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NONLINEAR EVOLUTION OF DIFFUSE AURORAL F REGION IONOSPHERIC IRR--ETC(U)
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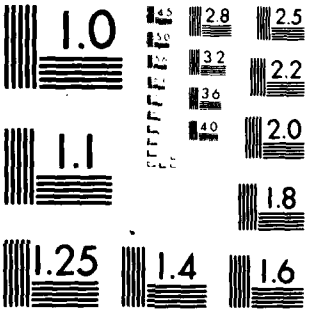

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Numerical simulations of the nonlinear evolution of the current convective instability in the diffuse aurora have been performed for conditions typical of the nighttime high latitude F region. Our results show nearly field aligned plasma irregularities developing in regions of well-defined northward gradients of total electron content (TEC) and field-aligned diffuse auroral particle precipitation. In addition, we find equatorward movement of plasma enhancements and northward (poleward)

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20. Abstract (Continued)

movement of plasma depletions (holes). Furthermore, one-dimensional spatial power spectra of the irregularities in both the north-south and east-west directions are well described by inverse power laws.

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Introduction

Recently, new information has been acquired concerning the phenomenology and structure of high latitude auroral F region ionospheric irregularities. After analyzing data from the Defense Nuclear Agency's Wideband satellite, Rino and Owen [1980a] and Rino and Matthews [1980b] have given additional evidence that the irregularities causing high latitude scintillation enhancements observed in regions with well-defined north-south TEC gradients and field-aligned diffuse auroral particle precipitation are L-shell aligned localized sheetlike structures [Fremouw et al., 1977; Rino et al., 1978] for wavelengths $\lambda \simeq$ 1-10 km [C. L. Rino, private communication, 1980], less than the ambient TEC gradient scale length. In addition, an equatorward moving dynamic slab-like scintillation source region is observed. Furthermore, depleted plasma zones (holes) have been recorded [Rich et al., 1980; M. C. Kelley, private communication, 1980] in regions of strong field-aligned currents and convection electric fields. Finally, using simultaneous rocket probe, scintillation and incoherent scatter, Kelley et al. [1980] have shown that the spatial power spectra of the irregularities in the auroral F region can be described by inverse power laws with spectral indices between 1.5 and 2.5.

The linear theory of the current convective instability in the diffuse aurora has been proposed [Ossakow and Chaturvedi, 1979] to account directly for large scale size irregularities in the diffuse auroral F region. Chaturvedi and Ossakow [1979] have discussed the nonlinear stabilization of the current convective instability by isolating

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two Fourier components of plasma density and computing their self-consistent evolution. Although these theoretical studies can show under what conditions density fluctuations will grow and can give reasonable growth rates, these studies are only valid locally and cannot determine gross nonlinear effects such as relative movement of enhancements and depletions and irregularity power spectra over a wide range of modes. Numerical simulation studies are much richer in that many modes (waves) can be kept with the result that nonlinear effects, both local and global, can be delineated.

In this letter we reproduce several of the aforementioned observations by performing the first numerical simulation of the nonlinear evolution of the current convective instability in the diffuse aurora.

Model

We study the nonlinear evolution of large scale size plasma density irregularities in the diffuse auroral F region by solving the equations modelling the current convective instability [Ossakow and Chaturvedi, 1979] in the following geometry: the total electron content gradient is in the northward direction (y), the ambient electric field $\underline{E}_o$ is westward (x), and the magnetic field is directed downward (z). The basic equations can then be written:

$$\frac{\partial n}{\partial t} + \frac{c}{B}\,\hat{z} \times \nabla\varphi_1 \cdot \nabla n - \frac{c}{B}\,\nabla \cdot n\left(\frac{\nu_i}{\Omega_i}\,\nabla_\perp\varphi_1 + \hat{z}\,\frac{\Omega_i}{\nu_i}\,\frac{\partial\varphi_1}{\partial z}\right) = 0 \qquad (1)$$

$$\nabla \cdot n\left[\nabla_\perp\varphi_1 + \hat{z}\left(\left(\frac{\Omega_i\Omega_e}{\nu_i\nu_e}\right)^2 + \left(\frac{\Omega_i}{\nu_i}\right)^2\right)\frac{\partial\varphi_1}{\partial z}\right] = \left(\underline{E}_o - \frac{\Omega_i}{\nu_i}\,\frac{B}{c}\,\underline{V}_d\right)\cdot\nabla n \qquad (2)$$

where $n(x,y,z,t)$ is the ion density, $\nabla\varphi_1 = \underline{E}-\underline{E}_o$ with $\underline{E}(x,y,z,t)$ the total electric field, ν_i is the ion-neutral collision frequency, ν_e is the electron-ion collision frequency, $\Omega_i(\Omega_e)$ is the ion (electron) gyrofrequency, c is the speed of light, B is the ambient magnetic field, $\underline{V}_d = \hat{\underline{z}}V_d = \hat{\underline{z}}(V_{eoz}-V_{ioz})$ is the relative velocity of the electrons and ions along the magnetic field, and $\perp$ denotes perpendicular to the magnetic field. Equations (1) and (2) are simply a restatement of the ion-continuity equation written in a reference frame with velocity $\underline{V}_o = - E_o/B(\hat{\underline{y}} - \nu_i/\Omega_i\ \hat{\underline{x}})$ and quasi-neutrality $\nabla\cdot\underline{J} = 0$, respectively. We have neglected inertial and pressure effects since we will be interested in modelling low-frequency long wavelength (greater than several km) fluctuations. In addition, we have neglected the electron-neutral collision frequency ν_{en} compared with ν_e and taken $\nu_\alpha/\Omega_\alpha \ll 1$ for $\alpha = i,e$ (F region approximation). Note that if one neglects the z-dependence of density and potential ($\partial/\partial z = 0$) equations (1) and (2) are similar to the equations modelling the long-wavelength collisional Rayleigh-Taylor instability (without recombination damping) in the equatorial F region ionosphere [Ossakow and Chaturvedi, 1978] and $\underline{E}\times\underline{B}$ gradient-drift instability in F region plasma clouds [Ossakow and Chaturvedi, 1978].

Linearizing equations (1) and (2), taking $n = n_o(y) + n_1$ with $n_1, \varphi_1 \propto \exp[i(k_x x + k_\parallel z) + \gamma_{\underline{k}} t)]$ we find the growth rate $\gamma_{\underline{k}}$ [Ossakow and Chaturvedi, 1979]

$$\gamma_{\underline{k}} = \frac{-\frac{1}{n_o}\frac{\partial n_o}{\partial y}\left[\frac{c}{B}E_o\frac{\nu_i}{\Omega_i} - V_d\frac{k_\parallel}{k_x}\right]}{\left[\frac{\Omega_i}{\nu_i}+\frac{\Omega_e}{\nu_e}\right]\frac{k_\parallel^2}{k_x^2}+\frac{\nu_i}{\Omega_i}} \tag{3}$$

We note that the linear growth rate $\gamma_{\underline{k}}$ from (3) is independent of $|\underline{k}|$ but depends only on the angle made by $\underline{k}$ and $\underline{B}$ through the factor $k_{\|}/k_x$. For total electron content plasma density increasing to the north ($\partial n_o/\partial y > 0$), unstable growth can be achieved if the field-aligned current velocity V_d is such that $V_d(k_{\|}/k_x) > 0$ and $|V_d k_{\|}| > (k_x c E_o/B)(\nu_i/\Omega_i)$. In the altitude range 350-400 km for typical ambient values of $E_o \simeq 10$ mV/m, $\nu_\alpha/\Omega_\alpha \simeq 10^{-4}$, $V_d = 500$ m/sec, $L \equiv n_o(\partial n_o/\partial y)^{-1} \simeq 50$ km, the maximum growth rate is $\gamma_{max} \simeq 2.7 \times 10^{-3}\text{sec}^{-1}$ which occurs for $k_{\|}/k_x \simeq 9.4 \times 10^{-5}$ [Ossakow and Chaturvedi, 1979].

Results

In the following simulations we take advantage of the fact that the fastest growing, most dangerous modes from linear theory are almost field-aligned ($k_{\|}/k_{\perp} \ll 1$). These modes are of most interest to us and, as a result, we solve equations (1) and (2) in a plane containing these modes which is nearly perpendicular to the magnetic field while fixing the value of $k_{\|}/k_{\perp}$. A similar approach has been adopted in numerical studies of drift-wave [Lee and Okuda, 1976] and trapped-particle [Matsuda and Okuda, 1976] instabilities in laboratory plasmas.

The simulation plane which is essentially horizontal at an altitude of 350 km with a north-south extent of 410 km and an east-west extent of 160 km is identical to the $x'y'$ plane as shown in Figure 1. The system of equations (1) and (2) was transformed to the $x'y'z'$ coordinate system by a simple rotation about the y-axis by the angle $\theta = k_{\|}/k_x \ll 1$. By solving the equations (1) and (2) in the $x'y'z'$ system a finite but small $k_{\|}$ is effectively introduced into the model.

After neglecting the z'-dependence of all quantities, equations (1) and (2) were then cast into dimensionless form and initialized with the profile of the following type $n_o(y')/N_o = (1-A(1-\tanh(y'-y_o)/L))(1 + \varepsilon(x',y'))$ where N_o, y_o, and L are constant with A = 5/11. This gives a total density maximum to minimum ratio of approximately 10. The function $\varepsilon(x',y')$ has a root-mean-square value of 3% and is generated from a randomly phased Gaussian power spectrum. The computational mesh consisted of 258 grid points in the y'-direction (north-south) with 102 points in the x'-direction (east-west). Periodic boundary conditions were imposed in the x'-direction with Neumann ($\partial/\partial y' = 0$) boundary conditions in the y'-direction. We drop the prime notation for clarity.

Figures 2-5 show contour plots of $n(x,y)/N_o$ at t = 0, 900, 1400, 1900 sec. The following set of parameters were used: L = 50 km, y_o = 200 km, E_o = 10 mV/m, $\nu_i/\Omega_i = 10^{-4}$, $\nu_e/\Omega_e = 10^{-4}$. The value of $\theta = 9.4 \times 10^{-5}$ is held fixed and is chosen so as to maximize the linear growth rate (3). Fig. 2 shows the initial configuration which includes the small random perturbation. Fig. 3 at t = 900 sec($\gamma_{\underline{k}} t \simeq 5$) illustrates the linear stages of the simulation and shows unstable growth in the region where $\partial n_o/\partial y > 0$ as predicted by linear theory. Fig. 4 exemplifies the early nonlinear regime where lower density plasma (depletions) are moving in the positive y-direction (poleward) while higher density plasma (enhancements) are convecting in the negative y-direction (equatorward). The approximate velocities of the depletions and enhancements are 270 m/sec and 30 m/sec, respectively. Finally, well-developed steepened enhancements and depletions (of over 90%) are seen in Fig. 5 at t = 1900 sec. This late-time configuration is

reminiscent of the motion of depletions (bubbles) moving vertically in the equatorial F region [Scannapieco and Ossakow, 1976a] and enhancements (striations) in ionospheric F region plasma clouds [Scannapieco and Ossakow, 1976b]. The length scales in Figures 2-5 are distorted with the depletions and enhancements longer and narrower than is depicted. Similar linear and nonlinear development is observed when L = 10 km, but on a faster time scale.

Figures 6a-b give sample one-dimensional spatial power spectra at t = 1900 sec both in the x-direction (east-west) and in the y-direction (north-south). These spectra are obtained by first Fourier analyzing $\delta n(x,y)/N_o$ and integrating over the direction in $\underline{k}$-space corresponding to the north-south and east-west directions, respectively. For both cases, these power spectra are well-fitted with an inverse power law. Similar power law dependences were seen when L = 10 km.

The following physical picture of the evolution of current convective instability in the diffuse aurora is supported by these simulations. In the evening a westward electric field E_o begins to form which convects plasma in the auroral region equatorward. In regions where the northward gradient in total electron content becomes well-defined nearly field-aligned fluctuations ($k_{\parallel}/k_{\perp} \ll 1$) will grow unstable in regions where the field-aligned current velocities V_d, caused by precipitating particles, are such that $V_d(k_{\parallel}/k_{\perp}) > 0$ and $|V_d k_{\parallel}| > (k_{\perp} c E_o/B)(\nu_i/\Omega_i)$. In the plane almost perpendicular to the magnetic field by an angle $\theta = k_{\parallel}/k_{\perp}$ plasma depletions and enhancements will move northward and southward, respectively, while steepening in the process.

More detailed studies of the current-convective instability in the auroral ionosphere are planned for a future report.

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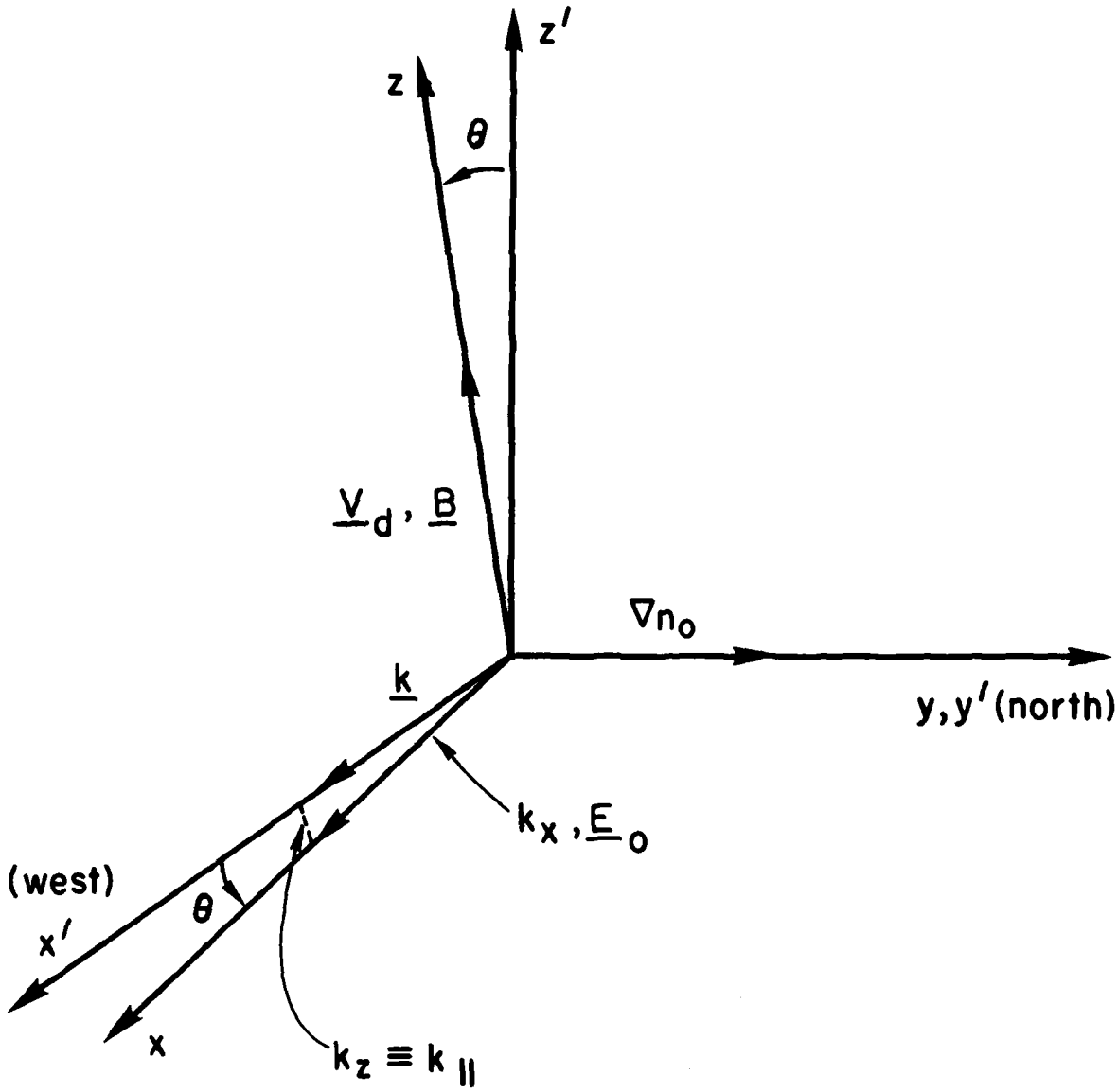

Fig. 1 — Coordinate system used in simulations. The x'y' plane is the simulation plane. The x',x,z',z axes are coplanar.

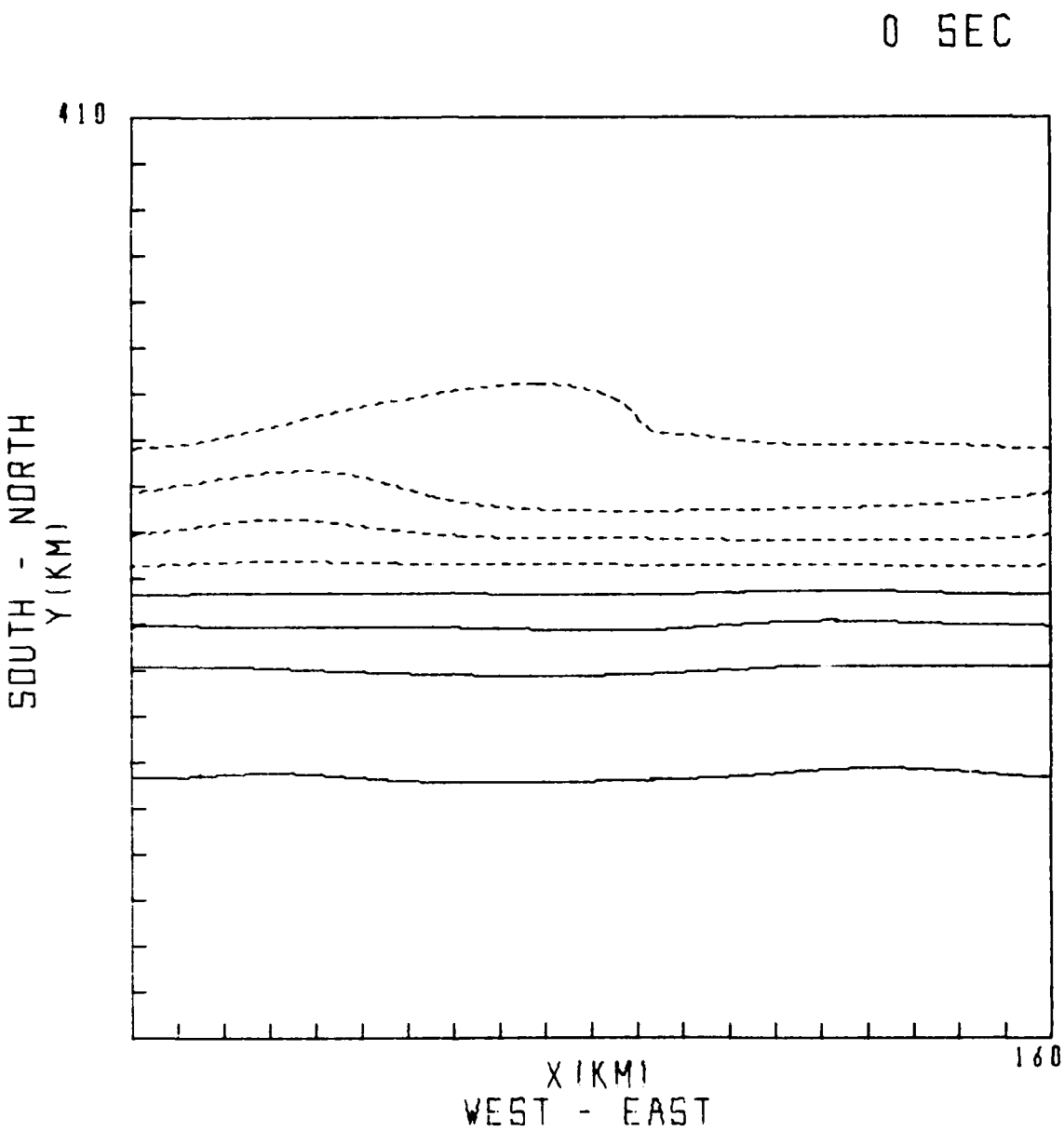

Fig. 2 — Real space isodensity contour plots of $n(x,y)/n_0$ for L = 50 km at t = 0 sec. Eight contours are plotted in equal increments from 1 to 10 with the lower (higher) density contours denoted by solid (dashed) lines. The magnetic field B is directed into the page with the observer looking down the magnetic field lines toward the earth.

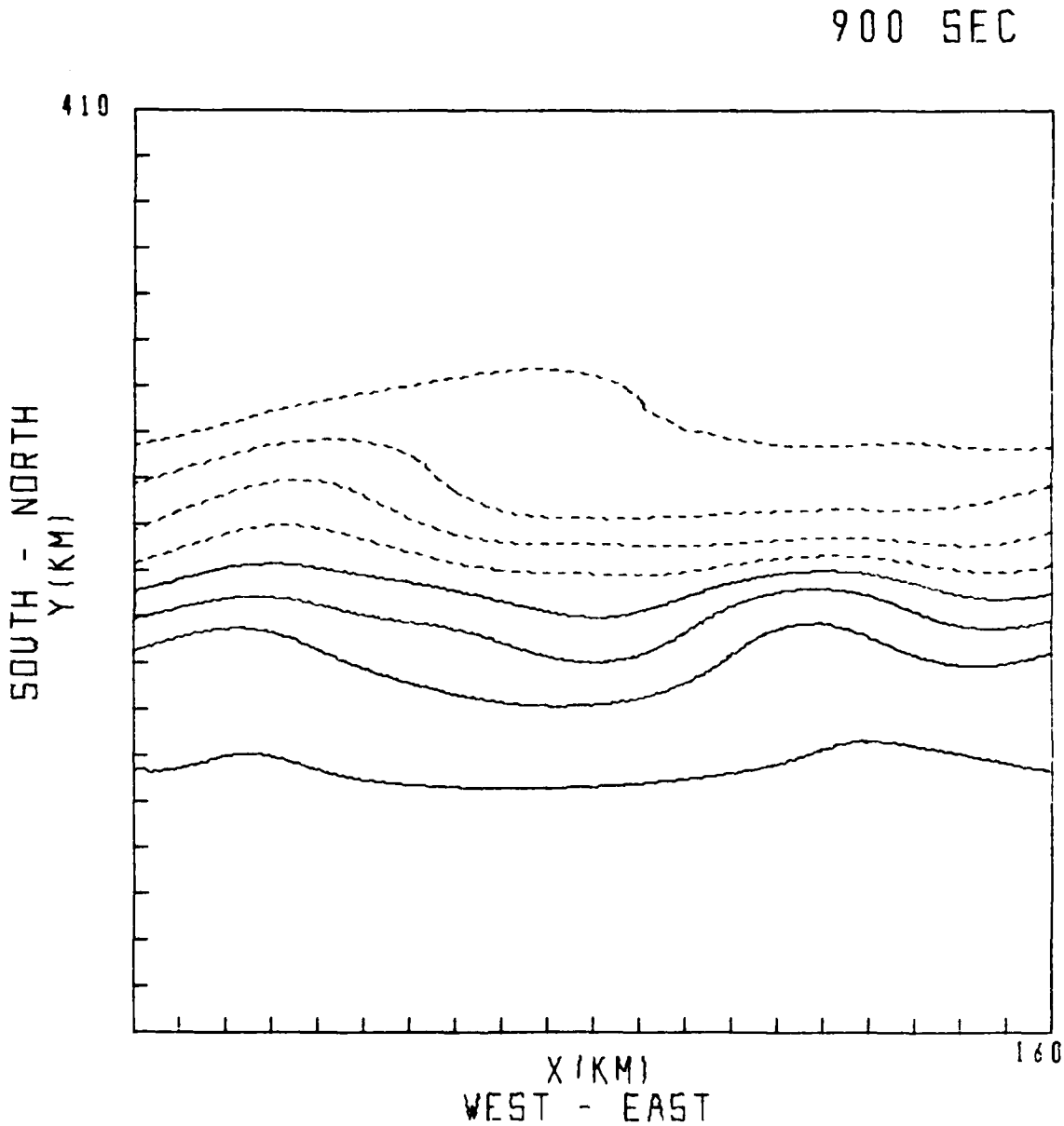

Fig. 3 — Same as Fig. 2 but at t = 900 sec. Note wavelike configuration of solid contours in linearly unstable region ($\partial n_0/\partial y > 0$).

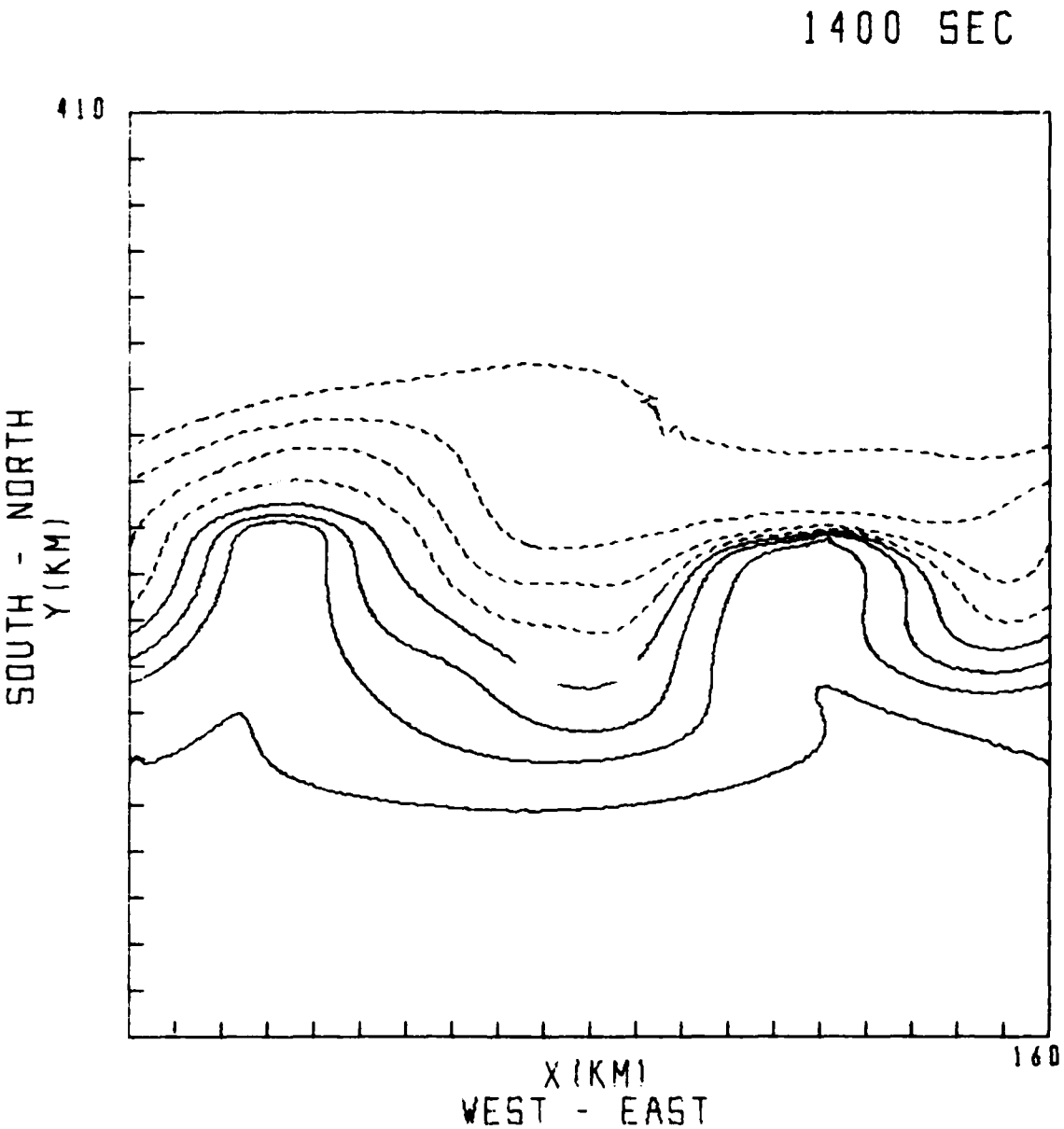

Fig. 4 — Same as Fig. 2 but at t = 1400 sec. Note movement of low densities (solid lines) into regions of higher relative densities (dashed lines).

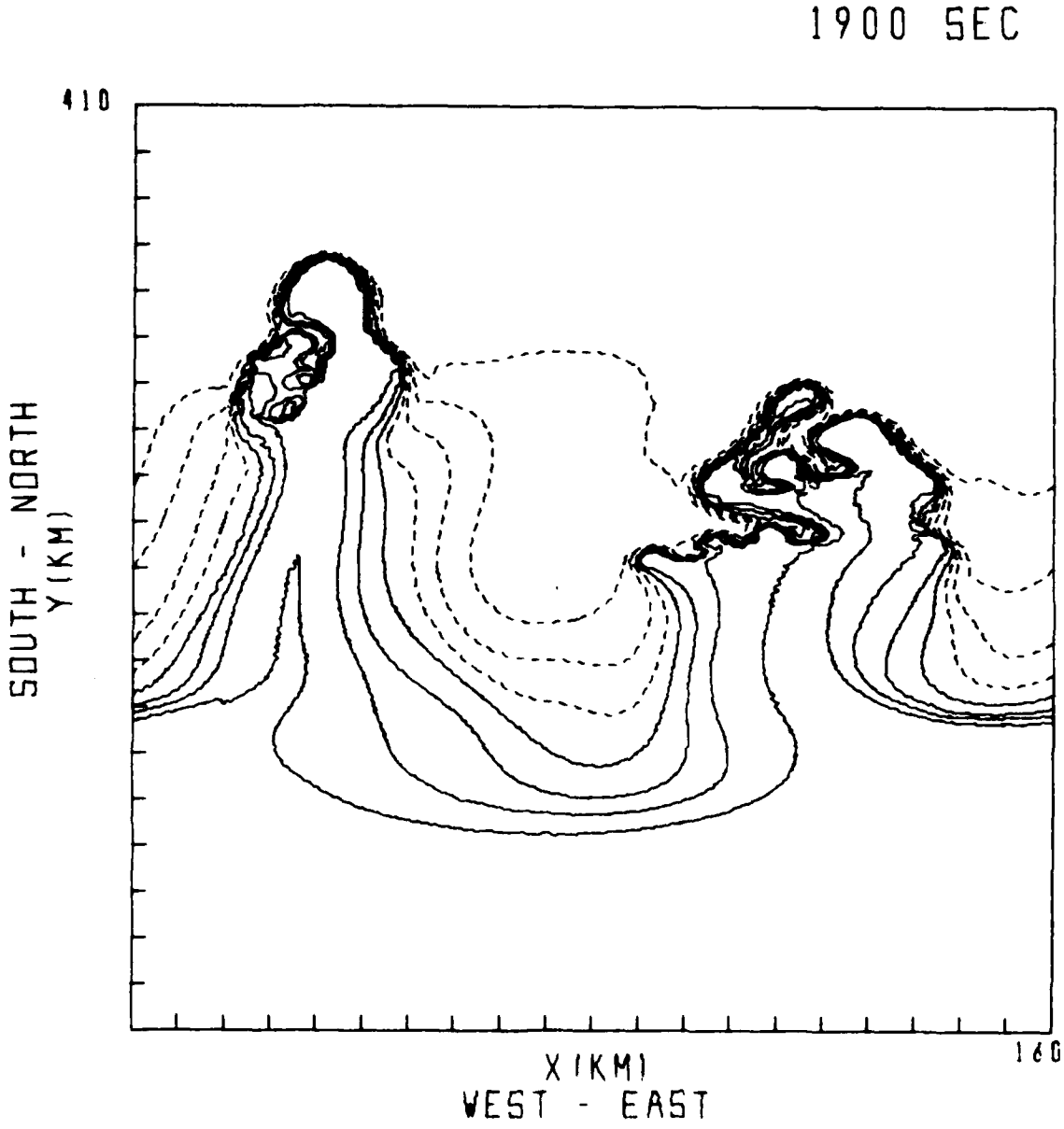

Fig. 5 — Same as Fig. 2 but at t = 1900 sec. Note southward movement of enhancements (relative to ambient) and northward movement of depletions (relative to ambient).

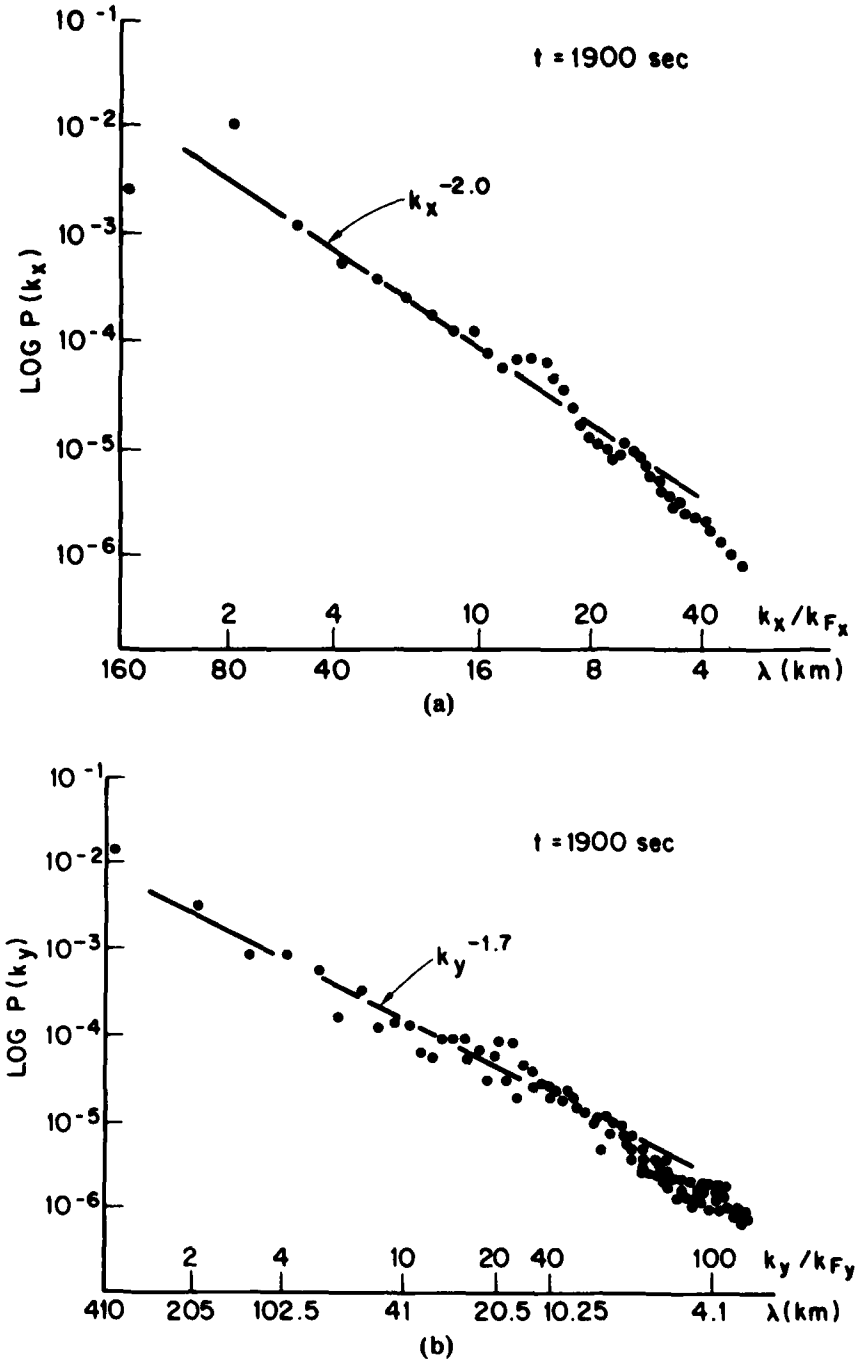

Fig. 6 — Log-log plots of one dimensional (a) x power spectra $P(k_x)$ and (b) y power spectra $P(k_y)$ for L = 50 km at t = 1900 sec. $P(k_x)$ and $P(k_y)$ are obtained by averaging $|\delta n(k_x,k_y)/n_o|^2$ over k_y and k_x, respectively. In (a) $k_{Fx} = 2\pi/160$ km^{-1} while in (b) $k_{Fy} = 2\pi/410$ km^{-1}. The dots represent the numerical simulation results while the solid line is obtained from a least squares fit.

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