The VLF fingerprint of elves: Step-like and long-recovery early VLF perturbations caused by powerful ±CG lightning EM pulses

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Subionospheric VLF recordings are investigated in relation with intense cloud-to-ground (CG) lightning data. Lightning impacts the lower ionosphere via heating and ionization changes which produce VLF signal perturbations known as early VLF events. Typically, early events recover in about 100 s, but a small subclass does not recover for many minutes, known as long-recovery early events (LORE). In this study, we identify LORE as a distinct category of early VLF events, whose signature may occur either on its own or alongside the short-lived typical early VLF event. Since LORE onsets coincide with powerful lightning strokes of either polarity (±), we infer that they are due to long-lasting ionization changes in the uppermost D region ionosphere caused by electromagnetic pulses emitted by strong ±CG lightning peak currents of typically>250 kA, which are also known to generate elves. The LORE perturbations are detected when the discharge is located within ~250 km from the great circle path (GCP) of a VLF transmitter-receiver link. The probability of occurrence increases with stroke intensity and approaches unity for discharges with peak currents greater than ~300 kA. LOREs are nighttime phenomena that occur preferentially, at least in the present regional data set, during winter when strong ±CG discharges are more frequent and intense. The evidence suggests LORE as a distinct signature representing the VLF fingerprint of elves, a fact which, although was predicted by theory, it escaped identification in the long-going VLF research of lightning effects in the lower ionosphere.