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ScienceDirect
Fluid Dynamics Research 39 (2007) 731–754
FLUID DYNAMICS RESEARCH

Gravity wave radiation from unsteady rotational flow in an *f*-plane shallow water system

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Received 10 June 2004; received in revised form 2 December 2005; accepted 18 July 2007
Available online 20 September 2007
Communicated by Y. Hayashi

Abstract

Spontaneous gravity wave radiation from an unsteady rotational flow is investigated numerically in an *f*-plane shallow water system. Unlike the classical Rossby adjustment problem, where free development of an initially unbalanced state is investigated, we consider development of a barotropically unstable zonal flow which is initially balanced but maintained by zonal mean forcing. Gravity waves are continuously radiated from a nearly balanced rotational flow region even when the Froude number is so small that balance dynamics is thought to be a good approximation for the full system. The source of gravity waves is discussed by analogy with the theory of aero-acoustic sound wave radiation (the Lighthill theory). It is shown that the source regions correspond to regions of strong rotational flow. The gradual change of rotational flow causes gravity wave radiation. We propose an approximation for these strong sources on the assumption that the dominant flow in the jet region is non-divergent rotational flow. In addition, we calculate the zonally symmetric component of gravity waves far from the source regions, solving the Lighthill equation. Using scaling analyses for perturbations, these gravity waves can be calculated with only one approximated source term that is related to the latitudinal gradient of the fluid depth and the latitudinal mass flux.

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0169-5983/$32.00
doi:10.1016/j.fluiddyn.2007.07.001

In spite of its simplicity, this approximation not only explains the physical cause of gravity wave radiation, but gives an amount of source close to that obtained by classical approximation derived from vortical motion.

Keywords: Jet; Rotational flow; Gravity wave radiation; Shear instability; Shallow water equation

1. Introduction

The purpose of this study is to investigate gravity wave radiation from a nearly balanced rotational flow. The motion of stratified rotational fluid has two distinct modes. One is balanced rotational mode of vortex, which evolves comparatively slow and has large scale in the horizontal direction. The other is unbalanced divergent mode of gravity wave, which, compared to the former mode, evolves relatively quickly and tend to have a small scale in the horizontal direction. Coupling of these modes are theoretically interesting (Hough, 1898; Longuet-Higgins, 1968). In the present study, we investigate the continuous gravity wave radiation from an unsteady jet flow, which is considered to be a nearly balanced rotational flow, using a numerical simulation of an *f*-plane shallow water system with forcing.

The mechanism of gravity wave radiation from a nearly balanced rotational flow is not fully understood in the atmospheric science. Gravity waves are ubiquitous in the atmosphere and play a fundamental role in driving the general circulation of the middle atmosphere by transporting significant amounts of energy and momentum (Holton et al., 1995). Although topography, convection, jets, fronts, cyclones and so on have been identified as origins of gravity waves (Fritts and Nastrom, 1992; Sato, 2000), the detailed source mechanism concerning how gravity waves are radiated remains an open problem, especially concerning non-orographic radiation of waves. It has been reported in observational studies that gravity waves are radiated from the polar night jet (Yoshiki and Sato, 2000), the sub-tropical jet (Kitamura and Hirota, 1989; Sato, 1994; Plougonven et al., 2003), and cyclones (Pfister et al., 1993; May, 1996). At the same time, it has been also reported in studies using global circulation models that strong gravity waves are observed near jet regions (Sato et al., 1999). However, these studies have reported the characteristics of radiated gravity waves only. The source of gravity waves and how gravity waves are radiated from rotational flows remain to be explained.

In the present study, we consider an idealized situation, in which gravity waves are radiated from barotropically unstable jet flow, and use a simplified model, *f*-plane shallow water system, for a numerical simulation. In the past decade, several numerical studies have been done to investigate gravity wave radiation from a life cycle of baroclinic instability. For example, O'Sullivan and Dunkerton (1995) studied gravity wave radiation from a baroclinic wave with a global circulation model, and showed that gravity waves were radiated from the exit region of jet streaks. Zhang (2004), using a mesoscale numerical simulation, obtained similar results. However, since the main goals of these studies are to investigate gravity wave radiation from particular geophysical phenomena, such as a baroclinic wave, many complicated processes that are not directly related to gravity wave radiation are included in the numerical models. In this study, we use an *f*-plane shallow water system, which is the simplest system in which both balanced rotational modes and unbalanced gravity wave modes exist. We consider a simple zonal jet flow, which is a steady state of *f*-plane shallow water system but barotropically unstable, and investigate gravity wave radiation from the unsteady jet flow.