

# GEOPHYSICAL VORTICES

ATS 710 (3 credits)

Fall 2014

**Course Description:** Dynamical and thermodynamical structure of geophysical vortices (especially hurricanes) from observational, experimental and theoretical viewpoints. Topics covered include two-dimensional vortex dynamics, invertibility principles, Green functions, point vortex and moment idealizations, vortex axisymmetrization, vortex merger, two-dimensional and three-dimensional quasi-geostrophic turbulence, vortex Rossby waves, Eliassen's balanced vortex model, Ooyama's 1969 hurricane model, spin down at small and large Rossby number, concentric eye-wall cycles, moats, hub clouds, warm rings, vortex alignment, tropical cyclogenesis and intensification, tornadoes, and water spouts.

**Instructor:** Wayne Schubert

**Prerequisites:** ATS601, ATS602 (ATS623 is also useful but not required)

**Meeting Time:** TuTh 10:30–11:45

**Class Procedures:** Reading and lecture material is from the journal literature (no required textbook). An extensive list of topics, grouped into twelve chapters, is given on the following pages. The course will not cover all these topics, but only selected topics that depend on student interest. The course lectures will be presented by the instructor (e.g., on the topics of Eliassen's balanced vortex model and Ooyama's 1969 hurricane model), by guest lecturers (Mike Fiorino, John Knaff, Kate Musgrave, Chris Davis, and George Bryan), and by the enrolled students. A detailed lecture schedule is given on the last page. There will be no exams. Grades will be based on the oral presentations.

## Course Syllabus

### 1. Axisymmetric Gradient-Balanced Vortex Model

- 1.1 Slow thermally or frictionally controlled meridional circulation in a circular vortex (Eliassen 1952)
- 1.2 Numerical simulation of the life cycle of tropical cyclones (Ooyama 1969)
- 1.3 Diagnostic application of Eliassen's transverse circulation equation to the secondary eyewall phenomenon (Shapiro and Willoughby 1982, Willoughby et al. 1982)
- 1.4 The role of inertial stability in hurricane intensification (Schubert and Hack 1982, Vigh and Schubert 2009, Musgrave et al. 2011)
- 1.5 Transformed Eliassen balanced vortex model (Schubert and Hack 1983)
- 1.6 Nonlinear response of atmospheric vortices to heating by organized cumulus convection (Hack and Schubert 1986)
- 1.7 Extensions and applications of Ooyama's model (Sundqvist 1970, Schubert and DeMaria 1985, DeMaria and Schubert 1984, 1985, DeMaria and Pickle 1990, Camp and Montgomery 2001)
- 1.8 The development of potential vorticity in a hurricane-like vortex (Schubert and Alworth 1987, Möller and Smith 1994)
- 1.9 Annular hurricanes (Knaff et al. 2003, 2008)
- 1.10 Generalization of the gradient balanced vortex model to three dimensions (Shapiro and Montgomery 1993)

### 2. Spin Down at Small and Large Rossby Number

- 2.1 Classic small Rossby number spin down (Greenspan and Howard 1963)
- 2.2 The role of surface friction in tropical cyclones (Smith 1968, 2003, Yamasaki 1977)
- 2.3 Swirling flow boundary layers (Carrier 1971)
- 2.4 The Ekman layer in a circular vortex (Eliassen 1971, Eliassen and Lystad 1977, Montgomery et al. 2001)
- 2.5 The asymmetric boundary layer flow under a translating hurricane (Shapiro 1983)
- 2.6 Sensitivity of hurricane simulations to planetary boundary layer parameterizations (Emanuel 1995, Braun and Tao 2000)
- 2.7 Rolls in the hurricane boundary layer (Fung 1977, Wurman and Winslow 1998)
- 2.8 The dynamics of boundary layer jets within the tropical cyclone core (Kepert 2001, Kepert and Wang 2001, Kepert 2010a,b)
- 2.9 Instabilities in hurricane-like boundary layers (Nolan 2005)
- 2.10 A simple slab model of the hurricane boundary layer (Smith 2003, Smith and Vogl 2008)
- 2.11 Shock-like structures in the tropical cyclone boundary layer (Williams et al. 2011)

### 3. Two-Dimensional Vortex Dynamics

- 3.1 Classical vortex theory (Rayleigh 1880, Kelvin 1880a,b)
- 3.2 Kirchhoff ellipse (Lamb 1932) and the Kida vortex (Kida 1981)
- 3.3 Contour dynamics (Zabusky, Hughes and Roberts 1979) and Contour surgery (Dritschel 1988)
- 3.4 Evidence for the existence of Rossby-like waves in the hurricane vortex (MacDonald 1968)
- 3.5 Quantification of the inelastic interaction of unequal vortices in two-dimensional vortex dynamics (Dritschel and Waugh 1992)

- 3.6 On the evolution and saturation of instabilities of two-dimensional isolated circular vortices (Kloosterziel and Carnevale 1999)
  - 3.7 Vortex waves: stationary  $V$ -states, interactions, recurrence, and breaking (Deem and Zabusky 1978a,b)
  - 3.8 The life-cycle of tripoles in two-dimensional incompressible flows (Carton and Legras 1994)
  - 3.9 Interaction of tropical cyclone scale vortices (Ritchie and Holland 1993, 1997, Prieto et al. 2003)
  - 3.10 Observations of polygonal eye walls and rainbands in hurricanes (Simpson 1952, Lewis and Hawkins 1982, Muramatsu 1986)
  - 3.11 Spiral bands (Kurihara 1976, Willoughby 1978, Willoughby et al. 1984, Guinn and Schubert 1993, Yao et al. 2002, Brunet et al. 2003)
  - 3.12 Vortex Rossby waves and spiral bands in numerically simulated tropical cyclones (Wang 2002a,b, Chen and Yau 2001, Chen et al. 2003, Chow et al. 2002)
  - 3.13 A possible mechanism for the eye rotation of Typhoon Herb (Kuo et al. 1999)
  - 3.14 PV Mixing in Hurricanes (Schubert et al. 1999, Hendricks et al. 2009, Rozoff et al. 2009, Hendricks and Schubert 2010)
  - 3.15 Formation of concentric vorticity structures in typhoons (Kuo et al. 2004, 2008)
  - 3.16 Inviscid axisymmetrization (Melander et al. 1987, Koumoutsakos 1997, Bassom and Gilbert 1998, 1999, Schechter et al. 2000, Schechter and Montgomery 2003, Sutyryn 1989)
  - 3.17 Role of Landau damping in crossed-field electron beams and inviscid shear flow (Briggs et al. 1970)
  - 3.18 On the persistence of non-axisymmetric vortices in inviscid two-dimensional flows (Dritschel 1998)
  - 3.19 Disturbing vortices (Balmforth et al. 2001)
  - 3.20 Experiments on stability of equilibria of two vortices in a cylindrical trap (Mitchell et al. 1993)
  - 3.21 Theory of vortex merger (Lansky et al. 1997)
  - 3.22 Vortex Rossby waves on smooth circular vortices (Brunet and Montgomery 2002)
  - 3.23 A formal theory for vortex Rossby waves and vortex evolution (McWilliams et al. 2003)
- 4. Behavior of Vertically Sheared Vortices**
- 4.1 The effect of vertical shear on tropical cyclone intensity change (Weightman 1919, Riehl and Shafer 1944, Wu and Emanuel 1993, DeMaria 1996)
  - 4.2 The evolution of vortices in a vertical shear (Jones 1995)
  - 4.3 Three-dimensional alignment (Reasor and Montgomery 2001, Schechter et al. 2002)
  - 4.4 Vortex resiliency (Reasor et al. 2004)
  - 4.5 Two-layer geostrophic vortex dynamics: Alignment and two-layer  $V$ -states (Polvani 1991)
  - 4.6 Co-rotating stationary states and vertical alignment of geostrophic vortices with thin cores (Sutyryn et al. 1998)
  - 4.7 On the alignment and axisymmetrization of a vertically tilted geostrophic vortex (Viera 1995)
  - 4.8 The vortices of homogeneous geostrophic turbulence (McWilliams et al. 1999)
  - 4.9 Reexamining the near-core radial structure of the tropical cyclone primary circulation: Implications for vortex resiliency (Mallen et al. 2005)
  - 4.10 Tropical storm formation in a sheared environment (Molinari et al. 2003)
- 5. Spontaneous radiation of inertia-gravity waves from an intense vortex**
- 5.1 Review of the aerodynamic generation of sound (Lighthill 1952, Webster 1970)

- 5.2 Kop'ev, V. F. and E. A. Leont'ev, 1985: Energy aspect of the acoustic instability of certain steady-state vortices.
- 5.3 The "musical" sound emitted by a tornado (Abdullah 1966)
- 5.4 Low-frequency atmospheric acoustic energy associated with vortices produced by thunderstorms (Bedard 2005)
- 5.5 Instabilities of two-dimensional inviscid compressible vortices (Chan et al. 1993)
- 5.6 Vorticity and the theory of aerodynamic sound (Howe 2001)
- 5.7 Acoustic emissions by vortex motions (Kambe 1986)
- 5.8 A review of sound radiation by localized vortices in a slightly compressible medium (Lyamshev and Skvortsov 1988)
- 5.9 The instability of an axisymmetric vortex with monotonic potential vorticity in rotating shallow water (Ford 1994a)
- 5.10 The response of a rotating ellipse of uniform potential vorticity to gravity wave radiation (Ford 1994b)
- 5.11 Balance and the slow quasi-manifold (Ford et al. 2000)
- 5.12 Conditions that inhibit the spontaneous radiation of spiral inertia-gravity waves from an intense mesoscale cyclone (Schechter and Montgomery 2006)
- 5.13 The transfer of angular momentum from vortices to gravity swirl waves (Chimonas and Hauser 1997)
- 5.14 Angular momentum transports by moving spiral waves (Chow and Chan 2003)
- 5.15 Generation of inertia-gravity waves in a simulated life cycle of baroclinic instability (O'Sullivan and Dunkerton 1995)
- 5.16 Internal gravity wave emission from a pancake vortex: An example of wave-vortex interaction in strongly stratified flows (Plougonven and Zeitlin 2002)
- 5.17 The coherent structures of shallow-water turbulence: Deformation-radius effects, cyclone/anticyclone asymmetry and gravity-wave generation (Polvani et al. 1994)
- 5.18 Exponentially small inertia-gravity waves and the breakdown of quasigeostrophic balance (Vanneste and Yavneh 2004)
- 5.19 Spontaneous-adjustment emission of inertia-gravity waves by unsteady vortical motion in the hurricane core (Hendricks et al. 2010)

## 6. Foundations for Modeling the Moist Atmosphere

- 6.1 Thermodynamic and dynamic foundation for modeling the moist atmosphere (Ooyama 1990, 2001)
- 6.2 Potential vorticity principle for a moist atmosphere (Schubert et al. 2001, Schubert 2004)

## 7. Axisymmetric Hurricane Models

- 7.1 Quasi-static axisymmetric models (Yamasaki 1968a,b, 1969)
- 7.2 Numerical model of the slowly varying tropical cyclone in isentropic coordinates (Anthes 1971)
- 7.3 Numerical simulation of tropical cyclone development with latent heat release by the resolvable scales (Rosenthal 1978)
- 7.4 Nonhydrostatic axisymmetric models (Yamasaki 1977, 1983, Rotunno and Emanuel 1987, Hausman et al. 2006)

## 8. Three-Dimensional Hurricane Models

- 8.1 Three-dimensional tropical cyclone models with parameterized cumulus convection (Yamasaki 1986)

- 8.2 GFDL (Kurihara et al. 1979, Kurihara and Bender 1980, Kurihara and Tuleya 1981)
- 8.3 MM5 (Braun and Tao 2000, Zhang et al. 2005, Frank and Ritchie 1999, Frank 2001, S. Chen)
- 8.4 WRF (C. Davis)
- 8.5 RAMS (Cotton et al. 2003)
- 8.6 TCM (Wang 2007)
- 8.7 A review of numerical modeling of tropical cyclones (Kurihara 1985)
- 8.8 Simulation of the landfall of tropical cyclones (Tuleya et al. 1984)
- 8.9 Extratropical transition

## 9. Tropical Wave Disturbances

- 9.1 On the stability of internal baroclinic jets in a rotating atmosphere (Charney and Stern 1962, Eliassen 1983)
- 9.2 The origin and structure of easterly waves in the lower troposphere of North Africa (Burpee 1972, 1974)
- 9.3 Barotropic instability of an easterly zonal flow (Yanai and Nitta 1968, Yamasaki and Wada 1972, Nieto Ferreira and Schubert 1997)
- 9.4 Modeling African easterly waves (Simmons 1977, Thorncroft and Hoskins 1994a,b, Dunkerton et al. 2009)
- 9.5 Numerical experiment of tropical cyclone formation in the Intertropical Convergence Zone (Yamasaki 1989)
- 9.6 Case-studies of developing east Pacific easterly waves (Raymond et al. 1998)

## 10. Theory of Available Potential Energy and Available Energy

- 10.1 Lorenz's Theory (Lorenz 1955, 1960)
- 10.2 Andrews' Theory (Andrews 1981)
- 10.3 Shepherd's Approach (Shepherd 1993)
- 10.4 Generalization to a Moist Atmosphere (Lorenz 1978, 1979, Randall and Wang 1992, Bannon 2003)
- 10.5 Generalization to a nonresting reference state (Codoban and Shepherd 2003, 2006, Andrews 2006)

## 11. The Maximum Intensity of Hurricanes

- 11.1 Grundlagen einer Theorie der Tropischen Zyklonen (Kleinschmidt 1951)
- 11.2 On the maximum intensity of hurricanes (Miller 1958)
- 11.3 The maximum potential intensity of hurricanes (Emanuel 1988)
- 11.4 The maximum potential intensity of tropical cyclones (Holland 1997)
- 11.5 Theory of mature tropical cyclones (Gray 1994)

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**12. Tornadoes, Water Spouts, and Dust Devils**

- 12.1 Numerical simulation of a laboratory vortex (Rotunno 1977)
- 12.2 Stability of a cylindrical vortex sheet (Rotunno 1978)
- 12.3 An investigation of a three-dimensional asymmetric vortex (Rotunno 1984)
- 12.4 Numerical simulation of multiple vortices (Rotunno 1982)
- 12.5 Typhoon-associated tornadoes (Fujita et al. 1972)
- 12.6 Internal dynamics of tornado-like vortices (Gall 1982)
- 12.7 Linear analysis of the multiple vortex phenomenon in simulated tornadoes (Gall 1983)
- 12.8 Structure and dynamics of tornado-like vortices (Nolan and Farrell 1999)
- 12.9 Laboratory experiments (Weske and Rankin 1963, Ward 1972)
- 12.10 Tornado development and decay within a three-dimensional supercell thunderstorm (Wicker and Wilhelmson 1995)

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