Selected Papers on Downslope Windstorms

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1. Introduction

This purpose of this note is to provide a brief overview of the literature that has been written on various aspects of mountain flow phenomemon. This is not a complete bibliography of all papers ever written, but rather a good starting list from which to start. The emphasis is on downslope windstorms, but other aspects of downslope flow in the lee of mountains are also discussed, such as rotors, Foehns, and gap flows. For a brief, basic overview of the various types of terrain-forced flows, see Whiteman (2000).

2. Downslope Windstorms

a. Theoretical Papers

In a series of three papers (Long 1953a; Long 1954; Long 1955) examines theoretical and experimental aspects of fluid flow over barriers. The last paper in particular (Long 1955) examines the flow of a continuously stratified fluid over barriers of various sizes. He determines several flow regimes based on Froude number and barrier height. A separate paper Long (1953b) examines steady motion around a symmetrical obstacle moving along the axis of a rotating liquid.

Scorer (1949) provides a theory of waves in the lee of mountains.

Klemp and Lilly (1975) discuss the dynamics of wave-induced downslope winds. They found that the surface winds observed near Boulder, CO are found to be surface manifestations of standing gravity waves whose wavelength is long compared to typical resonant lee wavelengths. The conditions for development of such windstorms are discussed.

Durran (1986a) conducts numerical experiments to examine the role played by different amplification mechanisms in the development of large-amplitude mountain waves. The nonlinear response is compared with the equivalent linear problem. When the nonlinear waves dominate, the flow resembles a hydraulic jump. Similarities between breaking and nonbreaking waves which undergo a transition to supercritical flow are also discussed.

Peltier and Scinocca (1990) examine the origin of severe downslope windstorm pulsations. Doppler lidar observations show that severe downslope windstorms near Boulder, CO are characterized by an intense pulsation with a characteristic period near 10 minutes. Wave breaking and Kelvin-Helmholtz instability play a role in the development of these pulsations. (See also Scinocca and Peltier 1989 - not in bibliography yet).

Rotunno and Smolarkiewicz (1995) look at vorticity generation in the shallow-water equations as applied to hydraluic jumps.

Also, see the review articles that have been written on this subject: Smith, Durran (1986b), and Durran (1990).

b. Papers about Front Range windstorms

Kuettner (1968) offers selected results from the 1968 multi-aircraft field project investigating downslope windstorms in the lee of Colorado's Front Range.

Julian and Julian (1969) characterize some aspects and societal effects of Boulder windstorms.

Brinkmann (1974) conducts a systematic study of

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twenty Boulder windstorms having maximum gusts exceeding 33 m s^-1. The mechanism is found to be a deep lee pressure trough He found that the windstorms are nonstationary in both space and time, with the zone of strongest winds often moving up and down the slope. The air mass characteristics leading to the Boulder windstorms are contrasted with those of windstorms higher up the slope.

Lilly and Zipser (1972) provide a meteorological narrative of the 11 January 1972 Front Range windstorm.

Lilly (1978) provide a detailed study of the 11 January 1972 Front Range windstorm case. They examine the synoptic factors that lead to the windstorm, then probe the windstorm structure using a dual aircraft analysis. They also cover various aspects of the turbulence associated with downslope windstorms.

c. Papers specifically about Fort Collins windstorms

Riehl (1971) discusses the short but spectacular 30 November 1970 Fort Collins, CO windstorm which featured in-town gusts as high as 86 mph (higher elsewhere). He discusses the possibility that the windstorm was caused by a transient pressure jump.

Cotton et al. (1995) examine an unusual summertime downslope wind event that occurred in Fort Collins on 3 July 1993. This extreme windstorm had in-town gusts of up to 82 kt. The authors simulated the event using RAMS and found that both explicit bulk microphysics and a grid spacing of 4 km were necessary to accurately represent the storm.

Lee et al. (1989) provide a study of the effects of cold pools on downslope windstorms in the Fort Collins area. They analyze the conditions in which such cold pools are flushed away from the mountains, allowing downslope winds to occur out on The Plains. They analyze 71 Fort Collins downslope windstorms that occurred between 1977-1988.

Weaver and Phillips (1990) describe an expert system for forecasting severe downslope windstorms at Fort Collins (this system was developed based on the meteorological data gathered and analyzed in the paper above).

d. Papers about downslope windstorms in other areas

Manley (1945) examines the Helm Wind of the Northern Pennines.

Wolyn (2003) provides a brief look at mountain-wave induced windstorms west of Westcliffe, CO.

Jones et al. (2002) examine a "wrong way" severe downslope windstorm that occurred west of Colorado's Park Range on 23 April 1999. This event is compared and contrasted with the 25 October 1997 event (see paper below).

Meyers et al. (2003) examine another "wrong way" severe downslope windstorm that occurred in the Routt National Forest on 25 October 1997, resulting in an extensive forest blowdown. This event occurred in association with the October 1997 blizzard over the northeast Colorado High Plains.

Lessard (1988) looks at the historical origins of the term 'Santa Ana' now used to describe the notorious winds in Southern California.

Raphael (2003) discusses a 33-y numerical dataset of occurrence of Santa Ana winds for the period 1968-2000, and Santa Ana characteristics derived from this dataset, including meteorological factors and frequency. The relation to ENSO is also discussed.

Blier (1998) examines the Sundowner winds of Santa Barbara, California, which are sometimes manifest aspects of downslope windstorms, Foehn flows, or both. One extreme historical case resulted in a near world record extreme maximal temperature of 133°F and the death of most animals and birds in the area. Evidence of a rotor circulation near Santa Barbara is also discussed.

e. Rotors

Queney (1955) discusses a theory of rotors in which the phenomenon is explained as a simple "cat's eye effect", or transformation of stationary wave motion into a system of vortices in the vicinity of a level where the basic wind velocity is vanishing.

Another theoretical paper (Scorer and Klieforth 1958) discusses an analytical model of rotors, method of solution, and comparison to observations.

Doyle and Durran (2002) investigate the dynamics of mountain-wave-induced rotors using a series of high-resolution simulations with a nonhydrostatic model (COAMPS). They found that boundary layer separation is a prerequisite for rotor formation.

A short article in BAMS (Doyle and Durran 2004) discusses recent developments in the theory of atmospheric rotors. They enumerate several conditions which appear necessary for rotor formation. They also highlight the role of the adverse pressure gradient and boundary layer processes in the generation of rotors.

Hertenstein and Kuettner (2002) discuss the history of rotor investigations, observations of rotor characteristics, and a brief survey of rotor theories. They classify rotor phenomena into two types. Type 1 rotors are the 'classical' rotors, appearing as a region of stagnating or reversed flow at some distance in the lee of the mountain. This type is thought to occur due to boundary layer separation along the lee slope. Type 2 rotors appear to have much in common with hydraulic jumps and are characterized by extreme turbulence (20-25 m $s^{-}1$ updrafts and downdrafts with an eddy size measured in dekameters; an instrumented sailplane experienced approximately 16 g accelerations when it was destroyed as it passed through a type 2 rotor). It is type 2 rotors that pose the greatest hazard to aviation. In the words of the authors

In Kuettner and Hertenstein (2002), the two rotor types are simulated for a Sierra-like mountain range using RAMS.

3. Foehn Flows

Brinkmann (1971) discusses the question: "What is a Fohen?" He provides an overview of the history of thought about the causes of the Foehn and how to define it from meteorological characteristics.

Glenn (1961) provides a descriptive overview of the Chinook phenomenon. He finds that four factors are responsible for the warming during Chinook winds: compression, latent heat of condensation, displacement of cold air by warm air, and nighttime mixing. Several cases are discussed, as are several peculiarities related to the Chinook.

Hamann (1943) provides a delightful account and analysis of a most unusual Chinook wind event in the Black Hills of South Dakota which produced extreme short-term temperature fluctuations.

Gaffin (2002) discusses a Foehn wind event in the lee of the Smoky Mountains. Temperatures warmed up to 10°C in affected portions of the Great Tennessee Valley.

4. Gap Flows

Hugh D. Cobb, III (2004) briefly discusses a hurricane force wind event that occurred in the Gulf of Tehuantepec on 30-31 March 2003. This gap flow wind event was associated with a large synoptic-scale pressure gradient across the Chievela Pass in Mexico.

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