<table>
<thead>
<tr>
<th>Time</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
</tr>
</thead>
</table>
| 9:15 | Introductions | The aim of this session is to describe the numerical technique used in the ECMWF model for integrating the transport equations of the hydrostatic primitive equation set. We will present an overview of the semi-Lagrangian method and how it is combined with semi-implicit time-stepping to provide a stable and accurate formulation for the ECMWF Integrated Forecasting System (IFS). By the end of this session you should be able to:  
* describe the fundamental concepts of semi-Lagrangian advect on schemes, their strengths and weaknesses | | | | | The aim of this session is to understand the main issues and challenges in parallel computing, and how parallel computers are programmed today. By the end of this session you should be able to:  
* understand the different aspects of the parallel environment and parallel computing |
The aim of this set of lectures is to systematically build theoretical foundations for Numerical Weather Prediction at all nonhydrostatic resolutions. In the first part of the lecture, we will discuss a suite of all-scale nonhydrostatic PDEs, including the anelastic, the pseudo-elliptic, and the fully compressible Euler equations of atmospheric dynamics. First we will introduce the three sets of governing equations written in a physically intuitive Cartesian vector form, in abstraction from the model geometry and the coordinate frame adopted. Then, we will combine the three sets into a single set that recasts in a form of the conservation laws consistent with the problem geometry and the unified solution procedure. In the second part of the lecture, we will build and document the common numerical algorithm for integrating the generalised set of the governing PDEs put forward in the first part of the lecture. Then, we will compare soundproof compressible solutions and demonstrate the efficacy of this unified numerical framework for two idealised flow problems relevant to weather and climate.

By the end of the lectures you should be able to:

• explain the form, properties and role of alternative systems of nonhydrostatic PDEs for all scale atmospheric dynamics;

• explain the importance and key aspects of continuous mappings employed in all-scale atmospheric models;

• explain the difference between the explicit and semi-implicit algorithms for integrating nonhydrostatic PDEs, the importance of consistent numerical approximation s, and the fundamental role of transport and elliptic solvers.

Willem Deconinck
Disc_HO_Methods.pdf

Piotr Smolarkiewicz
see first lecture for handout

Michail Diamantakis
SISL_2017.pptx
Using the 30-year history of ECMWF’s Integrated Forecasting System (IFS) as an example, this lecture is an introduction to the development and current state-of-the-art of global numerical weather prediction (NWP), as well as to the challenges faced in the future. It is intended to provide an overview and context for the topics covered in more detail during the course.

By the end of the session you should be able to:

- describe the development of global NWP, the current state-of-the-art, and future challenges
- identify relevant areas of research in numerical methods for Earth-System Modelling
- put into context every subsequent lecture and its purpose

Nils Wedi

Lecture_1_wedi.pptx

Animation 1 (Plumb-McEwan laboratory experiment):

Animation 2 (DNS simulation of laboratory experiment):
The aim of this set of lectures is to systematically build theoretical foundations for Numerical Weather Prediction at nonhydrostatic resolutions. In the first part of the lecture, we will discuss a suite of all-scale nonhydrostatic PDEs, including the anelastic, the pseudo-incompressible and the fully compressible Euler equations of atmospheric dynamics. First we will introduce the three sets of nonhydrostatic governing equations written in a physically intuitive Cartesian vector form, in abstraction from the model geometry and the coordinate frame adopted. Then, we will combine the three sets into a single set recast in a form of the conservation laws consistent with the problem geometry and the unified solution procedure. In the second part of the lecture, we will build and document the common numerical algorithm for integrating the generalised set of the governing PDEs put forward in the first part of the lecture. Then, we will compare soundproof and compressible solutions and demonstrate the efficacy of this unified numerical framework for two idealised flow problems relevant to weather and climate.

By the end of the lectures you should be able to:

- explain the form, properties and role of alternative systems of nonhydrostatic PDEs for all scale atmospheric dynamics;
- explain the importance and key aspects of continuous mappings employed in all-scale atmospheric models;
- explain the difference between the explicit and semi-implicit algorithms for integrating nonhydrostatic PDEs, the importance of consistent numerical approximation s, and the fundamental role of transport and elliptic solvers.

Piotr Smolarkiewicz

see first lecture for handout
The aim of this set of lectures is to systematically build theoretical foundations for Numerical Weather Prediction at nonhydrostatic resolutions. In the first part of the lecture, we will discuss a suite of all-scale nonhydrostatic PDEs, including the anelastic, the pseudo-incompressible and the fully compressible Euler equations of atmospheric dynamics. First we will introduce the three sets of nonhydrostatic governing equations written in a physically intuitive Cartesian vector form, in abstraction from the model geometry and the coordinate frame adopted. Then, we will combine the three sets into a single set recast in a form of the conservation laws consistent with the problem geometry and the unified solution procedure. In the second part of the lecture, we will build and document the common numerical algorithm for integrating the generalised set of the governing PDEs put forward in the first part of the lecture. Then, we will compare soundproof and compressible solutions and demonstrate the efficacy of this unified numerical framework for two idealised flow problems relevant to weather and climate.

By the end of the lectures you should be able to:

- explain the form, properties and role of alternative systems of nonhydrostatic PDEs for all scale atmospheric dynamics;
- explain the importance and key aspects of continuous mappings employed in all-scale atmospheric models;
- explain the difference between the explicit and semi-implicit algorithms for integrating nonhydrostatic PDEs, the importance of consistent numerical approximations, and the fundamental role of transport and elliptic solvers.

Piotr Smolarkiewicz
Course2017_smolar.pptx

Practical Session (elliptic solvers)
Andreas Müller, Willem Deconinck, Christian Kühnlein
Tuesday-Exercises-Handout.pdf

The aim of this session is to learn about recent developments in discontinuous higher order spatial discretization methods, such as the Discontinuous Galerkin method (DG), and the Spectral Difference method (SD). These methods are of interest because they can be used on unstructured meshes and facilitate optimal parallel efficiency. We will present an overview of higher order grid point methods for discretizing partial differential equations (PDEs) with compact stencil support, and illustrate a practical implementation.

By the end of the session you should be able to:

- describe how to solve PDEs with discontinuous methods
- identify the key elements that contribute to a PDE solver

Willem Deconinck
See first lecture for handout

Course wrap up and Certificates
The success of the spectral transform method in global NWP in comparison to alternative methods has been overwhelming, with many operational forecast centres (including ECMWF) having made the spectral transform their method of choice. The lecture will introduce the basic elements of the spectral transform, explain why it has been successful and describe recent developments such as the fast Legendre transform.

By the end of the session you should be able to:
- explain what the spectral transform method is, how it is applied, and describe the latest developments at ECMWF.
- give reasons why it is successful for global NWP and climate.
- identify potential disadvantages of the method.

Nils Wedi

Lecture 2_wedi.pptx

The aim of this session is to describe Eulerian based numerical techniques for integrating the equation sets encountered in NWP models. We will present an overview of different time-stepping techniques and discuss the advantages and disadvantages of each approach.

By the end of the session you should be able to:
- obtain a good understanding of the minimum theoretical properties required by time-stepping schemes
- describe differences, strengths-weaknesses of different time-stepping approaches such as split-explicit time-stepping, Runge-Kutta time-stepping
- describe the basic features of different time-stepping schemes used in other weather forecasting models such as WRF, ICON

Michail Diamantakis

tstepping2017.pptx

During this presentation, we will discuss two of the questions faced by numerical weather prediction scientists as forecast models reach horizontal resolutions of 6 to 2 km:
- Do we need to abandon the primitive equations for a non-hydrostatic system of equations?
- Do we still need a deep understanding of parameters and adaptation techniques?

And we will show what answers to the questions are given by very high resolution simulations of the IFS.

By the end of the presentation, you should be able to:
- obtain a good understanding of the minimum theoretical properties required by time-stepping schemes
- describe differences, strengths-weaknesses of different time-stepping approaches such as split-explicit time-stepping, Runge-Kutta time-stepping
- describe the basic features of different time-stepping schemes used in other weather forecasting models such as WRF, ICON

The aim of this lecture is to introduce basis of finite volume and continuous finite element discretisations and relate them to corresponding data structures and mesh generation techniques. The main focus will be on unstructured meshes and their application to global and local atmospheric models. Flexibility, communication overheads, memory requirements and user friendliness of such meshes will be contrasted with those of structured meshes. The most commonly used mesh generation techniques will be highlighted, together with mesh manipulation techniques employed in mesh adaption approaches and will be followed by a discussion of alternative geometrical representations of orography. An example of unstructured meshes' implementation on non-hydrostatic and hydrostatic atmospheric solvers will provide an illustration of their potential and challenges.

By the end of the lecture you should be able to:
<table>
<thead>
<tr>
<th>Time</th>
<th>Session Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.30</td>
<td>The goal of this session is to provide an overview of the use of generalised curvilinear coordinates in atmospheric numerical models. By the end of the session you should be able to:</td>
</tr>
<tr>
<td></td>
<td>• describe some important aspects of the formulation and implementation of the governing equations in generalised coordinates</td>
</tr>
<tr>
<td></td>
<td>• describe various vertical coordinates employed in atmospheric models</td>
</tr>
<tr>
<td></td>
<td>• indicate the use of generalised coordinates to employ moving mesh adaptivity</td>
</tr>
<tr>
<td></td>
<td>During this presentation, we will discuss two of the questions faced by numerical weather prediction scientists as forecast models reach horizontal resolutions of 6 to 2 km:</td>
</tr>
<tr>
<td></td>
<td>• understand applicability, advantages and disadvantages of selected mesh generation techniques for a given type of application.</td>
</tr>
<tr>
<td></td>
<td>• appreciate importance of data structures in relation to atmospheric models and mesh generation.</td>
</tr>
<tr>
<td></td>
<td>• gain awareness of issues related to flexible mesh generation and adaptation.</td>
</tr>
</tbody>
</table>
The goal of this session is to provide an overview of the use of generalised curvilinear coordinates in atmospheric numerical models.

By the end of the session you should be able to:

- describe some important aspects of the formulation and implementation of the governing equations in generalised coordinates
- describe various vertical coordinates employed in atmospheric models
- indicate the use of generalised coordinates to employ moving mesh adaptivity

Christian Kühnlein
See first lecture for handout.

The aim of two lectures is to introduce basis of finite volume and continuous finite element discretisations and relate them to corresponding data structures and mesh generation techniques. The main focus will be on unstructured meshes and their application to global and local atmospheric models. Flexibility, communication overheads, memory requirements and user friendliness of such meshes will be contrasted with those of structured meshes. The most commonly used mesh generation techniques will be highlighted, together with mesh manipulation techniques employed in mesh adaption approaches and will be followed by a discussion of alternative geometrical representations of orography. An example of unstructured meshes’ implementation on non-hydrostatic and hydrostatic atmospheric solvers will provide an illustration of their potential and challenges.

By the end of the lecture you should be able to:

- Do we need to abandon the primal variable equations for a non-hydrostatic system of equations?
- Do we still need a deep communication paradigm or can we use flat, oblivious paradigms?
- and we will show what answers to these questions are given by very high-resolution simulations of the IFS.
disuss the limits of the hydrostatic approximation for numerical weather prediction.

explain the dilemma of parameterizing deep convection versus permitting explicit deep convection at resolution in the gray zone of convection.

understand applicability, advantages and disadvantages of selected mesh generation techniques for a given type of application.

appreciate the importance of data structures in relation to atmospheric models and mesh generation.

gain awareness of issues related to flexible mesh generation and adaptation.

Sylvie Malardel
resolution.pdf

Joanna Szmelter
See first lecture for handout

<table>
<thead>
<tr>
<th>Time</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Topic</td>
<td>Session Description</td>
<td>By the end of the session, the students should be able:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.15</td>
<td>Introduction to the course</td>
<td>This session describes the representation of subgrid-scale variability of humidity, cloud and precipitation and how this can be parametrized in atmospheric models.</td>
<td>• recognise the reasons for representing the subgrid variability of humidity and cloud in an atmospheric model.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>This session will have two main components:</td>
<td>• explain how the key quantity of cloud fraction is related to subgrid heterogeneity assumptions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• An overview of the role of snow in the climate system from observations, models and forecasts; with a description of the current representation of snow in the ECMWF model.</td>
<td>• describe the different types of subgrid cloud parametrization schemes.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• An overview of the role of vegetation in NWP with a description of the evolution of vegetation representation in the ECMWF model, supported by some evaluation examples.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Richard Forbes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TC2017_Forbes_L2_cloud_cloudphase.pptx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>By the end of the session, the students should be able:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Identify the main processes associated with snow and vegetation in NWP.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Describe the main components related to snow and vegetation scheme in the ECMWF land surface model.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Souhail Boussetta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TC2017_PA_Surf_partII.pptx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>By the end of the session, the students should be able:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• relate flux and storage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• recognise land surface predictors and land diagnostic quantities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gianpaolo Balsamo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>new_surf2.pptx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>This three-hour lecture will start by explaining the role and main ingredients of data assimilation in general. The widely used framework of variational data assimilation will then be gradually introduced. The challenges associated with the necessary inclusion of physical parametrizations in the data assimilation process will be highlighted. The concept of adjoint model as well as the techniques to derive it will be introduced. The importance of the linearity constraint in 4D-Var and the methods to address it will be detailed. The set of linearized physical parametrizations used at ECMWF will then be briefly presented. Finally, various examples of the use of physical parametrizations in variational data assimilation and its impact on weather forecast quality will be given.</td>
<td>By the end of the session, the students should be able:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Philippe Lopez</td>
<td>• to name the main ingredients of a data assimilation system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>see first lecture for handouts</td>
<td>• to tell why physical parametrizations are needed in data assimilation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• to identify the role of the adjoint code in 4D-Var.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• to recognize the importance of the regularization of the linearized code.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Author</td>
<td>Title</td>
<td>Content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>-------</td>
<td>---------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:45</td>
<td>Robin Hogan</td>
<td>This module aims to introduce the fundamentals of radiative transfer theory and its role within the global atmospheric circulation. The lectures will also cover the techniques of numerical modelling of the radiative transfer equations in global-circulation models with a particular focus on the code in use in the ECMWF Integrated Forecasting System. By the end of the session students should be able to: • Identify the key processes controlling the atmospheric radiative balance • Recognize the role of the radiative transfer in the Earth energy balance • Estimate the impact of changes in the radiative parameterization on climate Additional outcomes: • Develop skills in data analysis and numerical modelling</td>
<td><strong>This module aims to introduce the fundamentals of radiative transfer theory and its role within the global atmospheric circulation.</strong> The lectures will also cover the techniques of numerical modelling of the radiative transfer equations in global-circulation models with a particular focus on the code in use in the ECMWF Integrated Forecasting System. By the end of the session students should be able to: • Identify the key processes controlling the atmospheric radiative balance • Recognize the role of the radiative transfer in the Earth energy balance • Estimate the impact of changes in the radiative parameterization on climate Additional outcomes: • Develop skills in data analysis and numerical modelling</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peter Bechtold</td>
<td>Convection affects all atmospheric scales. Therefore, the convection session aims to provide a deeper understanding of the atmospheric general circulation and its interaction with convective heating and vertical transports. The notions and techniques acquired during the course should be useful for developers of convective parametrizations, forecasters and for analysing output from high-resolution convection resolving models. By the end of the session you should become familiarised with • the interaction between the large-scale circulation and the convection including radiative-convective equilibrium and convectively-coupled large-scale waves • the notion of convective adjustment and the mass flux concept in particular • the basic concepts behind the ECMWF convection parametrization and some useful numerical tricks • forecasting convection including convective systems and the diurnal cycle • diagnose forecast errors related to convection.</td>
<td><strong>Convection affects all atmospheric scales. Therefore, the convection session aims to provide a deeper understanding of the atmospheric general circulation and its interaction with convective heating and vertical transports. The notions and techniques acquired during the course should be useful for developers of convective parametrizations, forecasters and for analysing output from high-resolution convection resolving models. By the end of the session you should become familiarised with</strong> • the interaction between the large-scale circulation and the convection including radiative-convective equilibrium and convectively-coupled large-scale waves • the notion of convective adjustment and the mass flux concept in particular • the basic concepts behind the ECMWF convection parametrization and some useful numerical tricks • forecasting convection including convective systems and the diurnal cycle • diagnose forecast errors related to convection.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sylvie Malardel</td>
<td>Convection affects all atmospheric scales. Therefore, the convection session aims to provide a deeper understanding of the atmospheric general circulation and its interaction with convective heating and vertical transports. The notions and techniques acquired during the course should be useful for developers of convective parametrizations, forecasters and for analysing output from high-resolution convection resolving models. By the end of the session you should become familiarised with • the interaction between the large-scale circulation and the convection including radiative-convective equilibrium and convectively-coupled large-scale waves • the notion of convective adjustment and the mass flux concept in particular • the basic concepts behind the ECMWF convection parametrization and some useful numerical tricks • forecasting convection including convective systems and the diurnal cycle • diagnose forecast errors related to convection.</td>
<td><strong>Convection affects all atmospheric scales. Therefore, the convection session aims to provide a deeper understanding of the atmospheric general circulation and its interaction with convective heating and vertical transports. The notions and techniques acquired during the course should be useful for developers of convective parametrizations, forecasters and for analysing output from high-resolution convection resolving models. By the end of the session you should become familiarised with</strong> • the interaction between the large-scale circulation and the convection including radiative-convective equilibrium and convectively-coupled large-scale waves • the notion of convective adjustment and the mass flux concept in particular • the basic concepts behind the ECMWF convection parametrization and some useful numerical tricks • forecasting convection including convective systems and the diurnal cycle • diagnose forecast errors related to convection.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alessio Bozzo</td>
<td>This short lecture is an introduction to the questions of time splitting and process splitting in a numerical weather prediction model and to the problems resulting from the interaction of different numerical solvers inside the same model. After this introduction, you should • be fully aware that each parametrisation is only a small part of a much larger system, usually one term in the full system of equations which needs to be solved by the forecast model, • remember, when working on your own parametrisation(s), that parametrizations are also subject to the constraints imposed by numerical analysis and algorithmic, as is the solver in the dynamical core.</td>
<td><strong>This short lecture is an introduction to the questions of time splitting and process splitting in a numerical weather prediction model and to the problems resulting from the interaction of different numerical solvers inside the same model. After this introduction, you should</strong> • be fully aware that each parametrisation is only a small part of a much larger system, usually one term in the full system of equations which needs to be solved by the forecast model, • remember, when working on your own parametrisation(s), that parametrizations are also subject to the constraints imposed by numerical analysis and algorithmic, as is the solver in the dynamical core.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
14.00 This session gives a brief overview of cloud parametrization issues and an understanding of the basic microphysics of liquid, ice, and mixed phase cloud and precipitation processes.

By the end of the session you should be able to:
• recall the basic concepts for the design of a cloud parametrization
• describe the key microphysical processes in the atmosphere
• recognize the important microphysical processes that need to be parametrized in a global NWP model.

Richard Forbes
TC2017_Forbes_L1_cloud_2017.pptx

11.55 This session gives a theoretical introduction of the planetary boundary layer, including its definition, classification, notations about turbulence within the boundary layer, differences between clear and cloudy boundary layers, and equations used to describe the mean state in a numerical model.

Expected outcomes:
• understand what is the boundary layer, its characteristics and why it is important to study it and represent it correctly in numerical models
• understand the difference between the various boundary layer types

Irina Sandu
pbl1_is_2017.ppt

This module aims to introduce the fundamentals of radiative transfer theory and its role within the global atmospheric circulation. The lectures will also cover the techniques of numerical modelling of the radiative transfer equations in global circulation models with a particular focus on the code in use in the ECMWF Integrated Forecasting System.

By the end of the session students should be able to:
• identify the key processes controlling the atmospheric radiative balance
• recognize the role of the radiative transfer in the Earth energy balance
• estimate the impact of changes in the radiative parametrizations on climate

Additional outcomes:
• develop skills in data analysis and numerical modelling

Robin Hogan
hogan_ecmwf_radiation_lecture2.pptx

This session focuses on representation of the surface layer, i.e., the layer between the surface and the first model level. More particularly, it explains how the surface fluxes are parametrized, and it gives insights on the representation of the surfaces roughness lengths which are one of the crucial aspects of the formulation of the surface fluxes.

Expected outcomes:
• be aware of the difficulties related to the representation of the surface layer in a numerical model
• understand how the surface fluxes are parametrized

Irina Sandu
pbl2_is_2017.ppt

Convection affects all atmospheric scales. Therefore, the convection session aims to provide a deeper understanding of the atmospheric general circulation and its interaction with convective heating and vertical transports. The notions and techniques acquired during the course should be useful for developers of convective parametrizations, forecasters and for analysing output from high-resolution convection resolving models.

By the end of the session you should become familiarised with
• the interaction between the large-scale circulation and the convection including radiative-convective equilibrium and convectively-coupled large-scale waves
• the notion of convective adjustment and the mass flux concept in particular
• the basic concepts behind the ECMWF convection parametrization and some useful numerical tricks
• forecasting convection including convection systems and the diurnal cycle
• diagnose forecast errors related to convection.

Peter Bechtold
CONVECTION_T2_2017.ppt

Building on the previous two Cloud sessions, the practical implementation of a cloud parametrization is described, using the ECMWF global model as an example appropriate for global weather forecasting.

By the end of the session you should be able to:
• explain the key sources and sinks of cloud and precipitation required in a parametrization
• describe the main components of the ECMWF stratus cloud parametrization
• recognise the limitations of approximating complex processes.

Richard Forbes
TC2017_Forbes_L3_cloud_subgrid.pptx

This session will give an overview of techniques and data sources used for the verification of the boundary layer scheme. We will use examples from the IFS to explore how verification methods can help to identify systematic errors in the model's boundary layer parametrization, and guide future model development.

By the end of this session you should be able to:
• identify data sources and products suitable for BL verification
• recognize the strengths and limitations of the verification strategies discussed
• choose a suitable verification method to investigate model errors in boundary layer height, transport and cloudiness.

Makke Ahligrimm
CldPblVerif2017.ppt

This three-hour lecture will start by explaining the role and main ingredients of data assimilation in general. The widely used framework of variational data assimilation will then be gradually introduced. The challenges associated with the necessary inclusion of physical parametrizations in the data assimilation process will be highlighted. The concept of adjoint model as well as the techniques to derive it will be introduced. The importance of the Linearity constraint in 4D-Var and the methods to address it will be detailed.

The set of linearized physical parametrizations used at ECMWF will then be briefly presented. Finally, various examples of the use of physical parametrizations in variational data assimilation and its impact on weather forecast quality will be given.

By the end of the session, the students should be able to:
• describe the relevant physical mechanisms related to sub-grid orography that have impact on flow in the atmosphere
• describe the impact of sub-grid orography.

Anton Beljaars
subgrid_orography_2017.ppt

On the basis of simple gravity wave theory, the concepts of sub-grid turbulent form drag, flow blocking, and gravity wave excitation will be introduced. The ECMWF formulations will be described, and the impact will be discussed.

By the end of this session students should be able to:
• describe the relevant physical mechanisms related to sub-grid orography that have impact on flow in the atmosphere
• describe the impact of sub-grid orography.
By the end of Tuesday Thursday Monday Friday
In this lecture we will give you a brief history of Games
and
9.15 16.40 15.30
Time
Erland Källén, Sarah Keeley Peter Bechtold Richard Forbes and Gianpaolo Balsamo
Games
By the end of the lecture you should be able to:
- developments that will soon become operational.
- challenges and present some of the latest research
- research that is currently being carried out in the ECMWF
- present the main areas of NWP

By the end of the session students should be able to:
- recognise land elements relevant to weather,
- review land modelling strategies to heterogeneity

Gianpaolo Balsamo
new_surf1.pptx

Erland Källén, Sarah Keeley
By the end of the lecture you should be able to:
- List the main research areas at ECMWF and describe the latest model developments.

Radiation exercises
Alessio Bozzo and Robin Hogan

Land Surface exercises
Gianpaolo Balsamo and Souhail Boussella

Boundary Layer & Cloud exercises
Irina Sandu, Maike Ahlgrimm and Richard Forbes

Moist Processes Exercises
Richard Forbes and Peter Bechtold

Moist Processes Games
Richard Forbes and Peter Bechtold
Radiation exercises
Alessio Bozzo and Robin Hogan
Land Surface exercises
Gianpaolo Balsamo and Souhail Boussella

Boundary Layer & Cloud exercises
Irina Sandu, Maike Ahlgrimm and Richard Forbes
Course wrap up and certificates

9.15
In this lecture we will give you a brief history of ECMWF and present the main areas of NWP research that is currently being carried out in the centre. We then look at current research challenges and present some of the latest developments that will soon become operational.

By the end of the lecture you should be able to:
- List the main research areas at ECMWF and describe the latest model developments.

Erland Källén, Sarah Keeley
This lecture will present the 3D-Var assimilation algorithm. This algorithm is based in the formulation of a cost function to minimize. Minimization methods will be presented together with some information on how to improve their efficiency.

By the end of the lecture the participants should be able to:
- Recognize the 3D-Var cost function
- Explain the various terms of the cost function
- Question the efficiency of methods designed to find the minimum of the cost function

Sebastien Massart
TC_lecture_2.pdf

The aim of this session is to understand how data assimilation can improve our knowledge of past weather over long time-scales. We will present recent advances that help capture changes over time in observing system networks, and project this variation in information content into uncertainty estimates of the reanalysis products. We will also discuss the applications of reanalysis, which generally put weather events into the climate context.

By the end of the session you should be able to:
- explain what are the goals of data assimilation in a reanalysis data assimilation system
- list the key aspects that require particular attention in reanalysis, as compared to numerical weather prediction
- describe the most common problems in reanalysis products

Patrick Laloyaux
Laloyaux_Reanalysis_2017.pdf

In this lecture the variational bias correction scheme (VarBC) as used at ECMWF is explained. VarBC replaced the tedious job of estimating observation bias off-line for each satellite instrument or in-situ network by an automatic self-adaptive system. This is achieved by making the bias estimation an integral part of the ECMWF variational data assimilation system, where now both the initial model state and observation bias estimates are updated simultaneously.

By the end of the session you should be able to:
- Identify the different observations used for snow and soil moisture data assimilation
- Define land surface data assimilation approaches used for NWP
- Describe the role of land surface data assimilation on medium-range weather forecasts

Patricia de Rosnay
deRosnay_TC_NWP_DA_2017.pdf

The aim of these sessions is to understand the role of land surface data assimilation on medium range weather forecasts.

We will give an overview of the different approaches used to assimilate land surface data and to initialise model variables in NWP. We will present the current observing systems and describe the land data assimilation structure within ECMWF system.

By the end of the session you should be able to:
- Identify the different observations used for snow and soil moisture data assimilation
- Define land surface data assimilation approaches used for NWP
- Describe the role of land surface data assimilation on medium-range weather forecasts

Niels Bormann
Bormann_2017_TC_BiasCorrection.pptx

Niels Bormann
Bormann_2017_TC_BiasCorrection.pptx

Course wrap up and certificates
<table>
<thead>
<tr>
<th>Time</th>
<th>Content</th>
</tr>
</thead>
</table>

| 10:45 | The goal of the ECMWF Earth System data assimilation is to provide an accurate and physically coherent description of the state of the atmosphere, ocean, sea ice and land surface as an initial point for our forecasts. This requires blending in a statistically optimal way information from a huge variety of observations and our prior knowledge about the physical laws of the Earth system, which is encapsulated in our models. In this lecture we will lay the general conceptual framework on how to achieve this from a Bayesian perspective. We will then highlight the approximations and hypotheses which are required to make the assimilation problem computationally tractable and which underlie the practical data assimilation algorithms which will be described in detail in this training course. By the end of the lecture you should be able to:  
- understand the basics of how a geophysical data assimilation system works;  
- understand the main approximations and hypotheses which are required to build practical data assimilation algorithms for large geophysical systems. Massimo Bonavita DataAssim_Overview_Bonavita_2017_1.pptx |

| 11:55 | This lecture will introduce how observations are an essential part of the data assimilation system. It will focus on in situ (also called conventional) observations, from surface stations, drifters, aircraft and radiosondes. They are important both for direct use in the data assimilation system and for diagnostics. Radiosonde and surface observations also help to control the biases in the assimilation system. However they are diverse and they can be complex, so close attention to quality control, observation uncertainty and (in some cases) bias correction is needed to optimise their use. The lecture will also introduce the actively sensed satellite observations used for data assimilation at ECMWF, radio occultation data, scatterometer winds, and altimeter wind /significant wave height. By the end of the lecture the student should be able to:  
- understand how in situ and actively sensed observations are used in data assimilation, including bias aspects and observation uncertainty aspects.  
- appreciate the diverse and complex range of in situ observations used in modern NWP.  
- understand how radio occultation data, scatterometer winds and altimeter data are used in data assimilation. Lars Ibsen L1_DA_TC_2017_Insitu_actively_sensed_Observations.pptx |
The primary purpose of this lecture is to explore the implications of the fact that satellites can only measure radiance at the top of the atmosphere and do not measure the geophysical variables we require for NWP (e.g. temperature, humidity and wind). The link between the atmospheric variables and the measured radiances is the radiative transfer equation - the key elements of which are discussed. It is shown how - with careful frequency selection - satellite measurements can be made for which the relationship to geophysical variables is greatly simplified. Despite these simplifications, it is shown that the extraction of detailed profile information from downward looking radiance measurements is a formally ill posed inverse problem.

Data assimilation is introduced as the solution to this inverse problem, where background information and satellite observations are combined to produce a best or optimal estimate of the atmospheric state. The main elements of the assimilation scheme (such as the chain of observation operators for radiances) and its key statistical inputs are examined. In particular it is shown that incorrect specification of observation errors (R) and background errors (B) can severely limit the successful exploitation of satellite data.

By the end of this lecture you will:
- understand exactly what a satellite actually measures (radiance)
- appreciate the complex relationship between what is measured and what we wish to know for NWP
- how information is extracted from satellite measurements in data assimilation

Tony McNally
DA_TC_satellite.ppt

The aim of this lecture is to
By the end of the lecture the participants should be able to:
- apply the optimal interpolation method
- solve the optimal minimum-variance analysis problem
- review how Information is extracted from satellite measurements

Massimo Bonavita
Bonavita_EDA_HYBR_ID_DA_TC2017.pptx

Practical Session with OOPS

At ECMWF atmospheric composition data are assimilated into the IFS as part of the MACC-II project. On a global scale, atmospheric composition represents the full state of the global atmosphere, covering phenomena such as desert dust plumes, long-range transport of atmospheric pollutants or ash plumes from volcanic eruptions, but also variations and long-term changes in the background concentrations of greenhouse gases.

The aim of this lecture is to give an overview of the work that is carried out at ECMWF regarding the assimilation of atmospheric composition data, and to address why this is of interest and which special challenges are faced when assimilating atmospheric composition data.

By the end of this session you should:
- have some understanding of the work carried out at ECMWF to assimilate data of atmospheric composition

Antje Inness
Inness_envi2017.pptx

At ECMWF we are striving to move towards an Earth System approach to our data assimilation techniques. We currently have models not only of the atmosphere, but of the ocean, the land surface, sea ice, waves, and atmospheric composition. These systems interact with each other in different ways and all need to be initialised through the incorporation of observational data.

The aim of this lecture is to recognise the benefits and challenges associated with data assimilation in coupled models.

By the end of the lecture the participants should be able to:
- recall the challenges associated with variational data assimilation in systems with different timescales and computer codes
- describe the benefits of having more consistently balanced coupled systems from coupled data assimilation
- explain the differences between weakly and strongly coupled data assimilation approaches
- discuss the various methods that are in use at ECMWF and explain the planned developments of the systems

Phil Browne
coupled_da_presentation.pdf

This lecture will explain the basic concepts of the assimilation algorithms. The terminology used in the next lectures will be introduced. Simple examples will conduce towards the formulation of the optimal minimum-variance analysis. The optimal interpolation method will finally be presented.

By the end of the lecture the participants should be able to:
- recognize the notations used for the rest of the week
- solve the optimal minimum-variance analysis problem
- apply the optimal interpolation method

Sebastion Massart
TC_lecture_1.pdf

Followed by drinks reception and poster session

Massimo Bonavita
BGEm_lecture_2017.ppt

The background error is central to the performance of the analysis system and tells how much confidence to put in the best available forecast which is to be updated with new observations. The lecture will review how background errors are estimated and represented for current variational algorithms.

The background error is central to the performance of the analysis system and tells how much confidence to put in the best available forecast which is to be updated with new observations. The lecture will review how background errors are estimated and represented for current variational algorithms.

Massimo Bonavita
BGEm_lecture_2017.ppt

Practical Session with OOPS continued

This lecture provides an overview of a typical ocean data assimilation system for initialization and re-analysis application. The lecture uses as an example the ECMWF ocean data assimilation system, which is based on the NEMOVAR (3DVar FGAT). This will be used to discuss design of the assimilation cycle, formulation of error covariances, observations assimilated and evaluation procedure, among others.

By the end of the lecture students should be able to:
- describe the different components involved in a ocean data assimilation system
- list the components and differences between ocean and atmosphere data assimilation
- describe the basics of the physical ocean observing system
- explain the essential multivariate relationships between ocean variables
- identify the limitations of the existing systems

Hao Zuo
DA_course_2017_ocean_Zuo.pptx

At ECMWF we are striving to move towards an Earth System approach to our data assimilation techniques. We currently have models not only of the atmosphere, the ocean, the land surface, sea ice, waves, and atmospheric composition. These systems interact with each other in different ways and all need to be initialised through the incorporation of observational data.

The aim of this lecture is to recognise the benefits and challenges associated with data assimilation in coupled models.

By the end of the lecture the participants should be able to:
- recall the challenges associated with variational data assimilation in systems with different timescales and computer codes
- describe the benefits of having more consistently balanced coupled systems from coupled data assimilation
- explain the differences between weakly and strongly coupled data assimilation approaches
- discuss the various methods that are in use at ECMWF and explain the planned developments of the systems

Phil Browne
coupled_da_presentation.pdf
9:30 - 10:45
Meet the students

The infrared spectrum - measurement, modelling and information content
Tony McNally
SAT_TC_The_IR_spectrum_TM.ppt

GPS Radio Occulation: Extended applications
Seán Healy
gpsro_lecture2_2017_nwpsaf.ppt

Satellites for environmental monitoring and forecasting
Antje Inness
NWP_SAF_training_Course_April_2017_Inness.pptx

Satellite information on the ocean surface (SCAT)
Giovanna De Chiara
GDeChiara_surface_obs_2017_1.1.pptx

11:15...

Theoretical background (1)
What do satellites measure?
Tony McNally
SAT_TC_What_do_Satellites_Measure_TM.ppt

GPS Radio Occulation: Principles and NWP use
Seán Healy
gpsro_lecture1_2017_nwpsaf_v1.ppt

The detection and assimilation of clouds in infrared radiances
Tony McNally
SAT_TC_Detection_and_assimilation_clouds_IR.ppt

Background errors for satellite data assimilation
Tony McNally
SAT_TC_Estimation_and_correction_systematic-error.ppt

Systematic errors, monitoring and auto-alert systems
Mohamed Dahoui
Dahoui_Satellite_2017.pptx

14:00...

Theoretical background (2)
Data assimilation algorithms, Key elements and inputs
Tony McNally
SAT_TC_Data_assimilation_key_elements_TM.ppt

Satellite information on the land surface
Patricia de Rosnay
Land_satellite_NWP_SAF_TC_2017.pdf

The detection and assimilation of clouds and rain in microwave radiances
Alan Geer
sat_microwave_2017_2.pptx

Observation errors for satellite data assimilation
Peter Weston
ObsErrors_2017.pptx

Current satellite observing network and its future evolution
Stephen English
CurrentAndFutureSatellite.ppt

15:45...

The microwave spectrum, measurement, modelling and information content
Alan Geer
sat_microwave_2017_1.pptx

A Practical guide to IR and MW radiative transfer – using the RTTOV model and GUI
David Rundle (UK Met Office)
SAT_RT_modelling_lecture_JAH_DR.ppt

Wind information from satellites (Atmospheric Motion Vectors)
Katie Lean
amv_4dtracing_training_KLean_2017.pptx

1DVar theory, simulator + practical session on background and observation errors
Tony McNally
SAT_TC_Background_errors_TM.ppt
SAT_TC_1DVAR_practical.pptx

Question and answer session, course evaluation

Time:
Monday
Tuesday
Wednesday
Thursday
Friday

9.15-10.15
Introduction to the course with Computer Hall tour

The aim of this session is to introduce the ECMWF ensemble of data assimilation (EDA). The rationale and methodology of the EDA will be illustrated, and its use in to simulate initial uncertainties in the ECMWF ensemble prediction system (ENS) will be presented.

By the end of the session you should be able to:
• know what is the ECMWF EDA
• illustrate how the EDA is used to simulate initial uncertainty in ensemble prediction
• understand the main differences between singular vectors and EDA-based perturbations

Simon Lang
lang_2_2017new.pdf

Increasing observation volumes and model complexity, decreasing errors, and a growing desire for uncertainty information, all necessitate developments in our diagnostic tools. The aim of these lectures is to discuss some of these tools, the dynamical insight behind them, and the residual deficiencies that they are highlighting.

By the end of the lectures you should be aware of:
• Some of the key weaknesses of the ECMWF forecast system
• Some of the diagnostic tools used to identify and understand these weaknesses

Mark Rodwell
20170511_TC_PR_Diags_2_03_static.pdf

Increasing observation volumes and model complexity, decreasing errors, and a growing desire for uncertainty information, all necessitate developments in our diagnostic tools. The aim of these lectures is to discuss some of these tools, the dynamical insight behind them, and the residual deficiencies that they are highlighting.

By the end of the lectures you should be aware of:
• Some of the key weaknesses of the ECMWF forecast system
• Some of the diagnostic tools used to identify and understand these weaknesses

Magdalena Balmaseda
TCPR_Balmaseda_2017_Initialization_b.pdf

Mark Rodwell
20170511_TC_PR_Diags_2_03_static.pdf
10:45 The aim of this session is to introduce the idea of chaos. We will discuss the implications this has for numerical weather prediction.

By the end of the session you should be able to:

- describe what limits the predictability of the atmosphere
- understand the need for probabilistic forecasting

Antje Weisheimer
Intro_to_ChaosPres_short_AW2017.pdf

Abstract: The lectures introduce methods of ensemble verification. They cover the verification of discrete forecasts (e.g. dry/wet) and continuous scalar forecasts (e.g. temperature). Various scores such as the Brier score and the continuous ranked probability score are introduced.

After the lectures you should be able to:

- explain what a reliable probabilistic forecast is and how to measure reliability
- understand why resolution and sharpness of a probabilistic forecast matter
- compute several of the standard verification metrics used for ensemble forecasts

Martin Leutbecher
v1handout.pdf

Franco Molteni
TCPR_Molteni_2017_regimes.pdf

The aim of this session is to provide a general overview of monthly forecasting at ECMWF. We will review the main sources of predictability for the sub-seasonal time scale, including the Madden Julian Oscillation, sudden stratospheric warmings (SSW), land initial conditions and their simulation by the coupled IFS NEMO system. The skill of the ECMWF operational monthly forecasts will also be discussed.

By the end of the session you should be able to:

- List the different sources of predictability for extended-range forecasts
- Describe the operational system used to produce the ECMWF monthly forecasts
- Assess the skill of the monthly forecasting system

Magdalena Balmaseda
TCPR_Vitart_2017.2.pdf

11:55 The aim of this session is to introduce the main sources of uncertainty that lead to forecast errors. The weather prediction problem will be discussed, and stated it in terms of an appropriate probability density function (PDF). The concept of ensemble prediction based on a finite number of integration will be introduced, and the reason why it is to be the only feasible method to predict the PDF beyond the range of linear growth will be illustrated.

By the end of the session you should be able to:

- explain which are the main sources of forecast error
- illustrate why numerical prediction should be stated in probabilistic terms
- describe the rationale behind ensemble prediction

Antje Weisheimer

After this lecture, students will be able to:

- explain the physical and practical motivations for using stochastic physics in an ensemble forecast
- describe the two stochastic parameterization schemes used in the IFS ensemble, and their respective purposes;
- be able to identify the improvement in forecasting skill from the inclusion of stochastic physics.

Sarah-Jane Lock
StochPhys2017_print.pdf

The aim of this session is to introduce the ideas of ensemble verification. By the end of the session you should be able to:

- explain how the cluster analysis works
- use the ECMWF clustering products

Laura Ferranti
TC_clustering_2017.pdf

Land surface is a potential source of predictability of weather variability, such as warm or cold spells or precipitation. We will review the way land surface affects the atmospheric conditions, and the criteria that need to be fulfilled to contribute to predictability. A number of land-atmosphere coupling metrics are discussed, as well as a number of studies on the effect of realistic land surface initialization reported in literature.

Bart van den Hurk
Land_surface_predictability_for_training_course.pdf

This lecture covers the essentials of building a numerical seasonal forecast system, as exemplified by the present prediction system at ECMWF.

By the end of this lecture, you should be able to:

- explain the scientific basis of seasonal forecast systems
- describe in outline ECMWF System 4 and its forecast performance
- discuss the critical factors in further improving forecast systems

Tim Stockdale
Tz2017_seasonal.pdf
<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
</table>
| 2.00   | The aim of this session is to understand how we are able to provide forecasts at long time horizons given the chaotic nature of the atmosphere. After this session you should be able to:  
- describe the Lorenz idea of Predictability of the first and second kind  
- list examples of the elements of the Earth system that provide predictability on longer timescales  
- understand the type of forecast that we are able to provide beyond the deterministic limit  
Sarah Keeley  
_Beyond_limit.pdf_ |
| 2.45pm | Discussion Session in the Weather Room  
The latest medium, monthly and seasonal forecasts will be discussed in terms of outlook and performance. This is a combined event with the weekly weather discussion that ECMWF staff attend. |
| 3.30   | This lecture gives an overview of ensemble and post-processing and calibration techniques. The presentation is made from the medium-range forecast perspective. The (relative) benefits of calibration and multi-model combination for medium-range forecasting are also discussed.  
By the end of this lecture, you should be able to:  
- describe a wide range of possible calibration methods for ensemble systems  
- explain which methods are suitable in which circumstances  
- discuss the merits of calibration and multi-model combination  
Andrew Charlton-Perez  
_charlton_perez_strat.pdf_ |
| 2.45pm | Practice Session:  
You get the opportunity to experiment yourself with an ensemble prediction system for a chaotic low-dimensional dynamical system introduced by Edward Lorenz in 1995. Experiments permit to study the role of the initial condition perturbations and the representation of model uncertainties. Various metrics introduced in the ensemble verification lectures will be applied in this session.  
After the practice session, you will be able to use the toy model as an educational tool.  
Martin Leutbecher  
_practice_session.pdf_ |
| 2.45pm | Practice Session:  
Louise Arnal, Sarah Keeley and Sarah-Jane Lock |

2.45pm Discussion Session in the Weather Room

The latest medium, monthly and seasonal forecasts will be discussed in terms of outlook and performance.

This is a combined event with the weekly weather discussion that ECMWF staff attend.

Magdalena Balmaseda  
_TCPR_Balmaseda_2017_ocean_updated.pdf_
<table>
<thead>
<tr>
<th>Time</th>
<th>Location</th>
<th>Event Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.30-5.15</td>
<td>Computer hall and Weather Room Tours</td>
<td>Lecture and Practice Session: Abstract: The lecture is a short introduction to operational hydrological ensemble prediction systems, with focus on flooding. The European Flood Awareness System (EFAS) is described. The lecture also contains a short interactive exercise in decision making under uncertainty using probabilistic forecasts as an example. By the end of the session you should be able to: - Describe the components in hydrological ensemble prediction systems (HEPS). - Describe the major sources of uncertainty in HEPS and how they can be reduced. - Explain the difficulties in using probabilistic flood forecasts in decision making.</td>
<td></td>
</tr>
<tr>
<td>5.15</td>
<td>5.15 ice breaker</td>
<td>Practical extension</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fredrik Wetterhall</td>
<td>fred_flooding2017.pdf</td>
</tr>
</tbody>
</table>