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METR 3133 – Mesoscale Meteorology
Fall 2016

Study Guide for Comprehensive Final Examination

Below are listed the principal topics, concepts, and capabilities for which you will be responsible on the first exam. The absence of a topic from this sheet does NOT imply that it will be absent from the exam!

<u>Fundamental Concepts</u>

1. Be able to explain the difference between kinematics and dynamics.
2. Understand the definition of a Newtonian fluid
3. Be able to explain the concept of an air parcel and how it relates to its microscopic counterpart, the air molecule
4. Understand the difference between dependent and independent variables

<u>Units, Dimensions, and Atmospheric Variables</u>

1. Be able to explain the difference between units and dimensions and give examples of each
2. Know the principal MKS units
3. Know and be able to explain the fundamental dependent variables in atmospheric dynamics and thermodynamics (e.g., temperature, mass, force, density)
4. Understand and be able to utilize the scales of the atmosphere to distinguish how various types of features and processes differ (e.g., the horizontal scale of a synoptic low pressure system versus a thunderstorm)
5. Know what an order of magnitude difference means
6. Understand the Orlanski system for horizontal atmospheric scales
7. Be able to explain the vertical scales and regions of the lower atmosphere
8. Know the time and space scales of various atmospheric phenomena
9. Understand the importance of phenomena in the atmosphere being linked across time and space scales
10. Understand the concept of dimensional homogeneity
11. Be able to convert from one set of units to another
12. Be able to determine the units or dimensions of a quantity given other quantities related to it
13. Know that arguments of transcendental functions (e.g., sine, logarithm) must be non-dimensional

<u>Coordinate Systems</u>

1. Understand the definition of a coordinate system and its components (e.g., origin, abscissa, ordinate)
2. Understand how to transform variables from one coordinate system into another that is coincident with it at the origin but rotated through a given angle. You will NOT need to memorize the formulas for the transformation.

3. Understand and be able to utilize the equation for a line in performing coordinate system manipulations.
4. Understand and be able to apply the geometric definitions of sine and cosine
5. Understand the concepts of reflection and scaling in coordinate transformations
6. Know and be able to utilize the structure of a polar coordinate system
7. Know the equation for a circle in polar coordinates
8. Know and be able to utilize the position vector in Cartesian coordinates
9. Know the definition of a unit vector
10. Understand the difficulty introduced in taking the derivative of a vector in a coordinate system that is rotating, or in which the unit vectors are otherwise functions of time
11. Understand how to convert between polar and Cartesian coordinates
12. Be able to give one or more physical examples of polar coordinates in meteorology
13. Know how to apply the chain rule in converting between polar and Cartesian coordinates
14. Understand the cylindrical coordinate system and its components
15. Understand the spherical coordinate system and its components
16. Be able to coordinate between Cartesian and cylindrical coordinates (you will not have to memorize the conversion formulas)
17. Be able to coordinate between Cartesian and spherical coordinates (you will not have to memorize the conversion formulas)
18. Be able to give meteorological examples in which cylindrical and spherical coordinates are used
19. Be able to express a vector in a rotated coordinate system
20. Understand how to find the angle between two lines in a Cartesian coordinate system (you will not have to memorize the conversion formulas)

<u>The Ekman Model</u>

1. Be able to explain physically what the Ekman model represents mathematically and understand all of the terms and variables in the equations
2. Understand the physical role of eddy viscosity in the Ekman model
3. Know the definition of the geostrophic wind and be able to express it in vector and scalar (component) form
4. Be able to explain plots of the horizontal wind [u(z),v(z)] as solutions to the Ekman model, and also the same information on a wind hodograph
5. Understand the extremes of the Ekman model solutions ($z = 0$ and infinity)
6. Know how to convert the Ekman wind solutions from the original coordinate system to one rotated through a specified angle. You will not have to memorize the conversion formulas but will need to know how to utilize the solutions.
7. Understand how to utilize the Ekman model to define the top of the atmospheric boundary-layer
8. Know what is meant by the Ekman spiral
9. Understand the significance of the actual winds deviating from the geostrophic winds in the Ekman model aka Ekman pumping
10. Be able to compute the angle between the geostrophic and actual wind, in the Ekman model, as a function of height (you will be given the equations), and be able to interpret it for specific altitudes if given plots

Scalars and Vectors

1. Know the formal definitions of a scalar and a vector and how they differ
2. Be able to give physical examples of scalars and vectors in the atmosphere
3. Understand how to add and subtract two vectors graphically and mathematically
4. Understand and be able to manipulate the components of vectors
5. Understand how the commutative, associative, and distributive properties apply to vector manipulations
6. Know the definition of a unit vector and how to create one given an arbitrary vector
7. Know the mathematical definition of a scalar (dot) product and how to compute it given two vectors
8. Understand the concept of projection for dot products
9. Know how to compute the magnitude of a vector
10. Be able to give physical examples of dot products in meteorology or explain them if given to you
11. Know the condition, using the dot product, for two vectors to be parallel or perpendicular
12. Know the condition for two vectors to be equal

Vector Operations

1. Know how to take the total derivative of a vector, of a vector times a scalar, of a dot product of two vectors, of a cross product of two vectors, and of the magnitude of a vector.
2. Understand and be able to use the velocity and acceleration vectors in both Cartesian and polar coordinates.
3. Understand and be able to apply the del (nabla) operator as well as the divergence and curl operators.
4. Know the meaning of a total differential.
5. Understand the concept of a directional derivative, be able to apply it in physical situations, and know how it relates to the projection of the gradient of a scalar.
6. Understand the difference between gradient and divergence and be able to use them in Cartesian and polar coordinates.
7. Know how to compute the cross product of two vectors using the determinant.
8. Understand what is meant by invariance with regard to vector operations.
9. Understand the vorticity vector and be able to use its components.
10. Understand physically and mathematically the Laplace operator and Laplacian.
11. Understand and be able to explain the divergence theorem and describe its relevance to meteorology. Note that you need not memorize the theorem but will be provided the equations.
12. Understand the concept of mass continuity and be able to use and explain the mass continuity equation in mass divergence and velocity divergence form (vector and component formulation).
13. Understand the concept of flux and flux divergence, including in the context of the mass continuity equation.
14. Know what is meant by an incompressible fluid.

15. Be able apply vector operators to simple 2D flow fields and determine their properties (e.g., divergent, rotational, deformational) using both Cartesian and polar coordinates.

Reference Frames, Newton's Laws and Real Forces

1. Know the difference between inertial and non-inertial reference frames and be able to give examples of each.
2. Know and be able to explain Newton's first and second laws of motion.
3. Understand the difference between body forces and surface forces and be able to give examples of each.
4. Understand physically and mathematically the pressure gradient force (per unit mass) in both vector and component form, and be able to use it.
5. Understand and be able to apply Newton's law of gravity (you will not need to memorize the equation).
6. Understand the concept of viscosity and shearing stress.
7. Be able to explain normal and tangential shearing stresses in a fluid.
8. Know how normal shearing stresses relate to pressure.
9. Understand and be able to apply the concept of viscous force and the kinematic viscosity.
10. Understand the analog between molecular and eddy viscosity.

Apparent Forces

1. Understand the concept of an apparent force and how it relates the nature of the reference frame (inertial, non-inertial).
2. Understand the nature of the centripetal force/acceleration and be able to utilize it in both Cartesian and polar coordinates. You will be given equations as necessary.
3. Understand the nature of the centrifugal force/acceleration and how it relates to the centripetal force/acceleration.
4. Understand how the centrifugal force and gravitational force are combined to yield the effective acceleration due to gravity.
5. Be able to show and explain the difference between effective gravity (including centrifugal force) and the standard gravitational force.
6. Be able to define the geopotential and utilize it.
7. Know the meaning of a conservative force and how it relates to a potential function.
8. Be able to explain the value of using a potential function instead of the corresponding vector function.
9. Understand and be able to explain the origin of zonal deflecting forces owing to the rotation of Earth and conservation of angular momentum.
10. Understand what is meant by curvature terms in the equations of motion.
11. Understand and be able to explain the origin of radial deflecting forces owing to the rotation of Earth and the centrifugal force.
12. Understand all components of the Coriolis force.
13. Understand and be able to use the Coriolis parameter (you DO need to memorize it).

14. Be able to solve problems involving accelerations and deflections associated with the Coriolis force. You will not have to memorize the Coriolis equations.
15. Be able to explain the Coriolis force expressed in 2D and 3D vector form (you do not need to memorize the associated expressions).
16. Understand and be able to explain situations in which the Coriolis force is or is not important.
17. Understand and be able to explain the concept of inertial oscillations (you do not need to memorize the associated equations).
18. Know how to compute the period of an inertial oscillation and give physical examples of them.

<u>Vector Equation of Motion</u> (will be on the final exam, and you must write it down <u>EXACTLY</u> as shown, including vector symbols, to receive ANY credit)

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho}\nabla p + \vec{g} - 2\vec{\Omega}\times\vec{V} + \nu\nabla^2\vec{V}$$

<u>Hydrostatics, Vertical Coordinates, Reference Frames, Derivatives</u>

1. Memorize, know the variables within, and be able to apply the equation of state (ideal gas law).
2. Understand the hydrostatic equation and be able to apply it.
3. Know the consequence of a hydrostatic atmosphere on the vertical acceleration.
4. Understand and be able to give examples of hydrostatic versus dynamic pressure.
5. Know how to derive and use the hypsometric equation.
6. Know the physical definition of geopotential and geopotential height.
7. Understand why the mean temperature of a layer in the atmosphere is related to the geopotential thickness.
8. Know the meaning of scale height and where it comes from.
9. Understand the concept of e-folding time or distance.
10. Understand pressure as a vertical coordinate and the advantages of it relative to height (z) as a vertical coordinate.
11. Know the difference between Lagrangian and Eulerian reference frames and be able to give physical examples of each.
12. Know the difference between a total and a local derivative.
13. Know the definition and physical meaning of flux, including mass flux and heat flux.
14. Know the definition and meaning of enthalpy and entropy.
15. Know how to utilize a Taylor series expansion and the consequences of neglecting terms in it.
16. Know how to expand a total derivative into the local derivative and fluid transport terms.
17. Know how the total derivative of a vector in a rotating reference frame leads to curvature and Coriolis terms (you do not need to memorize the equations).
18. Know how Newton's gravitational acceleration is combined with the centrifugal force to yield gravity.
19. Understand the basic principles of the equations of motion in spherical coordinates.
20. Be able to expand the vector equation of motion into its component equations.

Equations of Motion, Scale Analysis, Approximate Forms of Equations

1. Understand the concept of scale analysis and why we use it.
2. Know the characteristic length scales for synoptic scale flow.
3. Be able to apply scale analysis to the equations of motion and thermodynamics if the equations are provided to you.
4. Understand the geostrophic and hydrostatic equations in terms of approximations made by applying scale analysis.
5. Know the definition of the Rossby number and be able to explain it physically
6. Understand the difference between diagnostic and prognostic equations.
7. Be able to explain physically the ageostrophic wind.
8. Understand the relationship (no need to memorize the equation) between the ageostrophic wind and the acceleration of the wind.
9. Understand why we sometimes write the dependent variables as the sum of a basic or reference state and a perturbation on top of it.
10. Be able to apply the concept in item 8 above to any equation, remembering the products of perturbation quantities are small and can be neglected.

Conservation of Mass and Energy, First Law of Thermodynamics, Buoyancy and Static Stability

1. Understand the concept of mass conservation and the mass continuity equation.
2. Be able to distinguish among various forms of the mass continuity equation if provided with them (e.g., compressible, incompressible, anelastic).
3. Understand physically what approximation leads to an incompressible or anelastic atmosphere.
4. Be able to apply scale analysis to any form of the mass continuity equation.
5. Understand what is meant by the Boussinesq approximation.
6. Understand the concept of internal energy and know how it is defined and used.
7. Understand the concept of entropy and know how it is defined and used.
8. Understand the concept of enthalpy and know how it is defined and used.
9. Understand the concept of a thermodynamic system.
10. Understand total energy and how it is comprised of the internal and kinetic energies.
11. Understand the principle of energy conservation and diabatic heating.
12. Understand and be able to apply the concept of an adiabatic atmosphere.
13. Understand the concept of energy balance (kinetic and mechanical energy).
14. Be able to utilize the first law of thermodynamics in its two principal forms, understanding physically the meaning of each term.
15. Understand the concept of an isentropic atmosphere and how it relates to both entropy and potential temperature.
16. Know the difference between a diabatic and an adiabatic process.
17. Know how to apply scale analysis to the thermodynamic energy equation.
11. Know the meaning and origin of buoyancy and be able to utilize it in the vertical equation of motion.
18. Understand the buoyancy frequency and its importance in the atmosphere.
19. Understand and be able to apply the concept of static stability.
20. Understand how static stability relates to lapse rate.
21. Be able to explain the Brunt-Vaisalla frequency

Equations of Motion and Thermodynamics in Other Forms

1. Be able to expand the vector equation of motion into its three component equations and understand physically, and know the names of, all terms.
2. Understand and be able to utilize the total/material derivative for parcels or objects moving with the flow as well as with other speeds.
3. Understand the autoconvective lapse rate
4. Be able to express and utilize the pressure gradient force in isobaric coordinates
5. Understand and be able to apply the vector equation of motion, and its scalar counterparts, for horizontal flow
6. Understand and be able to apply the hydrostatic equation in isobaric coordinates
7. Know the total/material derivative in isobaric coordinates and how it differs from its counterpart in height-based vertical coordinates
8. Know the definition of the vertical velocity in isobaric coordinates and how it differs from its counterpart in height-based vertical coordinates
9. Know and be able to use the mass continuity equation in isobaric coordinates, and how it differs from its various counterparts in height-based vertical coordinates
10. Understand and be able to use the static stability parameter in isobaric coordinates
11. Understand and be able to use the heat balance equation in isobaric coordinates

Natural Coordinates

1. Understand and be able to explain the natural coordinate system, its value, and how it differs from Cartesian coordinates
2. Understand and be able to use the radius of curvature in natural coordinates, and know when R is positive or negative.
3. Be able to explain and apply the equations of motion in natural coordinates (the equations will be provided to you – you do NOT need to memorize them)
4. Understand the concept of balanced flow in natural coordinates and the special cases of geostrophic, inertial, and cyclostropic flow.
5. Be able to give physical examples of each type of balanced flow in natural coordinates.
6. Know what is meant by inertial oscillation and be able to give a physical example of it.
7. Understand the meaning of gradient wind and be able to evaluate various solutions to the governing equation based upon the sign and magnitude of its variables (f, R, geopotential gradient).
8. Know the difference between cyclonic and anticyclonic flow in the context of natural coordinates
9. Know when a solution to the gradient wind equation is physical or unphysical
10. Know when a solution to the gradient wind equation results in an anomalous or regular flow and how to assess, mathematically, this distinction using the concept of absolute angular momentum
11. Know the meaning of absolute angular momentum (you will not have to memorize the associated equation, though you must understand the terms)
12. Know the meaning of baric and antibaric flows and how they differ from one another.
13. Know the difference between a low and a high

The Thermal Wind

1. Know the definition of thermal wind
2. Understand why one cannot feel the thermal wind blow
3. Understand the relationship between mean temperature and thickness in the context of the thermal wind
4. Be able to draw the geostrophic wind, and assess its relative magnitude, if given a series of idealized height fields in vertical cross section.
5. Understand how the geostrophic wind is proportional to the height gradient (slope)
6. Understand physically and mathematically why a vertical shear of the geostrophic wind is correlated with a horizontal gradient in temperature/thickness
7. Understand the relationship between the thermal wind vector and the horizontal temperature gradient (i.e., thermal wind at your back)
8. Understand what is meant by veering and backing wind and the difference between them
9. Be able to explain the relationship between a veering or backing wind and horizontal temperature advection (and thus how the temperature changes locally with time as a result of advection)
10. Understand and be able to explain the physical mechanism behind the southern Plains low-level jet