Comparing Radio Scintillation Models with Observations

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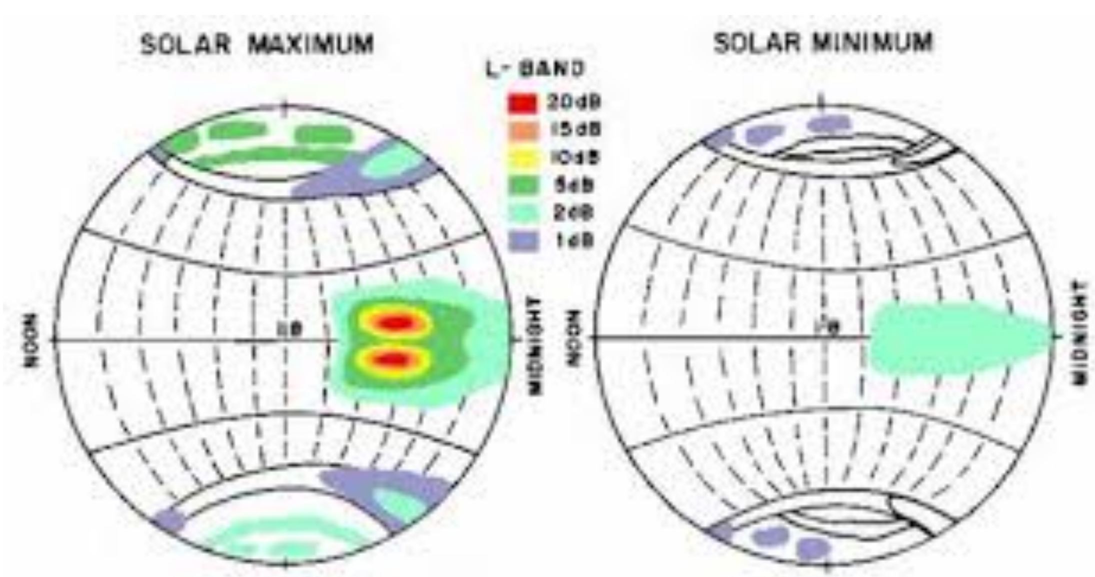
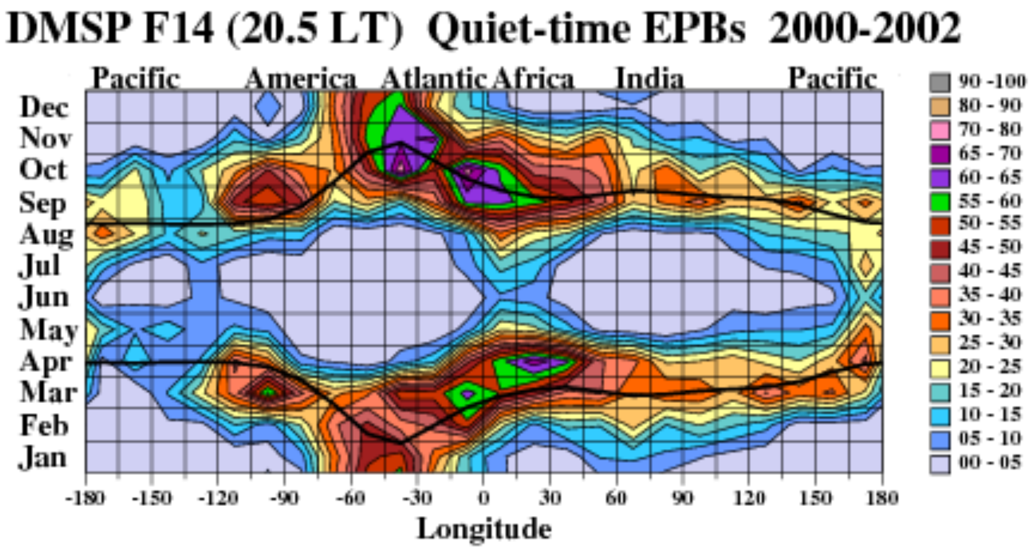
Introduction Scintillation – the fluctuations of the intensity and phase – of radio signals propagating through the ionosphere is one effect of plasma turbulence created there as the result of plasma instabilities. Because of the impact that scintillation can have on the performance of systems that rely on transionospheric radio propagation, i.e., communication and navigation systems, there is much interest in correctly modeling and potentially forecasting the occurrence of scintillation. In the low latitudes near the geomagnetic equator, this turbulence is often the consequence of the development of the Rayleigh-Taylor (RT) interchange instability that occurs when denser plasma is suspended over less dense plasma, where through the action of the instability, the motion of parcels of plasma creates narrow plumes of less-dense plasma rising through the ionosphere filled with turbulence. Cascades of energy to shorter wavelengths through nonlinear mode coupling in the turbulence can lead to density irregularities with wavelengths short enough to affect radio propagation (the Fresnel scale, ranging from 1 km to 100 m for UHF to GHz signal frequencies).

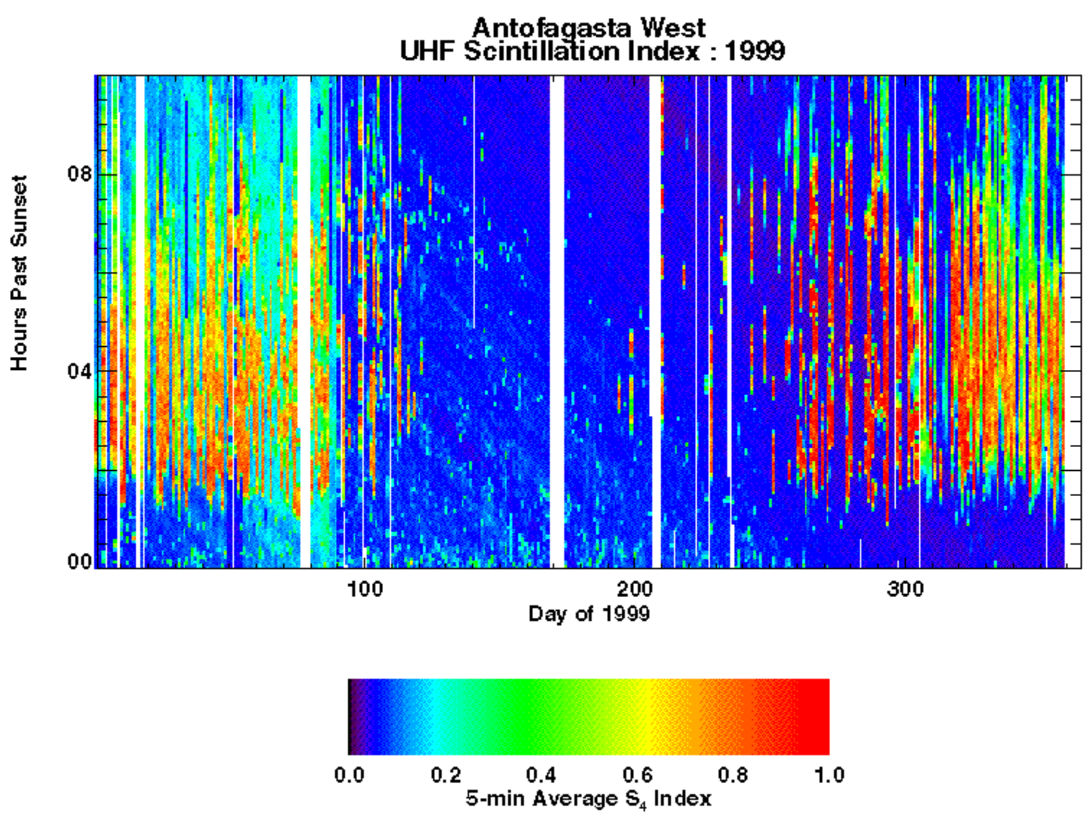
The plasma plumes (sometimes called Equatorial Plasma Bubbles, EPBs) and the radio scintillation (first noted on ionograms as spread-F) obey a number of climatological rules: they are more likely to occur in the evening or post-midnight time zones; in a given longitude sector, there are times of year when its occurrence is more likely and other seasons when it is less likely. But there is much day-to-day variability about these climatological means, which makes forecasting scintillation a challenge.



Radio scintillation climatology



Equatorial Plasma Bubble Climatology (the probability of bubble occurrence)



Daily Scintillation occurrence over a year, illustrating the day to day variability.

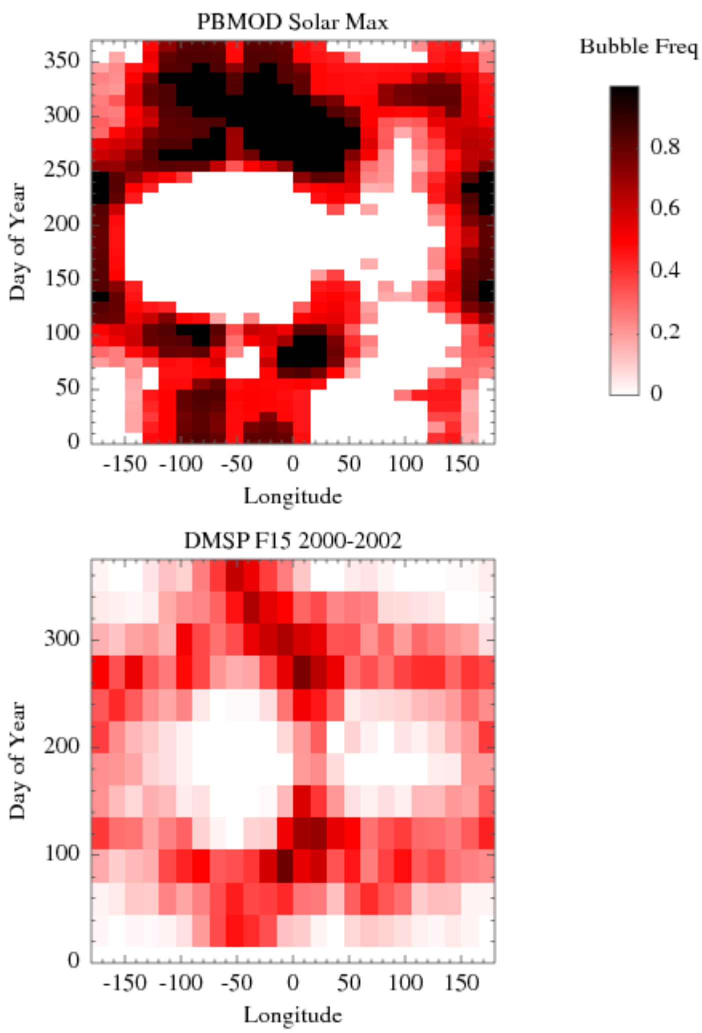
The plumes are a mesoscale phenomenon (100s of km) that are influenced by phenomena on a wide range of spatial scales (both longer and shorter). They are affected by variations in the energy input into the thermosphere through geomagnetic activity and solar EUV/X ray output, plus variations and structures in the wave and tides driven in the thermosphere by lower layers of the atmosphere. Much as it is impossible for meteorologists to predict the occurrence of an individual thunderstorm (despite the density of meteorological observations in the troposphere), the paucity of ionospheric observations on the appropriate scales on a global basis means it will likely be impossible to predict the occurrence of a particular plasma bubble (except those structures – like some pre-dawn depletions – which result from large-scale systematic electric fields). Much like the possibility of occurrence of thunderstorms can be predicted through the instability of the atmosphere, however, we should be able to predict the likelihood of the occurrence of the RT instability in the ionosphere, given a reliable forecast of the structure of the ionosphere on ambient spatial scales. We have, in fact, shown that the statistical properties of radio scintillation can also be modeled with a fair degree of accuracy (see below). One difficulty in achieving the goal of day-to-day forecasting is obtaining the spatially detailed data on a global basis that will permit these forecasts to be made.

Critical Issues in Modeling Scintillation Because scintillation is a consequence of the occurrence of a plasma instability in the ionosphere, its occurrence depends critically on when and where, and to what degree, the conditions for instability occur. The day-to-day variability of scintillation occurrence reflects the day-to-day variability of these conditions. For post-sunset scintillation, the key factor is the strength of the pre-reversal enhancement of the vertical plasma drift at the equator, because lifting the ionosphere increases the growth rate of the RT instability. Climatological models generally only describe the mean value of the plasma drift, and thus do not describe this variability (although a statistical sense of it can be inferred from the scatter plots in which multiple days of data are overplotted). Ultimately, for success in modeling scintillation, coupling to an ambient model that properly reflects the day-to-day conditions in the ionosphere will be required.

In addition to the conditions for plasma instability, the occurrence of scintillation depends on the presence of 'seed' irregularities in the plasma, which will be amplified exponentially in time by the instability (until nonlinear effects kick in). Traveling Ionospheric Disturbances (TIDs) excited by atmospheric gravity waves are thought to be one source of these seeds. It is thought by many that there is always some spectrum of these waves present, but nonetheless their nature must affect the outcome of the instability process. The spacing of plumes may reflect the wavelengths of the original TIDs, and in case of marginal instability strength, the strength of the original TID might make the difference in whether the nonlinear regime in which the plumes develop is reached or not.

PBMOD at CCMC The Boston College Ionospheric Irregularity model is installed and running at CCMC; see http://ccmc.gsfc.nasa.gov/RoR_WWW/pbmod-rt/pbmod_realtime.php This implementation uses general geophysical indices to drive climatological models for the critical drivers, e.g., the vertical plasma drift. Speaking statistically, we might say that the climatological models provide an estimate of the 50th percentile state of the ionosphere. With a presumed variance of 5 m/s about the climatological value (based on the scatter of daily values of the drift observed at

Jicamarca), a second run is performed with a larger vertical drift, at the 85th percentile level, to estimate an upper limit to the level of scintillation at that probability level. A statistical model for the distribution of drift velocities like this was fairly successful in estimating the probability of EPBs observed by DMSP:



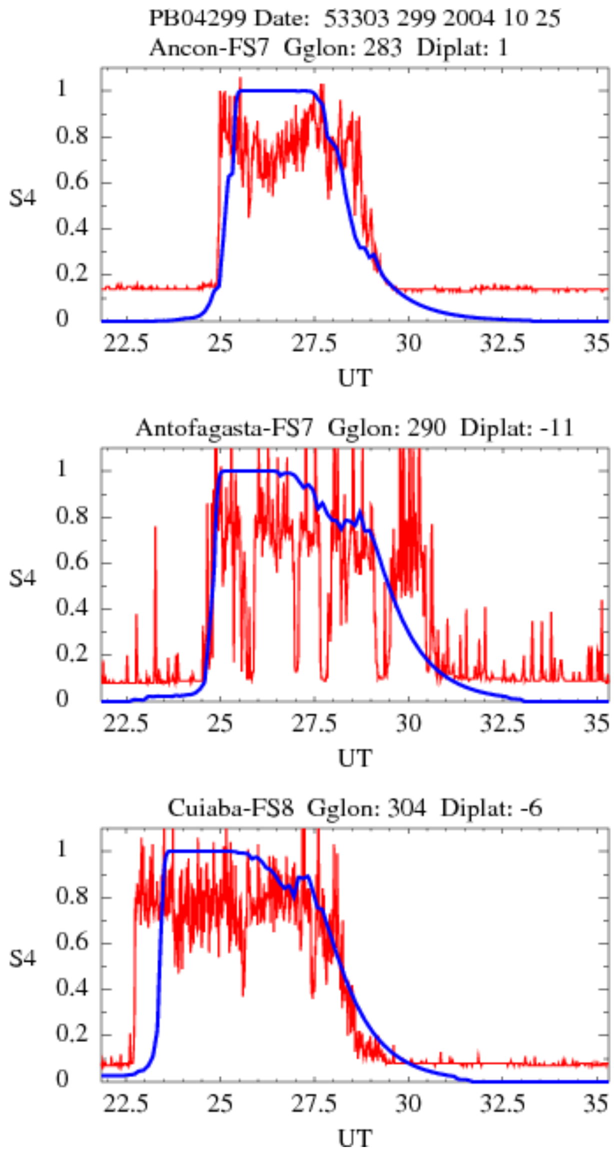
Calculation of probability of EPBs at DMSP altitude (top panel) and observed DMSP EPB probability (lower panel).

Measures of Scintillation There are a number of ways to characterize the strength of scintillation. One common way to describe the strength of fluctuations in the intensity of a signal is the S4 index, which is the square of the root mean square (rms) fluctuations in intensity divided by the square of the mean intensity. Thus, S4 is a dimensionless parameter which ranges in value from zero to about unity. Fluctuations in phase are described by their rms variance, σ_ϕ. Additionally, the associated equatorial plasma bubbles (EPBs) can be described by their scale size and the depth of their density depletion.

Scintillation Observations Data for scintillation comes from a number of sources. Direct measurement of the fluctuations of signals from steady beacons (either space-based or ground sources) of course provides measures that most directly reflect the impact of scintillation on systems. The Air Force SCINDA network of ground-based receivers monitoring the signals from UHF and GPS provides such measurements at a set of stations around the globe. It is unclear whether this data is accessible outside of DoD sponsored programs. Other monitors of GPS signals are available, for example, the CORISS instrument (a GPS receiver) on the C/NOFS satellite has been used to determine scintillation strength. For many of these, however, the determination of scintillation parameters from their data would have to be set up. Other in-situ in space instruments can monitor other characteristics of the plasma turbulence or the density depletions that accompany them: structure in airglow, plasma density, etc. The presence of spread-F in ionograms from ground-based ionosondes and coherent echoes in incoherent radars are at least a qualitative way of detecting the presence of scintillation.

Scintillation Models There are a number of ways to model scintillation and related phenomena. Empirical models, such as WBMOD, parameterize a large number of scintillation observations in terms of location, time, signal link parameters, and the levels of solar and geomagnetic activity, to allow the probability of a given level of scintillation on a given link at a given time to be estimated by extracting similar situations from an extensive database. There are first-principles models for the ionospheric plasma (e.g., those by Aveiro and Hysell; Huba et al.; and PBMOD by Retterer); these are generally fluid models with spatial resolution down to about 10 km that can describe the development of the plumes through the onset of the RT instability and its saturation. There are models that solve the Maxwell equations (at some level of approximation) to describe the effect of a given field of density irregularities on the propagation of radio signals. The difficulty in melding the latter two kinds of model to produce a first-principles model of ionospheric scintillation is the extreme range of spatial scales involved, from 1000s of km for the spatial scales of ionospheric variation down to the cm wavelengths of GHz radio waves.

One way in which progress has been made has been to extract statistical information on the density irregularities in the first-principle model for plasma structure, e.g., the spectral density of density irregularities as a function of wavelength, and extrapolate it down to the wavelengths that are effective for refracting and diffracting the radio waves of a signal. The extrapolation to shorter wavelengths is facilitated by the fact that the spectral density in this fluid turbulence is often a power law (although this is complicated by the presence of a break in the spectrum, at which the slope of the power law changes). Using the thin phase screen, weak scattering model, calculation of S4 and σ_ϕ are reduced to quadrature over the irregularity spectral density. Stronger scattering is then described through the saturation of S4 values near unity. A sample calculation and comparison with SCINDA observations is shown below:

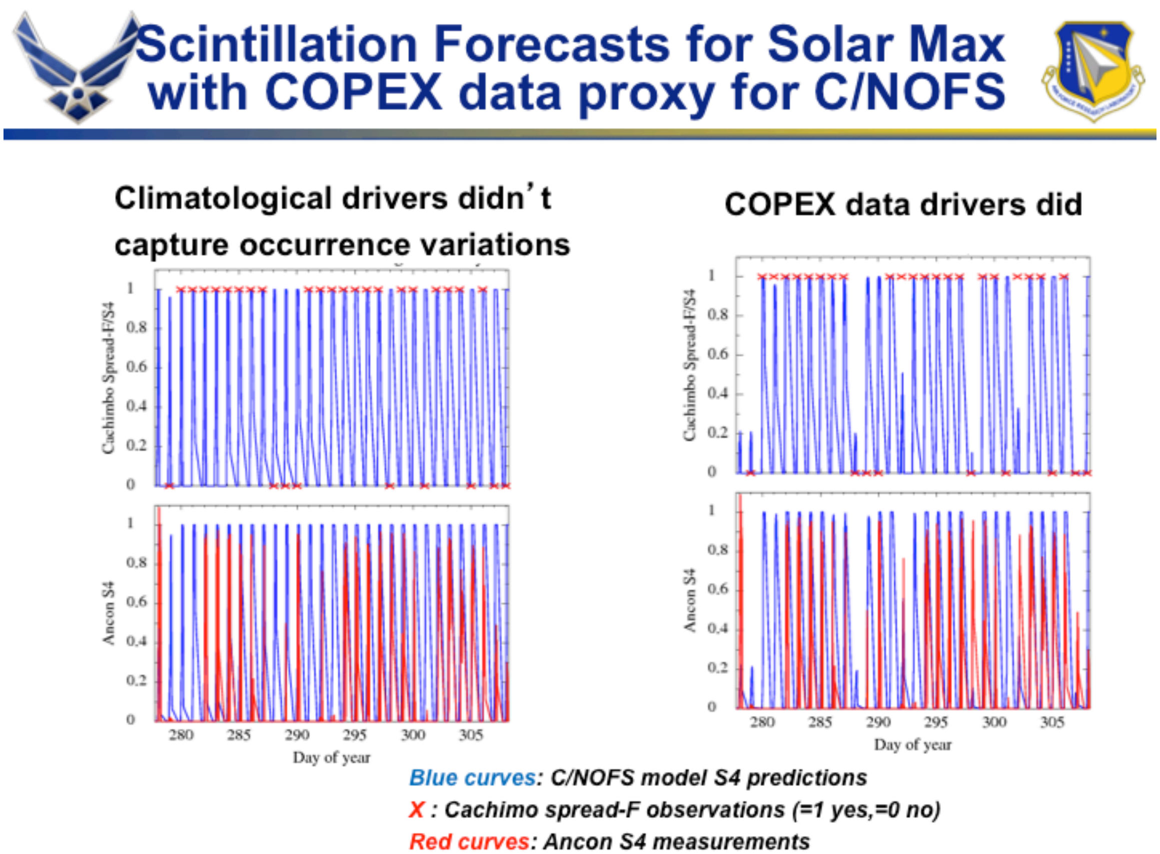


Comparison of SCINDA observations of scintillation (red curves) and first-principles modeling by PBMOD (blue curves) simulataneously at three South American stations.

<u>Metrics for Comparing Scintillation Models and Observations</u> Examination of these curves suggest a number of metrics for quantifying the agreement between the observations and the models: 1) The time of onset (of scintillation at a particular level); 2) The peak level of scintillation; 3) The duration of scintillation (above some specified level); 4) The average S4 level. Because of the variation of S4 through the course of an event Groves and Caton suggested a 5) Time integral of S4 as a metric parameter.

<u>Skill Scores</u> Meteorologists have developed metrics known as skill scores for evaluating forecast techniques. If we are in the middle of scintillation season or the middle of a 'dry' season at a location, we can readily predict that scintillation that evening should occur in the former case, and not occur in the latter. If, on the other hand, our forecast technique could predict the exceptions to the climatological expectation, e.g., no scintillation on a day in scintillation season, it would obviously be a better technique.

The following example is a study of scintillation over South American during the COPEX campaign. Data were taken in the Autumn of 2002, which is part of a scintillation season in this longitude sector. Thus, the variability of scintillation occurrence came in days when scintillation did not occur. (Correlation with the Dst geomagnetic index shows that this disruption occurred as the result of geomagnetic activity.) Two series of runs of PBMOD were performed, one using a climatological model for the vertical plasma drift, and the other using drifts inferred from the h'F height of the ionosphere measured by an ionosonde under in flux tubes involved (called the COPEX data drivers below), for two different stations (Cachimbo, Brazil and Ancon, Peru). The skill scores were calculated by Don Hunton:



Scintillation Forecasts for Solar Max with COPEX data proxy for C/NOFS

Forecast Statistics for 30-day interval

Cachimbo Climatology

	Pred. Scint.	No Pred. Scint.
Obs. Scint.	21 days	0
No Obs. Scint.	9	0

With Data Drivers

	Pred. Scint.	No Pred. Scint.
Obs. Scint.	19	2
No Obs. Scint.	5	4

Ancon Climatology

	Pred. Scint.	No Pred. Scint.
Obs. Scint.	21	0
No Obs. Scint.	9	0

With Data Drivers

	Pred. Scint.	No Pred. Scint.
Obs. Scint.	19	2
No Obs. Scint.	6	3

Accuracy

$$Accuracy = \frac{hits + correct\ negatives}{total}$$

Accuracy (fraction correct) -

Answers the question: Overall, what fraction of the forecasts were correct?

Range: 0 to 1. Perfect score: 1.

Characteristics: Simple, intuitive. Can be misleading since it is heavily influenced by the most common category, usually "no event" in the case of rare weather.

Cachimbo Climo, Accuracy = 0.70
Cachimbo Data Driven, Accuracy = 0.77

Little impact on accuracy

Heidke Skill Score

$$HSS = \frac{(hits + correct\ negatives) - (expected\ correct)_{random}}{N - (expected\ correct)_{random}}$$

Heidke skill score (Cohen's κ) -

where $$(expected\ correct)_{random} = \frac{1}{N}\left[(hits + misses)(hits + false\ alarms) + (correct\ negatives + misses)(correct\ negatives + false\ alarms)\right]$$

Answers the question: What was the accuracy of the forecast relative to that of random chance?
Range: minus infinity to 1, 0 indicates no skill. Perfect score: 1.
Characteristics: Measures the fraction of correct forecasts after eliminating those forecasts which would be correct due purely to random chance.

Cachimbo Climo, Heidke Skill Score= 0.0
Cachimbo Data Driven, Heidke Skill Score = 0.39

Significant impact of data on skill score

<u>Potential Research Program</u> There are several steps which would be logical follow-ons to the work described above:
1) Collect enough scintillation data to test the probabilities determined from the PBMOD runs with the Gaussian Vdrift model, as implemented at CCMC.
2) Use the ambient ionospheric state determined by a model like Full Physics GAIM which purports to determine the drivers like the electric fields for ionospheric structure, to drive the irregularity model, and then compare results with observations.
3) Couple with whole atmosphere model to get the driving effects from the lower layers of the atmosphere, like gravity waves and tides.
4) Profit