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Abstract

Long-term variability has previously been observed in the relative magnitude of annual and semi-annual variations in the critical frequency (related to the peak electron concentration) of the ionospheric F2 layer (foF2). In this paper we investigate the global patterns in such variability by calculating the time varying power ratio of semi-annual to annual components seen in ionospheric foF2 data sequences from 77 ionospheric monitoring stations around the world. The temporal variation in power ratios observed at each station was then correlated with the same parameter calculated from similar epochs for the Slough/Chilton dataset (for which there exists the longest continuous sequence of ionospheric data). This technique reveals strong regional variation in the data which bear a striking similarity to the regional variation observed in long-term changes to the height of the ionospheric F2 layer. We argue that since both the height and peak density of the ionospheric F2 region are influenced by changes to thermospheric circulation and composition, that the observed long-term and regional variability can be explained by such changes. In the absence of long-term measurements of thermospheric composition, detailed modelling work is required to investigate these processes.

1 Introduction

The annual variation in the peak electron concentration of the ionospheric F-region has long been known to vary with geomagnetic location. Measurements are made of the peak radio frequency, foF2, (the critical frequency) returned from the F-region by vertical sounding using ground based instrumentation known as ionosondes. The critical frequency, f_c (Hz), is related to the peak electron concentration, N (m^{-3}), by the formula $f_c \approx 9\sqrt{N}$. Observations above some stations, such as Slough, UK are dominated by an annual variation with highest peak electron concentrations during the winter months. The ionosphere above other stations, such as Stanley in the Falkland Islands, is dominated by a semi-annual variation, with peak F-region electron concentrations occurring at the equinoxes.

Modelling work by Millward et al (1996) and subsequently by Zhou et al (2000) has demonstrated that the variability of foF2 throughout the year at a given station can be explained by changes to thermospheric composition (which is influenced by a station‘s proximity to the geomagnetic pole) and ion production rate (which is influenced by solar zenith angle). For a station located on a ‘near pole’ geographic longitude such as Slough/Chilton, the annual variability in composition dominates over any zenith angle effect and so the variation of ionisation is predominantly annual. For a station at a similar geographic latitude but on a ‘far from pole’ longitude, such as Stanley, a semi-annual variation results as compositional changes between equinox and winter months are relatively small compared with the associated change in solar zenith angle. This leads to ionospheric densities that peak at the equinoxes.

Recently, Scott et al (2014) presented a spectral analysis of long-term ionospheric F2 data demonstrating that the relative contribution of annual and semi-annual components at a given station has varied since ionospheric records began in the 1930s. Using a method similar to Bravo et al (2011), they calculated the power ratio of semi-annual to annual variations in ionospheric peak frequency, foF2, above Slough/Chilton and Stanley. The long-term variability between these two stations was anti-correlated. While the data records at Slough/Chilton and Stanley are among the longest continuous sequences of such data that are availabe, many ionospheric monitoring stations have subsequently been set up worldwide, particularly during the International Geophysical Year (IGY) in 1957. While most of these additional records do not cover such large date ranges as those from Slough/Chilton and Stanley, they nevertheless provide a global context for these observations. A natural extension of the work of Scott et al (2014) is therefore to repeat the same spectral analysis for as many stations as are available in order to see if any global patterns emerge.

2 Method

Long-term digital data records of monthly median foF2 values for 190 stations are held by the UK Solar System Data Centre (www.ukssdc.ac.uk). This data centre incorporates all the holdings of the World Data Centre C2 for Solar Terrestrial Physics, set up as part of the

World Data Centre programme established during the International Geophysical Year in 1957. While the UKSSDC holds additional records from those used in the current study these data have either not been digitised or their monthly medians have not been calculated using URSI standards (Piggott and Rawer, 1961). As a result they are either not easily accessible or not directly comparable with the monthly medians used in the analysis of Scott et al (2014). Such stations have, for the time-being, not been included in the current analysis.

For the 190 stations for which standard digitised data were available, monthly median foF2 data from local noon at each station were analysed following the method of Scott et al (2014) which is briefly summarised here. The monthly data were first detrended by fitting and subtracting a cubic function in order to remove solar-cycle variations in the subsequent spectral analysis. A Lomb-Scargle periodogram was then produced for each station, generating a power spectrum for each frequency considered within the eleven year running window. Each data point is represented by the central time in this sliding time window. The log-ratio of the semi-annual to annual spectral power components was then calculated for each data point.

In order to compare the results obtained from such a large number of stations, the semi-annual/annual power log-ratio from Slough/Chilton was selected as the control sequence (since it is the longest continuous sequence). Similar data sequences calculated for each ionospheric station were then correlated with the control sequence for the epoch where both overlapped and the correlation coefficient for each and its significance were calculated. In order to account for the persistence within each time-series, the partial auto-correlation coefficients (PACFs) were calculated and these used to determine the appropriate technique to use when calculating the correlation coefficient and its significance (Chatfield, 2013). It was found that for the majority of stations (65 of 78) all lags beyond the first were smaller than the standard error, indicating that an AR(1) model was appropriate. To implement this, the data were first filtered by calculating;

$$x_t' = (x_t - \bar{x}) - \hat{\alpha}(x_{t-1} - \bar{x})$$

where x_t denotes a datapoint in the first time series at time t, $\bar{x}$ is the mean of the first time series, $\hat{\alpha}$ is the value of the autocorrelation function of the first time series at lag 1 and x_{t-1} is the same data lagged by one time interval. The same filter wasthen applied to the second time series to produce y_t' before the two time series are cross-correlated. For stations requiring additional lags to be accounted for, this process was iterated up to the maximum lag indicated by the PACF for each station. One station did not have enough data to enable calculation of the maximum number of lags required and so these data were removed from our analysis.

While there is no reason to expect all stations to show similar long-term variability, particularly since the datasets cover a variety of epochs, this method enables quick identification of consistent regional behaviour. Of the data sets contained within the WDC, 78 contained contiguous data sequences longer than sixteen years which were considered long enough to undergo this spectral analysis, resulting in at least five years' worth of spectral information. Varying this threshold influenced the number of stations included in the global analysis but did not affect the overall patterns that emerged.

3 Results

The control Slough/Chilton semi-annual to annual log power ratio as a function of time is plotted in the top panel of figure 1. The lower two panels of figure 1 contain the same parameter calculated for two example stations. The middle panel of figure 1 presents the log power ratio calculated from data taken at the ionospheric monitoring station at Sverdlovsk (56.7^{o} N, 61.1^{o} E). This shows a strong (0.81) and significant (>> 99.9%) correlation with Slough/Chilton. The lower panel of figure 1 shows the same parameter calculated from data taken at the ionospheric monitoring station at Conception (36.6^{o} S, 73^{o} W). These data are moderately anti-correlated with Slough/Chilton (-0.49) significant to >> 99.9%. It can be seen from the magnitudes of the quantities shown in figure 1 that the dominance of annual or semi-annual behaviours at each station varies a great deal. By correlating each time series with the behaviour seen at Slough we are investigating whether the relative dominance of the annual or semi-annual variation is being modulated in the same way as at Slough. While such modulations may not change the dominant annual behaviour of the ionosphere above a particular station, any correlation or anti-correlation demonstrates that the variations at Slough are not occurring in isolation but are instead due to coherent changes in the global ionosphere.

The temporal variation in semi-annual to annual log power ratio was calculated for each station and then correlated with the same time sequence calculated for Slough/Chilton. In order to see if there were any regional consistencies between these locations, these correlations were plotted on a map which is presented in figure 2. Positive correlations are plotted in colours ranging from yellow to red, while negative correlations in four shades of blue. Those correlations significant to greater than 95% are plotted as solid symbols while those below this threshold are plotted as open symbols, the size of the symbol denoting significance levels of >68% and < 68%. Stations for which the AR(1) noise model was used are displayed as circles while those for which greater lags needed to be considered are shown as triangles. For reference, the positions of the north and south geomagnetic poles are also plotted as green stars. While the position of these poles drift slightly over the timescales considered by this study, these values (for 1960) are representative of the epoch.

Some dominant regional variability is clear in figure 2. Firstly, there is a band at mid-geomagnetic latitudes in the northern hemisphere stretching from north America, through Europe and into north-east Asia which is dominated by stations that have moderate to strong positive correlations with Slough/Chilton. At mid to low geomagnetic latitudes, there is a wide region dominated by stations which anti-correlate with Slough/Chilton though for many of these stations the anticorrelation is not highly significant and a few even show a slight positive correlation.

4 Discussion

In order to characterise the regional differences in long-term changes to the height of the ionospheric F2 layer, Bremer et al (2001) presented a map of observed global trends in figure 5.5 of their paper. This figure contains several extended geographic regions that show similar trends in ionospheric F2 height over time. Ionospheric records from North Eastern Europe, Central and Eastern Asia and China tend to show a positive trend, as do those from Antarctica and North-Eastern America, Canada and Alaska. North Western America, South America and Eastern Australian stations record negative trends while the dense concentration of stations in Western Europe shows a mixture of positive and negative trends.

Both Slough/Chilton and Stanley revealed long-term changes in the log-ratio of their semi-annual to annual variations, indicating potential long term changes to thermospheric composition and/or circulation (Scott et al, 2014). If such changes are occurring, and differ between geographic locations, this may explain the scatter seen in long-term trends of F-region layer height presented by Bremer (2001).

While the global variability of seasonal changes in foF2 presented in this paper are not directly comparable with the trends in hmF2 presented by Bremer (2001) and others, they do display some interesting regional similarities. In particular, the general consensus in variability across Europe, North-Eastern Asia and South America and the lack of a dominant behaviour in data from Northern American stations. The regional similarities between the two studies may point to a common cause for the observed long-term changes in the height, density and seasonal variation of the F2 layer.

Modelling work by Millward et al (1996) and Zou et al (2000) indicates that the dominance of an annual or semi-annual variation in the ionosphere above a particular location can be explained by the relative influence of variations in the solar zenith angle and seasonal changes in thermospheric composition. That the relative influence of semi annual and annual variations changes with time above a particular location may therefore be interpreted as changes to the composition and/or thermospheric circulation (since, for a given location, the annual variabililty in solar zenith angle will remain unchanged).

When considering the change in height of the ionospheric F2 layer at a particular station, any short-term variation in thermospheric circulation and/or composition could influence the height of the layer (as discussed above), evidence for which is presented by Millward et al (1996, their figures 3 and 4). Even if two stations are affected by the same short-term variability, their observed trends in height over time will differ if the two data sequences span different time ranges and are responding to different short-term variations. Each station is also influenced differently by global changes to thermospheric circulation and composition due to its proximity to the geomagnetic poles, making a direct comparison between stations complex.

Long-term change to thermospheric composition was also cited as a possible influence on the observed change in the height of the ionospheric F2 region, hmF2, (Jarvis et al, 1998; Danilov, 2009) and on the critical frequency of the F2 region (Danilov 2008; Danilov and Konstantinova, 2013). In the F2-region ion recombination rates are sufficently low that transport becomes a factor in the equilibrium between production and loss of ionisation. Meridional winds can modulate the height of the layer through ion-neutral collisions which transport ionisation along the geomagnetic field (Rishbeth 1998). In this way, a poleward meridional wind will move ionisation downwards to altitudes where the ion loss rates are greater while equatorward meridional winds raise ionisation to greater altitudes where the ion loss rates are reduced. Such processes will modify the peak height of the layer. The magnitude of such an effect is dependent on the inclination of the local magnetic field and will therefore vary with geomagnetic latitude, being least effective near the equator. The extent to which changes in thermospheric winds would affect the annual or semi-annual variation of the ionosphere will depend on location. For a station such as Stanley where the annual variation in thermospheric composition is sufficiently low that seasonal changes in ion production dominate, any change in thermospheric winds that increased the annual variation in composition, would be expected to enhance annual variations in ionisation and therefore weaken the semi-annual/annual power ratio.

Compositional changes in the thermosphere are also known to occur in response to geomagnetic activity. Enhanced vertical convection generated by the deposition of energetic auroral particles at the base of the thermosphere combined with joule heating caused by auroral current systems result in an increased molecular composition within the upper thermosphere. The impact of vertical circulation on thermospheric composition was modelled by Rishbeth and Müller-Wodarg (1999) who demonstrated that season and the position of the auroral oval were factors in the location of upwelling regions. Global wind patterns subsequently transport this molecular-rich air to mid and low latitudes (e.g. Rishbeth, 1998). Modulating the thermospheric composition within the vertical atmospheric profile will influence the height of the ionisation peak since the loss rate of molecular ion species is much greater than for atomic ions (Rishbeth and Setty, 1961). Accounting for such modulation in layer height is important when considering long-term changes in the height of the ionosphere as an observable decrease in ionospheric altitude has been predicted (Rishbeth, 1990; Rishbeth and Roble, 1992) in response to an increase in CO_2 concentrations (Roble and Dickinson, 1989). Enhanced geomagnetic activity would be expected to move the average position of the auroral ovals equatorward. For a station such as Stanley, this would bring the location of the upwelling region closer to the station, enhancing the annual variation in thermospheric composition at this location. This would in turn reduce the magnitude of the observed semi-annual variation. In effect the ionosphere would behave more like a station located on a near-pole longitude, with a reduced semi-annual to annual power ratio.

This has led several authors to look for such changes in the long-term ionospheric records (Bremer, 1992; Bremer, 1998; Jarvis et al, 1998). While the data from some stations did indeed show a downward trend in the altitude of the ionospheric F2 region over time, others showed little or no trends or even showed an increase in ionospheric altitude over time (Bremer, 2001). The challenges in this type of analysis are that the long-term behaviour of the ionosphere could be influenced by other factors, and a considerable amount of research has been undertaken to investigate various potential sources for this variation (Laštovička, 2009).

Long-term changes in geomagnetic activity have been discussed by many authors (e.g. Clilverd et al, 1998; Stamper et al, 1999; Mursula and Martini, 2006). The influence of geomagnetic activity on the thermosphere results from the average position of the auroral oval, which expands to lower latitudes under geomagnetically active conditions, modulating the latitudinal extent of global circulation patterns (Rishbeth, 1998). For example, for a station on a far from pole geomagnetic longitude, an increase in geomagnetic activity would bring the auroral oval closer to the station's latitude on average. This could increase the annual variation in thermospheric composition above the station relative to any semi-annual variation in foF2. Scott and Stamper (2014) noted that long-term variations in the aa geomagnetic index resembled variations seen in the semi-annual/annual power ratio at Slough, especially for the early part of the data sequence. This is consistent with observations by Danilov (2008) that the influence of geomagnetic activity on the variability of hmF2 is more dominant before the 1980s. Danilov and Mikhailov (2001) investigated the relationship between changes in hmF2 and foF2 with Ap for two southern hemisphere locations. These relationships were as expected for geomagnetically induced thermospheric dynamics and so the authors concluded that long-term variability in geomagnetic activity could obscure any trends in hmF2 due to greenhouse cooling of the thermosphere.

Qian et al (2009) conducted detailed modelling to investigate the impact of changes in CO_2 concentration on the ionospheric F2-layer. Their results showed that a doubling of CO_2 influenced the height and density of the F2-layer with large latitudinal and longitudinal variations whose distribution correlated with the geomagnetic dip equator. The trends in these modelled parameters were generally negative, though positive trends in hmF2 resulted at some locations and local times caused by changes in the neutral wind transport of plasma. They also noted that changes in hmF2 also varied with season and solar activity. Any long-term change in these localised and seasonal variations in the F-region would also impact the relative magnitude of the annual and semi-annual behaviour of the F2 layer.

Modelling work by Cnossen and Richmond (2013) produced global variation in hmF2 and foF2 as a result of long-term changes to the Earth's magnetic field. The strongest effects were seen over the Atlantic where the vertical component of E x B drift, diffusion and transport of ionisation by meridional neutral winds were affected by changes to the local magnetic field. They concluded that variation of the geomagnetic field may dominate other mechanisms to produce the observed trends in hmF2 and foF2 in that region. Subsequent modelling work

(Cnossen, 2014) investigated the relative impact of long-term change in the geomagnetic field on the upper atmosphere compared with rising levels of CO_2. The author concluded that hmF2 was affected by long-term variation in the Earth's magnetic field and changes to the concentration of CO_2 in equal measure with the peak electron concentration being dominated by changes to the Earth's magnetic field. Variation in meridional wind patterns over time may alter the long-term behaviour of thermospheric composition at a given location. This in turn would modulate the relative magnitudes of annual and semi-annual variations in the ionosphere, as shown by Millward et al(1996) and Zou et al (2000). This work once again highlights the potential for long-term change in a global parameter to generate a range of localised responses in the ionosphere.

Some modelling studies have been carried out to consider the impact on the thermosphere and ionosphere caused by modulation of the lower atmosphere. While investigating the annual asymmetry in the F2-layer, Rishbeth and Müller-Wodarg (2006) concluded that, after accounting for all known influences, dynamical influences of the lower atmosphere were the most likely cause. Oliver et al (2013) proposed that gravity waves could influence the thermospheric temperature through long-term change in gravity wave behaviour (generated by winds over the oceans) and explain the greater than expected decline in thermospheric temperatures. Such research points to the possibility of long-term variation in regional thermospheric composition being due to forcing from the lower atmosphere. Any alteration in the seasonal nature of this forcing could again impact the annual/semi-annual behaviour of the ionosphere.

It should be noted that the observed thermospheric temperature trends are derived from incoherent scatter (IS) observations at Millstone Hill (Holt and Zhang, 2008). Temperatures are derived from IS data by fitting the ion temperature to ion mass ratio (Rishbeth and Williams, 1985). A reduction in ion temperature could therefore result from an underestimate in the assumed ion mass. Therefore the observed reduction in ion temperature could also be explained by long-term changes in thermospheric composition. Emmert et al (2012) report an observed increase in thermospheric CO_2 concentrations. They point out that this result could explain the difference between observations and modelled values of thermospheric density and suggest that their observations could be explained by increased gravity wave activity, driving changes to eddy diffusion at the turbopause. Long-term changes to thermospheric composition would also be expected to influence the magnitude of the annual ionospheric variation, in turn modulating the relative influence of the semi-annual and annual effects.

5 Conclusions

This paper is intended to highlight that there are global differences in the long-term annual variability of foF2. This global variation shares regional similarities with global trends seen in long-term changes in hmF2. Since both these parameters are influenced by thermospheric composition and/or circulation, we argue that changes to thermospheric composition may be responsible for global variability in both parameters, though the cause of such global compositional changes is still the subject of much research. Since compositional change is expected to affect long-term trends seen in hmF2, this could explain some, if not all of, the variability seen in the analysis of long-term trends in F region heights. Understanding the relationship between the long-term variability in composition, thermospheric circulation and the height of the F2 layer is important if we are to deconvolve the influence of these changes from other long-term effects such as the predicted reduction in hmF2 in response to increased levels of CO_2 in the troposphere. In the absence of long-term records of thermospheric composition, the impact of global circulation on the height and peak density of the ionosphere must be modelled in detail for each location using a global coupled thermosphere/ionosphere model similar to the one used by Millward et al (1996).

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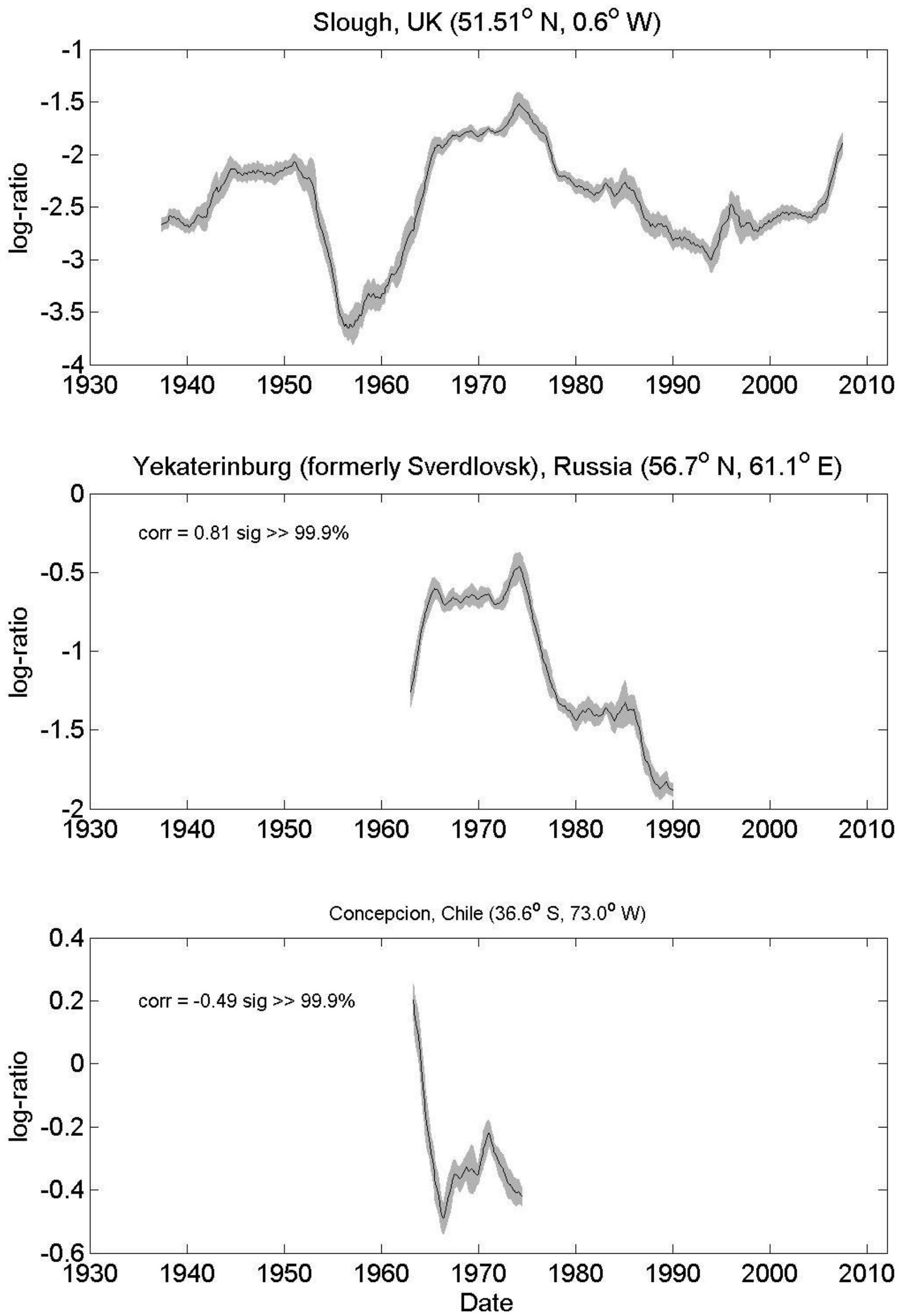

Figure 1. Log power ratios of the semi-annual to annual components of noon median values of foF2 (black lines) against time for three ionospheric monitoring stations; Slough/Chilton (top), Sverdlovsk (middle) and Conception (bottom). The standard error for each station is shown as a grey band around the black line. For the two lower panels, the value and significance of the correlation with the Slough is shown.

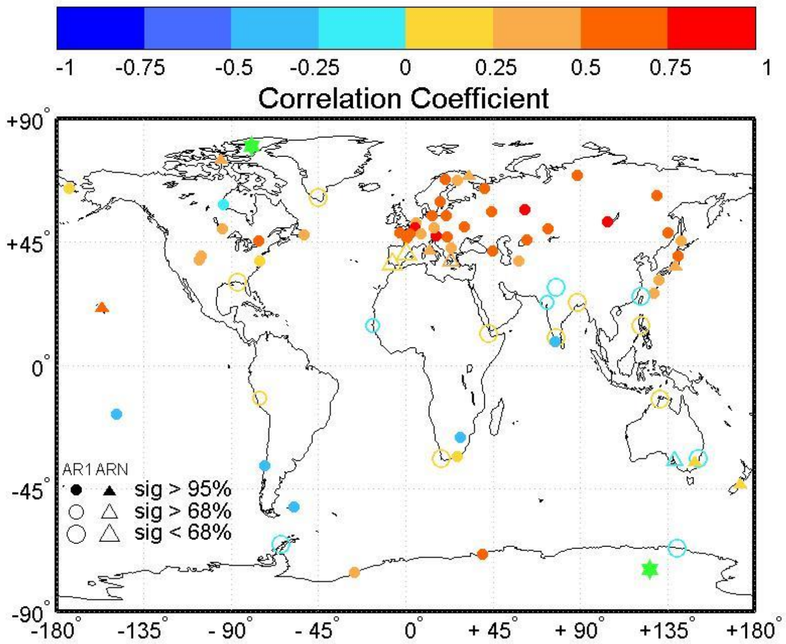

Figure 2. Correlation coefficients for log power ratios of semi-annual to annual variability in foF2 for each station compared with Slough/Chilton. Each correlation is represented by a symbol plotted at the location of the ionospheric monitoring station. Positive correlations are shown in colours ranging from yellow to red while negative correlations in are shown as shades of blue. Correlations exceeding 95% significance are represented by filled symbols while those correlations that are less significant than this are represented by open circles according to the scale shown. Circles represent correlations for which only the first lag of the autocorrelation function needed to be accounted for, while triangles represent correlations where more than one lag needed to be accounted for. The positions of the geomagnetic poles are indicated by green stars.