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Tutorial Lecture

by Joseph Salah
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MIT/Haystack Observatory

Ionospheric Effects and Storm Studies:
A Tribute to Michael Buonsanto

In memory of

Michael J. Buonsanto

(1952-1999)

On behalf of the Atmospheric Sciences Group at Millstone Hill, I would like to thank the CEDAR Science Steering Committee and the CEDAR community for taking time at this workshop to pay tribute to Michael Buonsanto and for giving us an opportunity to remember him and note his contributions.

As many of you know, Michael passed away in the early morning of October 21, 1999 due to a heart attack while he was at home. That evening he was planning to head down to the NSF for a CEDAR Steering Committee meeting and was looking forward to serving this community with the same dedication and commitment that he exhibited in all his work.

Michael's sudden and untimely death - he was 47 years old - had a major impact on our group at Millstone Hill from which we have not fully recovered, and of course, the impact on his family has been devastating. He left three young children ranging in age from 9 to 13.

A lot of us knew Michael as a scientific colleague – serious but unassuming, disciplined but cooperative, willing to share his data unselfishly and collaborate with openness on all his projects. I will briefly go over some of his attributes as a colleague, and then I want to share with you some personal aspects that will tell you that he was a special human being who enriched the lives of many people whose paths crossed his.

As a scientist, Mike was quite a prolific writer. His CV listed over 70 peer-reviewed papers, 60 of which were written in the last ten years since joining the MIT group at Millstone Hill. I counted 13 of these papers written by him as single-author and around 25 where he was the lead author and involved some 50 colleagues as co-authors. The rest were written by others who included Mike as a collaborating co-author to acknowledge his contributions. It is no wonder that the group received so many expressions of sympathy and condolences from scientists all over the world who had worked with Mike. We passed these on to his family, and we are grateful to all of you who wrote such kind words about your recollections of your interactions with Michael. As they grow up, his children will have these testimonials to better appreciate their father's career accomplishments.

In the last year of his life, Michael had 12 papers either published or in press, and he was at the peak of his career. An excellent review paper on storm effects in the ionosphere and thermosphere appeared in Space Science Reviews in the week before he passed away. He was quite proud of that paper and considered it a culmination of what had been learned by the CEDAR Storm working group that he led for the past ten years. In that study, his collaborators recognize that he was very well organized and methodical, documented all the workshops in great detail promptly after each meeting, kept careful logs of who promised what, and kept after us persuasively until we completed our commitments and wrote the promised papers on the results. His style of work at Millstone Hill was quite similar in that he insisted on the highest standards for the data which he used or sent to the radar users, and he tenaciously went over the calibrations until he was fully satisfied.

Mike paid special attention to students and young people, and enjoyed mentoring and nurturing them in atmospheric physics. This was at all levels – graduate students, post-docs, undergraduates. Each summer for the last ten years, he mentored one or two undergraduate interns, brought them to the CEDAR meeting to help attract them to our research field, and they appeared as co-authors on his papers. He was also very active in outreach – served on the AGU committee for education and public outreach - and gave a lot of his time to school children in the local area around Millstone Hill and Westford where he lived. He participated in career days, hosted student groups, and played a prominent role in the various education programs that we run at Haystack for pre-college students, teachers and the public. Whenever I asked for volunteers to get involved with pre-college or public outreach, he was always the first to volunteer his time. Later on, I realized that this commitment was part of his zeal and mission to help others.

I first met Michael when he joined our group in 1988, having come from Fiji. He appeared in my office wearing his trademark sweater as shown in the photograph. You could always find Mike by looking for that bright red sweater! Mike was born and raised in Boston, attended Northwestern University and earned a Bachelor's degree in Astronomy, then Tufts University for a Master's degree in education. He taught for a few years at high school and community colleges in Massachusetts, including a stint as a planetarium lecturer. He then decided to go back to graduate school and enrolled at Boston University, where he worked with Michael Mendillo and earned another Master's degree in Physics and Astronomy. He then decided to travel far – to Auckland, NZ, where he worked with John Titheridge and completed his PhD in ionospheric physics in 1980.

Why he went to New Zealand to study appears to have been motivated by his joining the Bahai religion and adopting the South Pacific as an area for his missionary contributions. We learned a bit about the Bahais at Mike's funeral – Bahais embrace all religions and are very ecumenical. There were Samoans, Native-American Indians, and representatives from Christian, Jewish, Hindu and Moslem religions at his funeral, all of whom spoke highly of him. It turns out that Mike established the Bahai church in the town of Westford and was one of its major functionaries. He did this, pursued vigorous research and education programs, cared for a young family, and we learned from a local priest at his funeral that Michael found time to reach out to the community and help children in violent family situations. It really touches you that he was truly a good human being.

After completing his PhD in New Zealand, he taught Physics and Math for a few years at Samoa College in Western Samoa, then moved to Fiji – to the University of the South Pacific where he was a senior lecturer in Physics for another five years. We learned that he was amongst few who mastered the samoan language while he was there and became quite fluent in it. During that time, he continued an independent program of research in a relatively isolated environment, and wrote a few papers on ionospheric physics. Henry Rishbeth wrote to us recently having uncovered a paper written by Michael while in Fiji that discussed the possible effects of the changing earth-sun distance on the upper atmosphere. Henry thought that this may be a prediction whose effect can be verified using ionospheric models.

Mike's oldest child was born in Samoa and he realized that she needed special medical attention, which brought him back to the US. We were very fortunate to get him to join our group and contribute to ionospheric physics. He rose within the MIT research ladder to the rank of Principal Research Scientist. His no-nonsense, dedicated, hard-working style was an example to all of us, and we all cherished the associations that we enjoyed with him.

Our group has discussed how best to keep his memory alive. The group is moving to a new building at the end of the year, and Michael's photo in the red sweater will be prominent there to remind us of him. But we also wanted to keep his memory alive through his interactions with the CEDAR community. Based on the group's deliberations, we have established the ***Michael J. Buonsanto Memorial Lecture*** which will be held annually in the Fall at the MIT Haystack Observatory, and we will invite members of the CEDAR community to give this lecture. We hope that you will accept our invitation to keep his memory alive. Thank you.

Joseph E. Salah
July 27, 2000.

Michael J. Buonsanto
[1952 - 1999]

John Foster's Review of Michael Buonsanto's Scientific Career

I am honored to come before you to talk about Michael Buonsanto's scientific work. Many aspects of Michael's life went beyond what we knew of him through scientific interactions either at CEDAR or AGU or at Millstone Hill. I first met Michael through his letter of application to for a research position at Millstone Hill. I was very impressed by his background. At this time he was in Fiji as a teacher and there he had been publishing a number of papers about the equatorial ionosphere and was doing serious scientific work pretty much [***Fig 1 Vita***] in isolation. He was writing very good papers while working from a very difficult position. I have always felt that one of my big successes at Millstone Hill was that we were able to hire Michael Buonsanto. He turned out to be everything he seemed he might be from that letter of application. He was an excellent, flexible scientist, extremely dedicated, and made a huge contribution to the Millstone group through his spirit, his dedication, and his way of doing science. And we are fortunate that as time went on, that spirit and dedication spread out into the more general research community.

Rather than picking up one topic of Michael's research and describing his science contribution there, I want to give an overview of the types of work he did and how he did it. He reached out beyond his individual research interests through his interactions with students and other scientists. Michael's life had many sides. He had strong religious convictions. One tenet of his Bahai faith was to 'Do your very best in your professional career'. Looking back on his scientific career, I can see how this principal underlay his day to day work at Millstone Hill. As a scientist, Michael was always serious and did not joke. If you asked him to become involved in a new research area or to take on a new responsibility, he stepped forward rapidly.

[***Fig 2 coauthors***] We can get a feel for the breadth of his scientific career by looking at a list of his coauthors (shown in chronological order). Students are marked with an asterisk, and many of these are undergraduate summer REU (Research Experiences for Undergraduates) students. This points out Michael's interest and dedication to bringing students into professional research. Michael would carefully design his REU projects to lead a student from almost no background in upper atmospheric research to being a true scientific co-author on a publication. Of Michael's 70 research publications, 5 of them have REU students as co authors. This was a great part of Michael's career, his outreach to students. He treated everyone he collaborated with equal respect, whether they were students or senior colleagues. He was a truly excellent mentor and collaborator.

His research started and ended with studies involving ionospheric storms. I will to save for another time a review of his work on ionospheric storms. Instead, I will give an overview of what Michael accomplished during his career by looking at a number of his publications and by pointing out the methodology he used in approaching a research topic. Michael had a personal need to be in the south Pacific region [to do mission work with his Bahai faith], and during the 10 years he was there he also strived to do his very best to describe the low-latitude ionosphere in publications using a combination of ionosonde data and modeling.

[***Fig 3 MS study L=4 in title***] Michael did his MS in Boston under the supervision of Michael Mendillo, and also found the time to obtain a teaching Masters degree in education. He taught high school in New England for a while and then went to New Zealand to do a PhD with John Titheridge. Following that, he took a succession of high school and college teaching positions in the South Pacific islands.

Michael combined data interpretation with modeling. One of the hallmarks of Michael's study was that his work was based in the data, but went beyond only what the data could show. He included an understanding of physics, combined with available models such as MSIS or simple first principle models of aeronomical processes to come up with more-extensive insights into the related processes. An example of his early work [Fig 4 - 2 plots, 2 hemispheres] combined ionosonde observations with MSIS to investigate the summer to winter differences in the neutral wind. Michael initially pursued similar studies when he left the South Pacific to come to Millstone Hill. During the next several years, his research evolved from local ionosonde studies to large scale studies of global phenomena. [***Fig 5 - 4 papers F2 Peak Heights...***] In his new position at Millstone Hill he had access to large databases in Boulder and elsewhere and with these he could investigate solar-cycle dependences, for example, combining Fabry Perot, incoherent scatter, and solar cycle-dependent neutral and ionospheric parameters. Michael's methodology was to combine accessible data, publicly available models, and his own modelling, to go beyond what any of them would conclude separately.

Looking over Michael Buonsanto's 70 publications, they break down into several categories.

1) Statistical studies using large data sets. Michael saw what kind of science could be done with the large radar data sets arising from the World Day observations, and he pushed forward to analyze and publish these data. [***Fig 6 3 plots; Mean Daily Variation...***]

2): Examination of specific ionospheric processes using multi-instrument CEDAR data sets combined with theory. For example, in a paper with D. Sipler and Y-K, Tung, one of his REU students, [***Fig 7 - paper w Sipler and Y-K Tung ; 4 papers***] he combined FPI/model/IS to address neutral oxygen densities.

3) Clustered data. One of the goals of CEDAR has been to establish clusters of instruments which could provide complementary observations. Michael asked himself, 'How can I use the CEDAR data as clustered-instrument data?' He was one of the first to step forward and use IS radar chain data. His work provided a good example and set the course for students and fellow workers on how to organize and combine the multi-instrument data resource to address significant problems.

4) Examination and intercomparison of different models. His work with Starks [cf. Fig 7] focused on neutral winds, making comparisons of 5 different techniques used to derive the neutral wind from observations. [***Fig 8, neutral wind comparison***] He undertook such comparisons in order to identify the differences in the techniques, not to say which model was better, but to address the physical processes which were included in each model and to see how the inclusion of a specific process could improve the model results.

5) Modeling. He broadened the reach of our Millstone HIll incoherent scatter radar research into the modelling area, adding chemistry or physical models of others to explain and understand observations and models in the larger scale picture.

One of the CEDAR topics which has received a great deal of work concerns the O+O collision frequency. The topic underlies the coupling between the neutral and ionized atmosphere, and an understanding of the O+O collision frequency is important in determining neutral dynamics based on ionospheric observations. It is instructional to look at how Michael approached this problem. An analysis of his research method can provide guidance to our younger researchers as to how such a problem could be addressed. The topic had been approached previously using first principles and laboratory studies, but comparison with observations had pointed out the need for a normalizing factor, over which there has been a large discussion. Burnside et al discussed this and there have been CEDAR working groups organized by Joe Salah to try to resolve uncertainties in its determination. [cf. Fig 7] Michael's method was to look at all data at the same time to try to provide an unbiased view of the problem. He took 30 days and nights of simultaneous ISR and

FPI data and determined the Burnside factor statistically to be 1.36 in the median and 1.56 in the mean. He set about studying numerical analysis and statistical techniques in order to understand the large spread in the distribution of this factor. After gaining an understanding of the statistical characteristics of the observations, he did simulation studies based on the statistical principles. [*Fig 9 Monte Carlo*] The Monte Carlo simulations were then used to reinterpret the spread of the data sets - producing a final estimate of the Burnside factor of 1.4+/-0.3,which is in keeping with what others had found. Michael believed that he could turn to the data to provide the answer to the O+O collision-frequency questions, but he also saw that if one included statistical and modelling techniques to interpret the observations, you could get a better answer than if you just looked at a distribution of data points and stated what appeared to be the answer. By getting to the heart of the matter, and by addressing the statistical issues properly, Michael was able to provide what appears to be a definitive evaluation of the Burnside factor.

Gradually, Michael went from single author, single-technique studies to papers including a variety of models and instruments and including multiple authors. A turning point in the second part of his career [*Fig 10 - 2 papers*] involved his studies of large magnetic storms. He began by examining long sets of radar data obtained during 6 day runs and these became the core of the IS Storm Study data. He looked at comparisons of the data with the servo models and addressed the many aspects of the storms using the large World Day data sets. His initial interest was in the peak altitude and coupling of the neutral atmosphere and winds to ionospheric parameters. As he pursued these studies, he became more exposed to the variety of storm-time phenomena which were being pursued at Millstone Hill and elsewhere. His own interests lay in the equatorward surges stimulated by stormtime heating, but as his work progressed, he became more exposed to the effects of the magnetosphere - Joule heating, electric fields, and shear flows (e.g.). He saw a need to investigate these effects on ionospheric chemistry and neutral composition during disturbed events. The storm studies broadened his field of view of the wide range of phenomena which take place in such conditions.

What came from this turning point in Michael's research was the CEDAR Storm Study - a natural consequence of his overview papers on the 1989 and 1990 storms. Those studies had shown that there were many processes taking place at the same time during major storms and that these were closely coupled to each other. The CEDAR Storm Study provided a forum for people doing individual storm research to share and interrelate these phenomena and to discuss the full extent of coupled storm processes. [*Fig 11 CSS*] Many of you have been to CSS workshops and are aware of the wide range of scientific contributions which have resulted from this broad approach to storm phenomena. All of this evolved as a consequence of the steadily expanding point of view taken by Michael Buonsanto as he became more involved with the research of other scientists in the CEDAR community. He was able to incorporate their points of view in his thinking, but could also step back and take an overview position as to how these various phenomena coupled with each other. He saw the need to establish a framework to facilitate this sort of coordination and understanding of this larger-scale phenomenon.

Michael's more recent work went on to examine several specific ionospheric effects. There is the dusk effect phenomenon, where there are large electron density enhancements near sunset on the first day of an ionospheric storm. [*Fig 12 Ne*] Michael said, 'Let's look at everything at the same time -- all mechanisms, topside atmospheric disturbances, propagating phenomena, advection of plasma, composition changes.' He designed a new radar experiment with John Holt to look at spatial gradients in the ionospheric parameters. Radars had been providing vector information for a number of years, and Michael wanted to go beyond this to examine the gradient terms in the equations for ionospheric dynamics. During a magnetic storm, the local ionosphere does more than just respond to mechanisms which happen at just that point in space. Electric fields lead to the transport of plasma into the viewing volume and nearby gradients in the plasma properties can be moved through the experiment field of view. Because of this, Michael and John designed a 9-position gradient-mode experiment which is now a standard operating mode at Millstone Hill. This experiment gave Michael observations of the temporal and spatial variability which were needed, in combination with his first-principle modeling, to understand the dusk effect.

The lesson to be learned is that if the data you have cannot address the physical problem, then redesign the experiment to do a better job. The gradient experiment addressed second order terms. When it was found that advection did not provide the whole answer, then the chemistry and neutral composition had to be addressed. Progressively this research tested and ruled out terms, and lead elsewhere to find a correct answer to the causes of stormtime phenomena. At this point, Michael was at the peak of his career. He was able to draw together the concepts, data, and models, and to form collaborations with other researchers to address broad research topics.

[***Fig 13 - 4 papers***] A very significant contribution in the latter phase of his career is his review of ionospheric storms. Michael had become an expert on ionospheric storms, and had coordinated storm studies for 10 years. He listened to, worked with, and understood modelers, chemists, atmospheric dynamicists. He combined their input with FPI and radar observations, and coalesced them all to form a more all-encompassing picture of storm phenomenon.

As a community, we will carry forward Michael's work. His legacy is more than just the science he accomplished. It is found with his 50 co-authors and the dozens of students he cared for and mentored. Each of these collaborators will carry forward some of the spirit of scientific research that Michael Buonsanto demonstrated throughout his scientific career. The science is excellent - the science will continue. The coordination of scientific research - his broad view of looking at ionospheric storms or any similar topic - is part of the legacy of Michael Buonsanto. Scientifically, I am pleased to have worked with Michael Buonsanto for a dozen years. I learned quite a bit on how to do science from Michael. He was unselfish and dedicated. He was very interested in reaching out to bring in everybody's point of view, understanding it, and trying to couple it into the whole. Michael left us with a lot to think about and to work with. I know that we have many excellent people in the CEDAR community who will carry forward his life's work.

Thank you for the opportunity to have reviewed this aspect of Mike's life and work with you.

Comment by Barbara Emery: Michael had a record at the CEDAR Workshop also. He was chair of the CEDAR Storm Workshop for 10 straight years in the last 14 years. He started in 1990 co-chairing the CEDAR Storm Workshop with John Foster. The next runner up was John Foster, who has chaired 8 workshops in the last 14 years. I am certain we will get someone to chair 10 sessions, but not the same workshop 10 years in a row like Michael. He was a remarkably persistent and good scientist.

MICHAEL J. BUONSANTO
[1952 - 1999]

Education

PhD	(1980) Engineering	University of Auckland, New Zealand
Thesis: Total Electron Content: SITECs and Interhemispheric Comparison		
MA	(1976) Physics and Astronomy	Boston University
MA	(1974) Education	Tufts University
BA	(1972) Astronomy	Northwestern University

Experience

7/94-	Principal Research Scientist MIT Haystack Observatory, Westford, MAs
1/88-6/94	Research Scientist MIT Haystack Observatory
1/83-1/88	Senior Lecturer/Lecturer in Physics University of the South Pacific, Suva, Fiji
1/80-12/82	Teacher of Physics and Mathematics Samoa College, Apia, Western Samoa
6-76-1/77	Lecturer in Astronomy Middlesex Community College, Bedford, MA

Figure 1

Coauthors of Michael Buonsanto

M. Mendillo
J. Titheridge
K. Miller
R. Burnside
J. Foster
D. SIpler
S. Solomon
W. Tobiska
B. Fejer
T. Fuller-Rowell
B. Emery
D. Melendex-Alvira
A. Pavlov
S. Gonzalez
X. Pi
M. Sulzer
J. Thayer
D. Yuan
G. Lu
A. Coster
C-F Chen
J. Taylor
M. Arriagada
D. Anderson

J. Klobuchar
J. Salah
W. Oliver
P. Richards
A. Galasso (*)
J. Holt
Y-K Tung (*)
M. Hagan
J. Fennelly
M. Codrescu
C. Fesen
M. Starks(*)
G. Davenport(*)
L. Pohlman(*)
J. Ruohonimi
W. Swartz
A. Schlesier(*)
O. Witasse(*)
B. Reinisch
J. Kozyra
A. Hedin
W. Pakula
J. Picone
K Omidar

70 Publications / 35 1st Author / 5 with REU Student co-authors

Figure 2

Ann. Géophys., t. 35, fasc. 1, 1979, p. 15-26

Figure 3

The ionosphere at L = 4 : average behavior and the response to geomagnetic storms

by

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and

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ABSTRACT. – *The average behavior of the sub-auroral $L = 4$ ionosphere has been determined by using four years of continuous observations of ionospheric total electron content (TEC), F-region peak density (N_{max}) and equivalent slab thickness ($\tau = TEC/N_{max}$). Diurnal curves of monthly median behavior show that TEC and N_{max} are generally lower at $L = 4$ than at midlatitudes. The F-region layer-thickness parameter τ is larger during the day than at night, except in winter, when auroral processes cause large nighttime increases.*

The response of the $L = 4$ parameters TEC, N_{max} and τ to increases in geomagnetic activity has been studied by determining seasonal/diurnal patterns of average disturbance (per cent) variations. Comparison with midlatitude TEC results reveals that many features of the $L = 4$ storm patterns are due to repeated motions of the electron density trough during the 3-4 days of the storm period. Slab thickness increases during storms are related to storm induced heating and auroral precipitation effects.

RESUME. – *On a déterminé le comportement moyen de l'ionosphère sub-aurorale ($L = 4$) à l'aide d'observations continues sur 4 ans*

5

Journal of Atmospheric and Terrestrial Physics, Vol. 46, No. 10, pp. 879–883, 1984.
Printed in Great Britain.

0021-9169/84 $3.00 + .00

Effects of composition and fountain effect on the annual variation of the day-time F-layer at low latitudes

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(*Received in final form* 24 *February* 1984)

Abstract--The annual variation of the daytime F2-layer peak electron density ($NmF2$) is studied at two low latitude stations, Okinawa and Tahiti (geomagnetic latitudes ±15°) for the sunspot maximum years 1979–1981. Observed values are compared with those calculated using the MSIS model and a simplified version of the continuity equation for day-time equilibrium conditions. Summer–winter differences imply an intensification of the fountain effect on the winter side of the equator at the expense of the summer side. This could be explained by a summer to winter neutral wind. Semi-annual variations, however, appear to be mainly due to changes in neutral composition.

1. INTRODUCTION

The day-time equatorial F-layer exhibits an equatorial anomaly, viz. low values of electron density at the geomagnetic equator and enhanced ones at low latitudes to the north and south. The morphology of this phenomenon has been studied by many workers, mainly using ionosonde data (for a recent review see WALKER, 1981). This anomaly is known to be caused by a 'fountain effect'. At the geomagnetic equator, eastward electric fields associated with the equatorial electrojet induce upward $E \times B$ plasma drifts. This is

2. DATA AND METHOD OF ANALYSIS

Ionospheric data for three years (January 1979 to December 1981) during the recent solar maximum period were obtained for two stations, Okinawa and Tahiti, which have nearly the same geomagnetic latitudes in the northern and southern hemispheres. Table 1 gives the coordinates of the two stations.

This study deals with the annual variation of the day-time peak electron density ($NmF2$) at the two stations. The observed variation is compared with that

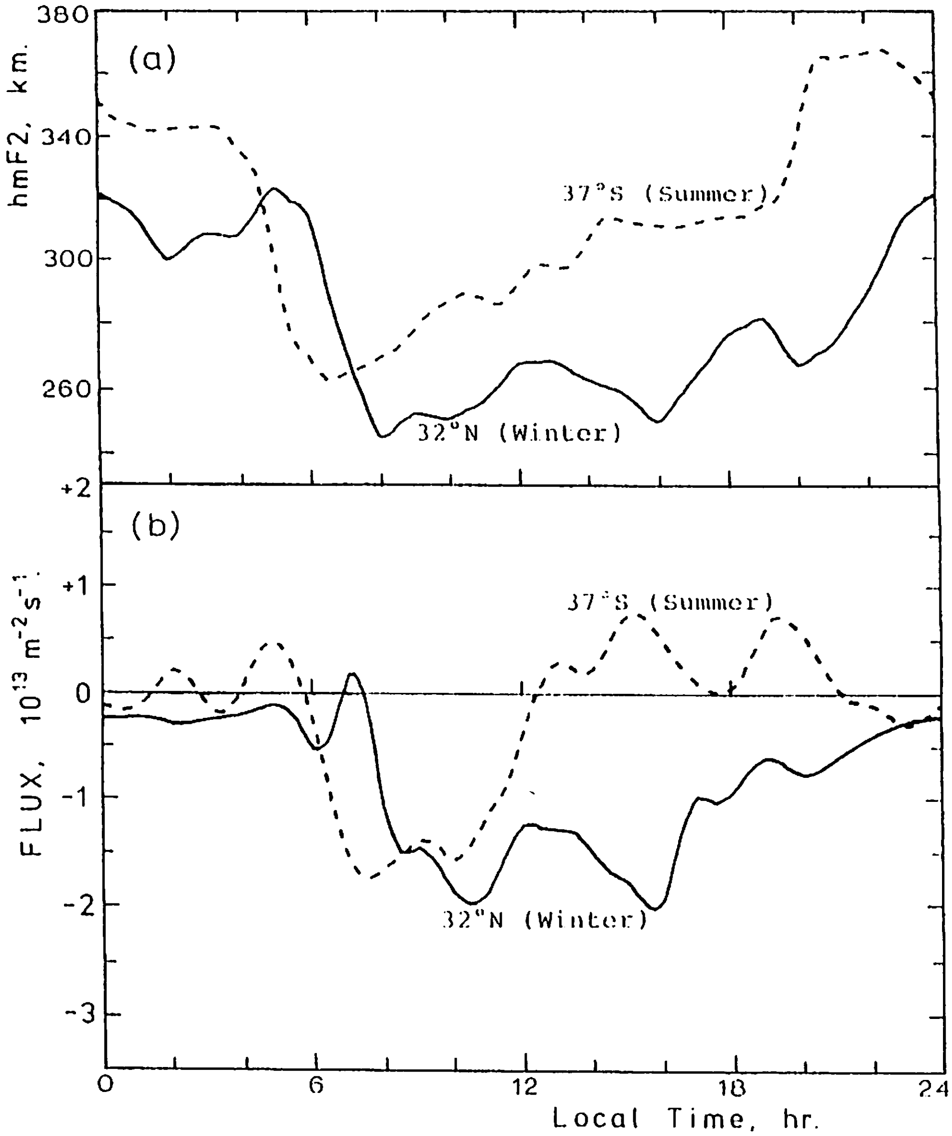

Fig. 12. (a) Median *hmF*2 and (b) calculated flux at White Sands (32°N) and Auckland (37°S) during December 1971.

Figure 4

Figure 5

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Pergamon Press plc

Observed and calculated $F2$ peak heights and derived meridional winds at mid-latitudes over a full solar cycle

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(Received in final form 20 November 1989)

Abstract — The peak height of the $F2$ layer, $hmF2$, has been calculated using the 'servo' model of RISHBETH *et al.* [(1978), *J. atmos. terr. Phys.* 40, 767], combined with the HEDIN *et al.* [(1988), *J. geophys. Res.* 93, 9959] neutral wind model. The results are compared with observed values at noon and midnight derived from ionosonde measurements at two mid-latitude stations, Boulder and Wallops Island, over a full solar cycle. The reduced height of the $F2$ layer, $zmF2$, is also computed for the same period using the observed $hmF2$ values and the MSIS-86 model. Day–night, seasonal, and solar cycle variations in $zmF2$ are attributed to neutral composition changes and winds. Anomalously low values of $hmF2$ and $zmF2$ during summer both at solar minimum and during the solar cycle maximum in magnetic activity may be associated with increases in the molecular to atomic ion concentration ratio. Under these circumstances the $F2$ peak may lie significantly below the O^+ peak height calculated by the servo model. Neutral meridional winds at Wallops Island are derived from the servo model using the observed $hmF2$ values and the calculated O^+ 'balance height'. It is shown that if the anomalously low $hmF2$ values are used, unrealistically large poleward winds are derived, which are inconsistent with both theory and observations made using other techniques. For most conditions the $F2$ peak is clearly an O^+ peak, and daily mean winds at $hmF2$ derived from the servo model are consistent with the HEDIN *et al.* (1988) wind model. Unexpectedly, the results do not show an abrupt transition in the thermospheric circulation at the equinoxes. Diurnal curves of the servo model winds reveal a larger day–night difference at solar minimum than at solar maximum.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. A9, PAGES 15,677–15,683, SEPTEMBER 1, 1993

Solar Cycle and Seasonal Variations in F Region Electrodynamics at Millstone Hill

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B. G. FEJER

Center for Atmospheric and Space Sciences, Utah State University, Logan

Incoherent scatter radar observations of ion drifts taken at Millstone Hill (42.6°N, 288.5°E) during 73 experiments in the period February 1984 to February 1992 are used to construct, for the first time at this station, average quiet-time E×B drift patterns for both solar cycle maximum and minimum, for the summer, winter, and equinox seasons. The daily variation of $V_{\perp N}$ shows a reversal from northward to southward drifts near noon, and a return to northward drifts in the premidnight hours. The weaker southward drift in the afternoon in summer noted by Wand and Evans (1981) is shown to occur only at sunspot minimum. The daily variation of $V_{\perp E}$ shows daytime eastward drifts and nighttime westward drifts, except in summer when the usual daytime eastward maximum near 1200 LT is suppressed. The daily mean drift is westward for all seasons, and is largest in summer. The daytime eastward drift and nighttime westward drift tend to be stronger at solar maximum than at solar minimum. Average drift patterns are also constructed for equinox for both extremely quiet and geomagnetically disturbed periods. $V_{\perp N}$ is appreciably more northward under extremely quiet than under disturbed conditions in the postmidnight and morning periods. During extremely quiet periods, $V_{\perp E}$ turns slightly eastward in the evening hours, while it is strongly westward for disturbed conditions. This result contrasts with the strong eastward drifts in the evening in summer reported for extremely quiet conditions at Millstone Hill by Gonzales et al. (1978). A strong anticorrelation is seen at Millstone Hill between $V_{\perp N}$ and $V_{\|}$, as is found at lower latitude stations. The quiet-time patterns are discussed in terms of the causative E and F region dynamo mechanisms. At Millstone Hill, conjugate point electric fields are also important in winter when the conjugate ionosphere is sunlit for much of the night.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. A3, PAGES 3711–3724, MARCH 1, 1991

Neutral Winds in the Thermosphere at Mid-latitudes Over a Full Solar Cycle: A Tidal Decomposition

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The magnetic meridional component of the thermospheric neutral wind at the $F2$ peak at Boulder, Colorado, is derived for days with magnetic index $Ap \le 20$ over a full solar cycle (July 1975 – June 1986). The servo model technique and ionosonde measurements of $hmF2$ are used, and the results are corrected for ionization drifts due to electric fields. A Fourier decomposition of the mean daily variation is carried out for each month. This reveals significant components with wave periods of 24, 12, 8, and 6 hours. The importance of ion drag in causing seasonal and solar cycle variations in the winds is inferred. Specifically, the conclusion of previous work that the diurnal amplitude is larger at solar minimum than at solar maximum is confirmed by the present study. The diurnal amplitude is generally in the range 60–80 m s^{-1} at solar minimum but only 25–45 m s^{-1} at solar maximum. The diurnal phase maximum of the northward wind lies in the range 1115–1625 LT with latest values in winter and at solar maximum, when the daytime effects of ion drag are greatest. The amplitude of the semidiurnal component shows little solar cycle variation but tends to be smaller in summer compared to other seasons. It has a mean value of 41 m s^{-1} over the solar cycle. The semidiurnal phase maximum is remarkably close to 0800 LT for all seasons throughout the solar cycle. The amplitudes of the 8 and 6 hour waves are both in the range 4–25 m s^{-1}. The 8 and 6 hour waves both have later phase maxima in summer than in winter. The present results are generally consistent with current models of atmospheric tides, except for the large solar cycle variation in the diurnal component.

INTRODUCTION

In a recent study [*Buonsanto*, 1990] (hereinafter referred to as paper 1), thermospheric neutral winds in the magnetic meridian were calculated at F2 peak heights over a full solar

of local time to be carried out for each month without the results being affected by variable storm effects. The results are interpreted in terms of atmospheric tides. In paper 1 the effects of vertical ionization drifts due to electric fields on the servo

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Climatology of neutral exospheric temperature above Millstone Hill

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Abstract. We present results of a comprehensive study of exospheric temperature T_∞ at Millstone Hill. T_∞ was calculated using zenith measurements of ion and electron temperature taken by the Millstone Hill incoherent scatter radar and a heat balance calculation during 201 experiments between 1981 and 1997. Fourier decomposition of the data is carried out to investigate how diurnal means and diurnal amplitudes and phases vary with season, solar, and magnetic activity and to search for a long-term trend in the diurnal mean. The results show generally good agreement with the mass spectrometer/incoherent scatter-86 model, and the data will be included in the next update to the model. It is found that the diurnal mean T_∞ increases with increasing solar and magnetic activity and depends on season, with largest values in summer. No significant long-term trend is found in this data set. If there is saturation of T_∞ at high levels of solar activity, it is not statistically significant in these data. The diurnal amplitude increases with increasing solar activity, but no other statistically significant dependencies are found. The diurnal phase has an earlier phase maximum in summer. Significant semidiurnal and terdiurnal components are found during some times but not others.

1. Introduction

The exospheric temperature T_∞ is an important parameter in ther-

Hagan and Oliver [1985] analyzed 54 24-hour seg from nearly a full solar cycle (1970–1980). They alsc diurnal temperature amplitude at solar maximum and

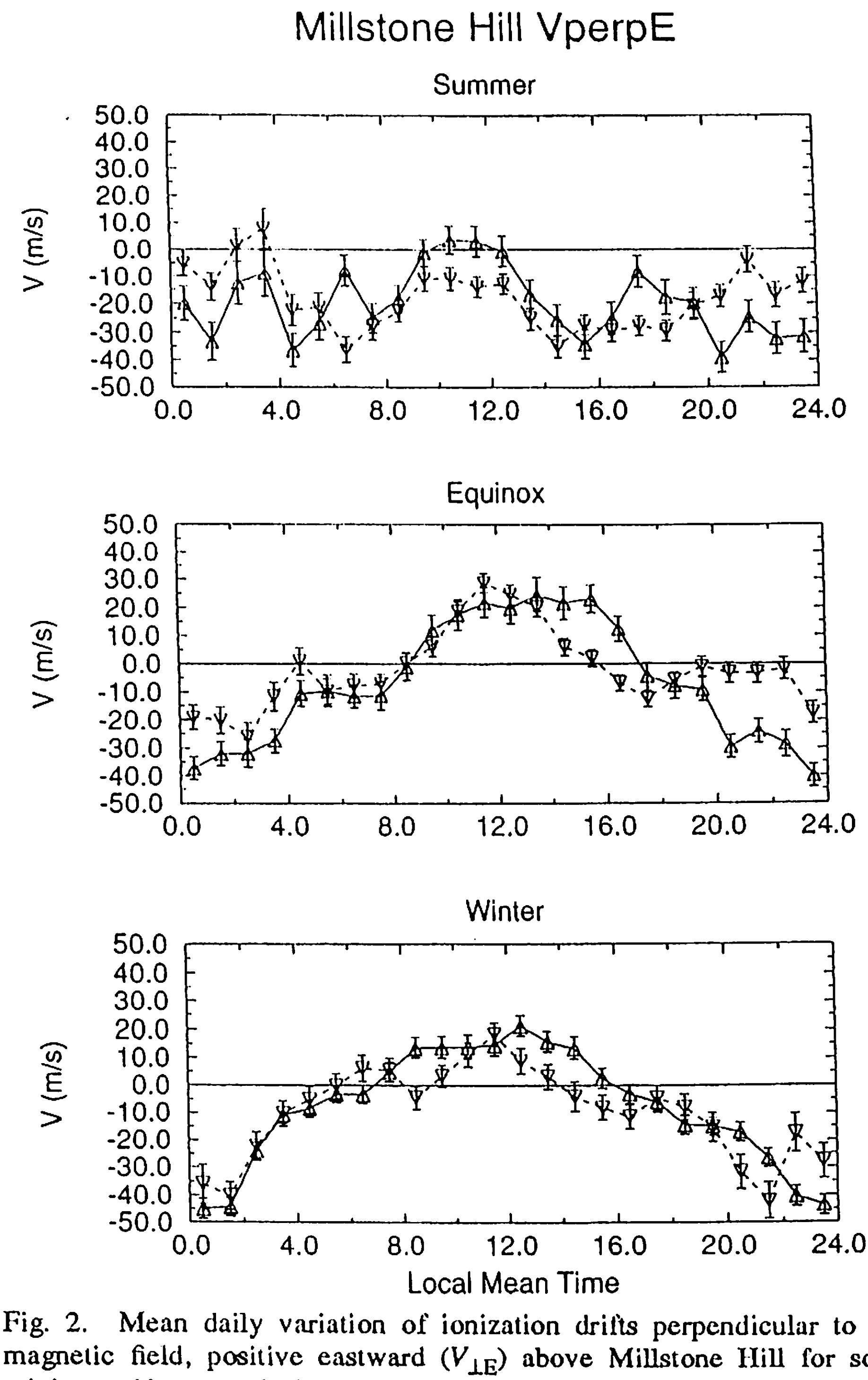

Fig. 2. Mean daily variation of ionization drifts perpendicular to the magnetic field, positive eastward ($V_{\perp E}$) above Millstone Hill for solar minimum (downward triangles) and solar maximum (upward triangles) for summer (top), equinox (middle), and winter (bottom).

Figure 6

Figure 7

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. A6, PAGES 8673–8679, JUNE 1, 1992

Neutral Atomic Oxygen Density From Nighttime Radar and Optical Wind Measurements at Millstone Hill

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Neutral atomic oxygen densities [O] in the thermosphere are calculated from analysis of coincident Millstone Hill incoherent scatter radar and Fabry Perot interferometer measurements taken during 14 nights with widely varying geomagnetic conditions in 1990 and 1991, and the results are compared with the mass spectrometer/incoherent scatter 1986 (MSIS-86) model. The results are generally satisfactory except during the most rapidly varying conditions, when some of our assumptions break down, such as those of a uniform ion velocity field and no vertical neutral wind. On the average, the results agree well with MSIS-86. However, systematic differences are found on two of the geomagnetically disturbed nights, with the observed [O] much smaller than the MSIS-86 values on one night, and much larger on another.

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Estimation of the O^+, O collision frequency from coincident radar and Fabry-Perot observations at Millstone Hill

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Abstract. The formula for the O^+, O momentum transfer collision frequency has been uncertain due to a discrepancy between results of theoretical calculations and some of the joint radar/optical studies. The former suggest a multiplicative factor equal to 1.2–1.3 times the formula derived by *Dalgarno* [1964] and *Banks* [1966], while the latter suggest a multiplicative factor $F = 1.7$ [*Salah*, 1993]. We present results of a new analysis of data from 30 nights of coincident incoherent scatter radar (ISR) and Fabry-Perot interferometer (FPI) experiments conducted at Millstone Hill between 1988 and 1992. The O^+, O collision frequency is estimated from FPI measurements of the horizontal neutral wind in the magnetic meridian, ISR measurements of the ion drift velocity parallel to the Earth's magnetic field and other data at the calculated height of peak 630 nm emission, and the mass spectrometer and incoherent scatter 86 model. A complete error analysis is carried out for each derived value of F. This allows us to carry out Monte Carlo simulations which confirm that random errors lead to an increase in the mean value of F and which provide us with an unbiased result, $F = 1.15 \pm 0.2$. However, this result was obtained from an analysis which neglected vertical neutral winds, about which we have little information. The most likely effect of these winds would be an increase in the value of F, so that our best estimate from this study is $F = 1.4 \pm 0.3$, which is consistent with theoretical calculations.

Introduction

The O^+, O momentum transfer collision frequency ($\nu_{O^+,O}$) is of critical importance for many aeronomical calculations. Several studies have been devoted to obtaining a formula to represent this collision frequency and its temperature dependence. See *Salah* [1993] for a review of work up to 1993. The similar theoretical formulations of *Dalgarno* [1964] and *Banks* [1966] were based on an extrapolation to low energies of the crossed-beam laboratory exper-

borne neutral wind data, noting that FPI measurements would provide the best return on effort.

Burnside et al. [1987] attempted to derive $\nu_{O^+,O}$ from nine coincident incoherent scatter radar (ISR) and FPI experiments carried out at Arecibo between 1982 and 1985. The FPI gives a fairly direct measure of the neutral wind. However, the ISR obtains the neutral wind from O^+ ion velocity data and a calculation of the O^+ diffusion velocity. The latter depends on the value of $\nu_{O^+,O}$, which Burnside

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Comparison of techniques for derivation of neutral meridional winds from ionospheric data

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Abstract. We carry out a detailed comparison between winds derived from F_2 peak heights and winds obtained from incoherent scatter radar (ISR) line-of-sight velocity measurements. A total of 34 incoherent scatter radar experiments at Millstone Hill spanning all seasons and levels of solar activity are included in this study. For two experiments we compare results from five different wind-derivation techniques. According to work by *Titheridge* [1993, 1995a, b], neutral winds derived from the servo model are inaccurate during the sunrise and morning period because of a shift in the zero-wind F peak downward from the balance height. To investigate this effect, we determine a correction factor c_{fac} to be applied to the servo model c parameter as a function of time of day for summer, equinox, and winter at both solar maximum and solar minimum. Our results confirm that a sunrise decrease in c_{fac} is necessary to bring about best agreement between the servo model winds and the winds derived from the ISR ion velocity data at Millstone Hill. However, the effect is not large, so that a constant c_{fac} for each season/solar activity level usually introduces less error than other factors which may result in differences between the servo model and ISR winds. These factors include measurement errors in hmF_2 and the ISR line-of-sight ion velocities, spatial variations in the wind field above the station, and the assumption that

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. A8, PAGES 14,569–14,580, AUGUST 1, 1

Ionospheric electron densities calculated using different EUV flux models and cross sections: Comparison with radar data

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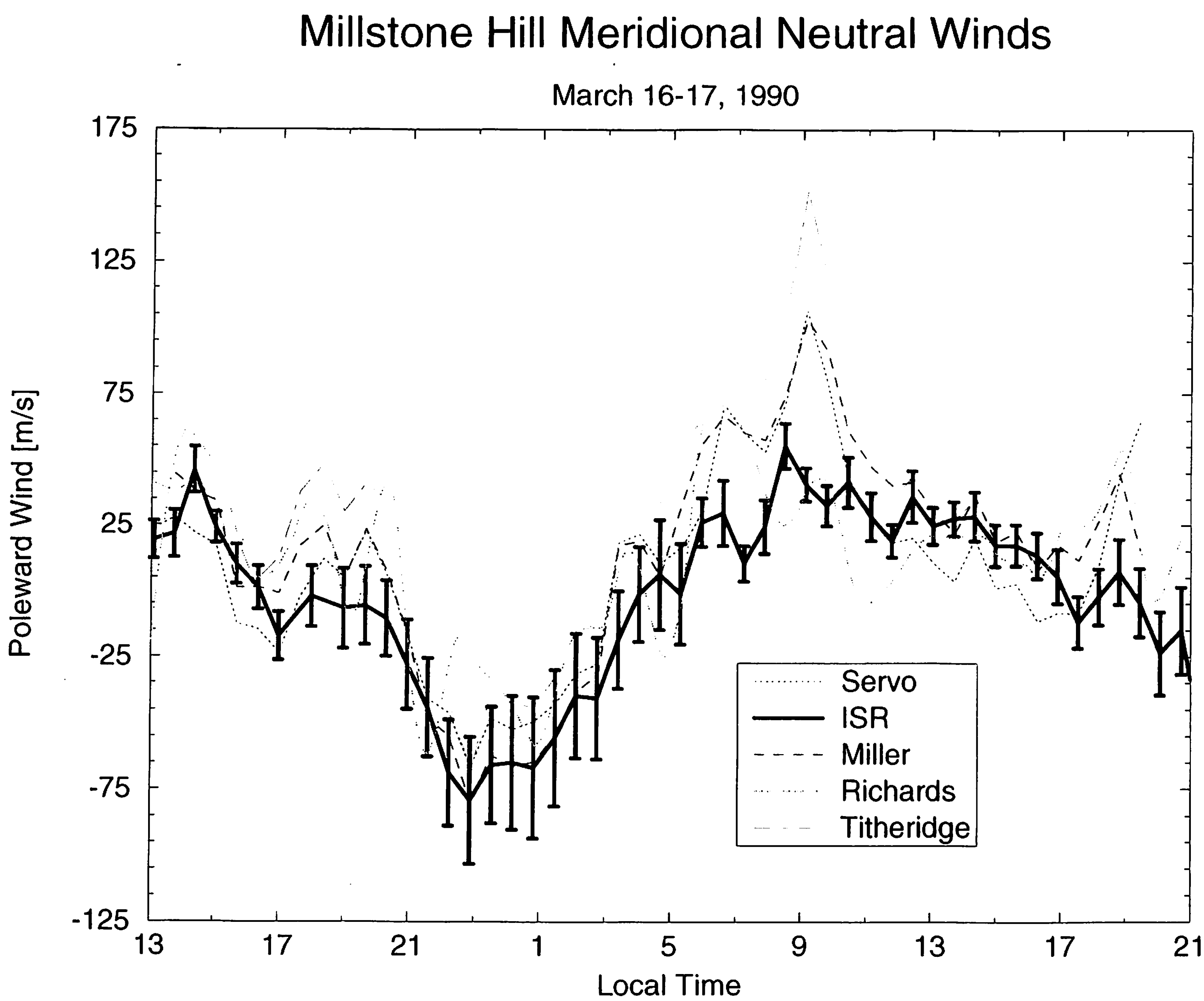
Abstract. The recent availability of the new EUVAC (Richards et al., 1994) and EUV94X (Tobiska, 1993b, 1994) solar flux models and new wavelength bin averaged photoionization and photoabsorption cross section sets led us to investigate how these new flux models and cross sections compare with each other and how well electron densities (N_e) calculated using them compare with actual measurements collected by the incoherent scatter radar at Millstone Hill (42.6°N, 288.5°E). In this study we use the Millstone Hill semiempirical ionospheric model, which has been developed from the photochemical model of Buonsanto et al. (1992). For the $F2$ region, this model uses determinations of the motion term in the N_e continuity equation obtained from nine-position radar data. We also include two simulations from the field line interhemispheric plasma (FLIP) model. All the model results underestimate the measured N_e in the E region, except that the EUV94X model produces reasonable agreement with the data at the E region peak because of a large Lyman β (1026 Å) flux, but gives an unrealistically deep E-$F1$ valley. The ionospheric models predict that the O_2^+ density is larger than the NO^+ density in the E region, while numerous rocket measurements show a larger NO^+ density. Thus the discrepancy between the ionospheric models and the radar data in the E region is most likely due to an incomplete understanding of the NO^+ chemistry. In the $F2$ region, the photoionization rate given by EUV94X is significantly larger than that given by the EUVAC and earlier models. This is due to larger EUV fluxes in EUV94X compared to EUVAC over the entire 300–1050 Å wavelength range, apart from some individual spectral lines. In the case of EUVAC, this is partly compensated for by larger photoelectron impact ionization due to the larger EUV fluxes below 250 Å. The differences between ionospheric model results for the different cross-section sets are generally much smaller than the differences with the data.



Millstone Hill Meridional Neutral Winds
March 16-17, 1990
175
125
75
25
-25
-75
-125
Poleward Wind [m/s]
13
17
21
1
5
9
13
17
21
Local Time
Servo
ISR
Miller
Richards
Titheridge

Figure 8

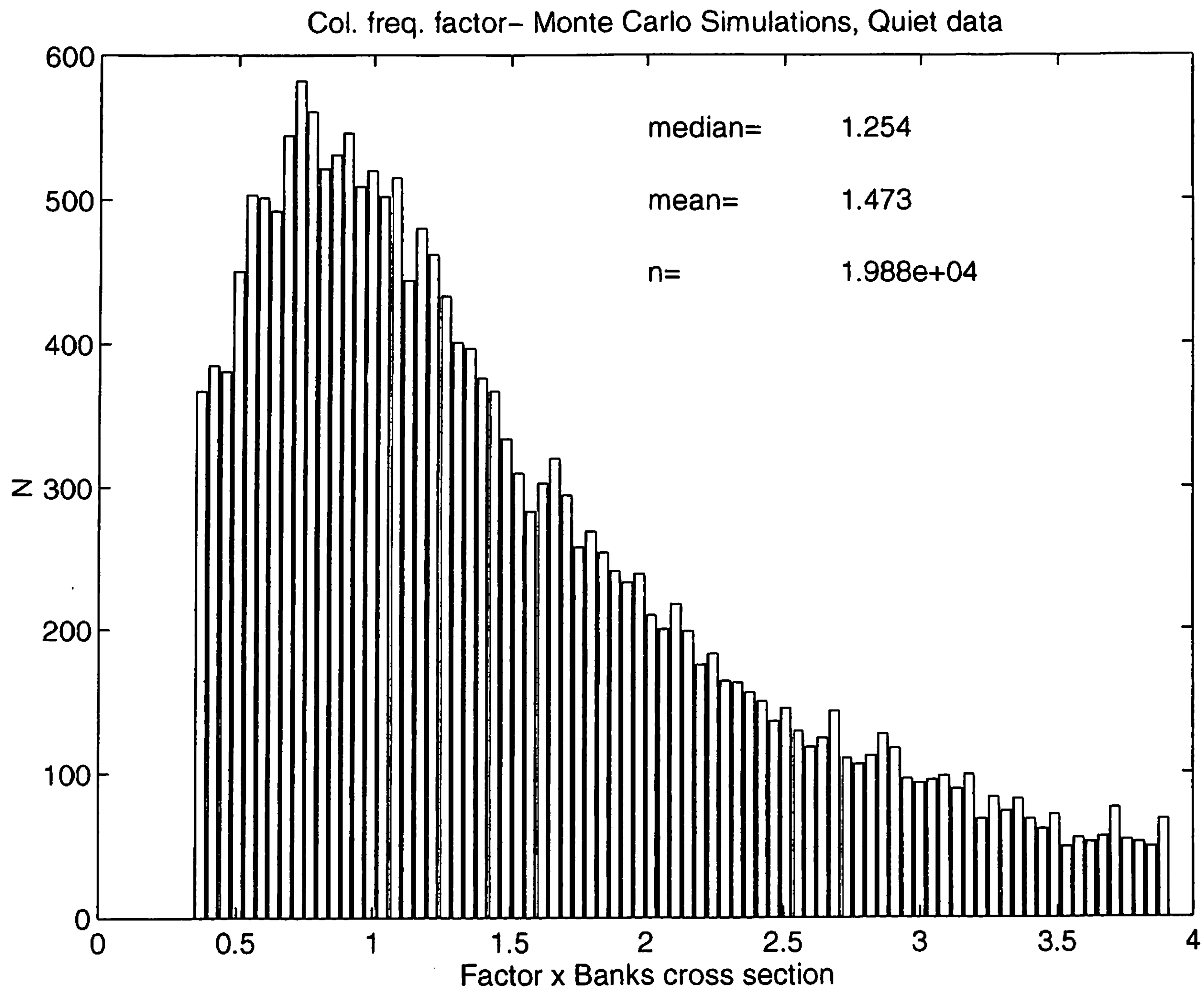


Figure 8. A histogram showing the distribution of all *F* values derived from analysis of data from 16 geomagnetically quiet nights after filtering out physically unrealistic values. For each data point a Monte Carlo simulation was performed giving 100 values of *F*, resulting in a total of 19880 values.

Figure 9

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. A12, PAGES 21,033-21,050, DECEMBER 1, 1990

Neutral Winds and Thermosphere/Ionosphere Coupling and Energetics During the Geomagnetic Disturbances of March 6–10, 1989

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Observations of electron density made using the fully steerable 46-m-diameter antenna at Millstone Hill have been used to derive the peak electron density (*NmF2*) and the peak height of the *F2* region (*hmF2*) as a function of latitude during the March 6–10, 1989, period. This period was characterized by varying levels of geomagnetic activity, with a magnetic storm commencing near 1800 UT on March 8. The radar data set presented for this period provides a detailed example of the mid-latitude ionospheric response to geomagnetic disturbances. The derived *hmF2* values are combined with measurements of electric field-induced ion drifts and the MSIS-86 model to estimate the meridional neutral winds at thermospheric heights over the geodetic latitude range 30° to 56°N. Strong postmidnight surges in the neutral wind were observed on March 7, 9, and 10 which reached well equatorward of Millstone Hill. The nighttime electron density trough was above Millstone Hill during the disturbances and *hmF2* exceeded 500 km in the trough on March 7 and 9. A dusk enhancement in *NmF2* followed the magnetic storm commencement on March 8. This is associated with a large increase in westward ion velocity due to the equatorward penetration of magnetospheric electric fields. Large daytime decreases in *NmF2*, apparently due to a neutral composition disturbance zone, were observed on March 9 and 10, with a sharp gradient on March 9, and a stronger equatorward penetration of the *NmF2* decreases on March 10. The Joule heating as a function of latitude is estimated for March 7 and March 9 from calculations of height-integrated Pedersen conductivity and incoherent scatter electric field measurements. In spite of considerably more Joule heating input at high latitudes on March 9, the postmidnight surge is stronger on March 7. This is explained by a combination of Coriolis and ion drag effects.

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Observations From Millstone Hill During the Geomagnetic Disturbances of March and April 1990

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The incoherent scatter radars at Millstone Hill operated continuously during the periods March 16–23 and April 6–12, 1990, providing observations of large-scale ionospheric structure and dynamics over a large portion of eastern North America. Major geomagnetic storms occurred during each of these periods, with deep nighttime ionospheric troughs and large magnetospheric convection electric fields observed equatorward of Millstone. The Millstone observations provide a comprehensive data set detailing storm-induced ionospheric effects over a 35° span of latitude during both of these intervals. At the latitude of Millstone the ionospheric peak height *hmF2* rose above 600 km in the trough on March 22 and 23 and reached ≈500 km at night on April 11 and 12. Increased recombination, apparently due to the strong electric fields, the temperature dependent recombination rate coefficient, and neutral composition changes, greatly depleted the *F2* region over a wide latitude range during the day on April 10, 1990. This resulted in an ionosphere dominated by molecular ions, with ionospheric peak heights below 200 km on this day. A number of frictional heating events during the disturbed periods are seen from comparison of ion temperature and velocity measurements. The most intense event took place near 1200 UT (≈0715 LMT) on April 10, 1990, when *Kp* reached 8. At 0110 UT on March 21, line of sight ion velocities in excess of 500 m s^{-1} were observed at the extreme southern limit of the Millstone steerable radar's field of view (40° apex magnetic latitude at an altitude of 700 km). These could be due to penetration of magnetospheric electric fields or electric fields associated with ring current shielding in the storm-time outer plasmasphere. About an hour later, ion outflow was observed just equatorward of Millstone. This is most likely due to heating from a latitudinally confined region of intense westward convection. Neutral meridional winds above Millstone were obtained by three different techniques employing radar and Fabry-Perot measurements. The latitude variation of the winds was also estimated from radar measurements of *hmF2* and electric fields using the servo model method. Strong equatorward nighttime neutral wind surges were found during both the March and April disturbances, which reached the equatorward limit of the observations at *F* peak heights.

Figure 10

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CEDAR Storm Study Workshops/Sessions

- Spring 2000 CEDAR Storm workshop at Millstone Hill NEW
- Workshop at 1999 CEDAR Meeting in Boulder
- Informal session at the 1998 Fall AGU Meeting
- Workshop at 1998 CEDAR Meeting in Boulder
- Special Session and Informal Workshop at 1997 Fall AGU Meeting
- Workshop at 1997 CEDAR Meeting in Boulder
- Spring 1997 CEDAR Storm workshop at Millstone Hill
- Workshop at 1996 CEDAR Meeting in Boulder
- Informal session at 1995 Fall AGU Meeting
- Workshop at 1995 CEDAR Meeting in Boulder
- **Informal session at 1995 URSI Meeting in Boulder**
- **Workshop at 1994 CEDAR Meeting in Boulder**
- **Informal session at 1993 Fall AGU Meeting**
- **Workshop at 1993 CEDAR Meeting in Boulder**
- **Special storm session at 1993 Spring AGU Meeting**
- Millstone Hill three day workshop, March 24-26, 1993
- **Workshop at 1992 CEDAR Meeting in Boulder**
- **Informal session at 1991 Fall AGU Meeting**
- **Workshop at 1991 CEDAR Meeting in Boulder**
- **Workshop at 1990 CEDAR Meeting in Boulder**

You may wish to return to the CEDAR Storm Study Home Page.

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Created July 6, 1995. Last modified July 8, 1999.

Figure 11

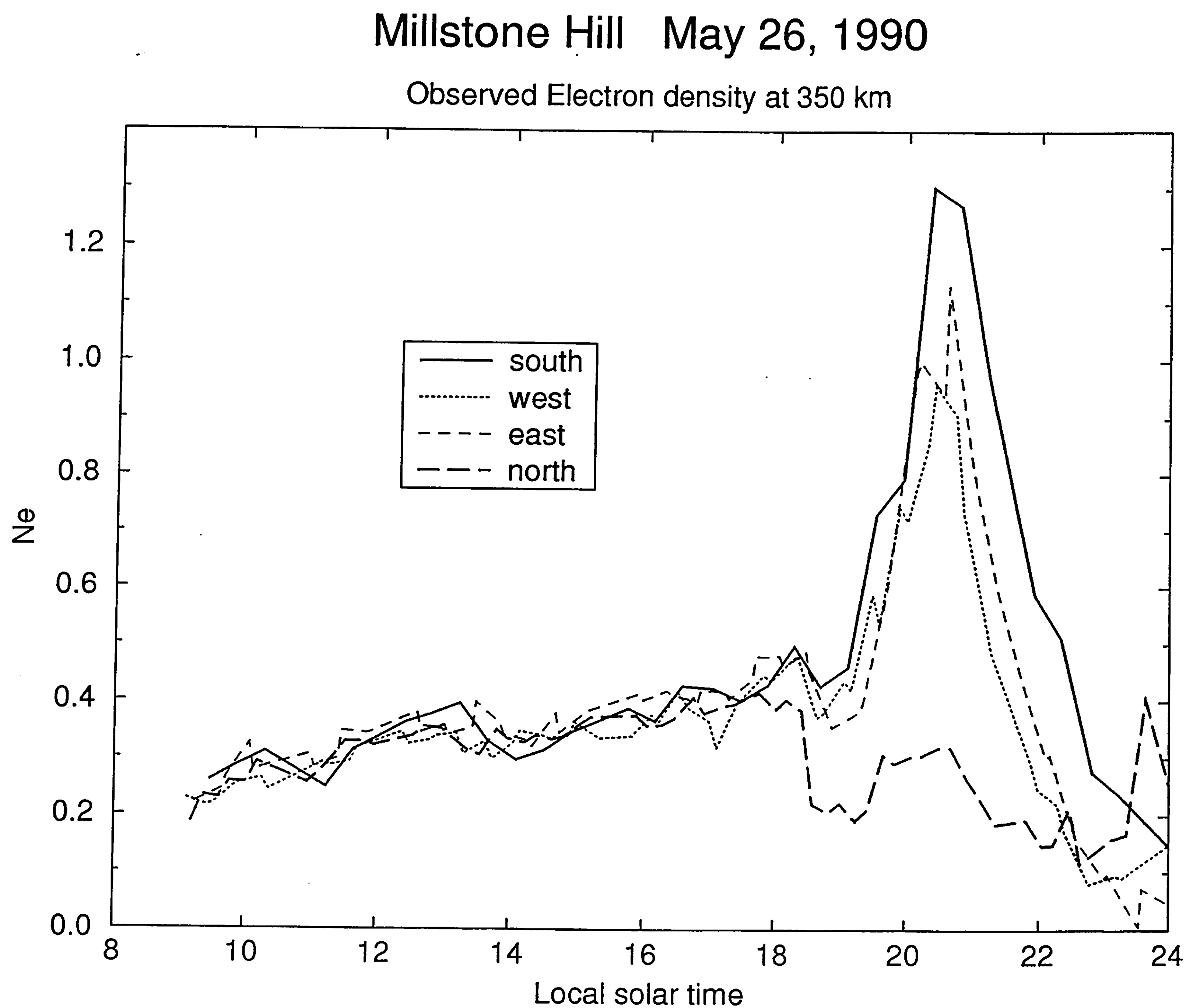
Millstone Hill May 26, 1990
Observed Electron density at 350 km
south
west
east
north
Ne
1.2
1.0
0.8
0.6
0.4
0.2
0.0
8
10
12
14
16
18
20
22
24
Local solar time

Figure 12

PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 61 (1999) 233–248

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

Radar chain study of the May, 1995 storm

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Abstract

PERGAMON

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Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

Comparison of models and data at Millstone Hill during the 5–11 June 1991 storm

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Abstract

We compare measurements of the ionospheric *F* region at Millstone Hill during the severe geomagnetic disturbances of 5–11 June 1991 with results from the IZMIRAN and FLIP time-dependent mathematical models of the Earth's ionosphere and plasmasphere. Some comparisons are also made with the Millstone Hill semi-empirical model which was previously used to model this storm. New rate coefficients from recent laboratory measurements of the $O^+ + N_2$ and $O^+ + O_2$ loss rates are included in the IZMIRAN and Millstone Hill models. The laboratory measurements show that vibrationally excited N_2 and O_2 ($N_2(v)$ and $O_2(v)$) are both important at high temperatures such as found in the thermosphere during disturbed conditions at summer solar maximum. Increases in the $O^+ + N_2$ loss rate due to $N_2(v)$ result in a factor ~2 reduction in the daytime F_2 peak electron density. On some days inclusion of $N_2(v)$ improves the agreement between the models and the data, and on other days it worsens it. In the present work we show for the first

IONOSPHERIC STORMS – A REVIEW

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Abstract. In this paper, our current understanding and recent advances in the study of ionospheric storms is reviewed, with emphasis on the F2-region. Ionospheric storms represent an extreme form of space weather with important effects on ground- and space-based technological systems. These phenomena are driven by highly variable solar and magnetospheric energy inputs to the Earth's upper atmosphere, which continue to provide a major difficulty for attempts now being made to simulate the detailed storm response of the coupled neutral and ionized upper atmospheric constituents using

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. A11, PAGES 24,625–24,637, NOVEMBER 1, 1999

Coordinated incoherent scatter radar study of the January 1997 storm

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Abstract. We describe many important features of the ionospheric *F* region as observed by the Sondrestrom, Millstone Hill, and Arecibo incoherent scatter radars (ISRs) and the Millstone Hill and Ramey Digisondes during January 6–10, 1997, with emphasis on the January 10, 1997 storm. Coordinated analysis of the data provides evidence for traveling atmospheric disturbances (TADs) and for two likely electric field penetration events linking these stations. Large and rapid changes in hmF_2 were seen at Arecibo and nearby Ramey which are related to the TADs and penetrating electric fields. Results are compared with simulations by the thermosphere-ionosphere electrodynamics general circulation model (TIEGCM), which utilizes high-latitude inputs given by the assimilative mapping of ionospheric electrodynamics (AMIE) technique. An important result of this study is that the TIEGCM is able to predict TADs similar to those observed. Exceptional features observed during this storm at Millstone Hill are a very large nighttime T_e enhancement on January 10 and a larger decrease in NmF_2 than predicted by the TIEGCM throughout the storm period. The latter appears to be related to an underestimation of the neutral temperature by the model.

1. Introduction

The chain of incoherent scatter radars (ISRs) near the 75°W meridian supported by the U.S. National Science Foundation (NSF) provides comprehensive measurements of ionosphere and thermosphere parameters which can be used to characterize the effects of geomagnetic storms on the Earth's upper atmosphere from the auroral zone to the equator.

Previous work with the ISRs [*Fejer et al.* 1990a, b; *Gonzales et al.*, 1983; Pi et al., Dynamical effects of geomagnetic storms and equatorward surges in the neutral meridional wind are observed by ISRs during major storms [e.g., *Babcock a* 1979; *Buonsanto et al.*, 1992].

Recently, *Buonsanto et al.* [1999] have used the ISR comprehensive study of the May 2–5, 1995, storm. That s tified three intervals of likely penetration of magn electric fields from high to low latitude. Unusual sto found were strong daytime equatorward wind surges, d evening enhancements in NmF_2 seen on three successi Millstone Hill, and an equatorward expansion of the

Figure 13