Vegetation Forcing and Convective Motion

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Introduction

A large irrigated vegetation area in a semiarid or relatively dry location is a strong surface forcing of thermal circulations (Hong et al., in press). Several observational studies have found that such thermally induced mesoscale circulation may contribute to the triggering and development of convective clouds (Barnston and Schickedanz 1984; Wilson and Schreiber 1986; Rabin et al. 1990).

In the western United States, extensive areas of irrigated farmland are surrounded by hot, dry surfaces, such as a steppe. Substantial gradients of sensible heating in the horizontal direction lead to a "farm breeze" circulation from the cooler agricultural area to the warmer steppes found at Boardman, Oregon (Doran et al. 1992). These thermally forced circulations may trigger convection by the related convergence and updraft motion under favorable atmospheric conditions (Anthes 1984).

The role of vegetative covering in convective motion is investigated using a mesoscale numerical model. Two- and three-dimensional simulations are described. The effects of atmospheric stability, moisture in the lower atmosphere, moisture in the upper atmosphere, and horizontal heating scale on thermally induced clouds are studied. The horizontal scale of inhomogeneity is also studied using the two-dimensional model. Finally, a realistic vegetation distribution similar to that of the Boardman Regional Flux Experiment (Doran et al. 1992) is used in the three-dimensional simulations.

Model Description

The mesoscale numerical model used here has been described in detail by Huang and Raman (1991a, 1991b). This model has been used in several numerical experiments (Huang and Raman 1992; Boybeyi and Raman 1992) with different meteorological conditions and topographical features. The new version of this model includes a vegetation scheme for surface energy budget (Hong et al., in press) and a five-phase cloud physics parameterization (Leach and Raman, in press). A detailed description of the new version of the model can be found in the above papers.

Discussion of Experimental Results

Effect of Atmospheric Stability

The effects of atmospheric stability were investigated using three different stability regimes in the lower atmosphere: absolutely stable, conditionally unstable, and neutral (Figure 1). The magnitude of the vertical component is less for the more stable case since greater stability, and therefore greater restoring force, leads to smaller amplitude buoyancy-generated disturbances. Two convective cells form in response to thermal circulation that develops at both the interfaces between vegetation and bare soil.

In the weaker stability cases, the smaller restoring force allows the two cells to merge into one updraft. This merger occurs because, with small restoring force in the lower atmosphere, the amplitude and the wavelength of the generated disturbance are such that no subsidence occurs between the two convectively generated cells at the surface. However, clouds persist only for an initially stable environment because the upper stable layer limits moisture transfer in the vertical direction, and large moist static energy is trapped in the lower atmosphere.

The effect of vertical mixing of cloud water can be inferred from the formation time of clouds for different initial stability conditions. In the weaker stable case, clouds formed earlier because of the earlier existence of turbulence. Eventually the clouds dissipate in the weaker stability cases as the cloud water is ventilated into the drier

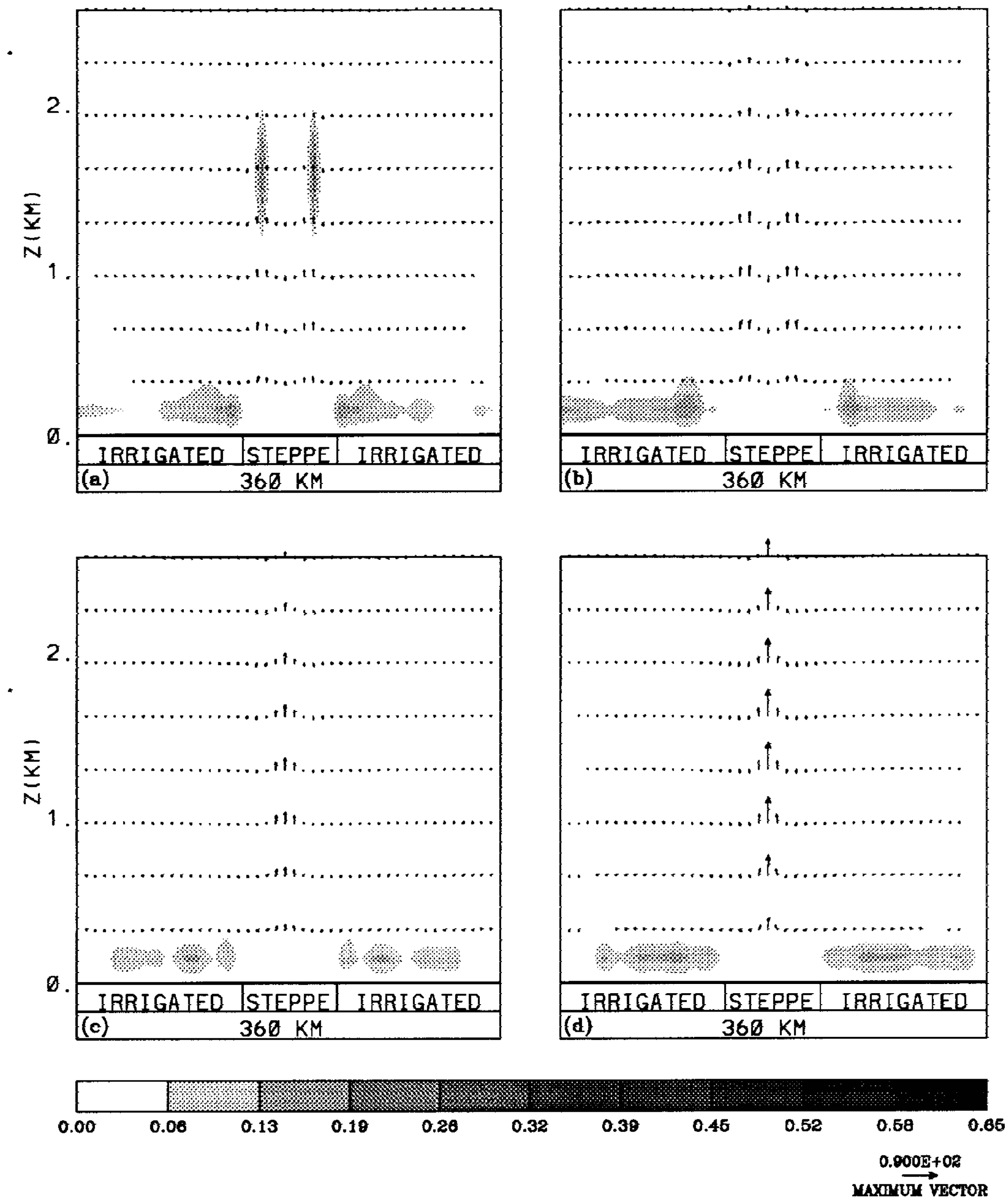

Figure 1. The four panels represent velocity vectors from the (u, w) components overlaid on cloud water after 6 hours simulation: (a) absolutely stable, (b) conditionally unstable, (c) neutral boundary layer with an absolutely stable layer aloft and (d) neutral boundary layer with a conditionally unstable layer aloft. The initial moisture in all cases was 90% relative humidity in the boundary layer with dry conditions aloft. The w velocity has been multiplied by a factor of 100 for illustration purposes.

atmosphere aloft. In the more stable case, the clouds formed later because the generation of turbulence took longer. Once clouds did form, they persisted for longer periods, as less vertical mixing into the drier air aloft occurred.

Effect of Atmospheric Moisture

The effects of moisture were investigated by initializing the model with different moisture profiles for the same static stability (Figure 2). The effect of moisture on the thermally induced clouds is remarkable.

With the initially absolutely stable environment, the intensity of the thermally induced circulation is directly related to the moisture content since increased low-level moisture increases the potential instability. The convective motion maintains two cells. Clouds are generated when the initial relative humidity is above 90% since the moister environment is more conducive to the formation of clouds through the increase of low-level moist static energy. The amplitude of the convectively driven disturbance increases slowly with increased moisture since turbulence generation and low-level moist static energy increase with increasing moisture. The density of fog increases with increasing initial moisture content, as expected.

With the initial conditionally unstable environment, the convective motion also maintains two cells. The surface convergence and vertical velocity are much stronger for this case than for the absolutely stable cases, and their magnitudes increase with moisture. The maximum turbulence for this case is larger than for the absolutely stable cases and increases with increasing moisture. However, no clouds form because greater mixing caused by larger turbulence dilutes the water vapor through a larger depth. More low-level clouds appear with increased moisture since vegetation cools the surface and, also, more moisture in the atmosphere reduces the solar radiation reaching the surface.

Effect of Horizontal Heating Scales

The effects of horizontal length scales of the surface forcing were studied by altering the length of the steppe region with irrigated surfaces on either side (Figure 3). Different horizontal heating scales produce convective cells of different structure and strength with favorable initial conditions. One convective cell is generated for a narrow horizontal heating scale and two convective cells for wider horizontal heating scales. The interaction between two convective cells is related to horizontal heating scales. The amount of cloud water present reflects the magnitude of the vertical velocity except for the narrowest horizontal steppe where the maximum cloud water and total cloud amounts preceded the maximum values of vertical velocity. The depth of turbulent mixing increases as the horizontal heating scale increases because of the greater surface heating over a larger horizontal area. When the horizontal heating scale becomes small, the increased evapotranspiration from the increased vegetated areas might increase surface layer fog or cloud water.

Three-Dimensional Simulations

Three-dimensional simulations were designed to use a realistic vegetation coverage similar to the Boardman Regional Flux Experiment (figures not shown). The difference in ground surface temperature between the irrigated farmland and the steppe is significant (the maximum is 20K). The air temperature over the irrigated farmland is uniform but inhomogeneous over the steppe area, as a vegetation breeze is produced. The maximum horizontal gradient of surface air temperature occurs at the interface between the two areas, which aligns with the ambient wind but opposes the vegetation breeze. The colder air over the irrigated area cannot penetrate further if the ambient wind opposes the vegetation breeze.

Homogeneous moisture distribution is prescribed initially. Evapotranspiration from the vegetation and greater vertical mixing over the steppe region create a sharp moisture gradient between the irrigated farmland and the steppe. Penetration of the vegetation breeze is strongly related to the direction of the ambient wind. The vertical velocity updraft is stronger when the vegetation breeze opposes the ambient wind, creating a likely triggering mechanism for cloud formation.

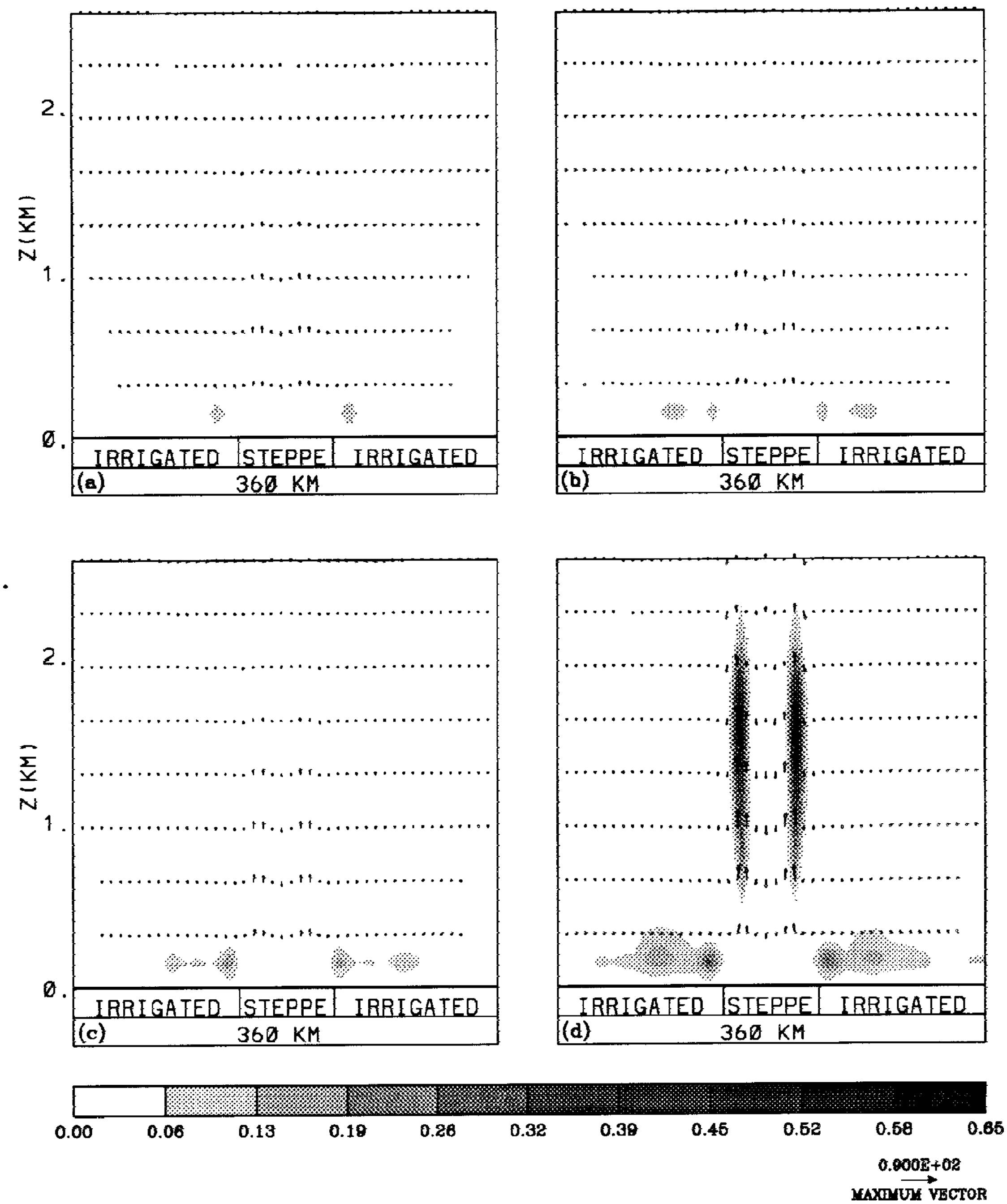

Figure 2. The same variables as plotted in Figure 1. The initial temperature profile was the absolutely stable. Atmospheric moisture content varied from (a) 50%, (b) 70%, (c) 80% and (d) 100% relative humidity.

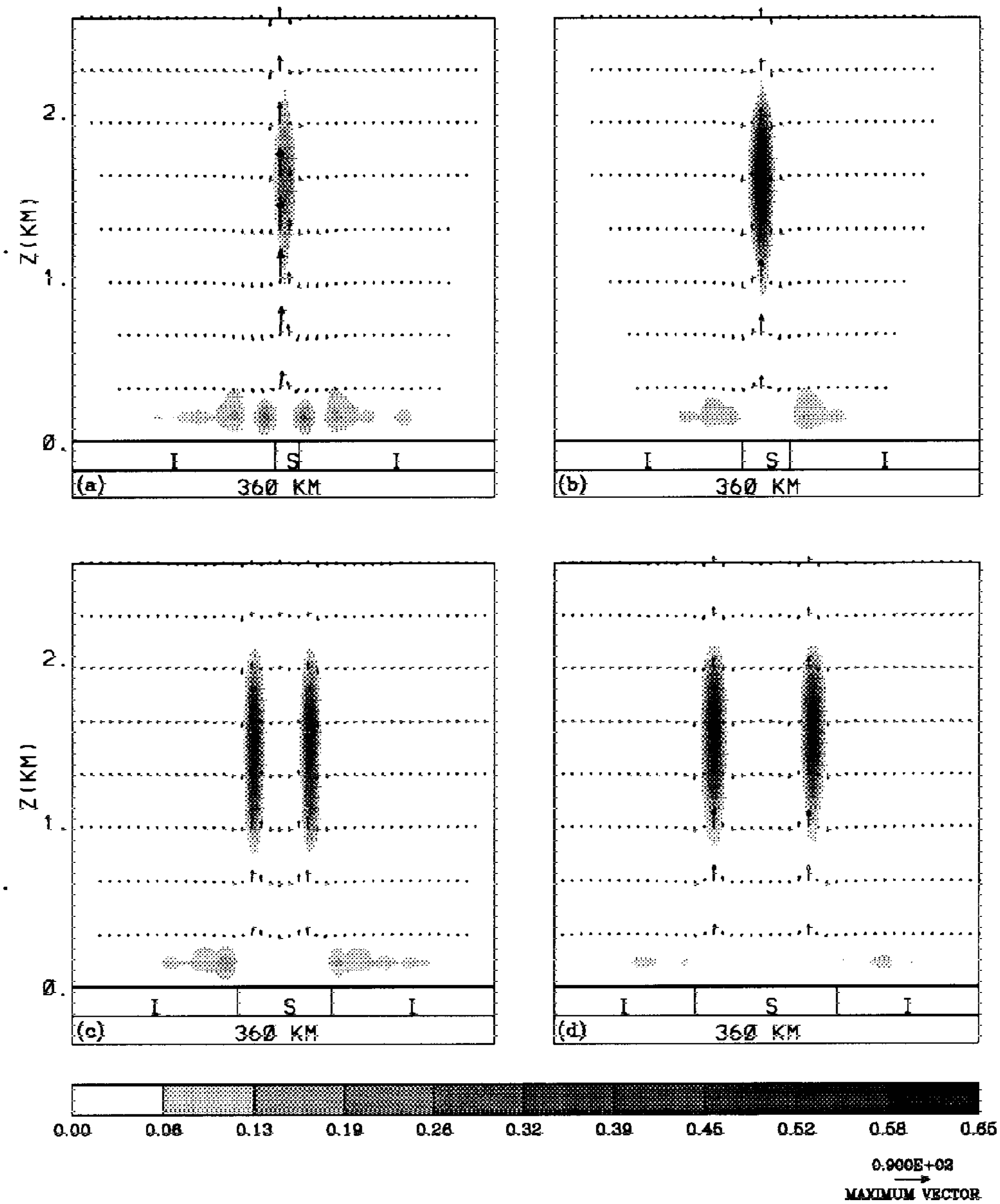

Figure 3. The four panels represent velocity vectors that the (u, w) components overlaid on cloud liquid water after 6 hours simulation for variable horizontal scales of surface forcing. A steppe area (labeled S) was placed between two irrigated (I) areas. The steppe was varied from (a) 20 km, (b) 40 km, (c) 80 kmn to (d) 120 km. The w velocity has been multiplied by a factor of 20 for illustration purposes.

Summary

The effects of variable vegetation coverage as a surface forcing are examined by incorporating a vegetation parameterization into a mesoscale numerical model. Variable vegetation coverage leads to differential surface forcing which then creates mesoscale circulation.

The mesoscale circulation and the interaction of the circulation with cloud production processes are examined under various atmospheric stability and moisture conditions. The sensitivity of the surface forcing to scale length is also investigated.

Finally, a realistic vegetation coverage similar to that of the Boardman Regional Flux Experiment is used in three-dimensional simulations

Clouds induced by vegetation forcing are investigated by varying the atmospheric stability and moisture in the boundary layer and the atmosphere above it. The magnitude of the vertical velocity that is due to the thermally induced mesoscale circulation decreases as the atmospheric stability increases. Two mesoscale circulation cells merge into one in the weak stability cases because of a smaller restoring force.

Clouds are generated earlier for the less stable cases, but eventually dissipate because of enhanced mixing. In more stable cases, clouds are generated later in the simulation but persist longer, as the vertical mixing is inhibited by greater stability.

Increased moisture in the lower layers strengthens the thermally induced mesoscale circulation by decreasing the stability. Increased moisture in the upper atmosphere leads to increased cloud water.

The scale of surface horizontal heating affecting cloud formation is also examined. One convective cell forms with narrow surface heating; as the scale of the heating increases, two cells eventually form. The depth of turbulent mixing increases as the horizontal heating scale increases, an increase that is due to greater surface heating over a larger horizontal area. When the horizontal heating scale is narrow, increased evapotranspiration in the vegetated areas increases surface layer fog or cloud water.

The temperature, moisture and velocity components from the three-dimensional simulations are related to the distribution of vegetation. The ground surface temperature is uniformly distributed over the irrigated area but is inhomogeneous over the steppe area because of the penetration of the vegetation breeze. The colder air over the irrigated area does not penetrate over the steppe when the vegetation breeze opposes the ambient wind. Evapotranspiration from the vegetation and greater vertical mixing over the steppe create a sharp horizontal moisture gradient between the two areas. Velocity perturbations at the interface between the steppe and irrigated land are largest when the vegetation breeze opposes the ambient wind.

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