MSc Atmospheric Science Module Handbook

Contents

Module & Course: Atmospheric dynamics (MET-M-ADYN)

Contributes to: Mandatory core of MSc Atmospheric Science

Coordinated by: Prof. Dr. Nedjeljka Žagar

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	winter semester	1 semester	Exercises and report	1	Yes

Structure

Weekly, 2h/weeks lecture and 2h/week exercise, Prof. Dr. Nedjeljka Žagar/ Dr. Frank Lunkeit

Learning objectives

The course teaches atmospheric dynamics by systematically introducing equations and concepts of increasing complexity and their use for understanding outputs of complex weather and climate models. Students learn to interpret atmospheric phenomena in observations and numerical models in terms of concepts and simplified models that describe scales and dynamical regimes of interest and can be solved mathematically. These solutions provide physical understanding of processes otherwise difficult to grasp.

Content

1. Basic Navier-Stokes equations. Scaling. Expansion in terms of the Rossby number. Separability of the vertical structure and horizontal flow.
2. Derivation of the shallow-water equations. Analytical solutions and conservations properties. Dynamical regimes: Rossby and gravity regime.
3. Waves in two-layer model. Basics of quasi-geostrophic dynamics.
4. Equatorial wave solutions. Convectively-forced waves in the tropics.
5. Vertically-propagating Rossby and equatorial waves.
6. Atmospheric energy spectrum. Interactions of waves and the mean flow. Wave-wave interactions.
7. Stationary Rossby waves. Rossby wave breaking.
8. Eliasen-Palm flux and SSW.
9. Linear wave theory applied to observations and weather and climate models.

Requirements and recommendations

Mandatory: basic knowledge of Newtonian physics

Recommended: atmosphere or ocean dynamics, numerical modelling of geophysical fluids

Work load

Attending lectures (60h), self-studies (90h), exam preparation (30h), Final oral exam.

Several mandatory home assignments requiring hand-in reports are a prerequisite to attend the oral exam.

Literature

- Lecture Notes by Nedjeljka Žagar
- Holton, J.: Introduction to dynamic meteorology.
- Vallis, G. K., Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation

Module & Course: Boundary Layer Modelling (MET-M-BLM)

Contributes to: Mandatory core of MSc Atmospheric Science

Coordinated by: Juan Pedro Mellado

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	summer semester	1 semester	Assignments + exam	2	Yes

Structure

Weekly, 2h/weeks lecture and 2h/week exercise, Juan Pedro Mellado

Learning objectives

This course is an introduction to the theory and the modeling of planetary boundary layers and their role in the Earth system. The students learn their characteristic properties and dominant processes in convective and stable regimes, learn about surface effects, about turbulence and entrainment. The students also learn about different modeling strategies such as mixed-layermodels, RANS models, large eddy simulation and direct numerical simulation.

Content

1. Boundary layer processes, structure and regimes. Governing equations.
2. Surface energy balance.
3. Integral analysis and mixed layer models. Parametric studies of boundary layer properties. Entrainment models. Dimensional Analysis.
4. Turbulence. Defining properties and Richardson's energy cascade.
5. Reynolds decomposition, mean equations and turbulent fluxes. Closure problem. Turbulence kinetic energy.
6. Turbulence modeling and simulation: RANS and K-theory, LES, DNS.
7. Neutral boundary layers. Application of K-theory. Surface wind, Ekman pumping and inertial oscillations.
8. The surface layer. Monin-Obukhov similarity theory. Bulk transfer coefficients. Roughness and heterogeneity. Application to mixed layer models.
9. Convective boundary layers. Entrainment and gravity waves. Mixed-layer models. K-profile parametrizations.
10. Stable boundary layers. Inertial oscillations and gravity waves, global intermittency. Stability corrections to K-theory and subgrid-scale models, total-energy models.
11. Scalars. Moisture, drying and moistening regimes, Bowen ratio and cloud formation.
12. Special topics: Boundary-layer clouds and cloud microphysics models; diurnal cycle and other transients; gravity currents (cold pools); internal boundary layers

Requirements and recommendations

Basic knowledge of fluid mechanics, turbulence and thermodynamics is recommended.

Work load

Attending lectures (60h), self-studies (90h), exam preparation (30h)

The students are expected to hand-in written reports of take-home assignments approximately every 2 weeks, working in groups of 2 or 3 people to foster teamwork. This will contribute to 30% of the final grade; 70% is the final exam.

Literature

- J. Vila Guerau de Arellano and co-authors, Atmospheric Boundary Layer: Integrating Atmospheric Chemistry and Land-Interactions, Cambridge University Press, 2015
- J. C. Wyngaard, Turbulence in the Atmosphere, Cambridge University Press, 2010
- J. R. Garratt, The Atmospheric Boundary Layer, Cambridge University Press, 1992
- R. Stull, An introduction to Boundary Layer Meteorology, Kluwer Academic Publishers, 1988

Course: Radiation and Climate (MET-M-RC)

Contributes to: Mandatory core of MSc Atmospheric Science

Coordinated by: Stefan Buehler

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	winter semester	1 semester	written exam	1-3	Yes

Structure

Weekly lecture and exercises (3 CP, 2h/weeks lecture and 3 CP, 2h/weeks exercise, Stefan Buehler)

Learning objectives

Student understands theory of radiative transfer and can apply it to understand and predict planetary climate.

Content

1. Earth's energy balance and greenhouse effect (first law, Stefan-Boltzmann law, Fourier, Tyndall, 1-layer grey greenhouse atmosphere, Earth's radiation budget)
2. Absorption spectra of carbon dioxide and water vapor (quanta and energy levels, theory of rotational and vibrational spectra, ARTS, modelled spectra, opacity, atmospheric windows)
3. The outgoing longwave radiation spectrum of Earth (thermal radiation and Planck's law, Schwarzschild equation and opacity rule, modelling and understanding Earth's outgoing longwave radiation spectrum)
4. Radiative forcing (spectral and total forcing, fast adjustments)
5. Equilibrium climate sensitivity (forcing-response framework, feedback parameter, Gregory method, Dessler/Römer method, spectral feedback parameter)
6. Water cycle and hydrological sensitivity (water cycle, Clausius-Clapeyron Eq., hydrological sensitivity, extreme precipitation, patterns of change)
7. Radiative-convective equilibrium (pure radiative equilibrium, stability – dry adiabat and moist adiabat, constructing a 1D RCE model, KONRAD)
8. Atmospheric clearsky feedbacks (Planck, water vapor, lapse rate)
9. Cloud forcing adjustment and cloud feedbacks (cloud impact on radiation balance, all-sky forcing, high cloud feedback and FAT mechanism, low cloud feedback)
10. The new estimate of ECS (historical ECS values, Bayesian framework, lines of evidence, estimated ECS pdf)

Requirements and recommendations

none

Work load
Attending lectures (30h), attending exercises (30h), self-studies (90h), exam preparation (30h)

Literature

- IPCC AR6 WG1 Report
- Dennis Hartmann, Global Physical Climatology (2nd edition), Elsevier, 2016
- Raymond Pierrehumbert, Principles of Planetary Climate, Cambridge University Press, 2010
- Petty: A First Course in Atmospheric Radiation (2nd edition), Sundog Publishing, 2006

Module & Course: Experimental Meteorology (MET-M-EXP)

Contributes to: Mandatory core of MSc Atmospheric Science

Coordinated by: Felix Ament

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	No	summer semester	1 semester	Presentation of project results	1-3	Yes

Structure

Weekly seminar (2 CP, 2h/weeks) + two-week field or lab campaign (4CP) after lecture time during summer.

Learning objectives
Students know how to design, conduct and analyze experiments in Atmospheric Science. They can analyze large, complex observational data sets to test theories in Atmospheric Science. They are able to asses the uncertainty of observational data.

Content
In the first phase of the seminar, students form teams and develop own research question to be addressed by the field or lab campaign. Thereafter they get used to all fundamentals of the chosen topic including a literature survey and an overview on measurement techniques. They design the campaign and summarize these preparations in a white paper.
During the filed campaign, students set up their experimental devices and maintain them. By constant monitoring of the measurement, they are able to adapt the configuration to optimize the results and to response to malfunctions.
Finally the project results are presented in research-oriented format, typical poster presentations.

Requirements and recommendations
none

Work load
Attending seminar (30h), self-studies seminar (30h), field or lab campaign (60h), exam preparation (30h)

Literature

Depending on selected topics

Course: Numerical Simulation (NUM)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Juan Pedro Mellado

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	summer semester	1 semester	Assignments + report	2	Yes

Structure

Weekly, 2h/weeks lecture and 2h/week exercise, Juan Pedro Mellado

Learning objectives

This is a hands-on course where the students learn about various numerical techniques to solve the wave equation that describes advection problems, the heat equation associated to diffusion processes, and the Poisson equation that results from divergence-free constraints, e.g., mass conservation. At the end of the course, the students know how to solve the Navier-Stokes equations, the dynamical core of Earth system models.

Content

1. Models. Resolved and unresolved scales and processes: parametrizations. Discretization and numerical solutions: Finite difference methods, finite volume methods, spectral methods and finite element methods. Semi-discrete approach (method of lines).
2. Finite difference approximations. Sampling and aliasing errors. Taylor tables. Local error analysis. Global error analysis (Fourier or von Neumann analysis). Boundary value problems.
3. Time-marching schemes. Explicit and implicit schemes. Single-step and multi-step methods (spurious or computational modes). Convergence, accuracy, consistency, stability. Stability region. Initial value problems.
4. Waves and hyperbolic equations. Stability and the CFL number. Error analysis, numerical diffusion and numerical dispersion (amplitude and phase errors). Conservation properties.
5. Multidimensional problems. The treatment of boundary conditions. Nonrotating, linearized shallow water equations.
6. Diffusion and parabolic equations. Stability and the diffusion number. Operator splitting. Non-uniform meshes. Stiffness.
7. Nudging and nesting.
8. Non-linear advection equation. Aliasing errors associated with non-linear operations. Method of characteristics. Formation of discontinuities.
9. Continuity, pressure and elliptic equations (Laplace, Poisson and Helmholtz equations). Barotropic model: quasi-geostrophic shallow water equations.

10. Unstructured meshes.

Requirements and recommendations

Basic knowledge of numerical methods, fluid mechanics and atmospheric dynamics is recommended.

Work load

Attending lectures (60h), self-studies (120h).

The students are expected to hand-in written reports of take-home assignments approximately every 2 weeks, working in groups of 2 or 3 people to foster teamwork. The final grade will be the average of the grade in these assignments. As programming language, python is recommended.

Literature

- D. Durran, Numerical Methods for Fluid Dynamics With Applications to Geophysics, Second Edition, Springer, 2010
- D. Randall, An Introduction to Numerical Modeling of the Atmosphere, U. Colorado, 2020

Course: Atmospheric Physics (PHY)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Juan Pedro Mellado

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	winter semester	1 semester	Assignments + exam	1	Yes

Structure

Weekly, 2h/weeks lecture and 2h/week exercise, Juan Pedro Mellado

Learning objectives

This course provides an introduction to atmospheric thermodynamics, cloud microphysics, and turbulence and boundary layers as necessary to further study the role of these diabatic processes in weather and climate.

Content

1. Thermodynamic description of the atmosphere: dry and moist thermodynamics.
2. Thermodynamic processes: dew point, wet bulb, mixing, adiabatic ascent, static energies and potential temperatures.
3. Static stability of the atmosphere: buoyancy, lapse rates, conditional instability.
4. Nonequilibrium thermodynamics: balance equations and transport phenomena.
5. Description of clouds: types, properties, droplet size distribution.
6. Warm clouds processes: Köhler curve and collision-coalescense.
7. Cold clouds processes: Bergeron process.
8. Turbulence properties and the Richardson energy cascade.
9. Statistical description of turbulent flows. Reynolds equations. Closure problem.
10. Planetary boundary layer: diurnal cycle, convective and stable regimes.
11. Atmospheric surface layer and entrainment.

Requirements and recommendations

Some background on general thermodynamics and fluid mechanics is recommended.

Work load

Attending lectures (60h), self-studies (90h), exam preparation (30h)

The students are expected to hand-in written reports of take-home assignments approximately every 2 weeks, working in groups of 2 or 3 people to foster teamwork. This will contribute to 30% of the final grade; 70% is the final exam.

Literature

- J. V. Iribarne and W. L. Godson, Atmospheric Thermodynamics, Second Edition, D. Reidel Publishing Company, 1981
- R.R. Rogers and M. K. Yau, A Short Course in Cloud Physics, Third Edition, Butterworth-Heinemann, 1989
- J. M. Wallace, P. V. Hobbs, Atmospheric Science, Second Edition, Elsevier, 2006
- J. C. Wyngaard, Turbulence in the Atmosphere, Cambridge University Press, 2010

Course: Urban Climatology (UrbClim)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: David Grawe

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
3 LP	Yes	winter semester	1 semester	written exam	1	Yes

Structure

Weekly, 2h/week lecture with exercise, David Grawe

Learning objectives

Participants of the course will know the relevant processes that determine the micro-climate in urban areas and will be able to assess the effectiveness of adaptation measures. They will have a solid knowledge of micro-meteorological processes and effects in urban areas as required for the preparation of a thesis in this area or in consultancy work.

Content

The course teaches micro-meteorological expert knowledge and introduces applied examples of urban climatology. The topics include:

1. specifics of the urban boundary layer and of the urban micro-climate,
2. momentum, energy, humidity and mass fluxes in urban areas,
3. human biometeorology,
4. urban air quality and regulations,
5. numerical modelling of urban climate,
6. urban climate change,
7. adaptation measures in urban areas.

Requirements and recommendations

none

Work load

Attending lectures (30h), self-studies (45h), exam preparation (15h)

Literature

- Lecture notes.
- Oke, Mills, Christen, Voogt: Urban Climates, Cambridge University Press, 2017.

Course: Tropical Clouds and Convection (TCC)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Raphaela Vogel

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	summer semester	1 semester	Assignments + report	1-3	Yes

Structure

Weekly, 2h/weeks lecture and 2h/week exercise, Raphaela Vogel

Learning objectives

The course teaches fundamental concepts of shallow and deep atmospheric convection as well as cloud physics and dynamics, discusses tools to better understand their interaction with the large-scale environment, and highlights the role that clouds play in climate. Students will understand why different cloud types form along the trade-wind trajectory and apply their knowledge directly in hands-on exercises using observations and simulations from the recent EUREC^{4}A field campaign. Students will develop critical reading skills of current literature and contribute to the public dissemination of climate science by writing a Wikipedia article on a course-related subject.

Content

1. Introduction to the tropics: Hadley and Walker circulation, Intertropical Convergence Zone, tropical waves, differences to midlatitudes and contrasts between land and ocean.
2. Fundamentals of convection: dry and moist convection, buoyancy, stability, thermodynamic variables, CIN and CAPE, radiative-convective equilibrium.
3. Cloud fundamentals: cloud formation, cloud microphysics and aerosols, precipitation, cloud macrophysics, cloud classification, organization of shallow and deep convection, role of clouds in climate system and cloud feedbacks.
4. Cloud regimes: phenomenology and fundamental processes of stratocumulus, shallow trade cumulus, and deep convective clouds, with an emphasize on the trade cumulus regime.
5. Modeling and observing clouds: mixed-layer and conceptual models, large-eddy simulations and cloud-resolving simulations, parameterizations in climate models. Ground-based and satellite remote sensing and in-situ observations, field campaigns.

Requirements and recommendations

Basic understanding of meteorological concepts and atmospheric thermodynamics.

Work load
Attending lectures and exercises (60h), homework assignments & self-study (90h), Wikipedia article preparation (30h).

The students are expected to hand-in by-weekly exercises and present one paper from a selection of key papers. Students should form working groups of 2-3 people, but hand in exercises independently. They will further develop one topic in more detail and write a Wikipedia article about it. The final grade will be composed of the grades from the exercises (50%) and the Wikipedia article (50%). Class room paper presentation will not be graded.

Literature

- K. A. Emanuel, Atmospheric Convection, Oxford University Press
- R. A. Houze, Cloud Dynamics, Elsevier
- A. P. Siebesma et al., Clouds and Climate, Cambridge University Press

Course: Climate Change – settled science and open questions

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Bjorn Stevens (Hauke Schmidt)

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
3 LP	Yes	winter semester	1 semester	Assignments + report	1-3	Yes

Structure

Weekly, 2h/weeks lecture

Learning objectives

To understand the conceptual foundations of our understanding of global warming and associated changes in climate, and the outline of the important open questions.

Content

1. Precipitation changes (patterns and amplitude)
2. Arctic amplification
3. Land sea contrast
4. Circulation Changes
5. Coupled modes of variability
6. Tipping points

Requirements and recommendations

TBD

Work load

TBD

Literature

TBD

Course: Earth System Modelling with ICON

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Daniel Klocke

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
3 LP	Yes	summer semester	1 semester	Assignments + report	1-3	Yes

Structure

1 semester course

Learning objectives

To understand the software infrastructure and software development environment of a modern Earth system model

Content

1. ICON software infrastructure
2. HPC computing infrastructure
3. Version control and software development with GIT
4. Best practices in software development (clear code, documentation, collaboration)
5. Analysis workflows
6. Modifying and running numerical experiments

Requirements and recommendations

Basic class in programming and familiarity with the UNIX environment.

Work load

TBD

Literature

Course Script

Course: Land-Atmosphere interactions

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Cathy Hohenegger

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
3 LP	Yes	winter semester	1 semester	Assignments + report	1-3	Yes

Structure

Weekly, 2h/weeks lecture

Learning objectives

The replication of the coastline a few kilometers inland by convective clouds on a summer day, the enhancement of precipitation over mountainous regions or potential changes in the precipitation regime following the deforestation in Amazonia are all examples of interactions between the land surface and the atmosphere. The aim of this course is to introduce and explain the effects of the land surface on the atmosphere, with a special focus on convection and precipitation, going from the small scales to the larger scales, and using conceptual models. At the end of the course, a student should be able to understand when and why the land surface is important, how a change in the land surface might influence the atmosphere and the climate and what the uncertainties are.

Content

1. Brief reminder on land surface processes and how they affect the atmosphere
2. Landscape-induced shallow circulations
3. Soil moisture-precipitation feedback
4. Soil moisture-temperature feedback
5. Monsoons
6. Effect of land-sea distribution on climate
7. Role of land-atmosphere interactions in the past climate record
8. Role of land-atmosphere interactions for future climate change
9. Tipping points

Requirements and recommendations

TBD

Work load

TBD

Literature

TBD

Course: Atmospheric General Circulation (ATM-GEN-CIRC)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Prof. Dr. Nedjeljka Žagar

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	winter semester (on demand)	1 semester	oral exam	1-3	Yes

Structure

Weekly lecture or exercise including labs, 4h/weeks lecture and/or exercise, Prof. Dr. Nedjeljka Žagar and Dr. Frank Lunkeit

Learning objectives

The course teaches atmospheric dynamics by systematically introducing equations and concepts of increasing complexity and their use for understanding outputs of complex weather and climate models. Students learn to interpret atmospheric phenomena in observations and numerical models in terms of concepts and simplified models that describe scales and dynamical regimes of interest and can be solved mathematically. These solutions provide physical understanding of processes otherwise difficult to grasp. Labs utilizing a global circulation model of intermediate complexity give hands-on practice on designing, conducting and analyzing numerical experiments on the general circulation.

Content

1. Basic Navier-Stokes equations. Basic approximations
2. Introduction to the problem of general circulation
3. Basic prognostic equations in log-p system
4. The global averaged view:
    - Lorenz energy cycle
5. The zonally averaged view:
   Lectures:
    - Equations for the zonally-averaged circulation
    - Hadley and Ferrel cell
    - Eliassen- Palm flux and transformed Eulerian mean
    - Zonal-mean potential vorticity equation

- Zonal-mean angular momentum equation

Lab:

- The zonally averaged circulation on an aqua-planet
- Simulation and diagnostics
- Sensitivity to greenhouse forcing, Eddy fluxes, rotation rate, etc.

6. The three dimensional view:
   Lectures:
   - Rossby waves: topographic, stationary, vertically propagating, storm tracks, wave breaking
   - Horizontal and vertical momentum fluxes
   - Hadley and Walker cell and the large-scale unbalanced circulation
   - Basics of stratospheric dynamics
   - Low frequency variability

   Lab:

   - The general circulation on an Earth like planet of your choice
   - Simulation and diagnostics
   - Sensitivity to solar and greenhouse forcing, topography, rotation rate, etc.

Requirements and recommendations
Mandatory: basic knowledge of geophysical fluid dynamics
Recommended: numerical modelling of geophysical fluids

Work load

Attending lectures (60h), self-studies (90h), exam preparation (30)
Final oral exam. Several mandatory home assignments requiring hand-in reports are a prerequisite to attend the oral exam.

Literature

- Lecture Notes by course lecturers
- Selected chapters from Holton, J.: Introduction to dynamic meteorology, and Peixoto, J.P. and A.H. Oort: Physics of Climate

Course: Data Analysis in Atmosphere and Ocean using Python (DAO-Py)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Dr. Sergiy Vasylkevych

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	summer semester	1 semester	Exercises and report	1	Yes

Structure

Weekly, 2h/week lecture and 2h/week exercise, Dr. Sergiy Vasylkevych

Learning objectives

The course provides an introduction to data analysis targeted at students, who plan career in meteorology, oceanography, or climate science. The course emphasizes hands-on approach oriented at solving most common data analysis tasks encountered in weather and climate studies. Python is used throughout as a numerical tool of choice. To make the course self-contained, a brief introduction to Python is provided. The students learn various techniques and tools used to analyze, interpret and visualize atmospheric and oceanic measurements as well as output of numerical models.

Content

1. Introduction to Python and basic plotting.
2. Accessing, manipulating and visualising geophysical data in NetCDF format (xarray, cartopy).
3. Basic statistical concepts and statistical data analysis: random variables, distributions, PDF, CDF, averages, mean, median and mode; standard deviation and variance, moments, quartiles, skewness and curtosis. measurement error and central limit theorem.
4. Parameter estimation and curve fitting. Linear regression. Correlations. Bias and variability.
5. Plotting statistical data.
6. Statistical tests: Statistical significance. Student’s, Pearson’s and Spearmen’s tests.
7. Spectral and time-frequency analysis.
8. Analyzing the spatial and temporal variability of geophysical fields: empirical orthogonal functions (EOFs) and singular value decomposition (SVD).

Introduction to machine learning with scikit-learn and TensorFlow. Overview of machine learning landscape: types of machine learning systems, deep and shallow learning, machine learning algorithms and packages. Model evaluation, cross-validation and optimization.

9. Shallow learning algorithms: random forest, decision trees, support vector machines, xgboost, gradient boost.
10. Deep learning with Tensor Flow and Keras. Basics of deep learning: neural networks, hidden layers, activation functions. Defining network architecture, Improving the model's performance. Customizing the model.

Requirements and recommendations

Mandatory: basic knowledge of geophysical fluids

Recommended: basic programming skills.

Work load

Attending lectures (60h), self-studies (90h), exam preparation (30h)

Students are expected to submit a report for each mandatory homework set (5-6 sets). Reports are graded and their average grade is the final grade of the course.

Students wishing to improve their grade can take a final exam in the form of lab programming session.

Literature

- Aurélien Géron (2019), Hands-On Machine Learning with Scikit-Learn, Keras, and TensorFlow, ORiley 2nd Edition.
- Robert Johansson. Numerical Python: Scientific Computing and Data Science Applications with Numpy, SciPy and Matplotlib, 2nd Edition, Apress, Berkeley, CA, 2019;
- Hakan Alyuruk , R and Python for oceanographers: a practical guide with applications, Elsevier, Amsterdam, 2019.
- Various online resources

Course: Geophysical Wave Lab (GWLab)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Prof. Dr. Nedjeljka Žagar

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	winter semester	1 semester	Exercises and report	-	Yes

Structure

Weekly, 2h/week lecture and 2h/week exercise, Prof. Dr. Nedjeljka Žagar, Dr. Sergiy Vasylkevych

Learning objectives

The course provides introductory theoretical and modelling training in atmosphere and ocean dynamics. Lectures on wave motions are supplemented by a hierarchy of numerical labs using in-house numerical prediction models.

The students receive an overview of basic wave concepts important for the atmospheric and ocean circulation, gain hands-on experience in analyzing specific phenomena, such as the Rossby and inertia-gravity waves in the midlatitudes and in the tropics, geostrophic adjustment, barotropic instability, impact of orography on the flow, as well as practical skills in designing numerical experiments and describing their results in a written form.

Content

1. Waves, basic concepts: amplitude, phase, group and phase velocity, wave number and wave vector, dispersion. Linear and non-linear waves.
2. Surface gravity waves in a non-rotating shallow water. The role of the background state.
3. Effects of rotation. Rossby waves, Rossby adjustment problem. Energetics and Potential vorticity of shallow-water equation sets.
4. Inertia-gravity waves in a rotating fluid. Kelvin and Poincaré waves. Topographic effects. Waves generated by horizontal boundaries. Coastal and continental shelf waves.
5. Waves in the tropics. Equatorial beta plane and equatorial trapping. Balance theories in the tropics versus midlatitudes.

6. Waves on the sphere. Shallow water and primitive equations on the sphere. Normal modes of atmospheric motion. The energy spectra in the atmosphere and in the deep ocean.
7. Free waves in the presence of horizontal temperature gradient. Barotropic and baroclinic instabilities.

Requirements and recommendations

Mandatory: basic knowledge of Newtonian physics

Recommended: basics of geophysical fluid dynamics, with application to the atmosphere and ocean, interest in numerical modelling.

Work load

Attending lectures (60h), self-studies (90h), exam preparation (30h)

Students submit written reports for selected mandatory labs (5-6 labs). Reports are graded and their average grade is the final grade of the course.

Students are given an opportunity of oral exams if a higher grade is requested.

Literature

- Vallis, G. K., Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation. Cambridge University Press.
- Gill, A., *Atmosphere-Ocean Dynamics*. New York, NY: Academic Press.

Course: Internal waves and instabilities (WavInst)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Prof. Dr. Nedjeljka Žagar

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	winter semester	1 semester	Oral exam	-	Yes

Structure

Weekly, 2h/week lecture and 2h/week exercise, Prof. Dr. Nedjeljka Žagar/Dr. Frank Lunkeit

Learning objectives

The course teaches internal gravity waves and mesoscale instabilities in the atmosphere by combining mathematical description with examples of real atmosphere phenomena and analytical and numerical exercises. Students learn to understand processes leading to the development of various instability and wave phenomena at mesoscale and their filtering in high-resolution numerical weather and climate models.

Content

1. Systematic scaling of the Navier-Stokes equations. Boussinesq approximation and equations for mesoscale motions.
2. Basic instabilities: static, inertial and symmetrical instability. Horizontal-shear instability and Kelvin-Helmholtz instability.
3. Internal gravity waves: Derivation of the Taylor-Goldstein equation (TGE). Simplified solutions of the TGE. Dispersion relationships. Vertical wave propagation. Critical level. Comparison of theory, observation and model simulations.
4. Mountain waves. Downslope wind storms.
5. Gravity wave momentum fluxes in observations and models.

Requirements and recommendations

Mandatory: basic knowledge of Newtonian physics

Recommended: atmosphere or ocean dynamics, basics of numerical modelling of geophysical fluids

Work load

Final oral exam. Several mandatory home assignments requiring hand-in reports are a prerequisite to attend the oral exam.

Literature

- Lecture Notes by Nedjeljka Žagar
- Markowski, P. and Y. Richardson: Mesoscale meteorology in midlatitudes
- Nappo, C.: An Introduction to atmospheric gravity waves

Course: Numerical Prediction of the Atmosphere and Ocean (NPAO)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Prof. Dr. Nedjeljka Žagar

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	summer semester	1 semester	Report	-	Yes

Structure

Weekly, 2h/week lecture and 2h/week exercise, Prof. Dr. Nedjeljka Žagar, Prof. Dr. Detlef Stammer, Dr. Sergiy Vasylkevych, Dr. Nuno Serra

Learning objectives

The course provides training in data assimilation, numerical weather prediction and predictability of atmosphere and ocean. Mathematical formulation of the initial-value problem is complemented by practical exercises with numerical models of different complexity that simulate atmosphere or ocean processes as an initial and (or) boundary value problem.

Knowledge and understanding include atmospheric and ocean observations, a hierarchy of data assimilation methods, formulation of numerical prediction models, theoretical and intrinsic predictability, ensemble forecasting, and interpretation of outputs of forecast models. Student develops understanding of various components of the numerical prediction models and how they contribute to reliability of model forecasts.

Content

1. Numerical weather and ocean prediction as an initial value problem: general introduction.
2. Components of the global observing system. Types of observations. Components of observation errors. Relative importance of various observations for numerical weather prediction (NWP).
3. Data assimilation for numerical weather prediction and for the ocean: probability calculus, function fitting, early methods of data assimilation, method of successive corrections, background state, statistical interpolation, variational methods, (3D-Var, 4D-Var), background-error covariance modelling, Kalman filter and assimilation methods based on ensembles of forecasts and analyses.

4. Initialization step of NWP models: Richardson's experiment in 1920s, geostrophic adjustment and evolving definition of balance, nonlinear normal-mode initialization, digital filter initialization.
5. Numerical aspects of NWP models: global and limited-area models, initial and lateral boundary conditions, nesting. Bottom and top boundary conditions. Formulation of lateral boundary coupling for limited-area weather forecast models. One-way and two-way nesting.
6. Predictability: fundaments of theory of chaotic systems, Lyapunov exponents, intrinsic and practical predictability, growth of forecast errors, simple models of the forecast error growth.
7. Ensemble forecasting: sources of uncertainties, formulation of initial conditions for ensemble forecasts, interpretation and application of ensemble products. Monthly, seasonal and long-range forecasting.

Requirements and recommendations
Mandatory: basics of Newtonian physics and linear algebra

Recommended: atmosphere or ocean dynamics, numerical modelling of geophysical fluids, interest in weather forecasting.

Work load
Lectures (60), self-studies (90), exam preparation (30)

Students are expected to submit a written report for each mandatory lab (4-5 labs). Reports are graded and their average grade is the course grade. Students are given an opportunity of oral exams if a higher grade is requested.

Literature

- E. Kalnay: Atmospheric modelling, data assimilation and predictability. Cambridge University Press 2003.
- Lecture notes by the course professors

Course: Applied atmospheric dispersion modeling (AADM)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Prof. Dr. Brend Leitl

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
3 LP	Yes	Annual	1 semester	Written report	-	Yes

Structure

Weekly, lectures and project seminar 2 h/week in total, Prof. Dr. B. Leitl, Dr. F. Harms

Learning objectives

1. Understanding non-CFD atmospheric dispersion models used for applied air quality / air pollution management and hazmat dispersion modeling
2. Proficiency in the proper generation and interpretation of model results
3. Skills in writing technical reports at basic consultant level

Content

1. Brief introduction to legal context of air quality management and environmental protection
2. Basic concepts of modeling / heuristic and deterministic modeling
3. Meteorological input for atmospheric pollutant dispersion modeling
4. Plume rise modeling
5. Gaussian dispersion modeling
6. Lagrangian dispersion modeling
7. Gradient transport / K models

Requirements and recommendations

Basic understanding of fluid dynamics (hydrodynamics, turbulence, boundary layer flows), basic applied math (algebra/calculus), generic/basic skills in coding and/or the use of spreadsheets.

Work load

Attending lectures and seminars (28h), self-study and independent study project (52h), preparation for the exam (10h).

Literature

- Lecture notes / optional script
- Bird, R.B.; Stewart, W.E.; Lightfoot, E.N. (1960): Transport Phenomena. John Wiley & Sons, New York 1960
- Hanna, S.R.; Briggs, G.A.; Hosker, R.P. (1982): Handbook of Atmospheric Diffusion. Technical Information Center, U.S. Department of Energy

- Hanna, S.R.; Briggs, G.A.; Hosker, R.P. (1982): Handbook of Atmospheric Diffusion. Technical Information Center, U.S. Department of Energy

- Engineering Science Data Unit – ESDU
- VDI guidelines 3782-x/3783-x/3945-x

Course: Fluid modeling of atmospheric flow and dispersion (FMOD)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Prof. Dr. Brend Leitl

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	summer semester	1 semester	written project plan / lab report and oral defense	-	Yes

Structure

Weekly, lecture/lab exercise 2 h/week, Prof. Dr. B. Leitl, Dr. F. Harms

Learning objectives

1. Understanding the concepts of fluid modeling of environmental flow and dispersion phenomena
2. Skills in designing and implementing fluid modeling experiments in wind tunnels and water flumes
3. Knowledge about relevant state-of-the-art laboratory measurement technology and instrumentation
4. Skills in developing experimental project proposals

Content

1. Fundamental equations, similarity concept and scaling principles
2. Characterization of relevant atmospheric boundary conditions and simulation of atmospheric boundary layer flows
3. Practical implementation of fluid modeling experiments
4. Wind tunnel instrumentation
5. Experimental Planning and Management / Technical Guidelines
6. Data Documentation and Analysis
7. Exemplary wind tunnel studies:
   - Neutrally stratified ABL flow

- Flow and dispersion in and above canopies
- Wind loads on structures

Requirements and recommendations

Basic understanding of fluid dynamics (hydrodynamics, turbulence, boundary layer flows), basic applied math (fundamentals of random data analysis).

Work load

Attending lectures and seminars (68h), self-study (90h), preparation for the exam (22h).

Literature

- Lecture notes / optional script
- VDI guideline 3783/12 – Wind Tunnel Modeling, Beuth Verlag
- ASCE: Wind Tunnel Studies of Buildings and Structures. Manual of practice no. 67, 1999, American Society of Civil Engineers, ISBN 0-7844-0319-8
- W.H. Snyder: Guideline for Fluid Modeling of Atmospheric Diffusion. US EPA Report 600/8-81-009, April 1981

Course: Atmospheric Remote Sensing (MET-M-ARS)

Contributes to: Module Advanced Core Elective (MET-M-ACE)

Coordinated by: Manfred Brath

Credit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
6 LP	Yes	winter semester	1 semester	oral exam	1-3	Yes

Structure

Weekly lecture and exercises (3 CP, 2h/weeks lecture and 3 CP, 2h/weeks exercise), Manfred Brath

Learning objectives

Student understands principles of atmospheric remote sensing and can apply it to retrieve atmospheric properties from remote sensing observations.

Content

1. Overview of atmospheric remote sensing
2. Electromagnetic radiation
3. Radiative transfer (passive and active)
4. Absorption/emission by atmospheric gases
5. Scattering by clouds
6. Observation/Measurement problem
7. Forward modelling
8. Optimal estimation retrieval (radiometer and radar)
9. Data driven retrievals (Bayesian Monte Carlo integration and artificial neural networks)

Requirements and recommendations

none

Work load

Attending lectures (30h), attending exercises (30h), self-studies (90h), exam preparation (30h)

Literature

- Liou, Kuo-Nan. An Introduction to Atmospheric Radiation. 2. ed. Academic Press, 2002.

- Efremenko, Dmitry, und Alexander Kokhanovsky. Foundations of Atmospheric Remote Sensing. 1st ed. 2021. Springer International Publishing, 2021

Course: Confronting Models with Observations (MET-M-CMO)

Contributes to: Advanced Core Elective of MSc Atmospheric Science

Coordinated by: Prof. Dr. Felix Ament, Dr. Frank Harms

Cerdit Points	Graded?	Interval	Duration	Exam	Recommended Semesters	Suitable as minor
3 LP	Yes	winter semester	1 semester	Written exam	1-3	Yes

Structure

Weekly, 2h/weeks lectures with exercises, Prof. Dr. Felix Ament/ Dr. Frank Harms

Learning objectives

Advances in atmospheric and climate sciences rely heavily on simulations by complex weather and climate models. We establish faith in these models by comparing simulation results with observations to evaluate their accuracy or their fit for purpose.

This course familiarizes you with all relevant facets of this process of confronting models with observations. In the first part you will learn how to generate reference observations and to assess the reliability / uncertainty of reference data set by using example from the environmental wind tunnel lab. In the second part you will be in position to apply all state-of-the art techniques to verify forecast from a numerical weather prediction perspective. This includes classical verification of point forecast, evaluation of spatial patterns, assessment of probabilistic forecast and the evaluation the forecasts of extremes. After the third part you will know standard concepts and frequently used reference data sets to evaluate climate models and have gained insights in recent research activities to confront the next generation of climate and weather models with novel observations at small scales that have not been resolved by models so far.

Content

1. Representativeness of reference data
2. Main factors influencing the representativeness of reference data
3. Transferring measurement results to a dimensionless view
4. Examples of evaluating numerical models with reference data from field and wind tunnel measurements
5. Foundation of NWP verification, Scores for deterministic categorical verification, Skill Scores,

6. Hedging, Metaverification, Economic Value
7. Introduction to probabilistic forecasts, Brier Score, Factorizations, reliability diagrams, Brier Skill Score decomposition, Relative Operating Characteristics, Proper scoring
8. Interpretation of ensemble forecasts, ensemble consistency, Rank Histograms.
9. Double penalty effect, systematic of spatial verification methods: filtering versus displacement, examples of neighborhood, scale separation, feature based and deformation methods.
10. Degeneration of scores in case of extreme events, power law decay of hit rate, advanced measures for extremes scores
11. Common observational data sets for climate model evaluation, frequently used concepts to evaluate climate models
12. Examples of recent activities to evaluate and constraint the next generation of high-resolution models for climate and weather forecasting applications

Requirements and recommendations

Mandatory: basic knowledge of statistics

Work load

Attending lectures (30h), self-studies including hands-on homework tasks (30h), exam preparation (30h)

Literature

- Lecture Slides
- Joliffe, 2011: Forecast Verification: A Practitioner's Guide in Atmospheric Science
- Wilks, 2011: Statistical methods in Atmospheric Sciences