A NUMERICAL MODELING STUDY OF THE MARINE BOUNDARY LAYER OVER THE GULF STREAM DURING COLD AIR ADVECTION

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Abstract. A two-dimensional mesoscale model has been developed to simulate the air flow over the Gulf Stream area where typically large gradients in surface temperature exist in the winter. Numerical simulations show that the magnitude and the maximum height of the mesoscale circulation that develops downwind of the Gulf Stream depends on both the initial geostrophic wind and the large-scale moisture. As expected, a highly convective Planetary Boundary Layer (PBL) develops over this area and it was found that the Gulf Stream plays an important role in generating the strong upward heat fluxes causing a farther seaward penetration as cold air advection takes place. Numerical results agree well with the observed surface fluxes of momentum and heat and the mesoscale variation of vertical velocities obtained using Doppler Radars for a typical cold air outbreak. Precipitation pattern predicted by the numerical model is also in agreement with the observations during the Genesis of Atlantic Lows Experiment (GALE).

1. Introduction

Sharp sea surface temperature gradients occur off the coast of the Carolinas during winters because of the existence of the Gulf Stream (Pietrafesa et al., 1985) with a surface temperature of about 24 °C. A mid-shelf front normally occurs between the coastline and the western edge of the Gulf Stream due to the advection and diffusion processes caused by the Gulf Stream filaments. Very cold air with below-freezing near-surface temperatures advects over the warmer ocean causing significant convection (Atlas et al., 1983). Cloud bands associated with these cold air outbreaks have been observed over the Gulf Stream (Chou and Atlas, 1982). One of the scientific objectives of the Genesis of Atlantic Lows Experiment (GALE) was to study the marine boundary-layer structure over the Gulf Stream during cold air outbreaks (Dirks et al., 1987). Many boundary-layer observation systems such as meteorological buoys, research vessels, Doppler Radars and research aircraft were used during GALE to study the mean and turbulent structure of the marine boundary layer (Raman and Riordan, 1988). Semi-permanent rain bands were often observed (Hobbs, 1987) during the GALE field phase using lightning detectors and weather radars. Existence of these rainbands is believed to be due to the formation of a sea breeze-type of circulation and associated convergence near the western edge of the Gulf Stream.
The purpose of this paper is to examine the air mass modification over the coastal waters and the Gulf Stream during a typical cold air advection using a two-dimensional mesoscale numerical model with a first-order closure scheme and compare different predicted variables such as mean velocities, surface turbulent fluxes and precipitation patterns with observations during GALE under similar synoptic conditions.

2. Model Description

2.1. Model Equations

After Reynolds decomposition and ensemble averaging for the governing equations of basic flow with Boussinesq’s assumptions and the transformation of vertical coordinate to terrain following coordinate \( \sigma \), the governing equations are given by (Huang, 1986)

\[
\begin{align*}
\frac{\partial u}{\partial t} &= -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - \bar{w} \frac{\partial u}{\partial \sigma} + f v - \theta \frac{\partial \pi}{\partial x} - g(1 - \sigma) \frac{\partial E}{\partial x} - g \sigma \frac{\partial H}{\partial x} \\
&\quad + \frac{\partial}{\partial x} \left( K_H \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_H \frac{\partial u}{\partial y} \right) + \frac{1}{H - E} \frac{\partial}{\partial \sigma} \left( -u' w' \right), \\
\frac{\partial v}{\partial t} &= -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - \bar{w} \frac{\partial v}{\partial \sigma} - f u - \theta \frac{\partial \pi}{\partial y} - g(1 - \sigma) \frac{\partial E}{\partial y} - g \sigma \frac{\partial H}{\partial y} \\
&\quad + \frac{\partial}{\partial x} \left( K_H \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_H \frac{\partial v}{\partial y} \right) + \frac{1}{H - E} \frac{\partial}{\partial \sigma} \left( -v' w' \right), \\
\frac{\partial \theta}{\partial t} &= -u \frac{\partial \theta}{\partial x} - v \frac{\partial \theta}{\partial y} - \bar{w} \frac{\partial \theta}{\partial \sigma} - \frac{L}{\pi} \frac{d q_s}{d t} \\
&\quad + \frac{\partial}{\partial x} \left( K_H \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_H \frac{\partial \theta}{\partial y} \right) + \frac{1}{H - E} \frac{\partial}{\partial \sigma} \left( -w' \theta' \right), \\
\frac{\partial q}{\partial t} &= -u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} - \bar{w} \frac{\partial q}{\partial \sigma} + \frac{d q_s}{d t} + \frac{1}{H - E} \frac{\partial}{\partial \sigma} \left( -w' q' \right), \\
\frac{\partial \pi}{\partial \sigma} &= -\frac{g(H - E)}{\theta},
\end{align*}
\]

where primes denote fluctuating quantities.

Equations (1) and (2) are the momentum equations for east-west velocity \( (u) \) and north-south velocity \( (v) \) components respectively, Equation (3) is the thermodynamic equation for potential temperature \( (\theta) \), Equation (4) is the conservation equation for moisture \( (q) \), Equation (5) is the hydrostatic equation for