High above the Earth

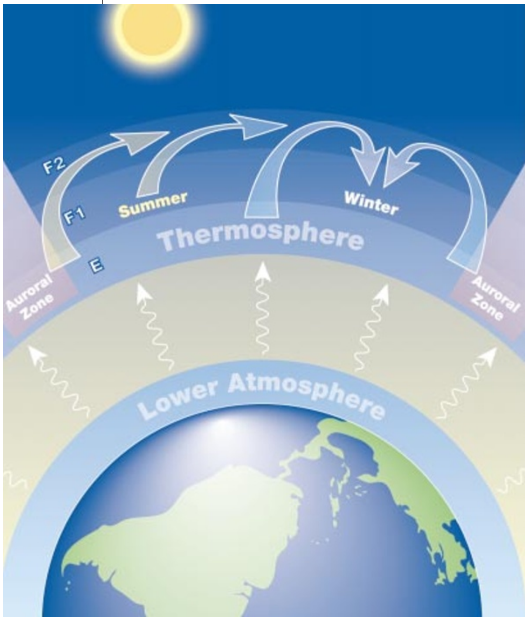
Ionosphere

For a century, the strange and variable behaviour of this 'mirror in the sky' has puzzled scientists and infuriated users of radio communications.

Henry Rishbeth

We have come far in the 100 years since Oliver Lodge gave the first physical explanation of why Marconi could send radio waves around the curved Earth. Using the new knowledge of electrons and ionization, Lodge realized that solar ultraviolet radiation produces a conducting layer that reflects radio waves. We call this the ionosphere, a term coined by Robert Watson-Watt in 1926 to replace its previous name, the Heaviside layer (after the physicist Oliver Heaviside). In modern terms, the ionosphere is a weakly ionized plasma or electron-ion gas embedded in the thermosphere, the hot, tenuous region above 80 km that comprises the top few millionths of the atmosphere's mass. We are now approaching the stage where we can link our models of the thermosphere and ionosphere with models of the lower atmosphere.

For a century the ionosphere has been used for communications, but it is by no means a constant 'mirror in the sky'. Although its E layer (100–120 km above the ground) and F1 layer (170–200 km) usually behave in a regular, solar-controlled way, the F2 layer (250–350 km) does not. It is this F2 layer, with the greatest density of free electrons, that is potentially the most effective reflector of radio waves. But its variability in height and density, its strange day/night and seasonal behaviour, and its complex response to geomagnetic disturbances have long puzzled scientists and infuriated users of radio communications. This matters because the ionosphere is still widely used for radio communication; furthermore, the ionosphere can severely affect satellite transmissions that pass through it, causing errors in the Global Positioning System, for example. Ionospheric disturbances can also create strong electric currents in the E layer that can disrupt cable communications and terrestrial electric power systems.



VICKY ASKEW

Rockets, satellites and radar have enabled us to build up a comprehensive picture of the upper atmosphere. The ionospheric plasma — being far easier to detect and measure than the neutral atoms and molecules — serves as a 'tracer', the ionospheric measurements acting as 'diagnostics' for the composition, temperature and dynamics of the greatly preponderant neutral air.

Like the lower atmosphere, the thermosphere is a heat engine on a global scale, driven by radiation from the Sun. Whereas the lower atmospheric engine is driven by infrared and visible radiation, the thermosphere is driven by short-wavelength ultraviolet and X-radiation which heats, dissociates and ionizes the air. It is also driven by the energy input from the particle stream known as the solar wind, which shapes and controls the Earth's magnetic envelope — the magnetosphere — and deposits heat in the auroral zones that surround the Earth's magnetic poles.

We model the workings of this 'engine' using computational 'global circulation models'. To generate these models, the equations that embody the principles of conservation of mass, momentum and energy, for electrons and for many types of ion and neutral particle, must be solved on a grid of latitude, longitude and height for every minute of the day, and the results validated by many measurements — no mean feat! Like their meteorological counterparts for the lower atmosphere, these models are indispensable for describing, explaining and ultimately forecasting the behaviour of this complex system.

The picture that emerges is one in which the ions in the F2 layer are mostly atomic oxygen (O^+), and their recombination with electrons involves reactions with neutral molecules (O_2 and N_2). For this reason, the ion and electron concentrations depend on the atomic/molecular ratio of the thermospheric air. This ratio, which is mainly controlled by solar radiation, is seasonally modified by the vertical and horizontal winds of the global circulation. The picture indicates the summer-to-winter flow of air in the thermosphere, and also the flows driven by auroral heating (the return flows at lower heights and through the night side are not shown). The circulation is distorted during geomagnetic disturbances, when the auroral zones become more active and move to lower latitudes.

These ideas help us to solve long-standing puzzles, such as why electron density in the F2 layer peaks in winter over Europe, North America and Australasia, but at the equinoxes at low latitudes and in the South Atlantic. Another tricky question is why electron density is usually drastically reduced (but is sometimes increased) during geomagnetic storms. Investigating these problems helps to validate the models and to make sense of the vagaries of radio propagation.

Not all ionospheric variability can be blamed on solar or geomagnetic disturbances. Some may originate from below, caused by waves and tides transmitted up to the ionosphere. So does lower-atmosphere 'weather' affect the ionosphere, or vice versa? Our linked circulation models, embracing the thermosphere and the lower atmosphere, include the interchange of momentum and energy carried by radiation, wind and waves.

The ultimate prize is a complete top-to-bottom, predictive model of the Earth's atmosphere that incorporates our rapidly advancing knowledge of Sun–Earth relationships and the magnetosphere. Running such a model on timescales of days, hours or even minutes should enable us to make better forecasts of the 'space weather' that affects spacecraft and communications. On timescales of years and decades, the models should give us a better understanding of solar and upper-atmospheric influences on climate and global change. There are many side questions, such as whether and how the ionosphere is affected by tropical storms, volcanic activity or earthquakes? All this may sound visionary, but Lodge, a visionary of his day, would surely have approved. ■

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FURTHER READING

Lodge, O. *Nature* **66,** 222 (1902).
Hargreaves, J. K. *The Solar–Terrestrial Environment* (Cambridge Univ. Press, 1992).
Roble, R. G. *Am. Geophys. Un. Monogr.* **123,** 53 (2000).
Schunk, R. W. & Nagy, A. E. *Ionospheres: Physics, Plasma Physics and Chemistry* (Cambridge Univ. Press, 2000).
Gardner, G. W. *Nature* **224,** 1096 (1969).
www.wdc.rl.ac.uk/ionosondes/ionosondes.html

See '100 years ago', News and Views, p. 26