The Basis of Atmospheric Mesoscale Dynamics and a Dynamical Method of Predicting Rainstorms

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CONTENTS

List of Tables vii

List of Figures viii

Preface xxi

Abbreviation and Meanings of the Terms used in the study xxv

Chapter One 1
Basic Atmospheric Dynamic Parameters and Their Context

Chapter Two 34
Basic Equations of Mesoscale Dynamics

Chapter Three 56
Dynamic Parameters of Inhomogeneously Saturated Air and Related Equations

Chapter Four 78
Vorticity: Introduction and Related Equations

Chapter Five 116
Divergence: Introduction and Related Equations

Chapter Six 128
Deformation: Introduction and Related Equations

Chapter Seven 148
Generalized Frontogenesis Theory

Chapter Eight 180
Atmospheric Potential Vorticity

Chapter Nine 198
Mesoscale Instability and Analysis Methods

Chapter Ten 236
Atmospheric Gravity Waves

Chapter Eleven 289
Mesoscale Balance and Unbalance

Chapter Twelve 316
Dynamic Forecasting Methods Based on Scalar Field Theory

Chapter Thirteen 394
Dynamic Forecasting Methods Based on Vector Field Theory

Chapter Fourteen 460
Methods of Forecasting Torrential Rainfall Using Dynamic Factors

Bibliography 495

Index 521

LIST OF TABLES

12.4.1. The correlation coefficient and the root-mean-square deviation between terms 1–8 and the sum of the terms in equation (12.4.1)

LIST OF FIGURES

1.1. Initial shear flow
1.2. Uniform flow after mixing enough
4.2.1. Path of typhoon Bilis
4.2.2. Horizontal distribution of winds in typhoon Bilis at 850 hPa at (a) 12:00 on 12 July 2006 and (b) 18:00 on 13 July 2006
4.2.3. Distribution of vorticity and trend in vorticity on the 850-hPa isobaric surface for 18:00 LST on 12 July 2006. The shaded area denotes positive values, the thick line marks the path of typhoon Bilis, and the typhoon symbol indicates the central position of the typhoon: (a) vorticity, (b) vorticity trend calculated using the classical vorticity equation, (c) vorticity trend calculated using the advection vorticity equation, (d) advection term, (e) pitching term, and (f) geostrophic vorticity and water advection term in the advection vorticity equation.
5.2.1. Meridional–temporal cross-section of the wave-activity density, $\langle |A| \rangle$, along the 120°E meridian (contour spacing: 10^{-5} K s^{-2}). The shadow area in the background denote the six-hour cumulative observed rainfall amount (mm).
5.2.2. Meridional–vertical cross-section of the wave-activity flux divergence, $\nabla \cdot \mathbf{F}$, along the 119°E meridian (contour spacing: 10^{-11} K m^{-1} s^{-2}) at: (a) 18:00 UTC, 7 August, (b) 18:00 UTC, 8 August, and (c) 18:00 UTC, 9 August 2009. The gray bars denote the six-hour cumulative observed rainfall amount (mm).

5.2.3. The time evolution of: (a) $\left\langle \left|\nabla \cdot \mathbf{F}\right| \right\rangle$, (b) $\left\langle \left|\nabla \cdot \mathbf{F}_1\right| \right\rangle$, (c) $\left\langle \left|\nabla \cdot \mathbf{F}_2\right| \right\rangle$, and (d) $\left\langle \left|\nabla \cdot \mathbf{F}_e\right| \right\rangle$. Units: 10^{-7} K s^{-2}, at the center region of the typhoon morakot.

6.3.1. Vorticity enstrophy (color-shaded area; units: 10^{-9} s^{-2}) and streamlines at 800 hPa. The black boxes enclose the whole vortex area. The red lines are the six-hour accumulated rainfall amount (mm). The triangle indicates the location of the formation of the vortex.

6.3.2. Distribution of (a) the VorE–DefE interaction term, (b) the VorE–DivE interaction term, and (c) the DivE–DefE interaction term at 800 hPa for 18:00 UTC, 16 August 2009. Units: 10^{-13} s^{-3}

6.3.3. Horizontal distributions of the two sub-terms of the VorE–DefE interaction term: (a) the term related to the Coriolis parameter and (b) the coupling of the divergence and the shear of the rotational wind (units: 10^{-13} s^{-2}). (c) The divergence at 800 hPa at 18:00 UTC, 16 August 2009.

7.1.1. The tangential velocity derived from the traditional Rankine combined vortex (solid line) and vortex (dashed line) which has a similar appearance to a smoothed version of the Rankine combined vortex.

7.1.2. Fig. 7.1.2. (a) Deformation, (b) divergence, and (c) vorticity fields (units: 10^{-5} s^{-1}) of the idealized flow shown in Fig. 7.1.1

7.1.3. A 2D relative humidity field subject to advection by an idealized deformational flow field at (a) 0 hours, (b) 12 hours, (c) 24 hours, and (d) 36 hours. The contour intervals have a spacing of 0.1, and all contours at time zero have an east–west orientation.

7.1.4. A 2D relative humidity field subject to advection by an idealized deformational flow field at (a) 0 hours, (b) 12 hours, (c) 24 hours, and (d) 36 hours. The contours have a spacing of 0.1, and all contours at time zero have a southwest–northeast orientation.

7.2.1. Schematic illustrating right-handed Cartesian coordinate systems (x, y) and (s, n) defined locally by rotating the standard (x, y) Cartesian coordinates system through an angle β to give the (s,n) system. The s-axis is tangent to an isoline of θ^* and is directed such that the n-axis points toward colder air. The angle between $\vec{n}$ and the x-axis is ϕ.

7.2.2. The temporal mean frontal surface (the region of intense iso-θ^*) at 00:00 UTC, 11 August 2004 together with the values of the different terms in the frontogenesis function (equation (7.2.6)). Thick real isoline is iso-θ^* (units: K). The shading denotes the regions where the intensity of the different terms in the frontogenesis function satisfies: (a) $T_{1234} > 1$, (b) $T_1 > 1$, (c) $T_2 < -1$, (d) $T_3 > 0.2$, and (e) $T_4 > 0.2$ (units: 10^{-9} K m^{-1} s^{-1}).

8.1. The change in $\psi(rh)$ with rh (k = 9, T = 280 K, p = 1000 hPa, and $q_s = 6 \times 10^{-3}$ g g^{-1})

9.2.1. The T-lnp map: r and r_d are used to determine the atmospheric stability. (a), (b), and (c) illustrate, respectively, $r > r_d$, $r < r_d$, and $r = r_d$, which are the three types of stratified stability.

9.2.2. Illustration of types of unstable energy: (a) absolute instability, (b) absolute stability, (c) real potential instability (the area above point c is larger than the area below point c), and (d) pseudo-potential instability (the area above point c is smaller than the area below point c)

9.3.1. Unstable symmetric unstable situation; momentum, $M = \bar{U} - fy$

9.4.1. Sketch of a vortex sheet

9.4.2. Disturbance at a discontinuous interface

9.4.3. Sketch of the vortex layer in a shear line

10.1. The phase velocity (C) and the phase-velocity components (Cy and Cz)

10.2. The relationship between the wave-number vector, $\mathbf{K} = (l, n)$, and the group-velocity, $\mathbf{C}g = (Cgy, Cgz)$.(a) $\lambda_y > 0$ and $\lambda_z > 0$; (b) $\lambda_y < 0$ and $\lambda_z < 0$

10.4.1 Schematic diagram of (a) natural light, (b) linearly polarized light, and (c) elliptically polarized light

10.4.2. Polarization diagram

10.5.1 The power spectral density of the vertical velocity. The contour represents the phase velocity $c = \omega / k$, which are 10m/s, 15m/s and 25m/s respectively.

10.5.2 Phase spectrum and condensation spectrum of vorticity and divergence.

10.5.3 Phase difference (a), cohesion spectrum (b) and amplitude spectrum (c) of vorticity and divergence with a frequency of 0.025 and cumulative precipitation (red line in a).

10.5.4 The height-zonal profile of vertical velocity of the gravity wave reconstructed by selecting the range of wavelength

40~50km and cycle 80~100 min.
12.1.1. The year-to-year change in annual mean temperature (K) and relative humidity (%) in Beijing and Tianjin from 1953 to 2003
12.1.2. Geopotential height (gpdm) and temperature (K) at 500 hPa at 00:00 UTC on 31 July 2002. The shaded area is the Tibetan Plateau.
12.1.3. Moisture transport at 850 hPa (based on the $\mathbf{v}q$ vector; gm g^{-1} s^{-1}) on 31 July 2002. The shaded area is the Tibetan Plateau.
12.1.4. Distribution of the average vertical velocity (Pa s^{-1}) from 31 July to 4 August 2002: zonal–vertical section along 39.9°N
12.1.5. Plot of T–ln p from observations made at 00:00 UTC at the Beijing station on 31 July 2002. The solid line at the left-hand side denotes the relative humidity (%), the dashed line denotes the dew-point temperature (K), and the thick and thin solid lines on the right hand side represent the state and stratification curves, respectively.
12.1.6. Generalized moist potential vorticity (GMPV: solid line with an interval of 0.2 PVU) and relative humidity (RH: dashed lines with an interval of 10%) at 925 hPa at 00:00 UTC on 31 July 31 2002. The shaded regions are regions where GMPV ≤ -0.25.
12.1.7. Vertical sections of GMPV at 00:00 UTC on 2 August 2 (units: PVU): (a) meridional–vertical section along 116.3°E; (b) zonal–vertical section along 39.9°N
12.1.8. The GMPV trend at 950 hPa (units: 10−4 PVU s−1) from (a) 18:00 UTC on 29 July to 00:00 UTC on 30 July 2002 and from (b) 18:00 UTC on 4 August to 00:00 UTC on 5 August 2002. Shaded regions have values less than −0.25.
12.2.1. Horizontal distribution of the NGMPV on the 700-hPa surface (shaded), superimposed on the geopotential height on the 1000-hPa surface (interval: 10 gpdm) for (a) 00:00 UTC, 7 April; (b) 06:00 UTC, 7 April; (c) 12:00 UTC, 7 April; (d) 18:00 UTC, 7 April; (e) 00:00 UTC, 8 April; (f) 06:00 UTC, 8 April; and (g) 18:00 UTC 8

April 2001

12.2.2. Horizontal distribution of the NGMPV on the 700-hPa surface (shaded), superimposed on the geopotential height on the 1000-hPa surface (interval: 10 gpdm) for (a) 00:00 UTC, 7 April; (b) 06:00 UTC, 7 April; (c) 12:00 UTC, 7 April; (d) 18:00 UTC, 7 April; (e) 00:00 UTC, 8 April; (f) 06:00 UTC, 8 April; (g) 12:00 UTC, 8 April; and (h) 18:00 UTC, 8 April 2001

12.2.3. Track of the low NGMPV center from 06:00 UTC on 7 April to 18:00 UTC on 8 April 2001 (dashed lined with rectangles) together with the surface track of the cyclone (solid line with circles).

12.3.1. Total precipitation from 22 June to 2 July 1999 (mm) and the distribution of the moist potential vorticity substance (shaded area)

12.3.2 (a). Distribution of moist potential vorticity substance at 700 hPa at 00:00 UTC on 23 June 1999 (units: 10^{-6} K m^{-1} s^{-1}; solid line: moist potential vorticity substance; dashed line: θ_e; the shaded area marks where the value of the moist potential vorticity substance ≤ −2.)

12.3.2 (b). 24-hour precipitation as observed at 00:00, 23 June 1999 (mm)

12.3.3 (a). As for Fig. 12.3.2 (a) but for 00:00 UTC, 24 June 1999

12.3.3 (b). As for Fig. 12.3.2 (b) but for 00:00 UTC, 24 June 1999

12.3.4 (a). As for Fig. 12.3.2 (a) but for 00:00 UTC, 25 June 1999

12.3.4 (b). As for Fig. 12.3.2 (b) but for 00:00 UTC, 25 June 1999

12.3.5 (a). As for Fig. 12.3.2 (a) but for 00:00 UTC, 26 June 1999

12.3.5 (b). As for Fig. 12.3.2 (b) but for 00:00 UTC, 26 June 1999

12.4.1. The (a) equivalent potential temperature (K) and (b) streamline fields at the 700-hPa level at 00:00 UTC, 5 July 2003

12.4.2. (a) Observed and (b) predicted 36-hour total rainfall (mm) in the middle and lower reaches of the Yangtze River from 00:00 UTC, 4 July to 12:00 UTC, 5 July 2003

12.4.3. Time–latitude cross-sections of 6-hour accumulated precipitation (mm) along 118°E from 00:00 UTC, 4 July to 12:00 UTC, 5 July 2003
12.4.4. Time–latitude cross-sections of mass divergence (10^{-5} kg m^{-3} s^{-1}) at the 4.287-km level along 118°E from 00:00 UTC, 4 July to 12:00 UTC, 5 July 2003
12.4.5. (a) The six-hour precipitation (mm) and (b) the absolute value of the six-hour mass divergence (10^{-5} kg s^{-1} m^{-3}) at the 4.287-km level at the center of the precipitation zone (119°E, 32°N)
12.4.6. Meridional–vertical section of the mass divergence along 118°E (10^{-5} kg m^{-3} s^{-1}) at 00:00 UTC, 5 July 2003. The shaded regions denote where the absolute value of the mass divergence is greater than 2.
12.4.7. Meridional–vertical sections along 118°E of (a) the horizontal component and (b) the vertical component of the mass divergence (10^{-5} kg s^{-1} m^{-3}) at 00:00 UTC, 5 July, 2003. The shaded regions denote where the absolute value of the mass divergence is greater than 2.
12.4.8. Meridional–vertical section of the vertical velocity (m s^{-1}) along 118°E at 00:00 UTC, 5 July 2003. The shaded regions denote where the absolute value of the vertical velocity is greater than 2.
12.4.9. Meridional–vertical section of R_{cm} along 118°E (10^{-6} kg m^{-3} s^{-1}) at 00:00 UTC, 5 July 2003. The shading denotes regions where the absolute value of R_{cm} is greater than 3.
12.4.10. Meridional–vertical section of q_{con} (the sum of the mixing ratios of cloud water, raindrops, ice, snow, and graupel; shown as isolines) along 118°E and q (the sum of the mixing ratio of water condensate and vapor; shown as shaded regions; units: g g^{-1} for (a) 00:00 UTC and (b) 06:00 UTC, 5 July 2003.

12.5.1. Time–latitude cross-section along 119°E for the six-hour cumulative precipitation (mm) from 06:00 UTC on 4 July to 12:00 UTC on 5 July 2003

12.5.2. Total deformation (10^{-5} s^{-1}) at 700 hPa at 00:00 UTC on 4 July 2003. The shaded areas are areas where the total deformation exceeds 5×10^{-5} s^{-1}.

12.5.3. Time–latitude cross-section of the total deformation (10^{-5} s^{-1}) along 119°E at 700 hPa from 06:00 UTC on 4 July to 12:00 UTC on 5 July 2003. The shaded areas are areas where the total deformation exceeds 6×10^{-5} s^{-1}.

12.5.4. Time–longitude cross-section along 37°N for the six-hour cumulative precipitation (mm) from 06:00 UTC, 10 October to 12:00 UTC, 11 October 2003.

12.5.5. Equivalent potential temperature (K) at (a) 00:00 UTC on 10 October and (b) 00:00 UTC on 11 October and the streamline at (c) 00:00 UTC on 10 October and (d) 00:00 UTC on 11 October 2003. The fields at 900 hPa are shown.

12.5.6. Total deformation (10^{-5} s^{-1}) at 900 hPa at 00:00 UTC, 11 August 2003. The shaded areas are areas where the value of the total deformation exceeds 5×10^{-5} s^{-1}.

12.5.7. Fig. 12.5.7. Time–latitude cross-section of the advection term (10^{-9} s^{-2}) along 119°E at 700 hPa from 00:00 UTC on 3 July to 00:00 UTC on 6 July 2003.The shaded areas are areas where the total deformation is smaller than −0.5.

12.5.8. Time–latitude cross-section of the horizontal divergence term (10^{-9} s^{-2}) along 119°E at 700 hPa from 00:00 UTC on 3 July to 00:00 UTC on 6 July 2003. The shaded areas are areas where the total deformation exceeds 1.

12.5.9. Time–latitude cross-section of the β -effect term (10^{-10} s^{-2}) along 119°E at 700 hPa from 00:00 UTC on 3 July to 00:00 UTC on

6 July 2003.The shaded areas are areas where the total deformation exceeds 0.5.
12.5.10. Time–latitude cross-section of the horizontal pressure term (10^{-9} s^{-2}) along 119°E at 700 hPa from 00:00 UTC on 3 July to 00:00 UTC on 6 July 2003.The shaded areas are areas where the total deformation exceeds 1.
12.5.11. Time–latitude cross-section of the vertical velocity term (10^{-9} s^{-2}) along 119°E at 700 hPa from 00:00 UTC on 3 July to 00:00 UTC on 6 July 2003. The shaded areas are areas where the total deformation exceeds 1.
12.5.12. Time–latitude cross-section of the sum of the terms on the right-hand side of the equation for the deformation trend (10^{-9} s^{-2}) along 119°E at 700 hPa from 00:00 UTC on 3 July to 00:00 UTC on 6 July 2003. The shaded areas are areas where the total deformation exceeds 2.
12.6.1. Path of the vapor potential vortex (in red) and the path of Typhoon Pu Gong Ying (in blue) from 27 June to 1 July 2004
12.6.2. The distribution of vapor potential vorticity advection at 00:00 UTC (shaded) and the vapor potential vorticity at 06:00 UTC (real line) at 500 hPa from 27 June to 1 July 2004
12.7.1 On July 21, 2012, (a) 24-hour cumulative precipitation, (b) TBB distribution of 1200 UTC, and (c) large-scale situation configuration of 0000 UTC superimposed on infrared cloud image
12.7.2 Horizontal distribution of the Q_{ms} absolute value by vertically integrating ($\langle |Q_{ms}| \rangle$ unit: 10^{-8} m^3 K s^{-2} kg^{-2}) of the second-order moist potential vorticity at 0000 UTC from 21 July 2012 to 22 July 2012 at 0000 UTC. The shaddow area shows 6-hour cumulative precipitation (unit: mm).
12.7.3 Time section of second-order moist potential vorticity along 40°N

0000 UTC-22 July 2012 (Unit: 10^{-8} m^3 K s^{-2} kg^{-2}). The shaddow area is 6-hour accumulated precipitation.
13.1.1. The distribution of the potential temperature
13.1.2. Horizontal distributions of (a) $[C_x]$ (10^{-2} s^{-1} K), (b) $[C_y]$ (10^{-2} s^{-1} K), (c) $[C_z]$ (10^{-4} s^{-1} K), and (d) PV (10^{-4} s^{-1} K) at 00:00 UTC on 13 August 2004. The shaded areas denote different values of CH (10^{-1} kg m^{-2}).
13.1.3. The evolution of the distribution of (a) $[C_x]$ (10^{-2} s^{-1} K), (b) $[C_y]$ (10^{-2} s^{-1} K), and (c) $[C_z]$ (10^{-4} s^{-1} K) averaged over the area from 37°N to 42°N and 112°E to 119°E for the period 00:00 UTC on 12 August to 12:00 UTC on 13 August 2004. The shaded areas denote different values of CH (10^{-1} kg m^{-2})
13.1.4. The evolution of (a) CH (10^{-1} kg m^{-2}), (b) the rainfall rate (mm h^{-1}), (c) $[C_x]$ (10^{-2} s^{-1} K), (d) $[C_y]$ (10^{-2} s^{-1} K), (e) $[C_z]$ (10^{-4} s^{-1} K), and (f) PV (10^{-4} s^{-1} K) averaged over the area from 37°N to 42°N and 112°E to 119°E for the period 00:00 UTC on 12 August to 12:00 UTC on 13 August 2004
13.2.1. The evolution of CZT (black), CZ1 (red), CZ2 (green), CZ3 (blue), CZ4 (cyan), and CZ5 (pink). The values are averaged over the area 34°N–43°N and 112°E–119°E for the period 00:00 UTC, 12 August to 12:00 UTC, 13 August 2004.
13.2.2 (a) The evolution of the distribution of the six-hour cumulative rainfall amount (left; contour spacing: 2 mm) and (b) the vertical component of the CVV (right; units: 10^{-4} s^{-1} K) along 116°E for 00:00 UTC on 12 August to 12:00 UTC on 13 August 2004.
13.5.1. Evolution of the distribution of the six-hour cumulative rainfall

amount (mm) along 118°E from 00:00 UTC on 4 July to 12:00 UTC on 5 July 2003
13.5.2. Evolution of the distribution of (a) Q_{umx} (10^{-12} hPa^{-1} s^{-3} m) and the relative humidity (%) and (b) Q_{umy} (10^{-12} hPa^{-1} s^{-3} m) and the relative humidity (%) at 750 hPa along 118°E from 00:00 UTC on 4 July to 12:00 UTC on 5 July 2003
13.5.3. Evolution of the distribution of (a) the horizontal divergence of Q_{umx} (10^{-16} hPa^{-1} s^{-3}), (b) the horizontal divergence of Q_{dry} (10^{-16} hPa^{-1} s^{-3}), and (c) the horizontal divergence of Q_m (10^{-16} hPa^{-1} s^{-3}) along 118°E at 750 hPa from 00:00 UTC, 4 July to 02:00 UTC, 5 July 2003. The shaded area denotes value of less than −2.
13.5.4. The evolution of the distribution of the vertical velocity ω (hPa s^{-1}) along 118°E at 750 hPa from 00:00 UTC, 4 July to 02:00 UTC, 5 July 2003. The shaded area denotes values of less than −0.05.
13.5.5. Time series of (a) the six-hour cumulative rainfall amount (mm) and (b) the horizontal divergence of Q_{um} (10^{-16} hPa^{-1} s^{-3}) over the rainfall center
13.6.1. Schematic diagram of the vertical circulations at the entrance and exit of high-level jets
13.6.2. Schematic diagram of the relationship between the divergence of the E vector and the development of a cyclone
13.8.1. The virtual pseudo-energy wave-action density (contours of 10^2 kg/(m·s^2)) and the observed six-hour rainfall (shaded; mm) at (a) 00:00 UTC, (b) 06:00 UTC, (c) 12:00 UTC, and (d) 18:00 UTC on 8 July 2009
13.8.2. The virtual pseudo-energy wave-action density (contours of 10^2 kg/(m·s^2) and the observed six-hour rainfall (shaded; mm) at (a) 12:00 UTC, 18 August, (b) 18:00 UTC, 18 August, (c) 00:00 UTC, 18 August, and (d) 06:00 UTC, 19 August 2009
14.1.1. Horizontal distribution of the moist thermodynamic advection parameter (10^{-8} K^2 m^{-1} s^{-13}) at 06:00 UTC, 11 July 2010. The shadow

area represent the cumulative six-hour observed rainfall amount (mm).

14.1.2. (a) The thermodynamic helicity (10^3 km^2 s^{-2}) and (b) vertical flux of the thermodynamic divergence (10^3 km^2 s^{-2}) during torrential rainfall associated with a cold vortex over northeast China at 18:00 UTC, 27 July 2010. The shadow area represent the cumulative six-hour observed rainfall amount (mm).

14.1.3. The horizontal distribution of the divergence of the Q vector with generalized potential temperature at 700 hPa on (a) 00:00 UTC 12 July and (b):00:00 UTC 13 July 2013. The shadow area represent the cumulative six-hour observed rainfall amount (mm).

14.2.1. (a) The generalized moist potential vorticity (10^{-2} K s^{-1}), (b) solenoidal vorticity (10^{-4} m s^{-3}), and (c) thermodynamic solenoidal vorticity associated with the torrential rainfall produced by a trough at 00:00 UTC, 19 July 2010. The shadow area represent the cumulative six-hour observed rainfall amount (mm).

14.2.2. Schematic diagram of horizontal wind vectors

14.2.3. Horizontal distributions of (a) potential divergence and (b) potential stretching deformation (10^{-4} K s^{-1}) for 00:00 UTC, 9 August 2009. The shadow area represent the cumulative six-hour observed rainfall amount (mm).

14.2.4. (a) The second-order potential vorticity (10^{-10} km^{-1} s^{-2}) and (b) the vertical component of the convective vorticity vector (10^{-3} K s^{-1}) associated with the torrential rainfall of Typhoon Fanapi at 06:00 UTC on 20 September 2010. The shadow area represent the cumulative six-hour observed rainfall amount (mm).

14.3.1. The wave-action densities of (a) the latent heat of condensation (10^{-7} s^{-1}), (b) potential vorticity of the latent heat of condensation (10^{-6} s^{-1}), (c) potential divergence of the latent heat of condensation (10^{-6} s^{-1}), (d) geopotential shearing deformation of the latent heat of condensation (10^{-6} s^{-1}), and (e) geopotential stretching deformation of the latent heat of condensation (10^{-6} s^{-1}). The shadow area represent the cumulative six-hour observed rainfall amount (mm).

14.4.1. Time series of the ETS scores of the six-hour cumulative rainfall amounts forecast in 24 hour using the ensemble rainfall forecast method with dynamic factors (solid red lines) and the GFS model (dashed lines). The results shown are for forecasts of (a) over 10 mm/6 hours and (b) over 20 mm/6 hours for southern China (20°N–35°N, 105°E–125°E) for 00:00 UTC, 2 June to 1 October 2010. (c) and (d) are the same as (a) and (b), respectively, but for 2012, and (e) and (f) are the same as (a) and (b), respectively, but for 2013.

PREFACE

This book is an academic monograph that focuses on atmospheric mesoscale dynamics and the prediction of rainstorms, based on research results obtained by our team in the course of my academic career. The book includes some new research achievements made by our team in recent years.

I am grateful to my Ph.D. advisor, Professor Shiyan Tao for his constant advices in the past, and also thankful to Professor Duzheng Ye, Professor Qingcun Zeng, Professor Jifan Chou and Professor Chongyin Li for their encouragement during my career. Over a long period of time, I have also benefited greatly from the cooperation and discussions on scientific issues that I have had with my graduate classmate, Dr. Qin Xu. In recent years, Professor Qiushi Chen has helped me to advise graduate students and has also brought his ideas and methods related to the decomposition of physical processes to my research. I also benifited from discussing topics on non-uniform saturation with Professor Xingrong Wang.

The book is divided into 14 chapters. In Chapter 1, the basic dynamical parameters of the atmosphere and their physical meanings are discussed, with an emphasis on the Väisälä frequency and Richardson number. In Chapter 2, based on the governing equations of barotropic and baroclinic atmosphere, combined with a consideration of atmospheric mesoscale dynamics, the mesoscale potential vorticity equation and potential vorticity substance equation are derived. In Chapter 3, the physical quantities related to water vapor are introduced. In particular, the generalized potential temperature in a non-uniformly saturated atmosphere is introduced and is shown to be a conserved quantity. This lays the theoretical foundation for the prediction of the area affected by a rainstorm. In Chapter 4, the vorticity equation and advection vorticity equation as well as the 'frozen-in' properties of the vorticity, streamline vorticity, and helicity are introduced. In Chapter 5, different forms of the divergence equation and potential divergence are discussed. In Chapter 6, the total deformation and deformation equation are brought in, and the interaction between the deformation, vorticity, and divergence is investigated. In Chapter 7, the generalized scalar frontogenesis function, which describes generalized scalar frontogenesis in a non-uniformly saturated atmosphere, and the trend of the frontogenesis function are described. In Chapter 8, the concept of potential vorticity and the potential vorticity equation are introduced. The concepts of second-order potential vorticity and generalized moist potential vorticity are developed. The moist potential vorticity anomaly with mass-forcing and the principle of the potential vorticity substance impermeability are demonstrated. In Chapter 9, based on a classification of the stability, several instability analysis methods, such as static instability, symmetric instability, and shear instability, are analysed. In Chapter 10, wave characteristics, wave polarization are given, and wave-action equation of three-dimensional inertial gravity waves and symmetric inertial gravity waves are discussed; a brief description of a method for identifying gravity waves from data is also presented. In Chapter 11, the mesoscale balance equation and its unbalance counterpart are investigated along with a related potential vorticity inversion technique. In Chapter 12, using a dynamic prediction method based on scalar field theory, the divergence, and deformation, as well as associated factors such as the potential vorticity, moist potential vorticity, and generalized moist potential vorticity, are used to identify and predict hot, humid weather in large cities during summer, as well as to trace and predict the movement of cyclones and to forecast torrential rainfall. In

Chapter 13, the convective vorticity vector, dynamic vorticity vector, ageostrophic Q vector, E vector, and wave-action vector are described along with related theories and dynamic prediction methods. In Chapter 14, rainstorm forecast methods with ensemble dynamic factors are discussed and demonstrated.

This book aims to deepen the understanding of mesoscale dynamics, to make the basic concepts clear, and to include new research results in the theory as far as possible. At the same time, the book also reflects the authors' own research interests and writing style, and strives to be innovative as well as being of academic value. In terms of content, the theories on which mesoscale dynamics relies are emphasized. For a long time, these concepts, including the theory of generalized potential temperature, convective vorticity vector, second-order potential vorticity, conservation of wave action, mesoscale balance equation, and generalized frontogenesis theory, have not received much attention, even though they provide the theoretical basis for the study of moist atmospheric processes. An improved method for analyzing gravity waves is also described in the book. One innovation is that some new types of vectors that can play an important role in dynamic prediction are proposed. Another feature of the book is the combination of theoretical knowledge and practical forecasting applications—this is seen in the method for forecasting rainstorms based on ensemble dynamic factors in particular. This method has been used in many operational provincial forecast centers in China. Some of the content of this book has been taught over a period of time at the University of Chinese Academy of Sciences, Zhejiang University, and Chengdu University of Information Science and Technology.

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—Shouting Gao

ABBREVIATION AND MEANINGS OF THE TERMS USED IN THE STUDY

2D	Two dimensional
ADAS	ARPS data assimilation system
ARPS	Advanced Regional Prediction System
CISK	conditional instability of the second kind
CMA	China Meteorological Administration
CRISTA	Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere
CSI	Conditional symmetric instability
CVV	Convective vorticity vector
DVV	Dynamic vorticity vector
ECMWF	European Center for Medium-range Weather Forecast
ETS	Equitable threat score
GFS	Global Forecasting System
GMPV	Generalized moist potential vorticity
GPS	Global Positioning System
GRAPES	Global/Regional Assimilation and Prediction System
IPV	Isentropic potential vorticity
JMA	Japan Meteorological Agency
K-H	Kelvin-Helmholtz
LIMS	Limb Infrared Monitoring of the Stratosphere
MLS	Microwave Limb Sounder
MOS	Model output statistics
MPVS	Moist potential vorticity substance
MVV	Moist vorticity vector

NCEP	National Centers for Environmental Prediction
NGMPV	Negative generalized moist potential vorticity
PV	Potential vorticity
QPF	Quantitative precipitation forecast
UCAR	University Center for Atmospheric Research
UTC	Coordinated Universal Time
WKB	Wentzel-Kramers-Brillouin
WKBJ	Wentzel-Kramers-Brillouin-Jeffreys
WRF	Weather Research and Forecasting

CHAPTER ONE

BASIC ATMOSPHERIC DYNAMIC PARAMETERS AND THEIR CONTEXT

In order to probe into the basic principles and dynamic structures related to the generation and development of mesoscale atmospheric systems, we must first understand some basic dynamic parameters that describe the mesoscale characteristics, such as the Rossby number, which is the ratio of the advective inertial force to the Coriolis force; the internal Froude number, which measures the atmospheric stratification effect; and the Richardson number, which represents the atmospheric stability. The specific contexts related to these parameters and how the parameters can be applied to the study of mesoscale atmospheric motion are also important, and so the first chapter of this book will introduce some important universal dynamic parameters.

1.1. Parameters Related to Rotation and Stratification and Their Dynamic Similarities

The atmosphere is a rotating, stratified fluid that surrounds the Earth. (It is stratified according to temperature and humidity.) The effects of the Earth's rotation play an important role in the motion of the atmosphere. Therefore, it is important to ask at which scale the ambient rotation becomes an important factor in the atmospheric motion. To answer this question, we can begin with the ambient rotation rate, which is given by

$$\Omega = \frac{2\pi}{day} = 7.29\times10^{-5} / s . \quad (1.1.1)$$

If the time scale over which the atmospheric motion occurs is comparable with the time taken for one rotation of the Earth, or is longer, then this motion will be affected by the Earth's rotation. We, therefore, define the dimensionless quantity,

$$\omega_\Omega = \frac{2\pi/\Omega}{T} = \frac{2\pi}{T\Omega} . \quad (1.1.2)$$

If $\omega_\Omega \le 1$, which corresponds to motion with a time scale of more than one day (24 hours), then it is necessary to consider the effect of the rotation. Usually, the ratio of the characteristic scale of the displacement, L, to its characteristic velocity, U, is used to represent the time scale of the atmospheric motion, T. The above dimensionless parameter is then defined as follows:

$$\tau = \frac{2\pi\Omega}{LU} = \frac{2\pi U}{\Omega L} . \quad (1.1.3)$$

If $\tau \le 1$, consideration of the Earth's rotation is important.

Apart from the rotation, the atmospheric stratification is also very important. If the reference density of the atmosphere is ρ_0, the density change through a height H is $\Delta\rho$, and the basic velocity of the motion is U, then the corresponding potential energy change per unit volume is $(\rho_0 + \Delta\rho)gH - \rho_0 gH = \Delta\rho gH$, and the basic kinetic energy is $\frac{1}{2}\rho_0 U^2$. The following dimensionless number can then be defined:

$$\sigma = \frac{\frac{1}{2}\rho_0 U^2}{\Delta\rho g H} \quad . \tag{1.1.4}$$

If σ ~ 1, then the stratification needs to be taken into account. Given such atmospheric stratification, for a disturbance to develop fully, the amount of potential energy required will be about equal to the kinetic energy. If σ << 1, then there is not nearly enough kinetic energy available in the stratified atmosphere for the disturbance to fully develop, meaning that the stratification plays a decisive role. If σ >> 1, the changes in potential energy will have a small effect on the fundamental kinetic energy: in this case, the stratification is not important and the stratification effects can be ignored (Benoit Cushman-Roisin, 1994)[1].

In atmospheric dynamics, there are some dimensionless parameters that are often used to represent the extent of the atmospheric rotation or stratification. These dimensionless parameters are obtained by making the atmospheric equations non-dimensional using the method of scale analysis. The parameters include the Rossby number, the internal Froude number, the Burger number, and the Richardson number.

The Rossby number, R_0, is the ratio of the advective inertial force to the Coriolis force: it can be expressed as

$$R_0 = \frac{U^2/L}{fU} = \frac{U}{fL} \, . \tag{1.1.5}$$

The Rossby number can be used to represent the rotation of the atmosphere.

The internal Froude number, Fri, is the ratio of the advective inertial force to the buoyancy force, or of the kinetic energy to the gravitational potential energy:

$$F_{ri} \propto [\frac{\rho_0 U^2 / L}{(\rho_2 - \rho_1) g}]^{1/2} = \frac{U}{\sqrt{g' L}} \ , \tag{1.1.6}$$

where $g' = g(\rho_2 - \rho_1) / \rho_0$ and ρ_1, ρ_2 are, respectively, the density of the upper and lower fluid layer; ρ_0 is the reference density.

$$g' = g(\rho_2 - \rho_1)/\rho_0 = -g \frac{1}{\rho_0} \frac{d\rho}{dz} H = N^2 H \ ,$$

Substituting this into (1.1.6) gives

$$F_{r_i} = \frac{U}{\sqrt{g' L}} = \frac{U}{N\sqrt{HL}} \ . \tag{1.1.7}$$

For mesoscale systems L~H, giving $F_{ri} = U / NH$.

The internal Froude number clearly represents the atmospheric stratification effect. The definition of the Burger number is

$$B_u = \frac{f^2 L^2}{N^2 H^2} \ . \tag{1.1.8}$$

Furthermore, the Burger number is related to the Rossby number and the internal Froude number as follows:

$$B_u = (\frac{f^2 L^2}{N^2 H^2}) = \frac{(\frac{U}{N\sqrt{HL}})^2}{(\frac{U}{fL})^2} = (\frac{F_{ri}}{R_0})^2 . \tag{1.1.9}$$

For typical deep convention systems, usually L ~ H, which gives