Meteorologische Zeitschrift, Vol. **16**, No. 6, 607-620 (December 2007)

Article

Sensitivity analysis of mountain waves using an adjoint model

JAMES D. DOYLE*[1], CLARK AMERAULT[2] and CAROLYN A. REYNOLDS[1]

[1]Naval Research Laboratory, Monterey, CA, USA
[2]National Research Council, Monterey, CA, USA

(Manuscript received February 25, 2007; in revised form May 31, 2007; accepted July 6, 2007)

Abstract

An adjoint modeling system developed for the COAMPS nonhydrostatic model is used to explore the sensitivity of lee-side winds to the upstream atmospheric conditions for flow over a two-dimensional obstacle. For relatively small hills in the hydrostatic wave regime, the sensitivity patterns exhibit a dual lobed structure that is a manifestation of a superposition of internal gravity waves with downward-directed energy propagation. Nonhydrostatic waves generated by small terrain have corresponding sensitivities that are tilted vertically against the shear, which when introduced into the flow as perturbations, evolve into structures that resemble vertically decaying evanescent waves. Flow over higher obstacles near the gravity wave breaking threshold exhibits complex sensitivity patterns characterized by a wave-like packet of maxima and minima upstream of the middle- and upper-tropospheric region of wave breaking. In general, as the mountain height is increased, the tangent linear approximation becomes less accurate. However, the strongest nonlinearity occurs for flows very near the wave breaking threshold, rather than fully within the wave breaking regime forced by higher terrain.

Zusammenfassung

Ein adjungiertes Modellsystem entwickelt für das COAMPS nichthydrostatische Modell wird verwendet, um die Empfindlichkeit von leeseitigen Winden hinsichtlich der stromaufwärtigen Strömungscharakteristiken bei Strömungen über ein zweidimensionales Hindernis zu untersuchen. Für relativ kleine Hügel im hydrostatischen Wellenregime zeigen die Empfindlichkeitsmuster eine Doppelstruktur, die eine Manifestation einer Überlagerung von internen Schwerewellen ist, mit nach unten gerichteter Energiefortpflanzung. Nichthydrostatische Wellen, erzeugt durch niedriges Terrain, haben entsprechende Sensitivitäten, die in der Vertikalen gegen die Scherung gerichtet sind, und die – wenn in die Strömung als Störungen eingefügt – sich in Strukturen entwicklen, die vertikal-abnehmenden evaneszenten Wellen entsprechen. Strömung über höhere Hindernisse nahe dem Grenzwert des Schwerewellen-Brechens zeigt komplexe Sensitivitätsmuster, die charakterisiert sind durch wellenähnliche Pakete von Maxima und Minima stromaufwärts des Gebiets des Wellenbrechens in der mittleren und oberen Troposphäre. Im allgemeinen wird die tangentenlineare Approximation ungenauer, wenn die Berghöhe zunimmt. Überraschenderweise tritt die stärkste Nichtlinearität für Strömungen sehr nahe dem Grenzwert des Schwerewellen-Brechens auf, und nicht innerhalb des durch höheres Terrain angeregten Wellenbrechen-Regimes.

1 Introduction

As stably stratified air flows over a topographic barrier, gravity waves are generated and propagate away from the mountain, often having a profound influence on the atmospheric flow. Vertically propagating internal waves may amplify, overturn, and break down particularly above the tropopause, due to factors such as the decrease of atmospheric density with altitude, nonlinearity, and vertical gradients of the ambient winds and stability. Mountain-waves can have a significant influence on the atmosphere for a number of reasons that include: clear-air turbulence; downslope windstorms; vertical mixing; potential vorticity generation; and the collective impact of orographic drag on the large-scale atmospheric circulation (see reviews by SMITH, 1979; DURRAN, 1990; FRITTS and ALEXANDER, 2003). The sensitivity of mountain waves to the upstream initial state and various topo-graphic shapes have been explored previously in many studies (e.g., SMITH and GRØNÅS, 1993; ÓLAFSSON and BOUGEAULT, 1996); however, sensitivity analyses have never been conducted in a systematic manner using the relatively new methods that involve adjoint models. These new techniques will allow for a more complete characterization of the initial condition sensitivity of mountain waves, which is a necessary step towards a better understanding of the predictability issues associated with gravity waves and topographic flows. In addition, the applicability of tangent linear perturbation growth has significant implications for four-dimensional data assimilation (4DVAR) applied at high resolution. In this work, we examine the sensitivity of mountain waves to topography and upstream conditions

*Corresponding author: James D. Doyle, Naval Research Laboratory Marine Meteorology Division, 7 Grace Hopper Ave., Monterey, CA 93943-5502, USA, e-mail: james.doyle@nrlmry.navy.mil

0941-2948/2007/0236 $ 6.30
DOI: 10.1127/0941-2948/2007/0236