “Can early warning signals be reliably detected in the Cenozoic palaeoclimate record?”
Ensemble approaches are becoming widely used in climate research. In contrast to weather forecast, however, in the climatic context one is interested in long-time properties, those arising on the scale of several decades. The well-known strong internal variability of the climate system implies the existence of a related dynamical attractor with chaotic properties. Under the condition of climate change this should be a snapshot attractor, naturally arising in an ensemble-based framework. Although ensemble averages can be evaluated at any instant of time, results obtained during the process of convergence of the ensemble towards the attractor are not relevant from the point of view of climate. In simulations, therefore, attention should be paid to whether the convergence to the attractor has taken place. We point out that this convergence is of exponential character, therefore, in a finite amount of time after initialization relevant results can be obtained. The role of the time scale separation due to the presence of the deep ocean is discussed from the point of view of ensemble simulations.
Aoibheann Brady

Detection & attribution of large scale drivers for environmental change

University of Bath

Aoibheann Brady

The UK has been hit by a number of large flood events in recent years, with concerns that the current infrastructure and level of protection of cities may not be fit for purpose. There is growing concern that climate change may result in an increased risk of flooding. The changes in flood risk, which are derived from climate change projections, are nevertheless not validated by the observed river flow data, from which no compelling evidence of increasing trends can be inferred. In fact, trend tests obtained from modelling each gauging station separately typically lead to some unclear signal. This might be largely due to the fact that river flow records typically cover a short period of time, and the site-by-site tests to assess whether change can be detected in observed data are not very powerful (in a statistical sense) and cannot fully differentiate between possible confounders.

To overcome these issues, we propose a Bayesian hierarchical model where all stations are modelled together, thus allowing for the borrowing of information from other stations. We discuss the use of this approach to detect and attribute changes in flooding and other environmental variables. This will result in methods for the detection of spatially coherent trends in environmental data. We also investigate methods to make an assessment on the main drivers of higher river flows and flooding at a regional or national scale, with a focus on climates indices (such as the North Atlantic Oscillation), annual temperature and annual CO2 emissions.

Davide Faranda

Dynamical systems proxies of atmospheric predictability and mid-latitude extremes

French National Centre for Scientific Research

Gabriele Messori1, Rodrigo Caballero1, Davide Faranda2

1 Stockholm University
2 French National Centre for Scientific Research

Extreme weather occurrences carry enormous social and economic costs and routinely garner widespread scientific and media coverage. Many extremes (for e.g. storms, heatwaves, cold spells, heavy precipitation) are tied to specific patterns of midlatitude atmospheric circulation. The ability to identify these patterns and use them to enhance the predictability of the extremes is therefore a topic of crucial societal and economic value.

We propose a novel predictability pathway for extreme events, by building upon recent advances in dynamical systems theory. We use two simple dynamical systems metrics – local dimension and persistence – to identify sets of similar large-scale atmospheric flow patterns which present a coherent temporal evolution. When these patterns correspond to weather extremes, they therefore afford a particularly good forward predictability. We specifically test this technique on European winter temperatures, whose variability largely depends on the atmospheric circulation in the North Atlantic region. We find that our dynamical systems approach provides predictability of large-scale temperature extremes up to one week in advance.
**Maria Jacob**

**Forecasting Peaks in Household Electric Load Profiles**

University of Reading

Maria Jacob

Low carbon technologies such as electric vehicles, heat pumps, solar and wind generation represent an exciting opportunity for a reduction in emissions of carbon dioxide into our atmosphere, but on the other hand represent a huge challenge to the electricity distribution organisations, in particular on the low voltage network level. The new loads created by these technologies in combination with their uptake result in the need for a detailed prediction of individual daily and seasonal loads several years in advance. With this in mind, the MRes will focus on two tasks: i) optimising forecasting techniques to model energy demand and, ii) deducing the properties of the tail behaviour of energy demands for both the present and the future, using Extreme Value Theory.

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**Peter Read**

**Spectrally Resolved Energetics of the Martian atmosphere**

University of Oxford

A. Valeanu, **P. L. Read**, F. Tabataba-Vakili & R. M. B. Young

Atmospheric, Oceanic & Planetary Physics, Department of Physics, University of Oxford, UK.

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The dynamics and pattern of energy distribution across different scales of motion in the atmosphere are a key component in understanding the general atmospheric circulation, and in the validation of atmospheric models. Much work on measuring and diagnosing the spectra of kinetic and potential energy in the Earth’s atmosphere has been carried out over the past 30 years, together with derivations of turbulent structure functions and estimates of spectral fluxes, showing complex exchanges of energy. Until recently, however, such exchanges for other planetary atmospheres has remain largely unexplored. In the present work, we have analyzed the kinetic and potential energy spectra of the atmosphere of Mars, derived from an assimilated analysis of spacecraft observations of temperature over several Mars years. We will present results of an analysis of both energy spectra and the fluxes of kinetic and potential energy, based on an approach developed by Augier & Lindborg (2013), and examine both the annually averaged exchanges and their variation with season. The results indicate that Mars is in a rather different dynamical regime to the Earth, with upscale kinetic energy transfers at large scales but predominantly downsacle energy transfers across much of the spectrum.
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<th>Luke Storer</th>
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<td>Global Response of Clear-Air Turbulence to Climate Change</td>
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<td>University of Reading</td>
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<td>Luke Storer¹, Paul Williams¹, Manoj Joshi²</td>
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<td>¹ University of Reading</td>
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Clear-air turbulence (CAT) is one of the largest causes of weather-related aviation incidents. Here we use climate model simulations to study the impact that climate change could have on global CAT by the period 2050-2080. We extend previous work by analyzing eight geographic regions, two flight levels, five turbulence strength categories, and four seasons. We find large relative increases in CAT, especially in the midlatitudes in both hemispheres, with some regions experiencing several hundred per cent more turbulence. The busiest international airspace experiences the largest increases, with the volume of severe CAT approximately doubling over North America, the North Pacific, and Europe. Over the North Atlantic, severe CAT in future becomes as common as moderate CAT historically. These results highlight the increasing need to improve operational CAT forecasts and to use them effectively in flight planning, to limit discomfort and injuries amongst passengers and crew.
Since the millennium two particular tsunamis, impacting the Indian Ocean rim in 2004 and Japan in 2011, caused enormous destruction and claimed very many lives. How can numerical modelling of tsunamis be made more efficient in order to provide better early warning systems, using which governments could mitigate the damage caused by such events?

One possible approach is to make use of adaptive meshes for use in numerical solution of the shallow water equations. Through adaptivity we can focus computational power where it is needed, accurately resolving the tsunami waves and especially those at important coastal locations, using a fine mesh. Using a coarser mesh elsewhere, we can keep the overall computational cost of the algorithm low. Adaptivity has been shown to be effective in solving tsunami-type problems by [Behrens et al., 14] and [Davis and LeVeque, 16], some of the results of the latter of which I have been able to reproduce during my MRes project.

Mesh adaptive approaches are traditionally categorised as either h-adaptive, whereby mesh entities, such as vertices and edges, (corresponding to degrees of freedom) can be inserted into and removed from the mesh, and r-adaptive, whereby the topology of the mesh remains constant, with the entities only moving geometrically. There are advantages and disadvantages of both of these approaches, motivating the development of a hybrid (hr) method. One possibility is provided by anisotropic mesh adaptivity, which seeks to allow both h- and r- adaptive capabilities, and it is this type of adaptivity which I consider in detail in my MRes project.

My preliminary experimentation in solving the shallow water equations over various model domains has been so far successful. Over the past months I have developed a standalone shallow water code using Firedrake, an automated system for solving partial differential equations using the finite element method. Outputs from the code so far illustrate the enormous potential of a mesh adaptive approach to solving fluid dynamics problems.

I have also considered the realistic ocean domain surrounding Fukushima and have made some first attempts at emulating the 2011 tsunami. The end goal of my project is to be able to accurately and efficiently hindcast the dynamics of this particular case study using anisotropic mesh adaptivity.
The EPSRC Centre for Doctoral Training (CDT) in the Mathematics of Planet Earth (MPE) are supporting the CliMathNet Conference this year, through the support and leadership of Professor Valerio Lucarini. The Conference this year offers a session specifically dedicated to young scientists to showcase their research on the first afternoon of the Conference and via the poster session.

About the EPSRC Centre for Doctoral Training (CDT) in the Mathematics of Planet Earth (MPE)
Climate change represents an urgent challenge for humanity. Quantifying uncertainty in long-term climate prediction and estimating the potential strength of extreme meteorological events in the face of global warming are very difficult research questions, with large economic and societal impacts that will only grow in the future. In response to this challenge, Imperial College London and the University of Reading have joined forces to create the EPSRC Centre for Doctoral Training (CDT) in the Mathematics of Planet Earth (MPE).

Funded by EPSRC, the MPE CDT offers cohort-based PhD training in the mathematical and computational techniques needed to understand, predict and quantify risk and uncertainty for extreme weather and climate change.

Contact: http://mpecdt.org/

About the Centre for Mathematics of Planet Earth
In January 2017 the Interdisciplinary Research Centre for the Mathematics of Planet Earth began its activities at the Department of Mathematics and Statistics of the University of Reading under the direction of Professor Valerio Lucarini assisted by the scientific board: Jochen Broecker, Tobias Kuna, Valerio Lucarini, Claudia Neves, Jennifer Scott, and Ted Shepherd.

The goal of the centre is to become a catalyser of ideas and initiatives in the broad interdisciplinary area at the intersection between mathematics, theoretical physics, and earth sciences. The centre will in particular organise international scientific events such as workshops, conferences, and training courses in Reading, elsewhere in UK, and overseas, and will host scientists through a visitor programme.

The Centre’s activities are in close connection with the EPSRC Centre for Doctoral Training Mathematics of Planet Earth, which is run jointly by the Imperial College London and the University of Reading.

Contact: www.reading.ac.uk/maths-and-stats/research/mathematics-of-planet-earth/Centre-for-the-Mathematics-of-Planet-Earth.aspx
The ReCoVER research network aims to develop and apply new mathematical tools and methods to understand environmental variability and the connections with environmental risks. From April 2015 to March 2018 we are funded by the EPSRC grant EP/M008495/1 to promote research in this area via a number of mechanisms, including a £315k fund for feasibility studies. ReCoVER is affiliated to the research network CliMathNet and is directed by Peter Ashwin and Tim Lenton, supported by an Expert Panel and an Advisory Board. There are three scientific focus areas: (i) Computing complexity, (ii) extreme events, tipping points and quantifying uncertainty and (iii) modelling coupled social-environmental systems.

To date, the ReCoVER Network has:

- Organized 8 interdisciplinary workshops, including several meetings jointly organized with related networks such as Past Earth Network (PEN), Building Resilience into Risk Management (BRIM) and of various sizes across the scientific focus areas. Supported a further 2 workshops as organized by partner networks.
- Funded more than 40 meetings and feasibility studies of various sizes across the scientific focus areas, including support for early career researchers, new collaborations and outreach projects.
- Promoted Outreach Activities through a Virtual Outreach Conference in June 2016.
- Supported the CliMathNet annual meetings: University of Exeter in 2016 and this current annual meeting.
- Supported other CliMathNet activities, notably the newsletter.

Membership

If you would like to become a member of CliMathNet and receive the newsletters, please see the website (www.climathnet.org/whoweare/members/) and fill out the online Membership Form. Membership is free, and we encourage interested non-UK scientists to sign up as associate members.
Reading

Reading is a large, historically important town in Berkshire. The town centre is well within walking distance of the University’s Whiteknights and London Road campuses, and buses from the Whiteknights campus run very frequently 24 hours a day.

Reading has a number of beautiful parks including Forbury Gardens, King’s Meadow, Caversham Court and Christchurch Meadows. The River Thames runs through a number of them, creating a haven for wildlife and rowers.

Places to eat:

You’ll find a range of large restaurant chains by the Riverside near the Oracle, but Reading is also home to many smaller places offering food from across the globe. There is a vast range of cuisines available, including French, Italian, Polish, Greek, Indian, Chinese, Thai, Nepalese, Brazilian, Lebanese and Ethiopian.

What's nearby:

The town is well connected, with direct trains running to major cities around the UK, including Birmingham, Manchester, Newcastle, Bristol and Cardiff. London is only half an hour away by rail and services run until late into the night. Additionally, the M4 motorway, which connects London with South Wales, is on the edge of town.

Beyond the city centre you will find the beautiful countryside Chilterns or the ancient woodlands of the North Wessex Downs.
Useful Information

**Internet Access:**

Wifi details and access passcodes will be provided on request when you arrive, either at the Conference Registration or at your Accommodation.

**Parking:**

Parking on campus has become severely limited and delegates are encouraged to use public transport wherever possible. Parking has been arranged for the conference in Car Park 1a at the Shinfield Road Entrance to the campus. Please print off the parking permit that was sent via email and display clearly in your vehicle.

Please follow signs for Conference Parking and then follow signs for Conferences until you see the relevant CliMathNet Signs.

**Travel Advice:**

Local buses, which come directly onto campus, and taxis run from outside Reading train station – please see www.reading-buses.co.uk for current timetables. A single ticket from the town centre to campus is £2, and a return ticket is £4. Please ensure you have the correct fare as the bus driver cannot give change, contactless payment is now available.

Taxi: Yellow cars is a local company and can be contacted on 0118 966 6555.

Sat Nav: use postcode **RG6 6UR**

**Campus Amenities:**

The University has a range of amenities on campus including:

- Park House Bar, which is adjacent to Eat at the Square. The bar will open at 12pm and closes at 23:00.
- Campus Central Convenience store, which is open during the week from 8.30 to 22.00
- Eat at the Square Restaurant on campus
- Café Mondial on the campus, open from 9.30 to 14.30 during vacations
Notes