Investigation of the Generation Source of Decameter-Scale Sub-Auroral Ionospheric Irregularities During Geomagnetically Quiet Periods

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Abstract

The mid-latitude SuperDARN radars have identified quiet-time decameter-scale density irregularities in the night-side sub-auroral ionosphere that have been proposed to be responsible for the observed low-velocity Sub-Auroral Ionospheric Scatter (SAIS). The physical mechanism responsible for such common irregularities is still unknown. Joint collaborative experiments using the SuperDARN HF radar located at Wallops Island, Virginia and the Millstone Hill incoherent scatter radar (ISR) have determined that these irregularities are located at the ionospheric footprint of the plasmapause and in a region of opposed electron density and electron temperature gradients [1]. In this paper, the temperature gradient instability (TGI) has been extended into the kinetic regime appropriate for HF radar frequencies and modeled as the potential source of these irregularities. The TGI growth rate for this event [1] is computed and compared to another common instability mechanism, the gradient drift instability (GDI) [6]. We conclude that the observed decameter-scale ionospheric irregularities are likely produced by the TGI or a cascade product from it. A "Particle In Cell" (PIC) simulation for TGI utilizing the gyro-kinetic approach has been successfully developed to study the nonlinear evolution of the TGI instability. This allows detailed study of saturation amplitude and particle transport. The simulation results show the saturation mechanisms and confirm the possible wave cascading of TGI into the decameter scale regime of the radar observations.

1. Introduction

The Super Dual Auroral Radar Network (SuperDARN) is a chain of HF radars covering mid- and high-latitudes in the northern and southern hemispheres that provides continuous observations of decameter-scale ionospheric irregularities in the E- and F-regions [2]. These irregularities result from plasma instabilities driven by combinations of plasma drifts, density and temperature gradients, electric fields, winds, collisions, and anisotropies in plasma temperature. The scale length of ionospheric irregularities can range from centimeters to several kilometers. The mid-latitude SuperDARN radars have revealed the common occurrence of backscatter from mid-latitude irregularities during low geomagnetic activity [3, 1]. The one question which remains unanswered is the specific plasma instability mechanism responsible for the growth of these irregularities.

The temperature gradient instability (TGI) is an instability within the general class of collisional drift wave instabilities. Greenwald et al. [1] have suggested that the TGI is a possible mechanism for generating the mid-latitude decameter-scale ionospheric irregularities. The TGI is generated in plasmas with opposed temperature and density gradients in the F-region in the plane perpendicular to the magnetic field [4]. It occurs in plasmas having density gradients, which leads to opposed zeroth order diamagnetic drifts of electrons and ions. If perturbations to the boundary occur, a charge accumulation at the interface between hot and cool regions can take place causing the formation of polarization electrostatic fields directed from the high to low density regions of the perturbed plasma. These fields in combination with the ambient magnetic field cause $E \times B$ drifts that further enhance the perturbation [1]. When the TGI plasma waves are observed with radars, they have already evolved into a nonlinear state. Such nonlinear evolution, e.g. wave cascading, is most likely critical for ultimately determining the scale size of the irregularities observed by the radar observations [5].

The SuperDARN radar observations are in the decameter-scale regime which is of the order of the ion gyro-radius ($\rho_{ci} \approx 3\,\text{m}$). Therefore, the objective of this work is to extend past theory of the ionospheric TGI and develop new computational models that extend into the kinetic regime and include finite ion gyro-radius effects for the first time. This will allow investigation of the TGI as a potential source for these radar irregularities.

2. Theory

The TGI kinetic electrostatic dispersion relation has been solved with full kinetic effects for Landau damping, finite gyro-radius $k_\perp \rho_{ci} \geq 1$, temperature anisotropy, and electron-neutral collisions [5]. The TGI kinetic dispersion relation [5] has been simplified to obtain approximate expressions for the TGI wave frequency and growth rate that can be seen to be extensions of past work using fluid theory appropriate for $k_\perp \rho_{ci} << 1$ [4]. Neglecting electron gyro-radius, parallel temperature gradient, and temperature anisotropy, the TGI wave frequency ω_l and growth rate γ are given by:

$$\omega_l = \frac{\omega^* \Gamma_0(b_i)}{\Gamma_0(b_i) - (1+\tau)} \tag{1}$$

$$\gamma = -\frac{2\nu_{en}\,\omega^*\,\omega_T\,\Gamma_0(b_i)}{k_\parallel^2 v_{te}^2 \left[\Gamma_0(b_i) - (1+\tau)\right]^2} \tag{2}$$

where $b_i = (k_\perp \rho_{ci})^2$, $\Gamma_0(b_i) = I_0(b_i)\exp(-b_i)$, $\tau = T_e / T_i$, $I_0(b_i)$ is the zeroth order Bessel function, $\omega_T = k_\perp (k_B T_e / eB)\kappa_T$ is the temperature gradient drift frequency, $\omega^* = k_\perp (k_B T_e / eB)\kappa_n$ is the diamagnetic frequency, κ_n is the inverse density gradient scale length, κ_T is the inverse temperature gradient scale length, e is the elementary charge, B is the geomagnetic field, v_{te} is the electron thermal velocity, k_B is the Boltzmann constant, T_i is the ion temperature, and T_e is the electron temperature. The TGI maximum growth rate occurs at $b_i = (\tau+1) - \sqrt{\tau^2 + \tau + 1}$. It should be noted that the growth rate due to TGI is proportional to the product of the diamagnetic frequency and the temperature gradient drift frequency.

3. Experimental Observations

On the night of 22-23 February 2006, the Wallops SuperDARN radar and Millstone Hill Incoherent Scatter Radar (ISR) were running co-located observations of sub-auroral ionospheric irregularities [1]. Figure 1a shows the observation geometry, where the Millstone Hill ISR (MHO) pointing direction is aligned with beam 9 of the Wallops radar (WAL). Panels b and c of Figure 1 show the backscatter power in dB and the Doppler velocity in m/s, respectively. Improving upon Greenwald et al. [1], the temperature and density gradients are calculated in the direction perpendicular to B in the top-side F-region.

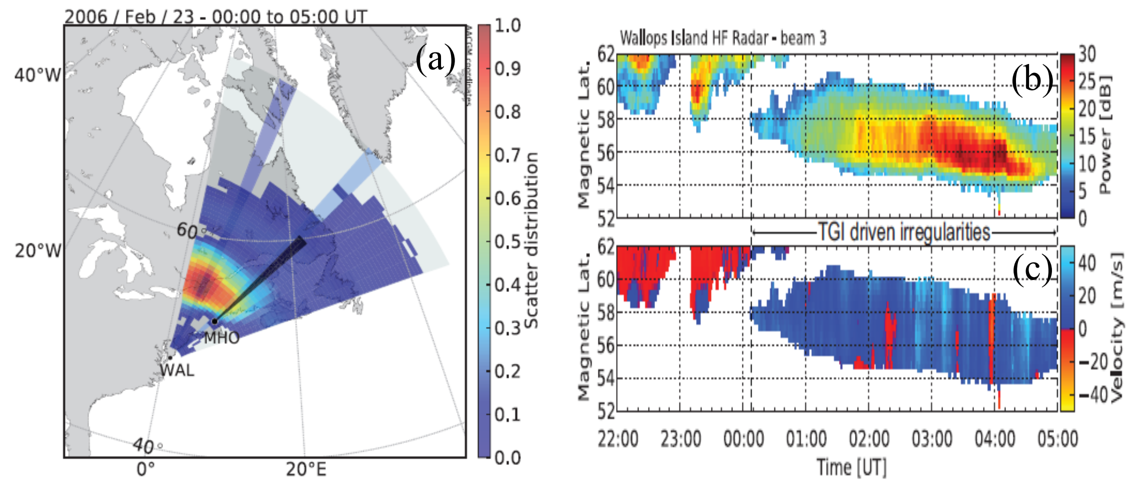

Figure 1: (a) SuperDARN backscatter distribution between 00:00 and 05:00 UT on the night of February 22-23, 2006. Beams 3 (left) and 9 (right) of the Wallops (WAL) SuperDARN radar are highlighted in blue. Also shown is the position and pointing direction (black beam) of the Millstone Hill ISR during that night. The backscatter power and the Doppler velocities are shown in panels b and c, respectively.

A complete comparison of the temperature gradient instability (TGI) and the gradient drift instability (GDI) has been done for SuperDARN observations at the night-side ionosphere for this experiment. The growth rates of both TGI and GDI shown in Figure 2 have been calculated as a function of universal time for the SuperDARN observed measurements corresponding to perpendicular gradients. Figure 2 shows that the TGI growth rate dominates at all times during the experiment. This result changes the suggestion of Greenwald et al. [1] that the dusk scatter associated with the gradient drift instability (GDI) may account for the irregularities observed between 00:00 and 01:40 UT. The TGI growth rate calculations can also explain the observed low-velocity SAIS between 00:10 and 05:00 UT shown in Figure 1c. At the beginning of the experiment (before 00:00 UT), the TGI growth may not be observed by the Wallops radar (WAL) due to the high conductivity of the E-region, which would short-out any electric fields generated by the TGI in the F-region. This work shows that the observed decameter-scale ionospheric irregularities are produced by the TGI or a cascade product from it while GDI does not play a significant role in the generation of these irregularities.

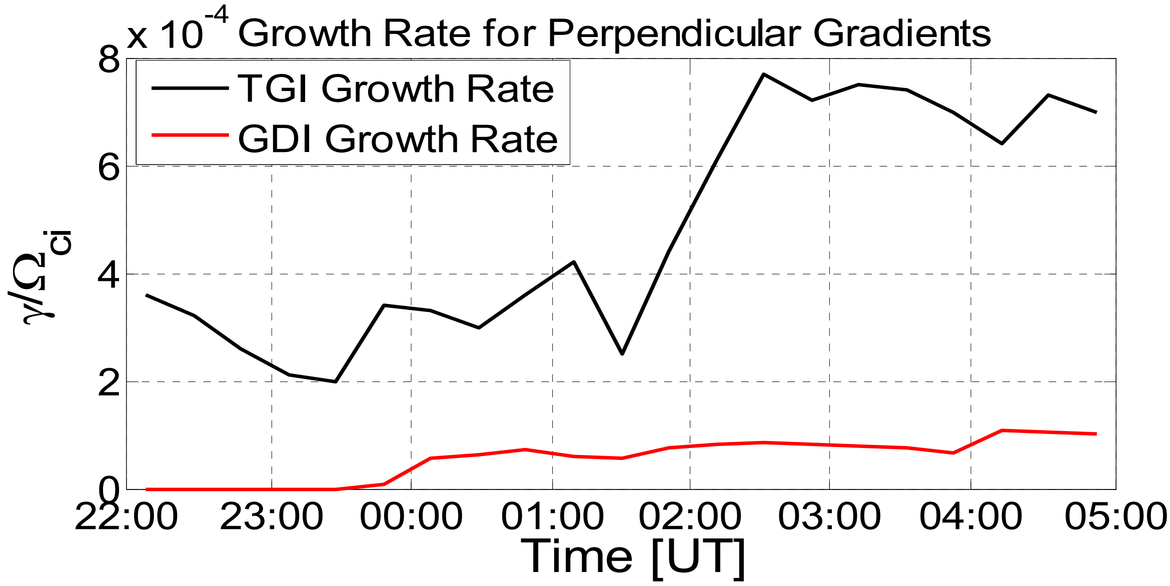

Figure 2: The time series of TGI and GDI growth rates in the top-side F-region for perpendicular electron temperature and density gradients [5]. The growth rates of TGI kinetic dispersion relation (equation 2) and GDI kinetic dispersion relation based on Gary and Cole [6] have been calculated according to the radar frequency during the period of the experiment.

4. Gyro-kinetic Simulation Model and Results

A two-dimensional electrostatic periodic computational model is used to investigate the nonlinear evolution of the TGI. The nonlinear gyro-kinetic equations, on which the present simulation scheme is based, have been described earlier [7]. In order to simulate collisional effects in the ionosphere, the model includes Monte Carlo Collisions (MCC) [8]. The dominant ion species at the altitude 300 km relevant to SuperDARN observations is O^+, $m_i / m_e = 16*1836$, however, a reduced mass ratio of 1.6*1836 is used for computational efficiency. The simulation parameters in units of grid size Δ and ion cyclotron frequency Ω_{ci} are $L_x \times L_y = 256\Delta \times 512\Delta$, time step $= \Omega_{ci}\Delta t = 2.5$, $\rho_{ci} = \Delta = 1$, $T_e / T_i = 1$, $\kappa_{n_e}\rho_{ci} = 2\times 10^{-3}$, $\kappa_{T_e}\rho_{ci} = 1\times 10^{-3}$, N (total number of simulation particles per species) $= 49 \times 256 \times 512$, and the number of time steps is 4000.

The simulation growth rate has a good agreement with the TGI linear theory. The collisional saturation level increases by a factor of $\sim\sqrt{\upsilon_e}$ and does not exceed an upper bound $(\omega_l / \Omega_{ci})/(k_\perp \rho_{ci})^2$. The electron density saturation of the TGI instability is due to the coherent advection of regions of nonlinearly enhanced density. These regions form and grow near the maxima of the potential because of the very well $E \times B$ trapped regions of electron gyro-centers. As shown in Figure 3, the potential wavenumber spectrum shows the cascade process from km-scale primary TGI irregularity structures down to the observed decameter-scale irregularities as would be observed by the SuperDARN radars. This suggests that the observed irregularities for this study may be due to wave cascading of the TGI.

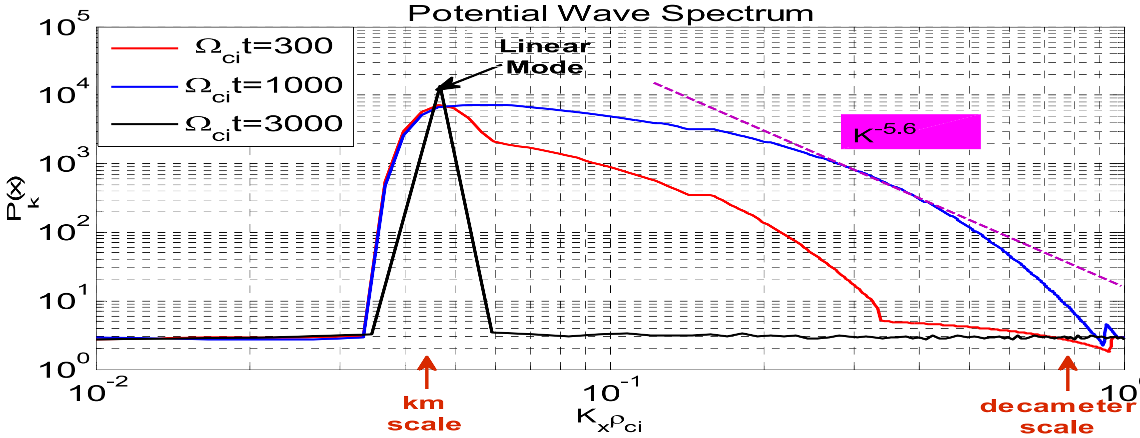

Figure 3: The time evolution of the 1-D potential wavenumber spectrum. The spectral index of $k^{-5.6}$ is calculated from the linear slope of potential wave spectrum as shown in the Figure.

5. Conclusion

Data from the Millstone Hill ISR and the Wallops SuperDARN radar have been analyzed to investigate the potential role of the TGI in the formation of widespread decameter-scale mid-latitude irregularities. A critical comparison of TGI and GDI was made for SuperDARN observations by the development of the growth rate time series of both TGI and GDI relevant to the SuperDARN observations [1]. Our growth rate calculations suggest that the TGI is the dominant plasma instability for the duration of the experiment and GDI does not play a significant role in primary SAIS irregularity generation. Nonlinear evolution of the TGI in this configuration has been studied utilizing gyro-kinetic "Particle In Cell" (PIC) simulations with Monte Carlo collisions for the first time. It has been shown that the $E \times B$ convection is the dominant mechanism for electron density saturation. The simulation results suggest that the observed ionospheric irregularities by SuperDARN may be produced by turbulent cascade from km-scale primary TGI irregularity structures down to the observed decameter-scale irregularities (consistent with experimental results). Additional insight could be obtained by reproducing the experiment described in this study under more varied sets of geomagnetic and seasonal conditions.

6. References

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