Since their first observation using radar in the 1970s [Behnke, 1979], there has been a discrepancy between the experimental evidence and theory for mid-latitude F-region structures. It is important to point out at the onset that these structures differ significantly from the traveling ionospheric disturbances (TIDs) first observed in the 1930s and described most notably by Hines [1960]. The main difference is that, whereas the classical TID is relegated to neutral atmospheric dynamics, the type of mid-latitude structure observed by Behnke [1979] requires plasma physics to understand their properties. In fact, to avoid confusion with the neutral atmospheric TID, it has been suggested that these electrodynamic structures be termed “electrobuoyancy waves,” which is the term employed below.

The properties of the electrobuoyancy wave are fairly well known and have been well established by many observations over the three decades since their first report [e.g., Fukao et al., 1991; Kelley and Fukao, 1991]. Important advances were made when modern optical instrumentation was used to measure the two-dimensional properties of these waves [e.g., Mendillo et al., 1997; Miller et al., 1997; Garcia et al., 2000; Saito et al., 2001]. In the northern hemisphere, the observations suggest the following properties for electrobuoyancy waves:

1. A depletion in electron density/airglow intensity aligned from northwest to southeast. Typically, the slant is on the order of 20° west of north.
2. A propagation direction towards the southwest at a velocity between 50-150 m/s.
3. A wavelength between 50 and 500 km.
4. A strong internal polarization electric field in the northward direction.
5. A finite length of the depleted region in the direction perpendicular to its propagation velocity.
6. A tendency to occur on the poleward edge of the Appleton Anomaly region.

A montage showing five examples of electrobuoyancy waves is shown in Figure 1, along with a sixth example (bottom right) from the magnetic equator showing an example of another physical process, caused by the Rayleigh-Taylor instability. The images from 1997 (top row and bottom left) were obtained using an all-sky camera located at the Arecibo Observatory. The middle image on the bottom was obtained from Hawaii while the bottom-right image was taken at Christmas Island. Similar images have been obtained from Japan, most notably during the F-region Radio and Optical measurement of Nighttime TID (FRONT) campaign conducted in May 1998 [e.g., Kubota et al., 2000; Saito et al., 2001].

The linear theory developed by Perkins [1973] is usually invoked to explain these observations. This is curious, since the Perkins mechanism only explains one of the observations robustly: the orientation of the depleted region with respect to the magnetic meridian. In fact, Perkins' linear theory predicts a propagation direction that is 180° from the observed direction. However, the orientation of these structures is so curious (not being aligned with the magnetic meridian), that the Perkins mechanism has remained in vogue as an explanation.

By combining the wealth of information obtained from optical, radar, and satellite observations, Kelley and Makela [2001] recently reconciled the discrepancies between the observations of electrobuoyancy waves and the existing theories. This was done by invoking a secondary nonlinear effect not accounted for in the linear theory of Perkins. First, it was noted by Kelley et al. [2000] and then later developed more fully by Makela and Kelley...
that the depleted regions in the optical data of the 630.0-nm emission could be used as a surrogate for the height-integrated Pedersen conductivity. This meant that the depleted regions seen in the 630.0-nm images were also regions of very depleted height-integrated conductivity, typically a factor of 4. Thus, the depleted bands with finite size are susceptible to becoming strongly polarized, in agreement with the ISR and satellite observations [e.g., Saito et al., 1995; Kelley et al., 2000; Shiokawa et al., 2003]. This conclusion would not have been possible without the two-dimensional information provided by optical imaging techniques. A sketch of the orientation of the relevant parameters is given in Figure 2. This northwestward-oriented polarization electric field is dominant over the background electric field and causes the observed southwestward drift of the structures.

Linear simulations of the Perkins mechanism have been carried out in the past to confirm that the most unstable wave number is indeed oriented for waves propagating to either the northeast or southwest. However, no new model simulations have yet been performed to test the mechanism proposed by Kelley and Makela [2001]. To do so would require a nonlinear simulation that includes the neutral atmosphere and a reactive ionosphere in three dimensions. With the recent advances in computing speed and the increasing sophistication of modeling techniques, a new push towards a nonlinear simulation of electrobouyancy waves seems appropriate, as suggested by Kelley et al. [2002].

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REFERENCES


Figure 2. Polarization of a low Pedersen conductivity region in the presence of a wind-driven current. (After Kelley and Makela [2001]. Reproduced by permission of the American Geophysical Union.)