April 17, 2005

Thunderstorm Effects on Sporadic E Propagation in 144 MHz

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Abstract. Radio amateurs speculate about the possibility of thunderstorm effects on ionospheric sporadic E radio propagation on very high frequencies. This speculation is however not generally accepted in the ham community because convincing evidence is not yet available. Considering scientific resources, thunderstorm effects on the ionosphere cannot be generally excluded though which is in particular evident when considering investigations on travelling ionospheric disturbances and spread-F irregularities in the equatorial F region. This paper discusses the model of thunderstorm-triggered gravity waves travelling from the troposphere and stratosphere into the ionosphere where the gravity waves may cause wind shears at E region level which are considered one cause of sporadic E layers in mid-latitudes. The GPS/MET radio occultation experiment appears to support this model by statistical analyses providing an impressive correlation between convectively generated gravity waves in the lower atmosphere and electron density irregularities in the E region of the ionosphere. OH nightglow measurements also provide clear evidence of mesospheric gravity waves associated with underlying thunderstorms. The paper presents a ham radio project which analyses the spatiotemporal correlation between 144 MHz sporadic E long-distance communication and VLF radio emissions from lightnings (sferics). The June 27, 2004 event shows a surprising correlation between the geographical position of sferics and the geographical position of sporadic E scatterers. In order to support statistical studies of sferic and sporadic E positions, the paper proposes a data analysis method which may be easily implemented in amateur radio propagation studies if scientific observatories would provide the required raw data material.

Contents

1 Introduction

Do thunderstorms create sporadic E layers enabling long distance VHF communication? KYRIAZIS (5B4AZ), for example, claims that sporadic E clouds located over the Balkans north of Greece are “strongly related” to “big [thunderstorm] formations” in that region [35]. We may even find radio amateurs considering a more general relationship between the weather and sporadic E activity in 144 MHz. GYDE (ZL3NE), for example, considers sporadic E propagation in 144 MHz a general misinterpretation, i.e. he denies all long distance sporadic E QSOs in Australia and New Zealand and interprets all this QSOs by tropospheric propagation [19], [20]. Many radio amateurs remain sceptical though. GRAYER (G3NAQ), for example, notes that none of the claimed connections between thunderstorms and sporadic E “have yet been demonstrated with scientific conviction” [13]. HAWK (*AM and FM Dxer’s resource*) concludes that thunderstorm effects on sporadic E “is a theory that refuses to die” [33]. Dealing with this subject may even result in harsh reactions, from professionals (see, e.g., [43]) and from radio amateurs too (see, e.g., [44]).

The authors of this paper were also sceptical and reluctant in accepting any relationship between thunderstorms and sporadic E activity. The weather and thunderstorms on one hand and sporadic E on the other hand represent very different geophysical phenomena vertically separated by 90 to 100 kilometers in very different regions of the Earth atmosphere. Furthermore, we are not aware of any study demonstrating a convincing correlation between the spatiotemporal occurrence of thunderstorms and 144 MHz sporadic E dx propagation. From this perspective, there is little reason to breathe new life in a theory which is supposed to die but refuses to do so.

In early 2004, one of us (DF5AI) has suggested a data analysis project to compare 144 MHz sporadic data (i.e. dx information from radio amateurs) with *sferic* observations in meteorology (i.e. burstlike radio emissions from lightnings). This suggestion was motived by two reasons: first, by using the benefits from the internet, radio amateurs may easily access meteorological data and sporadic E reports for data analysis purposes; second, he believed the above theory may be settled once and for all by demonstrating the failure of correlation between the data sets. CREMER (DL1DBC) has very soon initiated our project team, has implemented appropriate software tools and has managed the legal requirements for accessing commercial weather data.

To address the most important question of this paper already here: no, we haven’t found clear evidence for thunderstorm-triggered sporadic E events, i.e. we cannot demonstrate a convincing correlation between 144 MHz dx QSOs and sferic data in the 2004 sporadic E season. From this perspective, we may now contribute to the burial of the theory – we won’t. This does not mean, in no case, we consider thunderstorm effects on 144 MHz sporadic E propagation an existing phenomenon which still awaits its discovery. However, in the spectrum of arguments, i.e. between *yes* and *no* (where we have initially started at the *no* position), we were forced to consider a *maybe* too. In our view, there are more details which need to be examined and clarified before closing the case:

- We learnt from scientific resources that thunderstorm effects on the ionosphere are indeed seriously discussed by atmospheric scientists (see chapter 3.1).
- The *GPS/MET radio occultation experiment* shows an impressive statistical correlation between convection processes in the lower atmosphere and electron density irregularities in the E region of the ionosphere (see chapter 3.3).
- *OH nightglow* measurements demonstrate the impact of severe thunderstorms on the mesosphere in 85 kilometers height (see chapter 3.4). We may therefore speculate about similar effects on the ionosphere as well.

- We became aware that our current data analysis method must be possibly considered no appropriate tool, i.e. it has directed our studies in the wrong direction, perhaps. Hence, the above mentioned failure of correlation does not reflect final results because alternative analysis methods need to be considered too but have not been implemented yet (see chapter 4.5).

- Finally, we have found a striking example of sporadic E and sferic data which strongly motivates further analyses in this subject (see chapter 4.4).

Thus, we currently do not feel in a position to form final judgement at this stage of investigation and we wonder if somebody can. This paper therefore documents our current understanding, it addresses open questions and it discusses thoughts and ideas to solve the puzzle. We also wish to encourage fellow radio amateurs to conduct their own studies because we consider this subject a fascinating element in the world of amateur radio propagation studies.

2 Geophysical background information

2.1 Neutrals, ions and electrons in the ionosphere

Less than a thousandth of the atmospheric constituents are ionized in the ionosphere, i.e. neutral particles still dominate the chemical composition even in a fully developed E or F layer. To distinguish between the neutral and charged particles in the ionosphere, scientists generally refer to the *neutral gas*, the *ion gas* and the *electron gas*, respectively (altogether referred to as the *ionospheric plasma*). The ion gas is strongly coupled to the neutral gas, i.e. bulk motions of the neutral particles (e.g. high atmospheric winds) also affect the ion motion because of particle collisions transfering energy and momentum from the neutrals to the ions. The ions, on the other hand, drag the electrons by electrostatic forces, i.e. the dynamical behaviour of the ions (which are controlled by the neutrals) is also present in the electron gas. This is the reason, by the way, why radars may examine neutral particle dynamics in the upper atmosphere by detecting radiowaves scattered by the electrons.

However, the charged particles are also affected by electrostatic fields in the ionosphere and by the Earth magnetic field, i.e. mechanical and electromagnetic forces both control the ion and electron motion. This leads to a large variety of complex physical effects and phenomena. In the F region of the ionosphere (200 to 400 kilometers), the thin neutral atmosphere results in a small ion-neutral collision frequency, i.e. the ion motion is primarily controlled by electromagnetic forces (the so-called $\mathrm{E} \times \mathrm{B}$ drift) rather than particle collisions. In the E region (90 to 110 kilometers), on the other hand, the neutral atmosphere is relatively dense[1] resulting in frequent ion-neutral collisions, i.e. the ion motion is very much affected by particle collisions contrary to the small electrons which still experience the dominating role of electromagnetic forces. In consequence, the ion drift and the electron drift may differ significantly in speed and direction resulting in charge separation associated with electric fields which again lead to various complex

[1] Note that space scientists consider 100 kilometers the height where the Earth atmosphere ends and where space begins. This definition amuses many scientists in ionospheric physics because of the high particle density at E layer heights and even above. In fact, the upper atmosphere between, say 100 and 500 kilometers shows a large variety of phenomena (e.g. winds and tides) which wouldn't exist in a space vacuum and, in consequence, high atmospheric friction prevents satellites from orbiting around Earth at 100 kilometers height.

phenomena in the E region of the ionosphere, e.g. *plasma instabilities* which may cause strong backscatter of radiowaves.

Referring to the above terms, we may argue that thunderstorm related effects originate in the neutral component of the lower atmosphere (which is an obvious statement because the lower atmosphere shows no ion and electron components similar to the ionosphere). Sporadic E, on the other hand, represents a phenomenon of the ion and electron gas around 100 and 110 km height (the term *sporadic E* actually denotes short-term enhancements of the ion and electron density in the E region of the ionosphere). Discussing the possibility of thunderstorm effects on sporadic E, we may therefore speculate about the existence of two independent mechanisms, i.e.:

- A vertically directed *transport process* which transports those “thunderstorm effects” (which we need to define more precisely) from the lower into the upper atmosphere, somehow. Because thunderstorms represent a feature of the atmosphere’s neutral gas component, we may speculate that the E region signature of thunderstorms is initially visible in the ionosphere’s neutral gas component only. Thus, the postulated transport process may be considered an exclusive feature of the neutral atmosphere, we therefore do not need to take the ions and electrons into consideration here.

- A *coupling process* which transforms the thunderstorm’s signature in the neutral gas component into ion and electron density enhancements in order to generate sporadic E layers. This coupling process is effective within the E region of the ionosphere, i.e. we do not need to take large scale transport processes into consideration here (the local neutral, ion and electron drift will play a dominant role though).

2.2 Wind shear theory

Sporadic E layers contain a considerable amount of long-lived metallic ions (i.e. Fe^+ and Mg^+ besides O_2^+ and NO^+, the usual dominant ions at E region height) which are transported efficiently by wind fields, e.g. by tides in the upper atmosphere which exist similar to the tides in the oceans. In fact, the ion motion is very much controlled by the bulk motion of the neutral particles due to ion-neutral collisions as described above. At convergent nulls of the wind speed (see the broken line in **Fig. 2.1**), the ions may accumulate in dense sporadic E layers. However, convergent nulls (i.e. the height-dependent reversal of the wind speed) must not be considered the only wind shear scenario that can create sporadic E layers.

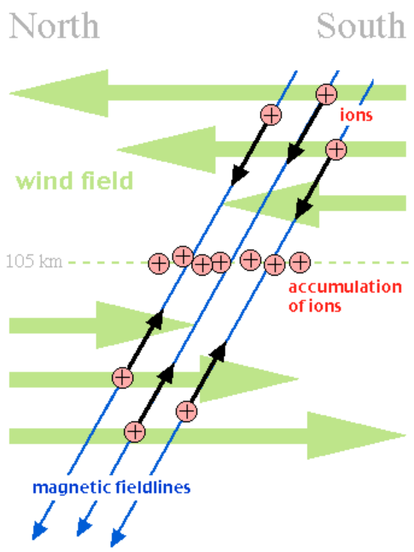

Fig. 2.1. Horizontal wind shear creating a sporadic E layer by wind speed reversal (northern hemisphere). The wind field (green) denotes bulk motions of the neutral particles which collide with the positive ions in the E region of the ionosphere causing momentum and energy transfer from the neutrals to the ions. Being charged particles in a magnetic field, the ions can only spiral upward or downward along the Earth magnetic fieldlines depending on the actual wind direction. Assuming a reversal of the meridional wind direction (wind shear) from south-north to north-south with descending height, the ions may accumulate in a dense sporadic E layer (broken line).

This so-called *wind shear theory* has been developed by WHITEHEAD (1961), AXFORD (1963) and others and has been featured in many amateur radio articles too, see, e.g., [13]. Because the vertical ion velocity is proportional to the cosine of the *dip angle* (i.e. the inclination of the local Earth magnetic fieldlines), it has been argued that the wind shear mechanism is more or less ineffective in polar latitudes where the dip angle is large. It is also ineffective over the magnetic equator where the horizontal magnetic field lines can hardly generate vertical ion displacements. The wind shear model therefore appears applicable only in mid-latitudes[2] and is here accepted as one cause of sporadic E layers.

However, with this model there is now a need to explain the origin of metallic ions[3] and the cause of wind shears in the E region of the ionosphere. In this paper, we cannot discuss the wind shear model's benefits and complications in detail but wish to emphasize that even the accumulation of ions and electrons cannot fully explain the origin of strong backscatter echoes at very high frequencies without taking further considerations into account too (see the discussion further below and a separate paper which will appear on the *Amateur Radio Propagation Studies* webpage [58]).

Nevertheless, the wind shear model can fulfil the requirement of the above mentioned coupling process (see chapter 2.1) because it represents a feature of the neutral atmosphere which can modify the density distribution of the ions and electrons in the E region of the ionosphere, i.e. neutral particle dynamics is identified a driving element in the generation of sporadic E layers.

Note that the wind shear model is only one of many which all wish to explain the generation of sporadic E layers. Another model, for example, refers to *sporadic neutral layers* which were discovered twenty years ago, i.e. layers of sodium and other chemical species "with a thickness between a few hundred meters and several kilometers … in the same height range as ionospheric sporadic E" [16]. Those sporadic neutral layers "are undoubtedly related to sporadic E although, at a given location and time, the presence of one does not necessitate the existence of the other" [16]. These layers also appear associated with atmospheric waves which indeed play an important role in the lower and upper atmosphere.

2.3 Wave phenomena in the Earth atmosphere

Smooth ripples on the sea surface, giant waves breaking on the shore, *tsunamis* travelling at high speed and slowly varying oscillations of global wavelength (i.e. tides) all represent wave phenomena in the oceans. Note that all this waves show different properties and features, are created by different mechanisms, are affected by different parameters and, finally, are described by different mathematical models. Thus, we are not facing the same type of waves at different scale lengths but we are facing waves of different characteristics and of different physical nature – in fact, we may find a large variety of wave phenomena in the oceans.

The Earth atmosphere is often referred to as the *atmospheric ocean*, it shows a variety of phenomena which do not exist in the real ocean though (e.g. charge separation in the ionosphere), we may nevertheless find a large variety of wave phenomena in the atmosphere too. We all know, for example, short wavelength pressure oscillations propagating in the air, i.e. acoustic waves which represent an example of the so-called *internal waves*.

[2] Recent analyses however indicate the model's relevance also in polar latitudes, see [34].
[3] The presence of metal ions in the E region of the ionosphere is interpreted, for example, by meteorits and cometary material deposited in the Earth's upper atmosphere, see, e.g., [14].

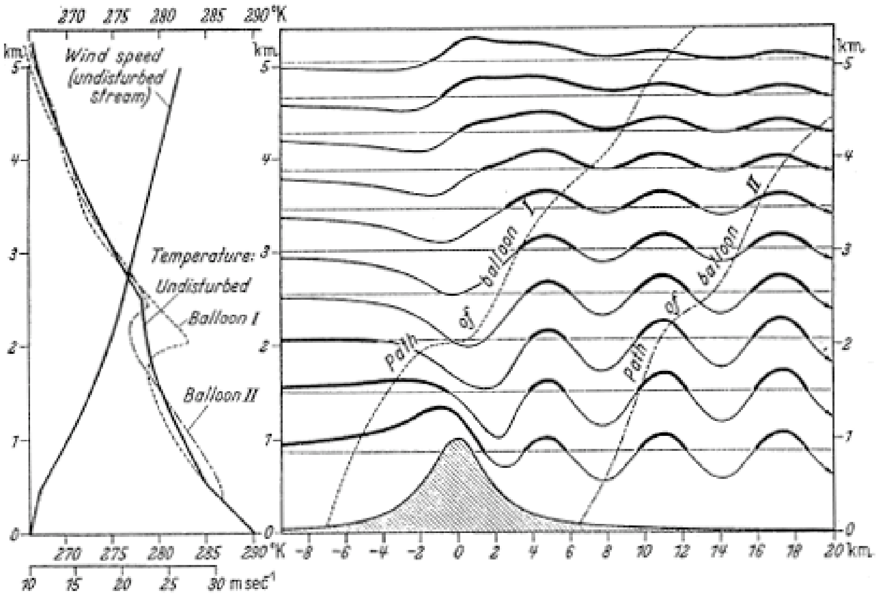

Fig. 2.2. Air flow over a mountain ridge generating a train of *lee waves* aloft. See [21] and the references cited therein.

Another example of internal waves is represented by *atmospheric gravity waves* (AGW), i.e. oscillations of air parcels caused by the lifting force of bouyancy and the restoring force of gravity[4]. Those waves were first described by HINES in a landmark paper in 1960 [1] (see also HINES' personal notes in [12] and the introductions, e.g., in [31] and [32]). Since then gravity waves have been exhaustively studied both experimentally and theoretically by many research groups and it became obvious that gravity waves play a dominant role in atmospheric physics. The so-called *travelling ionospheric disturbances* (TID), for example, were finally interpreted by the ionospheric manifestation of atmospheric gravity waves travelling in the neutral atmosphere, see, e.g., [15].

The nomenclature considers *large scale gravity waves* with periods of 30 minutes to 3 hours and wavelengths of thousands of kilometers, *medium scale AGW* with periods between, say 15 minutes and 1 hour and wavelengths of several hundred kilometers and the *small scale gravity waves* showing periods around 3 and 5 minutes [10]. Gravity waves are generated in various heights and by various mechanisms, e.g. by horizontal air flows streaming across mountains (i.e. the so-called *mountain or lee waves* in the lower troposphere, see **Fig. 2.2**), by convection processes and wind shears in the upper troposphere and lower stratosphere, by *Joule heating* originating from electron particle precipitation in the polar ionosphere during geomagnetic disturbances and by many other atmospheric phenomena too.

2.4 Convectively generated gravity waves

In the scope of this paper, we are in particular interested in convectively generated gravity waves. Severe thunderstorms are associated with strong convection that can create gravity waves in the full range of phase speeds, wave frequencies and vertical and horizontal scales [29] by strong updrafts causing air parcels to overshoot the equilibrium level and breaking through the tropopause causing oscillations by *buoyant disturbances*, see, e.g. [30] and [32]. In

[4] Note that atmospheric gravity waves have nothing in common with ALBERT EINSTEIN's gravitational waves. The term *gravity wave* results from the important role of the mathematical quantity g, i.e. the Earth's gravity acceleration which appears in the mathematical framework describing this type of atmospheric waves. The corresponding German term is, by the way, *Schwerewelle*.

a more elaborated picture, the requirement of a horizontally stratified atmosphere must be taken into consideration in order to describe the generation and propagation of gravity waves properly. This leads to a more or less complex scenario along the interface between the strongly stratified stratosphere and the weakly stratified troposphere, see **Fig. 2.3**.

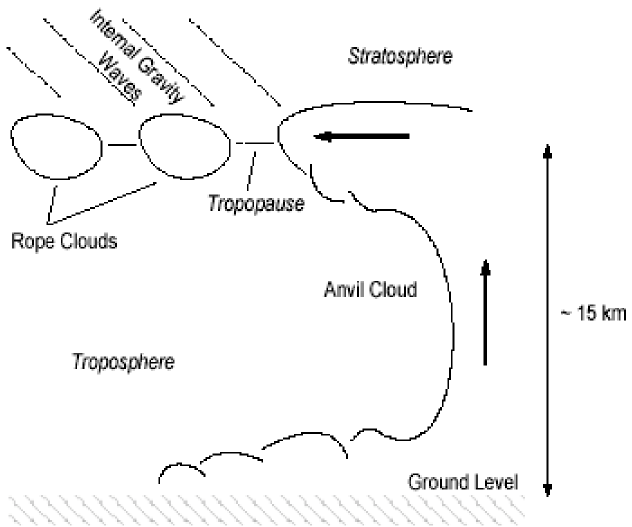

Fig. 2.3. Gravity wave generation along the interface between the strongly stratified stratosphere and the weakly stratified troposphere associated with a tall anvil cloud, from [40].

Gravity waves may also originate from individual *cumulonimbus* which act has transient heat sources of 10 to 30 minutes duration [39]. Those gravity waves have broad frequency spectra, its high-frequency components show large vertical group velocities and are observed only for short duration and at short distances from the convective source. At longer times and at longer distances from the heat source, the wave components show short vertical wavelengths and relatively slow group velocities, i.e. this components are more likely to be observed but their contribution to momentum transfer into the upper atmosphere is less than that of high-frequency waves [39].

In the scope of this paper, gravity waves may be interpreted the vertically directed transport process which has been postulated in chapter 2.1 in order to explain the possibility of thunderstorm effects on the ionosphere. In fact, severe thunderstorms may create convectively generated gravity waves which may travel from the lower atmosphere into altitudes of at least 85 km, see chapter 3.1 and chapter 3.4.

2.5 Sferics and global thunderstorm activity

Thunderstorm discharges represent the main source of atmospheric disturbances in radio communication. On a global perspective, we find 1.000 to 2.000 simultaneous thunderstorms creating 20 to 100 lightning strikes every second [2]. Each strike creates a radio burst (the so-called *sferic*) of 100 microsecond to 1 millisecond duration (t_0). The corresponding mean radio spectrum is more or less constant below $f = 1/t_0$, at high frequencies it decays with 1/f [2].

A useful introduction to sferics and VLF radio observations is given, for example, by NASA's *INSPIRE* project [46] which also distributes software for data recording, filtering and spectral analyses. Triangulating the sferic's azimuth by using low-frequency radio receivers with direction finding capabilities, the lightning's geographical position may be measured quite accurately.

This information is used, for example, by insurance companies, meteorologists and by geophysicists studying dynamical processes in the atmosphere.

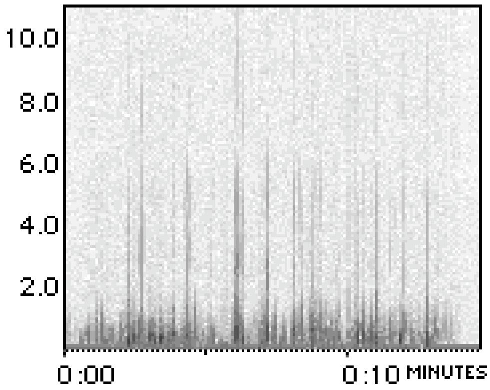

Fig. 2.4. Audio spectrum (zero to 10 kHz) of low-frequency radio bursts emitted by lightnings (sferics). Each of the vertical lines denotes a lightning stroke within a distance of a few hundred to one thousand kilometers from the radio sensor. Adopted from [46].

Fig. 2.5 to **Fig. 2.8** display the lightning activity in tropical latitudes during 2003. The tropics are in particular important in the scope of this paper because intense convection and intense thunderstorms may be best observed in this geographic region. Note that the belt of maximum thunderstorm activity oscillates around the equator during the year in accordance to the annual motion of the sun which is seen, for example, when comparing the thunderstorm activity in the western USA and China with southern Brazil and Argentina.

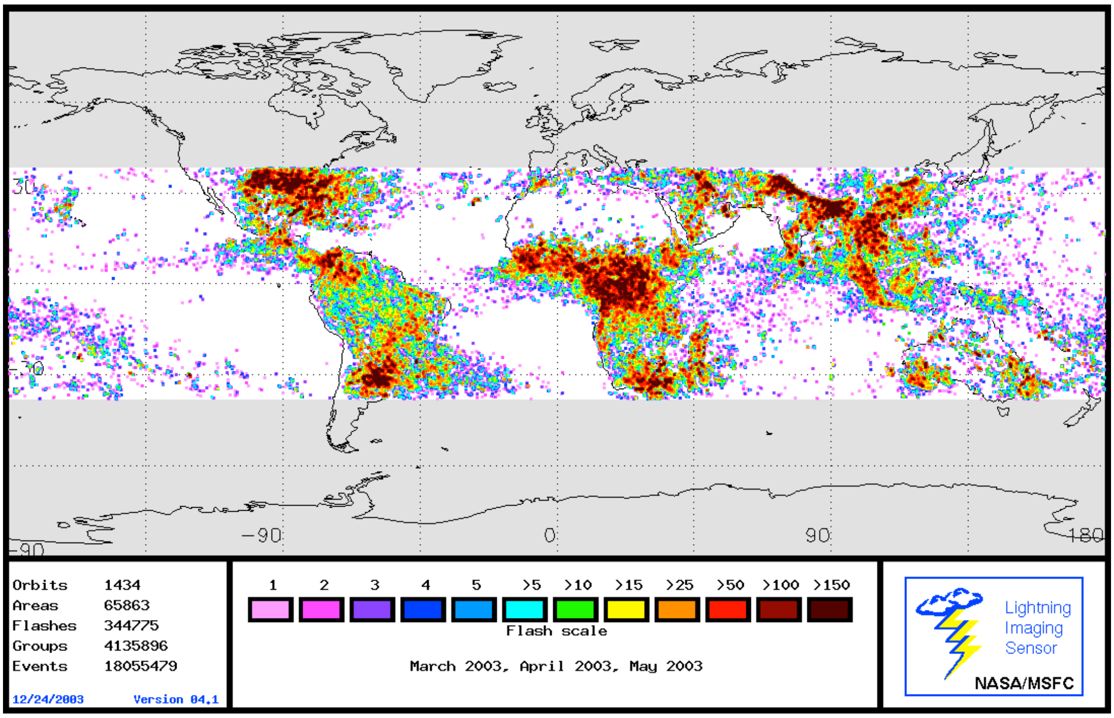

Fig. 2.5. Global lightning distribution during spring 2003 [49].

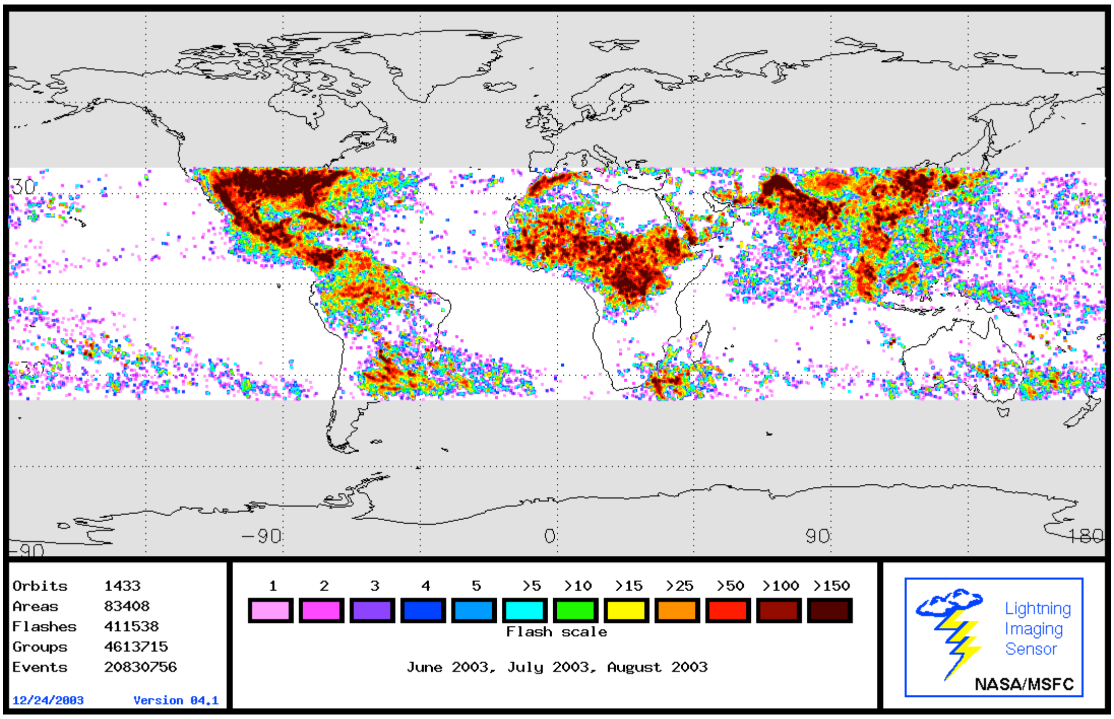

Fig. 2.6. Global lightning distribution during summer 2003 [49].

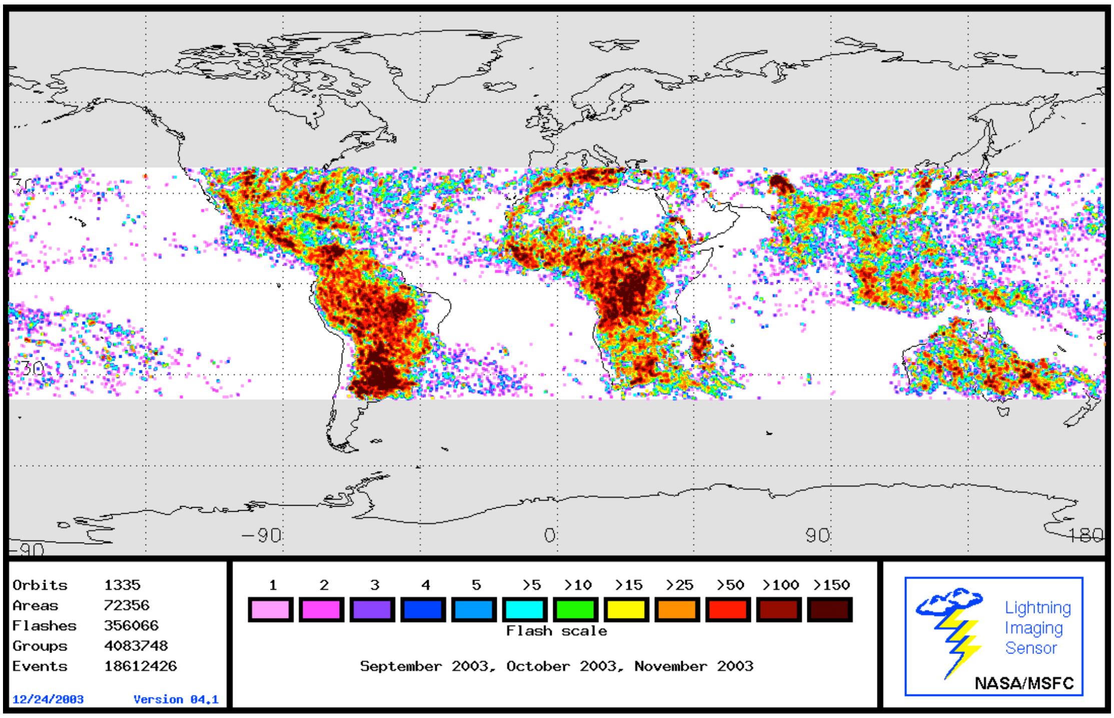

Fig. 2.7. Global lightning distribution during fall 2003 [49].

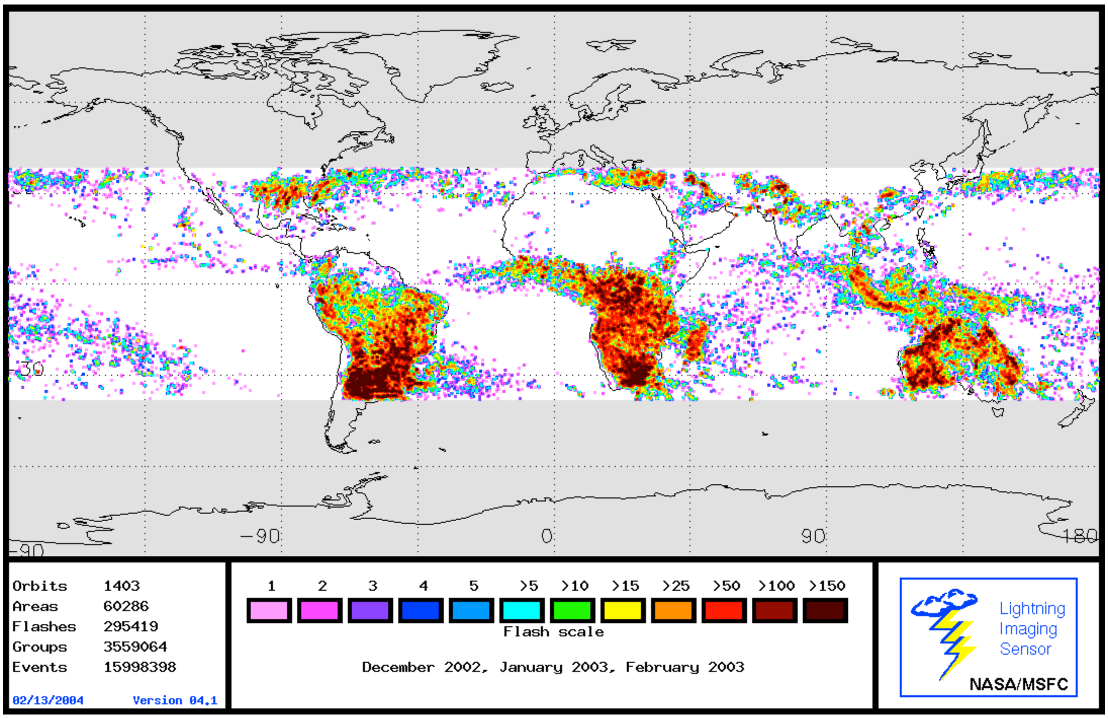

Fig. 2.8. Global lightning distribution during winter 2003 [49].

2.6 Seasonal and latitudinal variations of sporadic E

In paragraph 3.3 we will discuss the GPS/MET radio occultation experiment which can detect layered structures in the upper atmosphere with horizontal scales of around 100 km and vertical scales of a few hundred meters at the Earth's limb [28]. This experiment can therefore provide information on the vertical structure of sporadic E and its seasonal variation. **Fig. 2.9** to **Fig. 2.11** display the vertical distribution of electron density irregularities which are considered a measure for sporadic E occurrence.

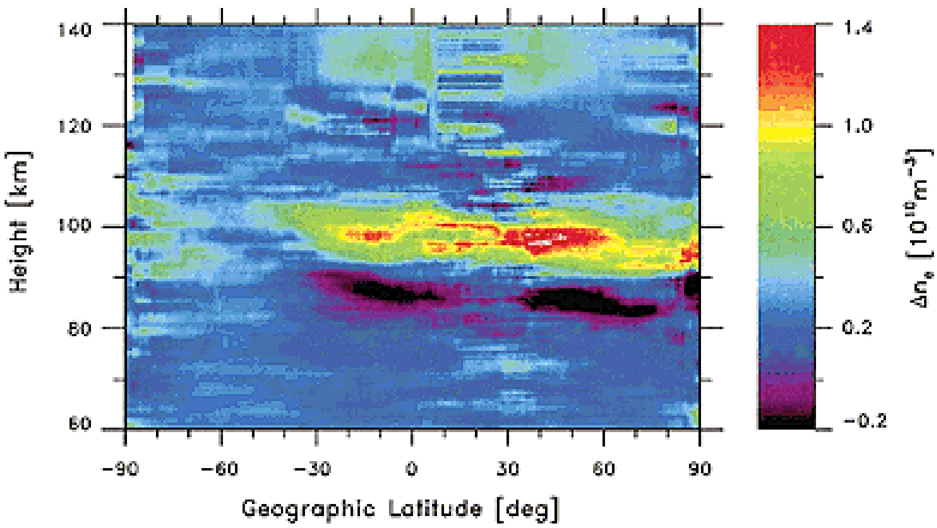

Fig. 2.9. Sporadic E occurrence for June 19 to July 10, 1995, from [28].

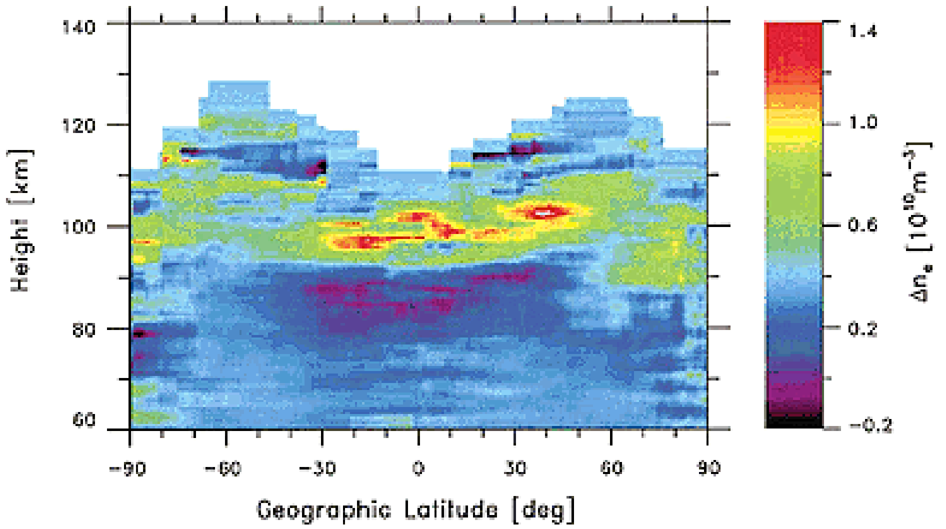

Fig. 2.10. Sporadic E occurrence for October 10-25, 1995, from [28].

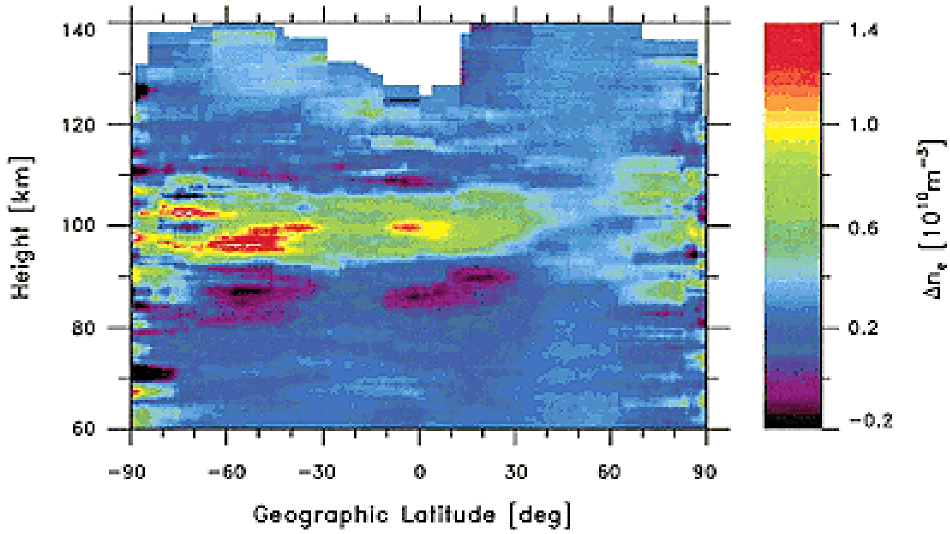

Fig. 2.11. Sporadic E occurrence for Febuary 2-16, 1997, from [28].

Fig. 2.9 displays the data from June/July 1995 with a band of sporadic E activity between 30° southern latitude and 60° northern latitude. The sporadic E height varies between, say 95 and 105 km including intermediate layers separated by around 6 km which are best seen between 0° and 30° northern latitude. HOCKE et al. [28] interpret this feature by the signature of "the vertical wavelength of the atmospheric waves forming these ionization layers." Note also the layers occurring at high geographic latitudes which are interpreted by *Polar Mesopheric Summer Echoes* (PSME) [28]. By comparing **Fig. 2.9** (June/July) to **Fig. 2.10** (October) and **Fig. 2.11** (February), we can see the sporadic E activity moving from northern to southern latitudes during the year similar to the latitudinal variation observed in thunderstorm activity.

3 Possible model of thunderstorm effects on sporadic E

3.1 Assembling the puzzle

The above details represent pieces of a puzzle which may be assembled to a quite complicated model of thunderstorm effects on the ionosphere. The model has been discussed in scientific literature (unfortunately, we couldn't identify the original source though) and even in ham radio, see, e.g., [13]. **Fig. 3.1** is an attempt at visualizing the scenario which links sporadic E activity in the ionosphere to lower atmosphere dynamics. There is perhaps reason not to be fully happy with this schematic diagram but it may demonstrate the principle idea behind the model.

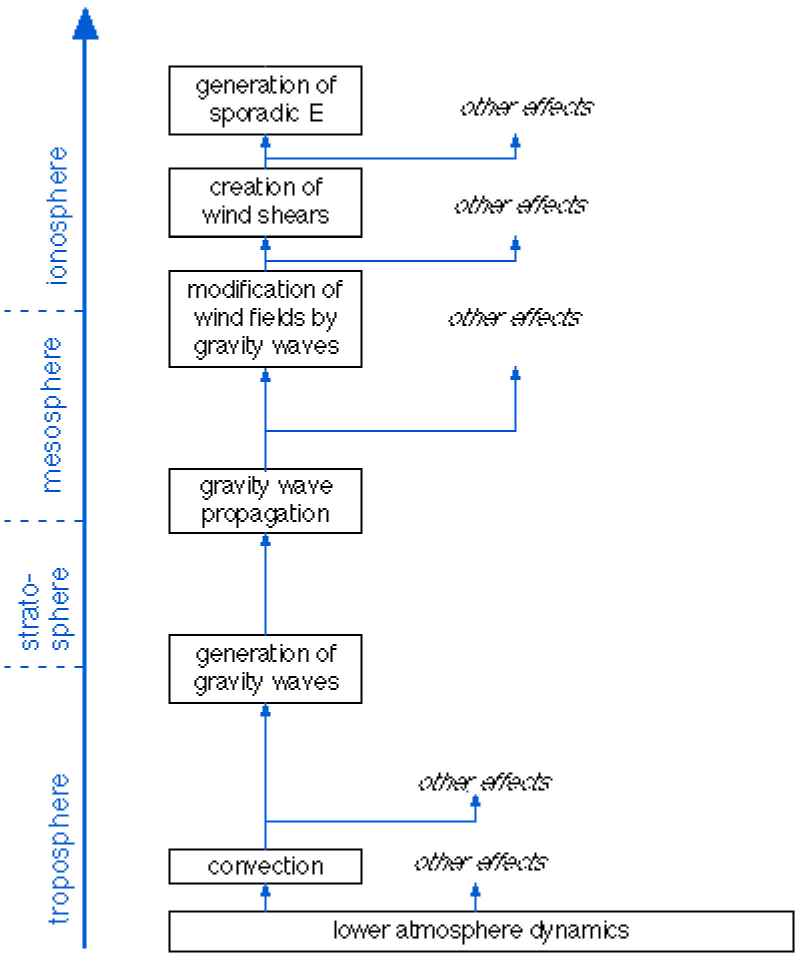

Fig. 3.1. Schematic diagram displaying the possible link between lower atmospheric dynamics and the generation of sporadic E in the ionosphere.

Intense atmospheric convection breaking the tropopause (which separates the troposphere from the stratosphere) is considered the driving element in the generation of those type of gravity waves which in particular attract our interest, i.e. convectively generated gravity waves. These gravity waves may propagate from the lower stratosphere into the mesosphere (this feature is verified by observation, see chapter 3.4) and may even arrive at E region level around 100 kilometers height (which appears verified by statistical analyses, see chapter 3.3). Representing an oscillatory perturbation of the neutral wind field, the gravity waves may support the generation of wind shears which are considered a possible cause of sporadic E. Thus, in this model sporadic E layers are associated with gravity waves originating in the lower atmosphere and propagating into the ionosphere.

This model appears plausible to many scientists but it isn't yet verified in all aspects, as far as we can see. This doesn't appear a surprising result because the study of thunderstorm effects on the ionosphere requires interdisciplinary cooperation between meteorologists and ionospheric scientists which wasn't available in the past. In fact, both disciplines appear to have little in common but this view has significantly changed in recent years. Meteorological model calculations (which were initially restricted to the troposphere) now attempt to model the influence of the middle atmosphere as well, i.e. meteorologists are more and more interested looking at processes occurring above the troposphere. Ionospheric research, on the other hand, has also broadened its scope considerably by taking mesospheric and even magnetospheric effects on the ionosphere into acount too. Many scientists therefore refer to *upper atmospheric physics* rather than *ionospheric physics* to document the change of view.

Before discussing possible thunderstorm effects on the E region of the ionosphere, we will provide some information on thunderstorm effects on the F region which are fully accepted by scientists and which are verified by measurements.

3.2 Thunderstorm effects on the F region of the ionosphere

Considering the F region of the ionosphere, we may indeed find a large variety of scientific resources providing evidence for ionospheric effects triggered by dynamical processes in the lower atmosphere. For example: By analysing the so-called *travelling ionospheric disturbances* (TID) in the equatorial F region, RÖTTGER found an evident correlation between the TID occurence and the tropical rainfall activity which he interprets by convective thunderstorms which cause heavy rainfall and, on the other hand, also cause gravity waves propagating from the lower into the upper atmosphere [6], [9] – those gravity waves finally manifest the TIDs' signature in the ionograms. WHITEHEAD (1971) has even proposed a spatial resonance mechanism (see [7] and the references cited therein) between the plasma drift velocity in the ionosphere and the phase velocity of atmospheric gravity waves resulting in a quasi-periodic modulation of the equatorial spread-F structures associated with a considerable amplification of the TID amplitude.[5]

The evidence that gravity waves initiate equatorial spread-F iregularities comes in particular from observations carried out with the Jicamarca radar located close to the magnetic equator near Lima, Peru (see, e.g. [41]). The radar transmits at 50 MHz with 1 megawatts pulse power from a 300m x 300m phased-array pointing nearly vertically. **Fig. 3.2** shows one of the spectacular events recorded by KELLEY et al. (1981), see, e.g., [11] and [42] and the references cited therein.

Penetrative cumulus convection caused by thunderstorms is however only one source of gravity waves observed in the F region of the ionosphere, i.e. other sources need to be considered as well. In the equatorial zone, the dawn/dusk terminator moves with supersonic speed through the ozone layer and it is believed that this feature may excite gravity waves propagating in a shock-front through the atmosphere. It is also believed that the electrical currents form-

[5] This feature appears also important in studies dealing with transequatorial radio propagation: As a consequence of the spatial resonance mechanism, electron density gradients are produced which may trigger or modulate the generation of smaller-scale spread-F irregularities moving upward in bubbles [7]. Note that plasma bubbles are also considered a possible explanation of transequatorial radiowave propagation on HF and VHF, see, e.g., [3], [13], [26] (RÖTTGER's investigations on TIDs indeed result from his TEP experiments in the 1970s, see, e.g., [4], [5], [8]).

ing the equatorial electrojet (EEJ) may also generate gravity waves due to Joule heating and Lorentz forces. The non-linear breaking of atmospheric tides is also considered a possible source of gravity waves and other sources have been discussed as well. In [6], all this possible sources are analysed in order to explain the above mentioned correlation between the TID occurence and the tropical rainfall activity together with the fact that the majority of TIDs appear to originate from the tropical rain forest located north of the HF radar system which was used in the TID measurements (all this measurements were carried out in Huancayo, Peru). RÖTTGER finally considers penetrative cumulus convection as the most probable source of the medium-scale TIDs observed in the equatorial regions [6].

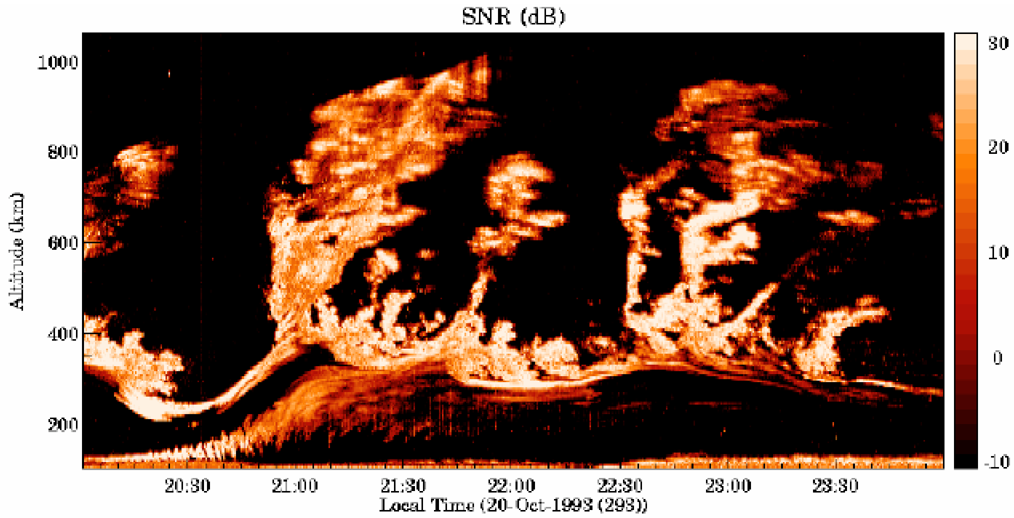

Fig. 3.2. Radar map showing echo traces due to backscatter from equatorial spread-F irregularities at altitudes higher than 200 kilometers, from [42].

In fact, F region effects caused by convectively generated gravity waves have been investigated theoretically and experimentally and represent a generally accepted phenomenon in upper atmosphere physics. Compared to F region studies, the amount of scientific resources dealing with thunderstorm effects on the E region of the ionosphere is however much smaller but, nevertheless, some scientific resources are indeed available, see, e.g., [6] and the references cited therein.[6]

From this perspective, the model discussed in paragraph 3.1 does not appear revolutionary at all – with one exception though: all the scientific scenarios consider the tropical atmosphere because severe thunderstorms are best observed in this part of the world. The above model however adopts this results in order to explain sporadic E events in mid-latitudes. Thus, if radio amateurs can document thunderstorm effects on mid-latitude sporadic E (the June 27, 2004 event may lead in this direction, see paragraph 4.4), ham radio may indeed contribute to ionospheric research.

In the following paragraphs, examples of scientific results are given relevant to the E region of the ionosphere and to the mesosphere underneath, i.e. the GPS/MET radio occultation experi-

[6] RÖTTGER in particular cites studies from DATTA (1971) but, unfortunately, we couldn't access this document (Ind. J. Pure Appl. Phys., 9, 394, 1971) which apparently provides some indication of thunderstorm-triggered sporadic E events in the tropical atmosphere.

ment and optical observation of gravity waves associated with a severe thunderstorm. In chapter 3.5 we will examine the differences between the scientific approach and the radio amateur's perspective in this subject.

3.3 Example 1: E region irregularities over tropical convection zones

3.3.1 The GPS/MET radio occultation experiment

Similar to radio occulation experiments for studying planetary atmospheres in radio astronomy, the GPS/MET program uses the 24 satellites of the *Global Positioning System* (GPS) for active remote sensing of the Earth atmosphere. A receiver aboard of a *Low Earth Orbit* (LEO) satellite tracks the 1575.42 MHz and 1227.6 MHz radio signals originating from GPS satellites occulted by the Earth atmosphere, i.e. the GPS signals travel through the dense layers of the atmosphere along a tangent to the Earth's surface. The LEO satellite can observe more than 500 radio occultations per day which provide information on the vertical structure of the Earth atmosphere in various geographical regions of the world (more information on this experiment is available on the GPS/MET web site [47]).

3.3.2 Analysis of the Febuary 1997 prime-time data

HOCKE and TSUDA [27] have analysed GPS/MET observations of the tropical atmosphere during February 1997, i.e. during the so-called *prime-time* where the encryption of the GPS signals (antispoofing) was turned off to support best data quality. The results are considered relevant to this paper because intense solar radiation in the tropics cause strong cumulous convections which excite various atmospheric waves, atmospheric tides and gravity waves transporting energy and momentum from the lower into the upper atmosphere [37].

Fig. 3.3 displays the GPS/MET results summarized over ten days between 5° and 25° southern latitude as a function of geographical longitude. The lower panel (e) shows the number of occulation events analysed. Panel d displays the Earth surface topography, i.e. the black peaks correspond to high mountains in Brazil (80° W), Africa (40° E) and Indonesia (120° E), respectively. Curve c denotes the average water vapor pressure in the troposphere between 4 and 6 km altitude. Note that water vapor clouds at higher tropospheric altitudes indicate an increase of tropical convection, i.e. this panel provides a measure of the intensity of tropical convection and convectively generated gravity waves. Panel b shows the relative temperature variance $\left(\Delta T/\overline{T}\right)^2$ in the stratosphere where the solid and dotted line refer to the height of 22-28 km and 32-38 km, respectively. These curves may be considered a measure for gravity wave activity modulating the stratosphere's background temperature. Finally, the maximum of the small-scale fluctuation amplitude (vertical scale less than 7 km) of electron density between 80 and 120 km altitude is displayed in panel a.

The results provide an impressive indication of E region irregularities correlating with dynamic processes in the lower atmosphere. The high correlation between the data curves may be interpreted by enhanced gravity wave activity in the lower stratosphere (22-28km, see the solid line in panel b) associated to areas of strong tropical convection in the troposphere (4-6 km, see panel c). The correlation between gravity waves (panel b) and E region irregularities (panel a) suggests "convergence of electron density occuring due to the wind shear, associated with gravity waves and geomagnetic effects" [37].

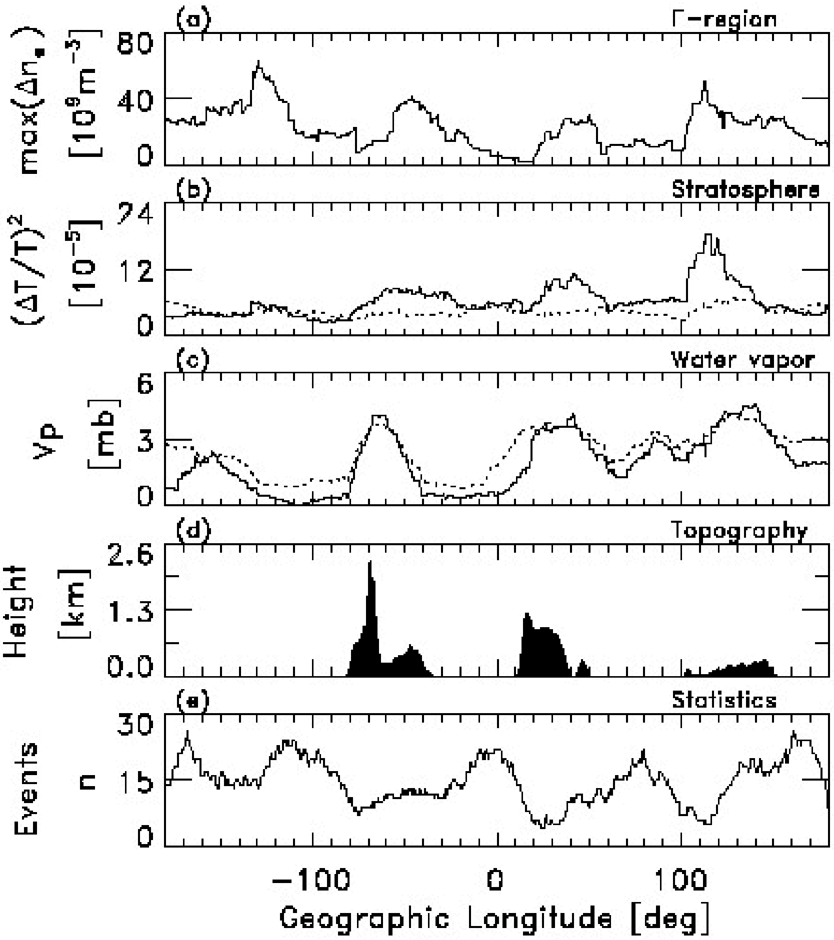

Fig. 3.3. Various parameters of the southern tropics as a function of geographical longitude during GPS/MET prime-time in February 1997, from [27]. See text for more details.

However, referring to the dotted line in panel b, we find little gravity wave activity in 32-38 km altitude and the correlation with all the other curves is rather low, in fact. Similar changes, by the way, are also reported from GPS/MET data observed at northern mid-latitudes, i.e. high gravity wave activity in the lower stratosphere around 25 km altitude but low activity around 35 km [36]. In [27], this feature is considered an indication of gravity waves created by tropospheric rather than stratospheric sources which raises an important question in our view: attributing the generation of sporadic E to gravity waves travelling from the troposphere (or, alternatively, from the lower stratosphere) into the E region of the ionosphere, we would expect detection of gravity waves at all intermediate heights which is evidently not the case here. Thus, gravity wave activity around 25 km height shows correlation with E region irregularties but gravity wave activity around 35 km doesn't – this feature is difficult to understand in our view (in chapter 3.3.5 we will discuss more open questions in the interpretation of the GPS/MET data). However, GPS/MET data can also provide data examples in which sporadic E is clearly correlated with gravity wave activity in the lower and in the upper stratosphere as well (see, e.g., figure 7 in [37]).

3.3.3 Orographic effects

Another important feature of the GPS/MET data addresses the generation of sporadic E associated with orographic features, i.e. high mountains acting as obstacles in the low atmospheric air flow. The distribution of gravity wave activity (see panel b in **Fig. 3.3**) shows in particular maxima over mountain ridges (see panel d and also figure 7 in [37]) which suggests "wave generation by the interaction of surface wind with topographical obstacles" [36]. However, the results communicated in [36] (which are not shown here), also mentions significant gravity wave activity in the lower stratosphere over the Atlantic Ocean and Eurasia which cannot be explained by orographic effects, obviously (see also the discussion in chapter 3.3.5).

Radio amateurs have also discussed the geographical correlation between sporadic E and high mountains but were forced to accept that orographic effects can hardly explain the geographical distribution of sporadic E in Europe, see, e.g. [13]. GRAYER, G3NAQ, therefore concludes that the effect of mountains on the generation of sporadic E – assuming it would exist – is “clearly rather small” [13]. Thus, GPS/MET data and amateur radio observations provide the same inconsistent picture, i.e. examples in which sporadic E appears correlated to mountain ridges and, on the other hand, counter-examples which do not support this assumption at all.

3.3.4 Geographical distribution of E region irregularities

Fig. 3.4 shows a summary of electron density irregularities in the lower ionosphere observed by GPS/MET in 1995 and 1997 (compare to **Fig. 2.9** to **Fig. 2.11** on page 11 and 12, respectively). Note, in particular, the observations over southern Spain and north-western Africa. Unfortunately, no data is available showing all the parameters similar to **Fig. 3.3**, i.e. we cannot compare the sporadic E activity in **Fig. 3.4** neither with water vapor pressure data in the troposphere nor with temperature variances in the stratosphere.

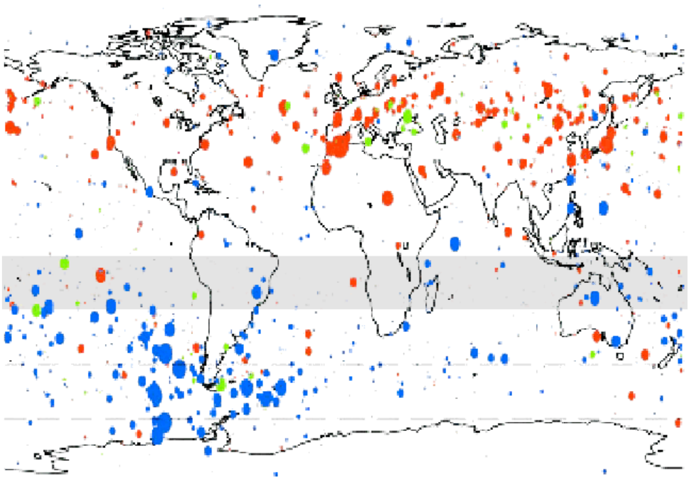

Fig. 3.4. Electron density irregularities observed by GPS/MET [37]. Each dot indicates a radio occultation event, its radius denotes the corresponding electron density enhancement at 105-110 km height. Red dots are observed in June/July 1995, green dots are in October 1995 and blue dots are in February 1997. The gray band comprises the data apparently used in **Fig. 3.3**.

3.3.5 Comments

The data displayed in **Fig. 3.3** is apparently identical to the blue dots located in the gray band of **Fig. 3.4** because both figures refer to prime-time data from February 1997. Thus, we may compare the data within the gray band of **Fig. 3.4** to the features displayed in **Fig. 3.3**. Doing so, we are facing a couple of questions which we currently cannot solve at all.

- We would expect, for example, full consistency between **Fig. 3.3** and **Fig. 3.4** with respect to the longitudinal distribution of electron density irregularities, i.e. between the peaks of the quantity $\max(\Delta n_e)$ in panel a of **Fig. 3.3** and the horizontal distribution and size of the blue dots within the gray band of **Fig. 3.4**, respectively. However, no such conformance becomes visible to us in the data.

- The same is true when considering the orographic features suggested by panel d in **Fig. 3.3** because we cannot identify appropriate counterparts in **Fig. 3.4**, i.e. the blue dots do not appear accumulated in geographical regions in which high mountains exist.

- Furthermore, in accordance to **Fig. 3.4** the most intense electron density irregularities are found around the southern tip of South America which does not indicate any special importance of high mountains (e.g. the Andes) contrary to panel d in **Fig. 3.3**. In our view, the massive concentration of blue dots around Tierra del Fuego (50° southern latitude) simply reflects the high season of sporadic E occurrence in the southern hemisphere around February.

- In fact, considering all data in **Fig. 3.4**, the distribution of data points seems to reflect the known latitudinal variance of sporadic E during the year without showing centers of activity in the tropical regions which, in our view, is inconsistent with the results shown in **Fig. 3.3**.

Thus, words of caution appear justified to prevent incorrect conclusions because we currently cannot understand **Fig. 3.3** together with **Fig. 3.4**. In our view, tropospheric convection and, in consequence, gravity waves may indeed play an important role in the generation of sporadic E (which is supported by the impressive results shown in **Fig. 3.3**) but, on the other hand, we are reluctant to interpret all sporadic E occurrences by gravity waves without considering alternative mechanisms and processes too (which appears supported by **Fig. 3.4**, in our view).

It is also worth to mention that the term *sporadic E* is used synonymous for *electron density irregularities* and vice versa in [27] but it is doubtful that the quantity $\max(\Delta n_e)$ indeed provides a direct measure of sporadic E activity as described by 144 MHz radio amateurs. Note that the maximum amplitude of $\max(\Delta n_e)$ is less than $80 \cdot 10^9 m^{-3}$, see panel a in **Fig. 3.3**, which corresponds to only one hundredth, or so, of the total electron density in a fully developed E layer insufficient to explain sporadic E propagation on very high frequencies. In [28], the term sporadic E is considered “a name convention in the science community which does not fit to the thin ionization layers observed in the D, E and F1 regions” – this statement indeed indicates that the term sporadic E does not address identical subjects when applied in GPS/MET data and in amateur radio, respectively.

We also got the impression that the analysis and geophysical interpretation of the GPS/MET results is still a matter of dynamical development and improvement (see, e.g., [48]). However, it is generally accepted that radio occultation experiments indeed bear high potential not only in the understanding of the weather and the Earth climate but also in studying atmospheric wave phenomena and processes affecting the upper atmosphere [25]. In the scope of this paper it means: we do not consider the GPS/MET data clear evidence for sporadic E dx propagation generated by thunderstorms but a valuable indication which motivates further analyses in this subject.

3.4 Example 2: Thunderstorms generating sprites and gravity waves

In around 85 kilometers height, we may find the OH nightglow layer created by vibrationally excited hydroxyl (OH) in the nighttime mesosphere as a result of a series of chemiluminescent reactions between odd oxygen and odd hydrogen species [38]. Gravity waves may modulate this infrared airglow in the night sky by generating ripples in the airglow distribution. Thus, by using suitable CCD cameras (see, e.g. [23] and [24]), the signature of gravity waves may be observed even by optical instruments. In this paragraph, we will discuss a spectacular event documented by the *University of Alaska* when studying a severe thunderstorm over Nebraska on August 18, 1999.

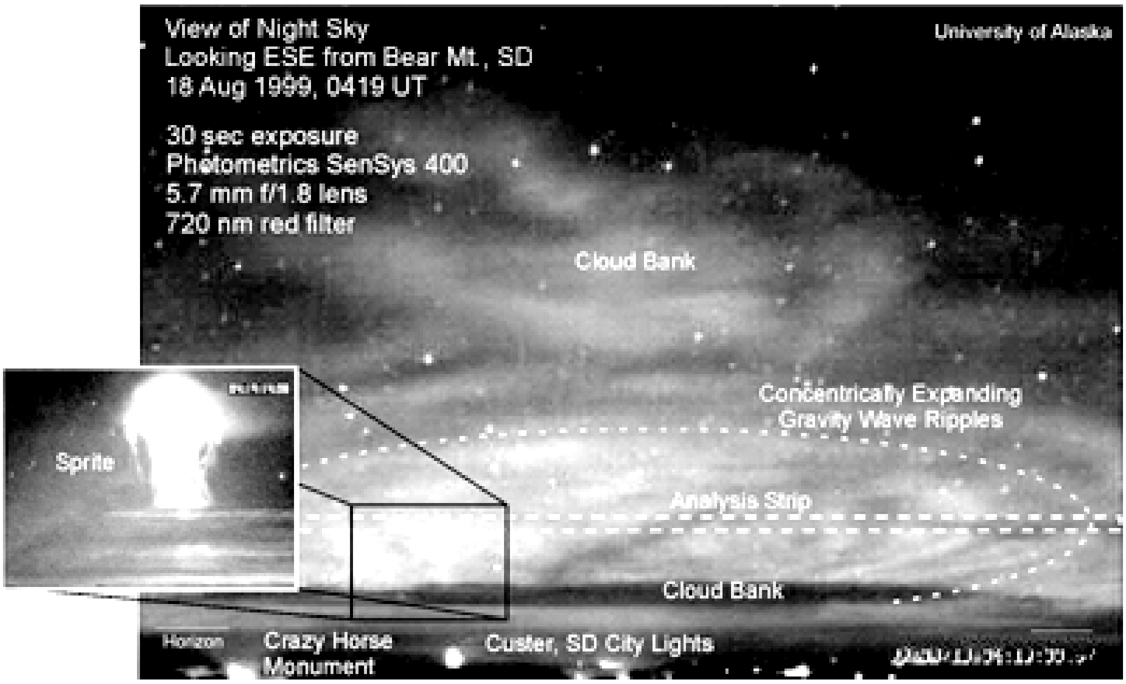

Fig. 3.5. Concentric ripples observed in OH airglow caused by thunderstorm triggered gravity waves propagating vertically to a height around 85 km. The sprite on the main page was also recorded by a separate CCD camera as shown in the inlet. [38]

As part of a scientific campaign, SENTMAN et al. performed OH airglow observations at a U. S. Forest Service fire observation tower on Bear Mt., South Dakota. In this particular night, a very intense thunderstorm moved from south-central Nebraska to eastern Nebraska/Iowa along a storm track perpendicular to the observation line of sight. **Fig. 3.5** shows one of the CCD images displaying the night sky above the city lights of Custer (note also the display lights of the *Crazy Horse Monument* in the lower left corner). The inlet shows a large *sprite* in high resolution, i.e. one of this recently discovered lightning discharges extending from the lower atmosphere into high altitudes at 50 to 90 kilometers (see, e.g. [17] and the references cited therein). The hazy elliptical feature in the lower central part displays the rippled signature of a gravity wave modulating the OH airglow. Analysing the full video sequence, “these elliptical features exhibit a distinctive outward propagation pattern originating from a well defined center” [38]. Mapping this features onto the horizontal plane and comparing the findings to the corresponding GOES weather map of the Nebraska storm, SENTMAN et al. found strong correlation between this gravity wave and the underlying thunderstorm [38].

Contrary to the GPS/MET data which reflects statistical results, this is an example of an explicit thunderstorm event (lower atmosphere) that causes gravity waves in the middle atmosphere in a height around 85 kilometers. This example demonstrates in particular that thunderstorm effects must not be considered restricted to the troposphere and stratosphere but may also affect higher altitudes more or less close to the E region of the ionosphere.

3.5 Scientific investigations versus ham radio studies

How do the speculations on thunderstorm effects on 144 MHz sporadic E propagation relate to the scientific results discussed above? First of all, we need to clarify the meaning of the terms *thunderstorm effects* and *144 MHz sporadic E*, respectively. From our perspective, the actual meaning of the term *thunderstorm effects* remains more or less unclear in ham radio discussions, i.e. all this speculations do not specify what property may actually support the generation of sporadic E. In fact, many radio amateurs seem to consider lightnings the driving force in the generation of sporadic E. This assumption is certainly not justified and has possibly contributed to the many sceptical comments on thunderstorm effects on 144 MHz sporadic E propagation. We may also find speculations considering those *sprites* and *jets* a possible trigger in the generation of sporadic E but all this recently dicovered phenomena (see, e.g., [17] and the references cited therein) do not yet allow far-ranging conclusions at this early stage of investigation.

We are willing to admit that even our project's working title is perhaps misleading because thunderstorms do certainly not affect sporadic E layers directly. All what we may expect is the above mentioned *chain of cause and effects* (see chapter 3.1) with thunderstorms at one end and sporadic E dx propagation at the other end of the chain and a large variety of geophysical phenomena in between. Thus, thunderstorms may only be considered a tracer indicating dynamical processes in the lower atmosphere which may initiate a sequence of atmospheric effects that may possibly lead to sporadic E layers.

The term *sporadic E* needs to be clarified as well. In the GPS/MET data and in ham radio, the term sporadic E apparently denotes different subjects, i.e. E region irregularities on one hand and 144 MHz long distance communication on the other hand (see the discussion in chapter 3.3.5). It is important to note that electron density irregularities in the E region of the ionosphere do not necessarily support forward scatter of radio waves on very high frequencies. Also, the presence of a sporadic E layer (i.e. enhanced electron density around 105 km) does not necessarily indicate the availability of sporadic E dx QSOs in VHF.

In fact, forward scatter of VHF radio waves must not be considered identical to ionospheric skip propagation similar to short radio waves below 30 MHz because such high electron density does not exist in the Earth's ionosphere. 144 MHz sporadic E QSOs are associated with complicated plasmaphysical processes which create various wave phenomena in the E region of the ionosphere capable to support *coherent scatter* of VHF radio waves at high field strengths. Contrary to the simple model of radio waves reflected by an ionized media (which applies in short wave propagation), electrostatic fields in the E region, the Earth magnetic field and, in particular, the drift motion of the electrons and ions and particle collisions need to be considered in order to explain this scatter mode properly.

Considering the scientific material from above in the scope of this paper, we must therefore conclude that scientists and VHF radio amateurs are discussing similar but no identical subjects. Hence, the scientific material can provide valuable information but cannot prove what we are looking for, i.e. a possible link between thunderstorm activity and long distance QSOs in 144 MHz. **Fig. 3.6** makes an attempt at integrating the scientific results and ham radio speculations in a framework. The yellow area denotes the scientific model already discussed in **Fig. 3.1**, i.e. it shows the possible link between dynamical processes in the lower atmosphere and the generation of sporadic E irregularities. The green area, on the other hand, considers those additional topics which were introduced by VHF radio amateurs, i.e. 144 MHz sporadic E and sferic activity, respectively. This additional elements are attached to both ends of the scientific model which we have called *chain of cause and effects* in chapter 3.1. Although this chain of cause and effects isn't yet verified in all aspects, radio amateurs apparently wish to extend this chain beyond its original limits.

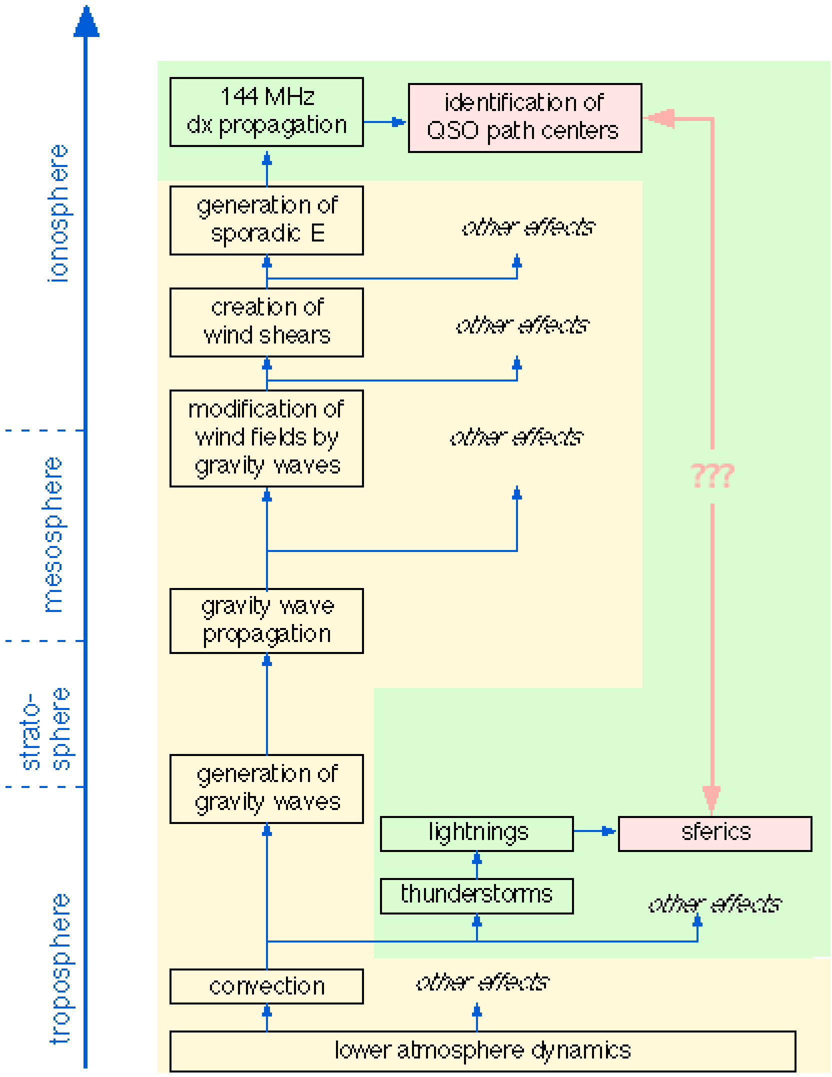

Fig. 3.6. Schematic diagram visualizing the radio amateur's approach to thunderstorm effects on ionospheric sporadic E. The yellow area denotes the scientific model, the green area denotes additional elements discussed by radio amateurs.

Fig. 3.6 may in particular indicate the principle difference between the scientific approach and ham radio studies: scientific instruments can investigate each individual chain link, may compare adjacent links and may analyse the entire chain of cause and effects systematically. Radio amateurs, on the other hand, can only address both ends of this chain, i.e. all the processes and mechanisms in between remain unknown to us. Because sporadic E events and sferic events are found in opposition on both ends of this chain, we can hardly expect strong correlation between this two features. In fact, if such a strong correlation would exist, thunderstorms would influence sporadic E dx propagation considerably which is not the case, obviously. Also, considering sferic observations a tracer of thunderstorms and thunderstorms a tracer of the dynamical processes which may create gravity waves, we must conclude that sferic observations can only provide a highly indirect measure of the geophysical phenomena we are actually interested in.

Thus, radio amateurs are challenged by a complicated problem when exploring the possibility of thunderstorm effects on 144 MHz sporadic E propagation: our situation is very much described by a pilot navigating in an unknown airspace without reliable navigational instruments. Therefore, no guarantee is given that we may close this case in amateur radio propagation studies successfully, in one or the other direction.

4 The thunderstorm analysis project

4.1 The project team

The thunderstorm analysis project was launched in early 2004 and comprises six team members: CREMER, DL1DBC, develops and operates the data acquisition and data analysis software tools, maintains the data base and manages contacts to commercial weather information services providing actual sferic data. LANGENOHL, DK5YA, contributes sporadic E observations resulting from his European *sporadic E summary reports* [60] and he organizes access to weather information archives. MUNTERS, PE1NWL, operates the *DXrobot* internet service [61], i.e. he can access the latest sporadic E information communicated by radio amateurs. The interconnection between his and CREMER's computer system exchanges data with short reaction times, see below. SAMPOL, EA6VQ, contributes his experience in the analysis of 144 MHz sporadic E openings and provides data and results originating from his studies [62]. KRAFT, DL8HCZ, editor of the *Dubus* and *Funktelegramm* magazines, analyses ham radio publications relevant to this project and investigates the details of ham radio observations which need to be analysed in more detail. GRASSMANN, DF5AI, communicates the latest project status reports on the *Amateur Radio Propagation Studies* web site [58] and manages the contacts to the scientific community.

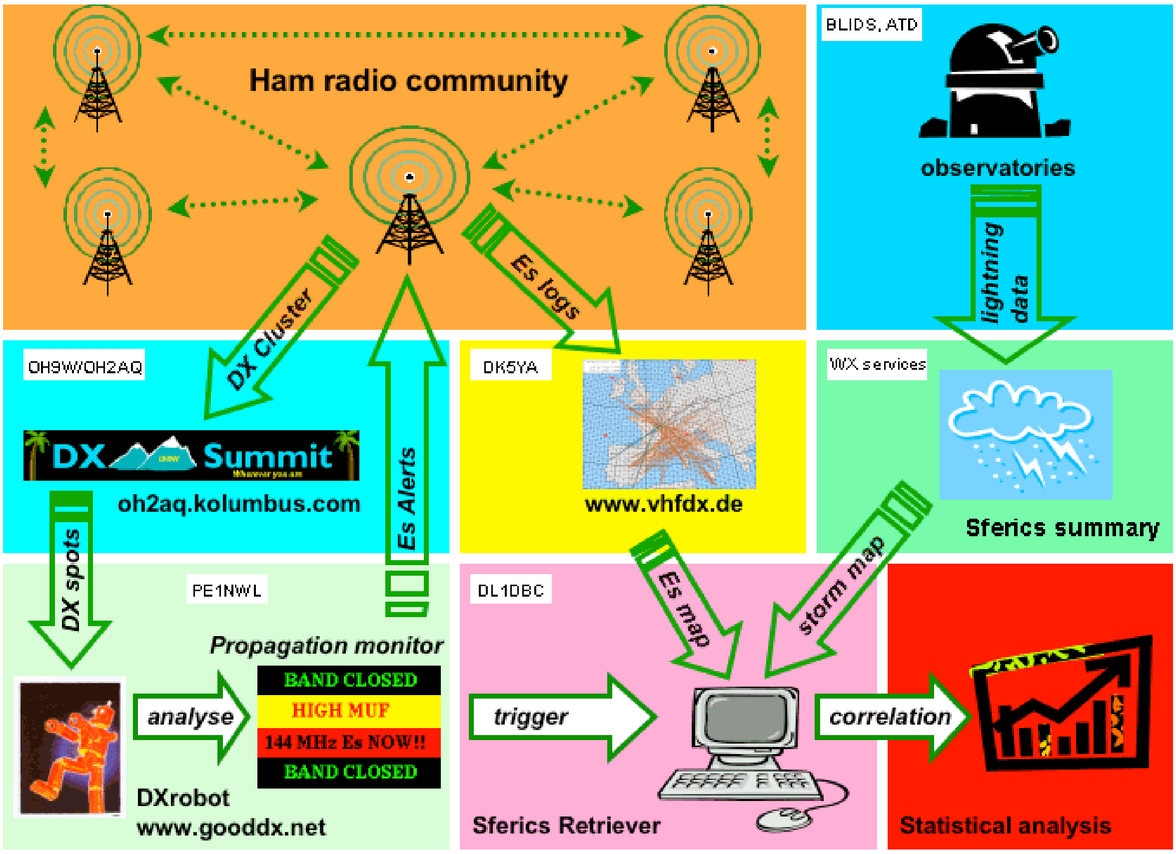

Fig. 4.1. Schematical diagram of the data flow in the thunderstorm analysis project.

4.2 Data acquisiton and data analysis

4.2.1 General overview

The project benefits from existing infrastructure in the meteorological community and from various alerting and analysis services in ham radio, see **Fig. 4.1**. Because of the high geographical density of VHF ham radio stations in Europe, radio amateurs can hardly fail detecting at least the majority of 144 MHz sporadic E events in the European sector.

Thus, the ham radio community (orange box) provides the raw data by uploading dx information to the OH9W/OH2AQ *dx cluster network* and by submitting logbook information, for example, to DK5YA's *sporadic E summary service* in the internet [60] (yellow box). The dx cluster information is permanently scanned by PE1NWL's *DXrobot* service [61] which distributes dx alerts to emails, mobile phones and pagers (green box). This service also triggers DL1DBC's *Sferics Retriever* software which now downloads actual sporadic E and sferic data (pink box) from the internet. Thus, all relevant data concentrates on DL1DBC's computer system which finally launches the data analysis and graphical post processing routines (red box).

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4.3.2 Sferic data

The sferic data is distributed by various weather services in the internet, see, e.g., the *Wetterzentrale* [51] and the *WetterOnline* [50] service which compile and analyse radio observation data, for example, from the *European Cooperation for Lightning Detection (EUCLID)* [53], from the *Blitz Informationsdienst von Siemens (BLIDS)* [52] or, alternatively, from the British *Tornado and Storm Research Organisation (TORRO)* [54] which is a privately supported research body using data from the *ATD system* operated by the *UK Met Office* [55]. The BLIDS service, for example, operates sixty low-frequency radio sensors in Germany, Switzerland, France and neighbouring contries, the British service operates sensors in Cornwall, on the Shetland Islands and in overseas locations such as Iceland, Finland, the German North Sea coast, Gibraltar and Cyprus, respectively. The *British Met Office* specifies the geographical accuracy to be around five kilometers in the UK and between 20 and 100 kilometers in the rest of Europe. Before using sferic information from the internet, there is an important need to examine the service's individual data coverage carefully. The *Wetterzentrale* service, for example, provides data only for one half of every hour which affects data analyses considerably.

4.3.3 Automatic data retrieval systems

All sferic data is directly retrieved from the relevant internet sources which generally reflects a just-in-time effort in order to take the data's transient nature into consideration. The data retrieval is maintained by a TCP client software which is triggered by PE1NWL's DXrobot service [61]. The DXrobot comprises two modules, i.e. a front end TCP client searching data patterns in the OH9W/OH2AQ dx cluster network [56] which might indicate an actual sporadic E dx event and, on the other hand, an alerting system which addresses radio amateurs subscribed to the DXrobot's mailing list. MUNTERS has also introduced a status table denoting *quiet*, *high MUF* (i.e. high *maximum usable frequency*) and *E-skip alert* propagation conditions, respectively.

During the so-called *idle mode*, CREMER's Sferics Retriever software reads the DXrobot's status table every 15 minutes. In the case of a high MUF warning, the Sferics Retriever software accesses the DXrobot's status table every five minutes. If the E-skip alert has been received, the software activates its individual alert status which now addresses the internet weather services to transfer actual sferic data into a local SQL database. The DXrobot also terminates the Sferics Retriever's alert status by indicating the end of the actual band opening which returns the Sferics Retriever software to the idle mode. The Sferics Retriever software and all the other tools are written in the *Perl* programming language and are operated in a LINUX server environment.

4.3.4 Sporadic E dx information

The team members LANGENOHL (DK5YA) and SAMPOL (EA6VQ) both operate web sites which compile and analyse VHF dx information from radio amateurs for many years (see [60] and [62], respectively). Their data was used in our studies when analysing 144 MHz dx QSOs from the 2004 sporadic E season. All data originates from the European community of VHF radio amateurs which represents a large number of radio operators submitting actual observation reports by uploading station logbooks and dx summaries.

However, ham radio logbooks show a large variety of data formats, i.e. the dx information cannot be uploaded into a database without a considerable amount of data pre-processing in order to identify, for example, the radio callsigns, UTC information, geographical coordinates (i.e. QTH locators), signal reports and other type of information. CREMER has therefore developed a Perl script which can read more than 97 percent of the dx information automatically, i.e. only the remaining three percent still require manual editing. Without this software tool, we wouldn't be able to manage our studies in reasonable time because of the large amount of dx information that needs to be analysed.

4.3.5 Current data analysis tools

In the setup phase of the project, we have focused on geographical analyses using sferic distribution maps published in the internet (we have in particular used material from the *WetterOnline* service [50]). Note that the internet resources do not provide numerical information on the sferics' geographical position, i.e. those maps must be used "as they are" which limits our flexibility in graphical visualization considerably. The midpoints of the above mentioned sporadic E QSOs are therefore plotted on the original sferic data maps. We however plan to implement a much broader spectrum of analysis tools in the future, one of this tools is discussed in chapter 4.5.

Fellow radio amateurs wishing to implement their own data analyses are advised to examine the internet maps carefully because the majority of internet weather services does not provide sufficient information on the actual map projection. Calculation routines and programming code may be found in various internet resources, see, e.g., [18] and [57]. We in particular consider the *General Mapping Tools* [45] very useful which are distributed by WESSEL and SMITH, University of Hawaii, under the *GNU General Public Licence* (see [45] and the references cited therein.)

4.4 First results obtained during the sporadic E season 2004

In May/June 2004, the setup went operational but, unfortunately, we were facing were few sporadic E dx events during 2004. However, we found an example of sporadic E activity which indeed attracts our interest in the scope of this paper, i.e. the sporadic E opening on June 27, 2004.

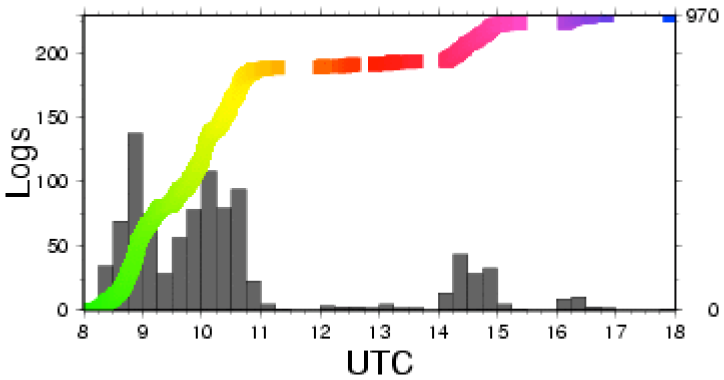

Fig. 4.2. The June 27, 2004 sporadic E opening. The vertical bars denote the number of two-way dx QSOs per 15 minutes (left scale), the line denotes the accumulated number of QSOs during the day (right scale).

Fig. 4.2 displays the distribution of 144 MHz dx QSOs during that day indicating various phases of sporadic E activity between 08 and 17 UTC. By calculating the geographical center of the corresponding dx QSOs, we may estimate the location of the actual scatter volume in the E region of the ionosphere, see **Fig. 4.3**. In the early hours (i.e. between 08 and 09 UTC), the centers of sporadic E forward scatter were all located in a wide area in the Adriatic Sea (green) which has then moved towards northern Italy (yellow). In the afternoon, the geographical distribution of sporadic E positions shows a remarkable feature, i.e. a band of activity extending over more than 1.500 kilometers from southern France to eastern Germany (red, purple) within a corridor of 200 to 400 kilometers width.

Referring to the sferics data distributed by the *Wetteronline* service [50], we found little sferic activity in central Europe between 08 and 12 UTC. No thunderstorm activity was in particular available close to the green and yellow scatter area, i.e. this sporadic E openings are definitely not associated with any thunderstorm effects.

However, beginning 12.30 UTC the sferic activity has permanently increased and some areas show more than 60 sferic events per 30 minutes between 16 and 17 UTC (a localized spot in central France even displays more than 80 sferics/30min which indicates severe thunderstorm activity). Surprisingly all these sferic events are more or less perfectly aligned along that red and purple band of sporadic E activity, see **Fig. 4.4** (readers may visit CREMER's webpage [59] which provides an animated sequence of this scenario).

We are reluctant to cite this feature as evidence for 144 MHz sporadic E propagation triggered by thunderstorms because we cannot exclude an accidental occurrence of sferics and sporadic E activity in this example (in fact, central European thunderstorms indeed appear to be aligned from south-west to north-east quite often in summertime). Nevertheless, we consider this a striking feature which motivates further analyses in this subject.

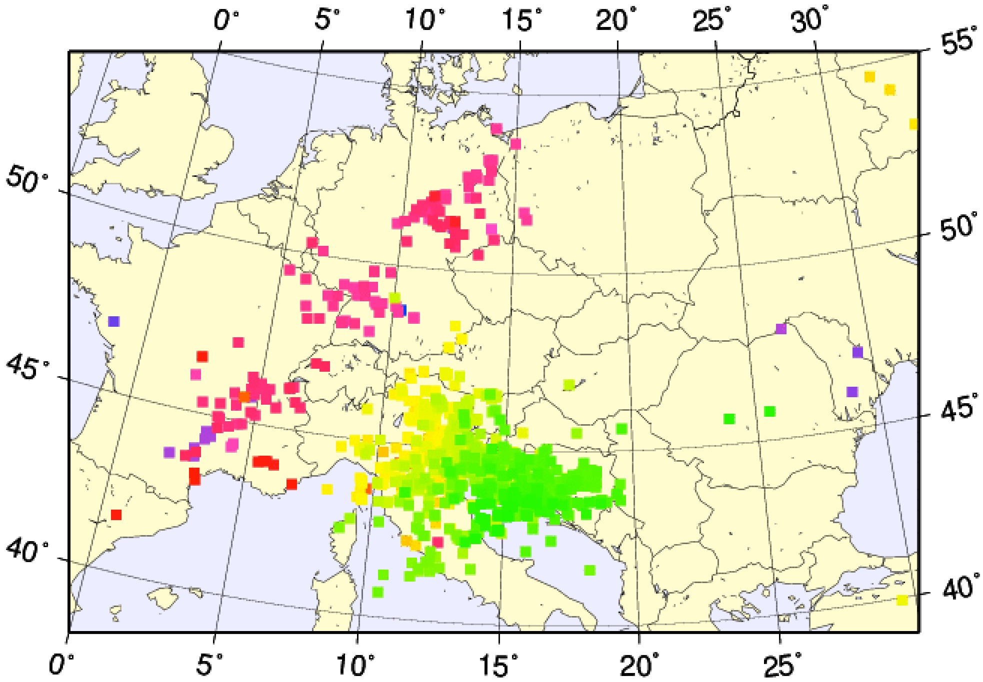

Fig. 4.3. QSO midpoints representing the geographical position of sporadic E on June 27, 2004. The color code is identical to **Fig. 4.2**, i.e. the red and purple positions correspond to dx QSOs between 12.30 and 15.30 UTC.

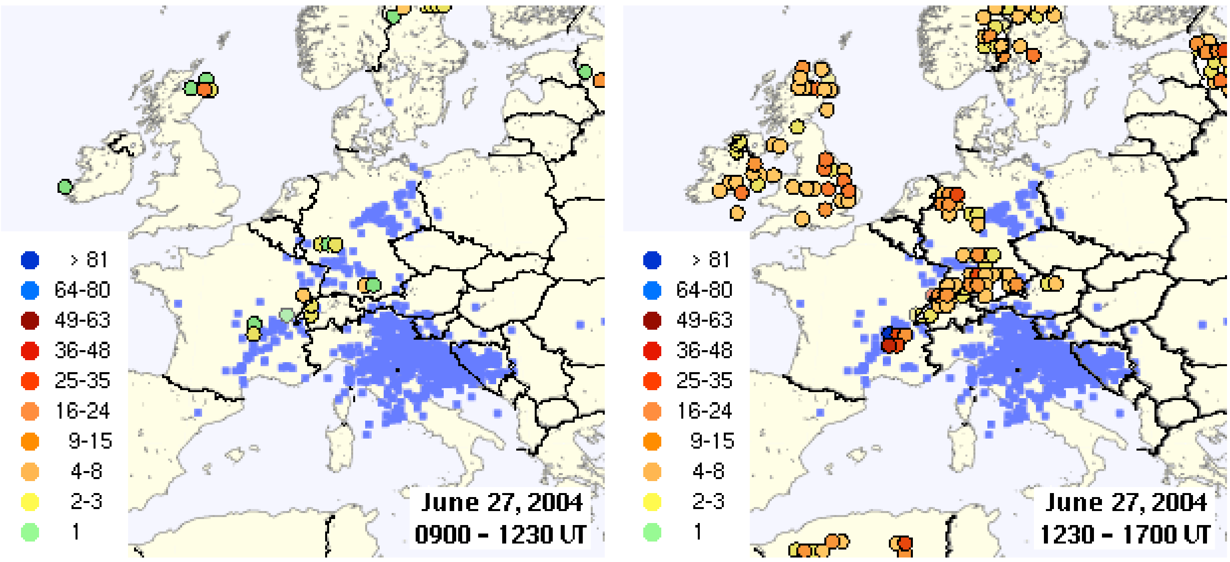

Fig. 4.4. Geographical distribution of sferics observed on June 27, 2004 at 0900-1230 UT (left) and 1230-1700 UT (right). The color code denotes the number of sferics per 30 minutes. Original data from [50], post processed data from [59].

4.5 Next steps in data analysis

Geographical presentations similar to **Fig. 4.3** and **Fig. 4.4** can provide information on particular sferic and sporadic E events but cannot support statistical analyses dealing with long time series resulting from long-term observations. For example: analysing all sporadic E events between, say 1990 and 2004, the many data points would overlap and would finally overload the map display destroying all systematical features in the graphics. Even if thunderstorm effects on 144 sporadic E may be considered a real phenomenon, doubt will continue to exist when studying individual events only, i.e. there is a need to employ statistical methods in our studies.

Fig. 4.5 therefore suggests an alternative approach when analysing sporadic E and sferic events: by calculating the actual time difference Δt and the actual distance d between all sferics and all the sporadic E events, a transformation is obtained replacing all absolute data (i.e. geographical coordinates and UTC information) by relative data (i.e. time differences and distances). Assuming the number of sferic events is N and the number of sporadic events is M, the new data set will comprise N times M data records in total. With this transformation, all available data may be plotted in only one diagram, see **Fig. 4.6**, i.e. we obtain an easy but powerful tool for analysing the spatiotemporal correlation between sporadic E and sferic events.

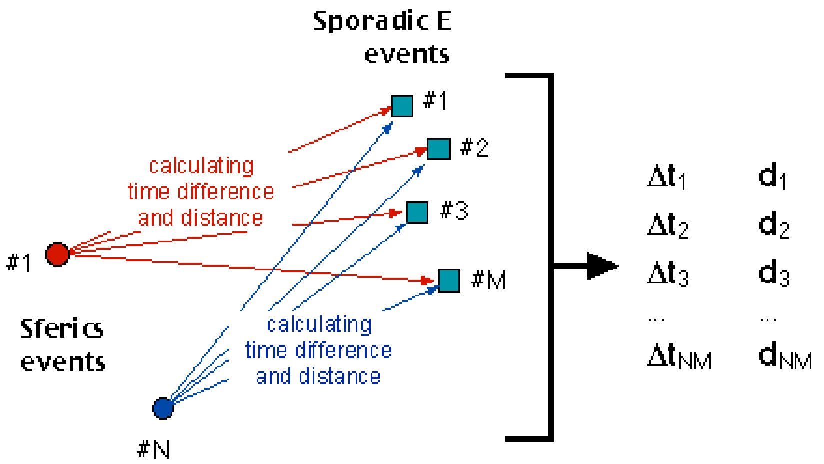

Fig. 4.5. Data set indicating the time difference and geographical distance between all sferics and all sporadic E events.

Assuming, the sferic and sporadic E data would show no spatiotemporal correlation at all, the above procedure will result in a random distribution of data points (graphical noise) similar to panel a in **Fig. 4.6**. Any existing correlation will however result in some sort of accumulation of data points as shown be fictive examples in the next panels.

Panel b, for example, shows fictive data indicating sporadic E positions close to sferic positions associated with a variable time-delay though. Such a scenario would indicate gravity waves propagating in vertical direction at variable speed. Panel c shows a fictive example of gravity waves propagating with contant velocity in vertical and also in horizontal direction, i.e. the sporadic E and the sferic events show a time-delay proportional to the distance between the thunderstorm cells and the scatter position in the E region of the ionosphere. Panel d, on the other hand, shows a fictive scenario in which the sporadic E activity occurs more or less simultaneously in close vicinity to the sferic activity (which appears an unlikey scenario though). This type of graphical presentation can therefore disclose the spatiotemporal correlation between sporadic E and sferic events and, if an evident correlation would indeed become visible, can also provide valuable information on the horizontal and vertical propagation characteristics of gravity waves.

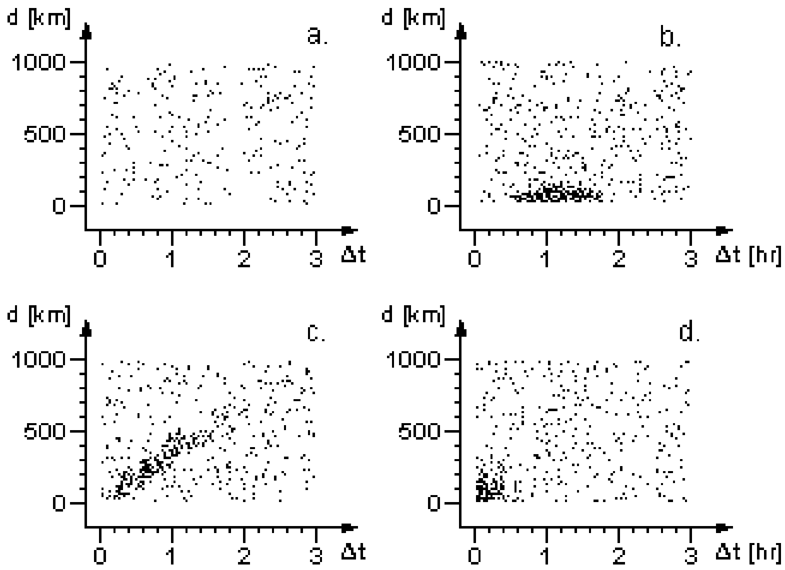

Fig. 4.6. Diagrams displaying the relative time difference and distance between sferics and sporadic E events. The plots show fictive data, see text.

We cannot predict what pattern may be expected when using real data but we may speculate on the time differences and distances that need to be considered in this type of analysis. Considering the correlation between the TID occurrence in the F region of the ionosphere and the tropical rainfall activity reported by RÖTTGER ([6], see also chapter 3.2), the displacement of sporadic E events relative to the sferic events will be only a few hundred kilometers, probably even less than 100 kilometers. This assumption results from the TID measurements carried out south of the Peruvian rainforst (see figure 8 in [6]) and by considering the height difference between the F and E region (assuming gravity waves in the tropics and in mid-latitudes propagate with an identical elevation angle relative to the Earth surface). Because the correlation between the TID occurrence and the rainfall activity also shows a time lag around three hours [6] (which is interpreted the period of time in which gravity waves propagate from the upper troposphere into the F region of the ionosphere), we may also conclude that sporadic E and sferic events will exhibit a time delay of approximately one hour or so.

Although we are indeed curious carrying out this type of analysis in practice, we cannot present results in the near future, unfortunately. A severe practical complication results from the fact that we currently cannot access neither the numerical geographical coordinates nor the event time of individual sferic events because this type of data is not available with the internet resources which only provide summary plots instead. We therefore plan to apply for direct cooperation with the sferic observatories in order to access the raw data material required in this type of analyses.

5 Summary and concluding comments

The existence of thunderstorm effects on the ionosphere appears generally accepted in atmospheric sciences for three reasons:

- Various ionospheric effects are clearly associated with atmospheric gravity waves travelling in the E and F region of the ionosphere. Gravity waves are in particular considered one cause of wind shears around 100 km height which may stimulate the generation of sporadic E layers.

- Gravity waves originating in the troposphere and in the stratosphere may propagate upwards into the mesosphere (80 km) and, very likely, may also arrive at D and E region heights around 90 to 110 km.

- It is a well known fact that thunderstorms may create convectively generated gravity waves in the upper troposphere and in the lower stratosphere.

Scientists believe that this three individual effects may also occur in combination, at least partially. Hence, thunderstorms are interpreted the origin of gravity waves propagating from the lower into the upper atmosphere where they may create wind shears in the E region of the ionosphere which, finally, stimulate or support the generation of sporadic E. This model appears plausible to many scientists but, as far as we can see, it isn't yet verified in all aspects and details. However, scientific measurements can provide some indications leading in this direction. In this paper, we have presented two examples communicated in the scientific community:

- The Nebraska thunderstorm documented by the *University of Alaska* in August 1999 provides strong evidence of thunderstorm-triggered gravity waves propagating upwards into the mesosphere (detected by optical instruments measuring the spatial distribution of the OH nightglow at 85 km). However, the mesosphere is not identical to the ionosphere but little imagination is required to assume gravity waves travelling even higher than 85 kilometers.

- The statistical results of the GPS/MET experiment provides additional information indicating an impressive correlation between thunderstorm and gravity wave activity in the lower atmosphere on one hand and E region irregularities on the other hand. However, we have raised words of caution because that E region irregularities must not be considered similar to sporadic E events as discussed by VHF radio amateurs.

Unfortunately, radio amateurs have no instrumentation capable to detect the presence of gravity waves, therefore we need to deal with tracers as an alternative. Thunderstorm-triggered gravity waves are associated with strong updrafts (convectively generated gravity waves) causing charge separation within the thunderstorm cloud which results in cloud-to-cloud and cloud-to-ground lightning strikes, respectively. Each strike creates a *sferic*, i.e. an electromagnetic impulse of short duration which direction-finding radio receivers may detect quite easily. Thus, by analysing the geographical position of sferics we may localize the geographical position of thunderstorms more or less accurately. However, gravity waves travel in vertical and also in horizontal direction, i.e. the position of gravity waves penetrating the E region of ionosphere may differ considerably from thunderstorm positions. Thus, sferics may trace thunderstorm positions but can hardly predict the geographical position of sporadic E.

Nevertheless, in our project's early analyses we have compared sferic positions and sporadic E positions based on observations made during the 2004 sporadic E season in Europe. The sferic positions were derived from the *Wetteronline* internet service and the sporadic E positions were calculated from 144 MHz dx QSOs reported by radio amateurs. It was no surprise finding many examples of sporadic E not associated with any thunderstorm at all. In fact, we believe that less than, say ten percent or even less of mid-latitude sporadic E is triggered by thunderstorms, if any. It is important to note that previous researchers did not find any convincing correlation between thunderstorms and 144 MHz sporadic E propagation, i.e. all what we may expect is a small effect or, alternatively, no effect at all. However, we are surprised about one data example (June 27, 2004) which shows a geographical pattern of sporadic E activity almost identical to the geographical distribution of sferics.

Map presentations do not appear an appropriate tool for identifying possible correlations in the spatiotemporal distribution of sporadic E and sferic activity. Map displays can only consider short observation periods with few data points (too many data may overload the map display) and cannot reveal possible time delays between sfercis and sporadic E events. We have therefore suggested an alternative approach which considers relative rather than absolute data, i.e. distances and time differences instead of geographical coordinates and UTC information. With this method even long-term observations may be plotted in only one diagram which will hopefully support future statistical analyses. However, we cannot access numerical sferic data required to calculate the distance between sporadic E and sferic events, i.e. our project currently faces practical complications which our team needs to address in the near future.

Considering the scientific material and, perhaps, our findings from June 27, 2004, the possibility of thunderstorm effects on 144 MHz sporadic E propagation cannot be generally excluded. On the other hand, it is much too early taking those effects for granted at this stage of investigation. Also, this paper focuses on one particular model but alternative models are also worth to be investigated in more detail. GRAYER, for example, draws our attention to cumulonimbus generating "electic fields [which] are known to cause a drift of atmospheric electrons towards the E layer, charging it up to about 100 –300 kV" [63]. He even considers this "an equally interesting (and perhaps more persuasive) mechanisms for coupling between thunderstorms and Es".

Thus, thunderstorm effects on VHF sporadic E propagation remain an open issue in amateur radio propagation studies worth to be investigated in more detail. The authors hope that this paper may provide some new aspects and considerations and may stimulate ham cooperation in this fascinating subject which combines elements from meteorology (thunderstorms), ionospheric physics (sporadic E), VLF radio techniques (sferic detection), VHF radio operation (144 MHz dx QSOs), internet applications (weather services and dx alerting systems), software engineering (data acquisition and data processing) and data analysis methods.

Acknowlegements: The authors are to the *WetterOnline Meteorologische Dienstleistungen GmbH*, to the *Blitzinformationsdienst von Siemens (BLIDS)* and to the *Wetterzentrale Georg Müller* for granting permission of accessing their online data in our analyses. We thank Prof. J. RÖTTGER (DJ3KR) for providing valuable material on TIDs and spread-F irregularities relevant to the scope of this paper. We thank G. GRAYER (G3NAQ) for reading the manuscript and for providing many valuable comments. We are also grateful to the many VHF radio amateurs having submitted their sporadic E observations to our web sites which has supported our studies considerably.

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