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14. ABSTRACT
From 2008 through 2011 this grant supported ground-based instrumentation in Peru and Chile to measure the neutral winds on the magnetic equator in an effort to test recent theories concerning the role that such winds play in the generation of equatorial spread-F [ESF]. The multi-instrument, multi-institutional, ground-based effort further supported the Air Force Communications/Navigations Outage Forecasting System (C/NOFS) program. At the end of the grant period, the first continuous measurements of the thermospheric winds have been made which show huge daily variability; indicating that the current use of empirical models in Air Force ESF forecasting models is insufficient in predicting synoptic ESF occurrence. There has also been an expansion on the observational capabilities of these instruments and this suite of instrumentation currently stand as the only means to measure thermospheric winds over a full 24-hour cycle. Two observational campaigns from 2001 were also conducted with the C/NOFS program and those results are currently in press.

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Final Report to Air Force Office of Sponsored Research

Final Report: Multi-Instrument Study to Investigate the Formation and Growth of Equatorial Irregularities

PI: Andrew J. Gerrard

Grant Period: 2/28/08-11/30/11 [3-year award with two ½ year extensions]

Submitted: 1/11/11

Executive Summary/Abstract

From 2008 through 2011 this grant supported ground-based instrumentation in Peru and Chile to measure the neutral winds on the magnetic equator in an effort to test recent theories concerning the role that such winds play in the generation of equatorial spread-F [ESF]. The multi-instrument, multi-institutional, ground-based effort further supported the Air Force Communications/Navigations Outage Forecasting System (C/NOFS) program. At the end of the grant period, the first continuous measurements of the thermospheric winds have been made which show huge daily variability; indicating that the current use of empirical models in Air Force ESF forecasting models is insufficient in predicting synoptic ESF occurrence. There has also been an expansion on the observational capabilities of these instruments and this suite of instrumentation currently stand as the only means to measure thermospheric winds over a full 24-hour cycle. Two observational campaigns from 2001 were also conducted with the C/NOFS program and those results are currently in press.

1. Project Overview/Review

The study of the physics of the low-latitude (i.e., geographic latitude <20^{o}) thermosphere/ionosphere (i.e., altitude range spanning ~100 km to ~800 km) is important for both pedagogical and practical purposes. For example, understanding the development of localized equatorial spread-F (ESF) is a problem of fundamental plasma physics and an important engineering issue, as ESF causes scintillation along trans-ionospheric radio links, particularly at and below the L-band (~1 GHz, VHF, UHF, and micro-wave), much like atmospheric turbulence causes stars to twinkle in the visible portion of the EM spectrum. This scintillation can cause a wide variety of problems due to the associated ~10-30 dB signal power loss, including: 1) decreased satellite-to-ground message throughput, 2) degradation in GPS navigation performance, 3) delayed signal acquisition, and 4) radar tracking errors.

Furthermore, recent research has indicated that measurements of the thermospheric winds at all times are crucial in the forecasting of the upper atmospheric environment. Unfortunately such wind measurements are rare. Without knowledge of these winds to initialize and constrain various space weather models, it has been shown that forecasts of ESF, for example, do not replicate the observations. In fact, thermospheric wind measurements have been cited as prime measurements needed in today's space weather research.

As a consequence, through funds made available from an U.S. Air Force-sponsored Defense University Research Instrumentation Program (DURIP) grant while proposal PI Gerrard was at Clemson University, the Second-generation Optimized Fabry-Perot Doppler Imager (SOFDI) was constructed with the purpose of measuring continuous 24-hour (i.e., nighttime and daytime) winds and temperatures from the upper mesosphere and lower thermosphere. This particular project was initially funded so that the 24-hour ground-based wind measurements from SOFDI could be used to validate in-situ wind measurements from the Air Force Communications/Navigations Outage Forecasting System (C/NOFS) satellite, which is part of an intensive satellite and data assimilation/operational space weather modeling program that will attempt to predict the low latitude occurrence of ESF. SOFDI's validation role has considerably expanded, however, because of later changes made to the C/NOFS satellite altitude coverage that limits its wind observations to above 400 km, higher than the origination altitude of ESF. As such, SOFDI is the only instrument capable of measuring thermospheric winds during daytime and nighttime conditions at altitudes closest to ESF formation. It is vital to understand, however, that SOFDI measurements alone will not be able to entirely explain the ESF problem. Additional data are necessary to ascertain the background atmospheric base-state and the spatial-temporal nature of individual ESF events.

Accordingly, this grant established a multi-institutional experimental collaborative which includes the New Jersey Institute of Technology [NJIT], Clemson University [CU], University of Illinois at Urbana-Champaign [UIUC], Cornel University, and the Geophysical Institute of Peru [IGP] that extends across Peru and Chile with the intention of advancing our understanding of the generation of ESF in support of the C/NOFS program. These instruments included [as seen in Figure 1]:

a) 24-hour winds and temperatures from the 630-nm OI emission (thermosphere, centroid ~250 km) and nighttime winds from the 557-nm OI emission (mesopause, centroid ~97 km) observed by SOFDI (Gerrard is the PI of the SOFDI instrument) located at Huancayo, Peru (geographic: 12.01 ^{o}S, 284.80 ^{o}E; geomagnetic: 0.62 ^{o}N, 356.23 ^{o}E; see Figure for the experimental geometry) [Figures 2 and 3],

b) nighttime 630-nm OI and 557-nm OI all-sky imagery from the Cornell All-Sky Imager (CASI, Gerrard is the PI of the CASI instrument) co-located within the SOFDI trailer housing,

c) nighttime winds and temperatures from the 630-nm OI emission observed by the Fabry-Perot interferometer (FPI) located at Arequipa, Peru (geographic: 16.47 ^{o}S, 288.52 ^{o}E; geomagnetic: 3.4 ^{o}S, 0.0 ^{o}E, proposal Co-I Meriwether is the instrument PI), and

d) nighttime 630-nm narrow-field imagery from the Portable Ionospheric Camera and Small-Scale Observatory (PICASSO) currently located at the Cerro Tololo Inter-American Observatory (CTIO) near La Serena, Chile (geographic: 30.17 ^{o}S, 289.19 ^{o}E; geomagnetic: 16.72 ^{o}S, 0.42 ^{o}E, proposal Co-I Makela is the instrument PI).

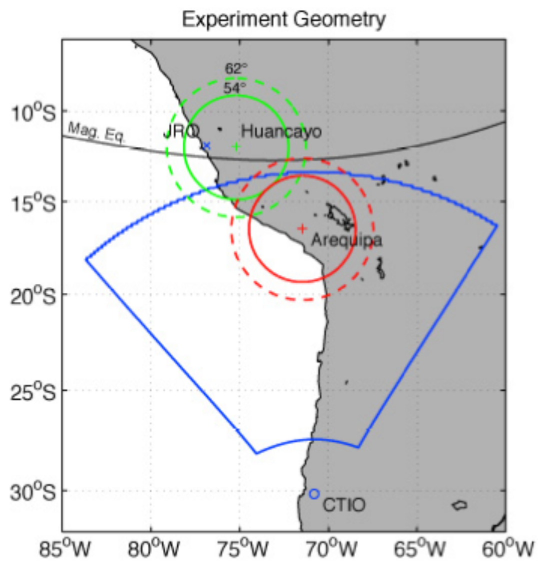

Figure 1: Experimental setup showing locations of JRO (blue X), Huancayo (green +), Arequipa (red +), and CTIO (blue circle). Also shown are field-of-views of SOFDI (green circles at 62° and 54° zenith angles) and the Arequipa FPI (red circles), the field of view of the PICASSO instrument assuming an emission height of 250 km (blueline) and the magnetic equator (black line).

The data from this instrumentation, along with supporting data from the Jicamarca Radio Observatory (JRO) located west of the SOFDI trailer in Lima, Peru (geographic: -11.95 °N, 283.13 °E; geomagnetic: 0.62 °N, 354.61 °E), were to be analyzed in a collaborative and synoptic manner whenever ESF is and is not observed.

Senior Project Personnel [with students] included:
PI: Dr. Andrew Gerrard [NJIT]
Mr. Zhaozhao Li [NJIT Ph.D. student]
Mr. Dhvanit Mehta [NJIT MS student]
Co-I: Dr. John Meriwether [CU]
Co-I: Dr. Jonathan Makela [UIUC]
Mr. Dan Fisher [UIUC Ph.D. Student]
Co-I: Dr. Erhan Kudeki [UIUC]
with collaborators
Dr. Michael Kelley [Cornell University, collaborator]
Dr. Gregory Earle [Virgina Tech]
Dr. Jorge Chau [IGP]
Mr. Erick Vadal Safor [IGP]
Mr. Marco Milla [IGP]
Mr. Luis Navaro [IGP]
Mr. Oscar Veliz [IGP]

In the following sections we discuss our numerous research activities and findings as a function of time. Specifically, in Section 2 we discuss the work done from 2008-2010; a period preceding the collaborative 2011 CORRER campaigns discussed in Section 3. In Section 4, we discuss the research activities and findings from the CORRER efforts. In Section 5 we discuss companion (i.e., associated) work supported in part by this grant, and conclude in Section 6. A list of papers associated with this grant follows the conclusions.

Figure 2. The SOFDI trailer in Huancayo, Peru, along with two students from the Geophysical Institute of Peru.

Note that the tallest dome houses the CASI instrument for Cornell.

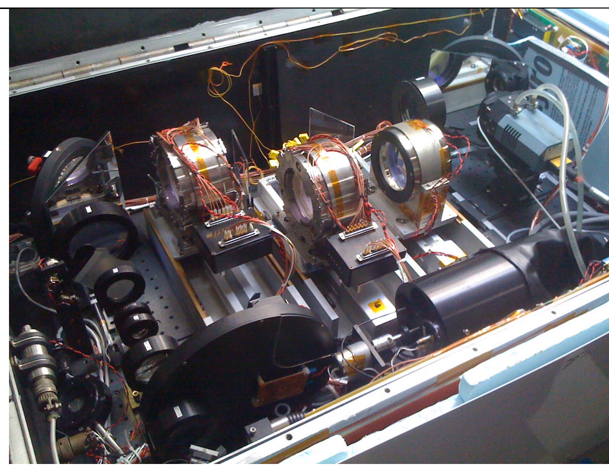

Figure 3. The layout of the SOFDI optics, including the three Fabry-Perot etalons.

2. Research Activities and Findings from Pre-2011

The original grant period was to extend from February 2008 until November 2010, with the first year to be dedicated to instrument deployment and testing. However, unanticipated events associated with the shipping of the SOFDI instrument to Peru [which was covered by a different grant] greatly delayed the effort. Furthermore, the weather at Huancayo, Peru during 2009 and 2010 was very cloudy/rainy and made for poor optical observing conditions. These two factors ultimately forced us to extend the grant by 1 full year, utilizing 2 one-half year extensions, in order to accomplish our proposed objectives.

Below, we summarize the pre-2011 period activities in regards to the individual participants of SOFDI/NJIT, CU, and UIUC.

SOFDI/NJIT

Semester	*Activities*	*Notable Experimental Challenges*
Spring 2008	Notified that AFOSR grant was funded. Initiate South American Campaign and transfer of equipment (i.e., customs paperwork, ITAR, etc.) to South American locations.	
	January 2008 site visit to Peru to inspect Huancayo Observatory and Jicamarca Radar Facility.	
	In April 2008 SOFDI was packed for shipment to Peru.	
	Cornell CASI instrument received new PC and new CCD camera.	
	In May 2008 SOFDI was transported to NJ to shipping yard for transport to South America.	While at shipping yard, intense rain flooded SOFDI trailer and ruins some electronics and optics.
Summer 2008	Repair of SOFDI instrument from aforementioned flood damage. Gerrard transports SOFDI to his driveway in NJ and does all repairs. This is a major repair effort.	
Fall 2008	September and October: testing of repaired SOFDI instrument in NJ. New daytime data collected.	
	November repacked SOFDI for shipment to Peru.	
	December returned SOFDI to shipping yard for shipment to Lima. [SOFDI on boat to Peru from January to March].	
	Present all research results to date at 2008 Fall American Geophysical Union Meeting.	
Spring 2009	SODFI processed through Peruvian customs.	
	SOFDI transported up the Andes Mountains to Huancayo site.	Delay of 2 months due to 1) AC refrigerant issues in Peru and 2) late rains in the Andes have damaged the one and only road to Huancayo.
	June 2008: Gerrard travels to Huancayo [trip 1] to setup/install SOFDI instrument at Huancayo.	In transport, primary focusing lens, nighttime 630-nm filter, and computer power supplies damaged.
Summer 2009	Travel to Huancayo again [trip 2] to repair of broken SOFDI optics. Phase 1 of SOFDI instrument grounding started [no small feat in the Andes at 11,000 ft].	Heaviest rain in Huancayo in August on record. SOFDI not affected, but no data or calibrations can be done with cloudy skies.

Fall 2009	Travel to Huancayo again [trip 3] to finish instrument install, including Cornell CASI instrument	Continued heavy rain and clouds prohibit data collection. SOFDI is “stored” for the rainy season of December to March in Huancayo.
Spring 2010	Travel to Huancayo again [trip 4] to ready SOFDI for summer 2010 operations.	
	1-week of SOFDI data collected and presented at summer meetings.	
Summer 2010	Gerrard travels to Peru [trip 5] for 2-week campaign in South America with all instruments operational! SOFDI instrument success!	
Fall 2010		Another early [South American] summer brings early rain and clouds to Huancayo. Heavy clouds and rain in Peru is brought to the attention of the AFOSR, who allow an extension of the SOFDI grant. SOFDI is “stored” for the rainy season of December to March in Huancayo.

As noted above, the skies at Huancayo, Peru have been very cloudy in the summers of 2009 and 2010 [Figure 4]. This is due to an extended and strong La Nina/El Nino cycle that was associated with both increased cloud motion from the Pacific and also increased convection from the Amazon, as was observed in 1998 and 1999. Record rainfall was measured in August 2009; a month that is climatologically known for clear skies. As such, SOFDI data during these years was spotty at best, with almost no continuous daytime data [Gerrard, 2009; 2010].

Figure 4. Cloudy skies at the Huancayo observatory. The left photo was taken during a break in the August 2009 rains.

However, in August 2010, over a span of 1 week, daytime skies were clear enough to obtain both daytime and nighttime winds from Huancayo [Figure 5, Gerrard and Meriwether 2011]. We note that the consistent discrepancy between the SOFDI winds and HWM07 initially gave us large concern for our inversion methods, until we compared these data to recent equatorial zonal wind data from the CHAMP satellite [Liu et al. 2006; Liu et al. 2009]. Both CHAMP and SOFDI wind data compare very well and are in disagreement with HWM07 [and previous versions] winds. Because the HWM07 equatorial winds are highly influenced by the WINDI-spacecraft wind measurements from the 1990's, there are some potentially interesting issues that may need to be resolved influencing the geophysics between these two time periods. Moreover, we note that both CHAMP and SOFDI consistently see a wind reversal from westward to eastward around local noon, as opposed to the local evening. This appears to coincide with a thermally direct neutral wind circulation. The timing of this reversal is vitally important to current ESF formation theories and ongoing C/NOFS operational forecasts. With the initiation of another solar cycle, concurrent C/NOFS neutral wind observations and SOFDI observations will provide an exciting opportunity to investigate the role of the neutral winds on ESF.

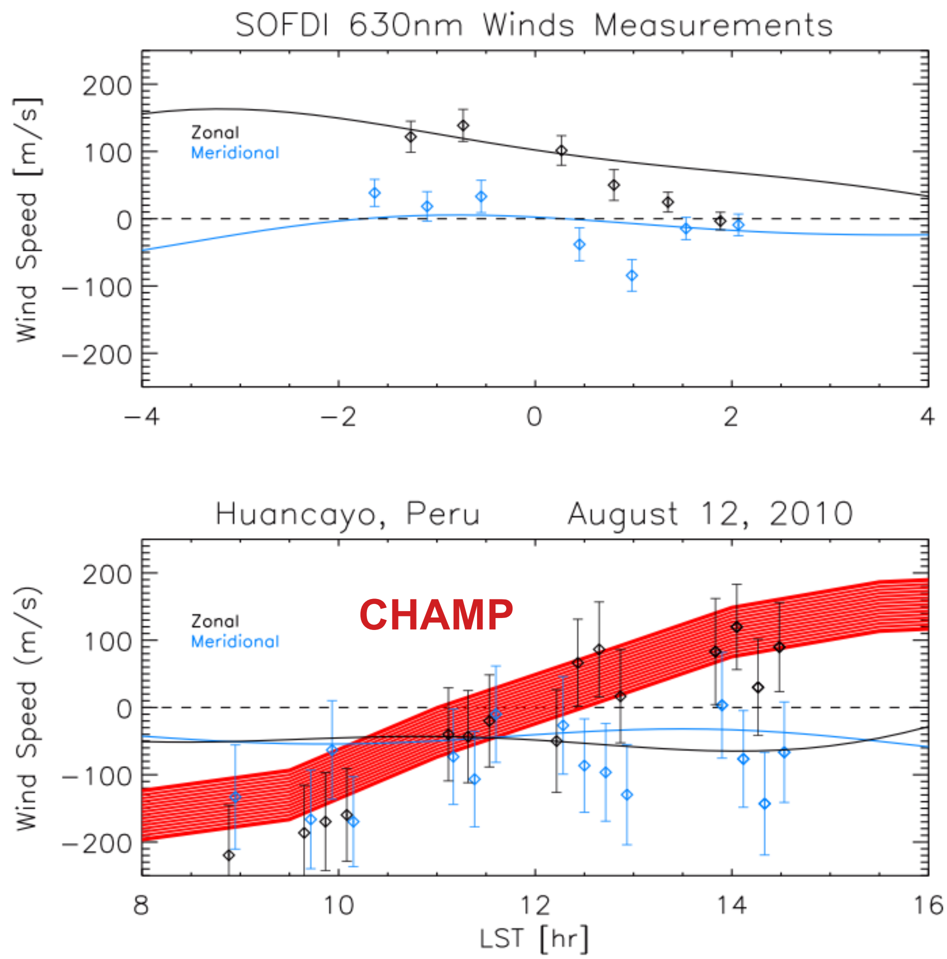

Figure 5. [top] Nighttime OI 630-nm thermospheric winds obtained by SOFDI, represented by diamond points with 1-sigma uncertainty bars, from the night of August 11 to August 12, 2010. The thin lines are from the HWM07 empirical model. Black data points/lines represent the zonal wind while blue data points/lines represent the meridional wind. [bottom] Daytime OI 630-nm thermospheric winds as measured from one field-of-view by SOFDI in Huancayo, Peru on August 12, 2010. The red band represents the 1-sigma geophysical variability of the CHAMP observations.

Clemson University

The work performed by Meriwether as part of the NJIT sub-contract award to Clemson University used the funding provided to construct a new nighttime-only Fabry-Perot interferometer observatory (referred to as MRH for MeriHill Observatory) that would be located at Jicamarca Radio Observatory (JRO) on a ridge overlooking the valley. It had been noted by people at JRO that this location would be above the inversion layer and so located where the skies tend to be quite clear at night even though in the valley below the haze and clouds prevent any successful observations of thermospheric winds and temperatures. The scientific motivation for wanting a FPI co-located with JRO was to achieve simultaneous measurements of the zonal wind and the zonal ion drift within the thermosphere region. Such simultaneous comparisons have been conducted using Arequipa FPI measurements but these are subject to the criticism that the measurements are not co-located. This observatory was commissioned for regular observations in August 2009.

Subsequent to this installation, it was then decided to build another nighttime-only Fabry-Perot interferometer observatory that would be located midway between Arequipa and Jicamarca. This observatory would be installed in a trailer that would allow relocation of the observatory whenever there might be cause to support a new location. The foremost purpose of building this observatory was to achieve the capability of common volume measurements of thermospheric winds and temperatures by overlapping line of sight measurements within a common volume. The advantage that this provides is the capability of observing within a small spatial region of ~25 km the fluctuations in the zonal, meridional, and temperature components of a gravity wave structure.

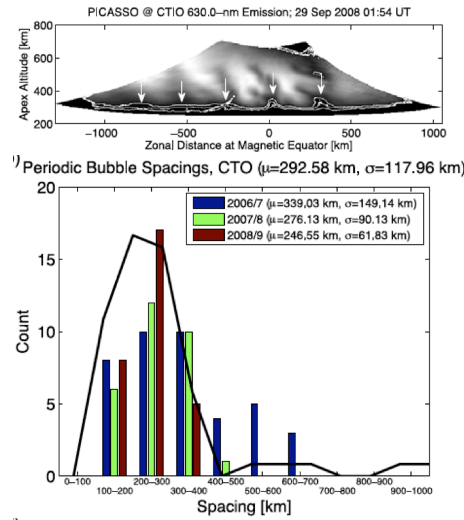

Figure 6. (top) Example of periodic EPB structure observed from Chile. (bottom) A histogram of the spacings observed in images obtained from Chile. The spacings are collected into 100-km wide bins. The dark line shows the distribution of horizontal wavelengths associated with secondary GWs measured by Vadas and Crowley (2010). After Makela et al. (2010).

The location of Nazca proved to be an excellent choice as the baseline separation was ideal, ~250 km, and the zenith angle needed for the overlapping line of sight measurements was reasonable, typically 40 to 50 degrees. This observatory (referred to as NZK for Nazca) was commissioned in May 2011, and simultaneous observations involving both MRH and NZK have been taking place since June, 2011. The FPI observatory located at Arequipa was not operational this year because the Andor camera needed to be repaired due to a vacuum seal leak, and no spare camera was available.

Both of these FPI observatories utilize a design of the FPI instrument in which field-widening is utilized to increase the instrumental sensitivity. Both observatories obtain interferograms that feature 10 rings rather than the 1 or 2 rings characteristic of the Arequipa FPI instrument. The use of the ICOS etalon in both instruments fitted in a very stable etalon mount provides a FPI instrument that is extremely stable with a characteristic drift of no more than several tens of m/s per night. The sensitivity is such that accurate measurements of 3 to 5 m/s are possible during the period of the MTM enhancement of intensity.

UIUC
In addition to the work performed at the University of Illinois in collaboration with Clemson University to analyze the thermospheric wind and temperature data collected at the new nighttime-only Peruvian FPI sites, the funding received from NJIT also supported the study of potential linkages between gravity waves and the development of equatorial plasma bubbles (EPBs) using two imaging systems. In Makela et al. (2010) we analyzed three-years of data collected from an imaging system located in Chile, whose field-of-view is magnetically conjugate to the primary region studied during the CORRER campaigns. Selecting nights exhibiting periodic bubble structures, we found that the distribution of spacings between bubbles was similar to that of the distribution of gravity wave wavelengths expected to be able to reach the lower thermosphere, where they could seed bubbles [Figure 6]. This work was carried out in collaborations with colleagues at Colorado Research Associates, NorthWeast Research Associates and Atmospheric and Space Technology Research Associates as well as an undergraduate and graduate student at the University of Illinois.

3. CORRER Campaigns of 2011

With the success of the August 2010 SOFDI observations, the continuing rise in solar activity [which would allow for the C/NOFS Neutral Wind Monitor (NWM) to be activated], and the relaxation of the strong La Nina/El Nino cycle, it was evident that an excellent opportunity was presenting itself for collaborative data collection in 2011. As such, the COoRdinated obseRvations of the Equatorial thermosphere [CORRER] campaigns were formulated to take place in early June (Campaign 1) and August (Campaign 2) of 2011 [Figures 7 and 8]. These particular periods were chosen so as to a) occur during the Huancayo clear season, b) occur during new moon, c) match the Jicamarca ISR operations schedules, and d) allow the participation of the C/NOFS NWM instrument (i.e., having perigee over the Peruvian sector). The goals of the campaigns were to a) form collaborative measurements to allow for inter-instrumental comparisons and validation, b) address the state of empirical thermospheric wind models over the South American magnetic equator over a full diurnal cycle, c) to allow for synoptic nighttime measurements of thermospheric winds, and d) Measure the state of the ionosphere-thermosphere in relation to ESF conditions.

The campaigns had a week-long focused period where all possible instruments were kept up and running, along with a support period immediately before and after the main focus for instrument calibration and testing.

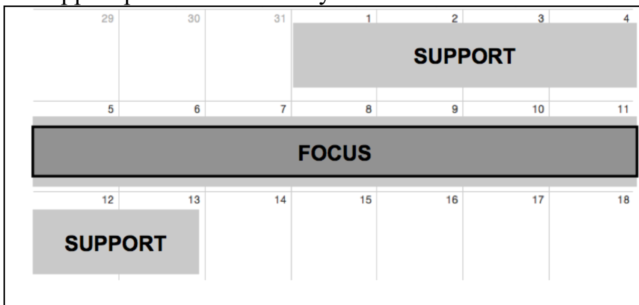

Figure 7. June 2011 CORRER 1 Campaign

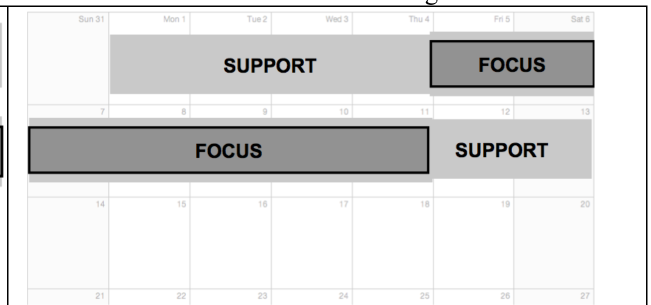

Figure 8. August 2011 CORRER 2 Campaign

In regards to SOFDI data collection, we had unprecedented coverage as is demonstrated in Figures 9 and 10.. The June campaign was marked early clouds, but later by very clear skies. Two site power failures, which turned off the SOFDI thermal controller, occurred during this period and made subsequent data processing more difficult because of etalon misalignment. The August campaign was also preceded by heavy rain, but then gave a period of uninterrupted data collection.

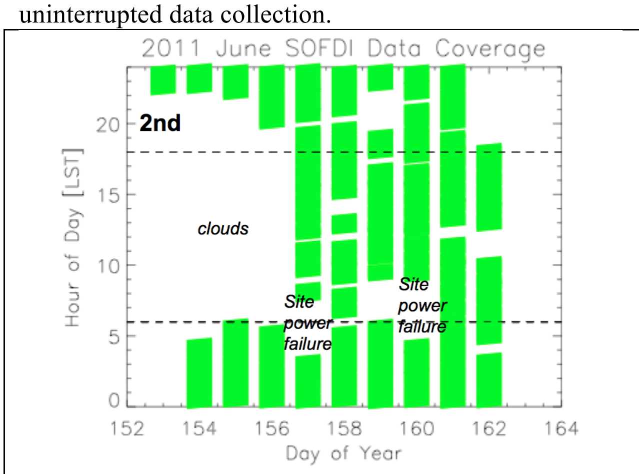

Figure 9. June 2011 CORRER-1 Campaign SOFDI coverage. The 2nd of June is denoted, along with explanations of data gaps. The dashed horizontal lines show local sunrise and sunset.

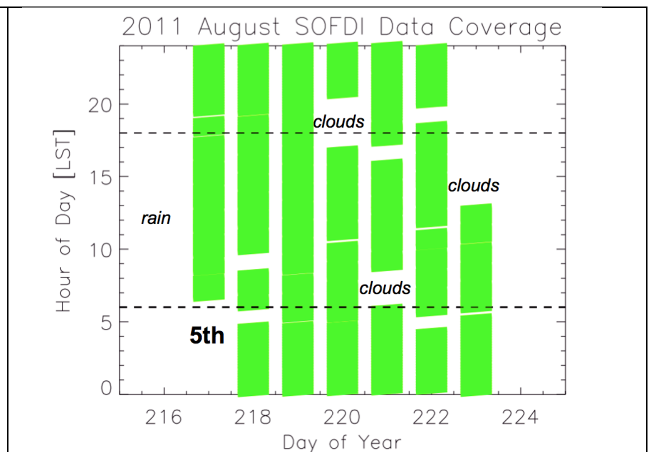

Figure 10. August 2011 CORRER-2 Campaign SOFDI coverage. The 5th of August is denoted, along with explanations of data gaps. The dashed horizontal lines show local sunrise and sunset.

On August 5th, the largest geomagnetic storm since 2006 occurred and was observed with all instrumentation. Figure 11 below shows how the SOFDI signal levels varied on the night of August 5-6, which was similar to other FPI instrumentation in Peru [and Brazil]. However, unlike the other instrumentation, SOFDI was able to make data measurements both before and after the "nighttime" period during the day of the 5th and 6th, respectively.

The C/NOFS NWM instrument was not active during the CORRER-1 campaign, but was later turned on for the CORRER-2 campaign. As such, we have collaborative data from both the spacecraft and the ground-based instrumentation. The Arequipa FPI was not operational during either CORRER-1 or -2, but the MRH and NZK systems were operating in a common volume data collection mode. The CTIO imager was also operational for both campaigns.

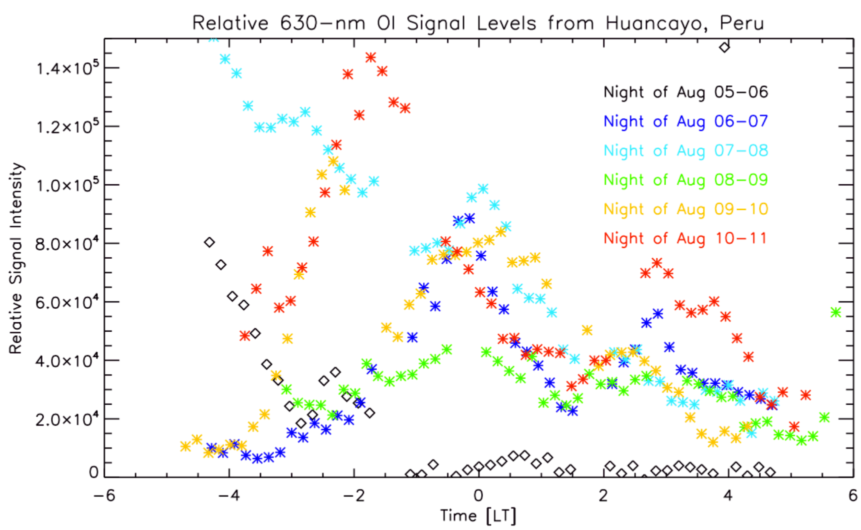

Figure 11. Nighttime OI signal levels from CORRER 2.

4. CORRER Results from SOFDI

Results from the CORRER campaigns were first presented in Gerrard et al. [2011]. As was presented therein, the following figures represent the reduced data for the zonal winds for the August CORRER-2 campaign. There is similar data for the meridional winds and for the CORRER-1 campaign. The following plots are of the form shown in Figure 12.

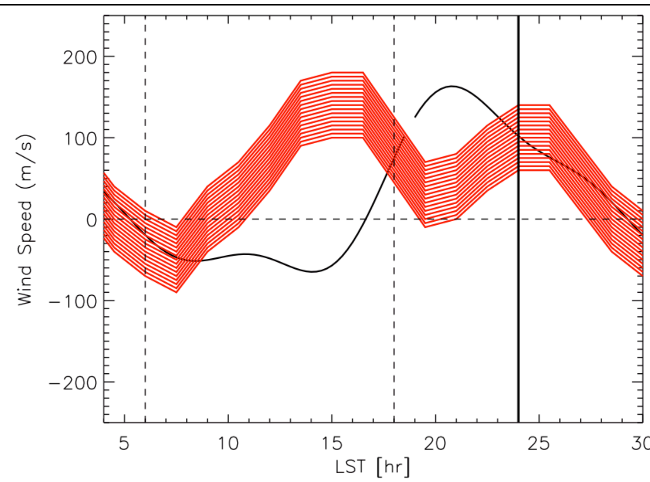

Figure 12. Plot format for subsequent figures.

where the red band(s) represent the equinox CHAMP zonal wind climatology [with variability] from Liu et al. [2006], the black line represents the August zonal wind from the empirical climatology of HWM07 [Drob et al., 2008], the vertical dashed lines represent the sunrise/sunset, the horizontal dashed line is the zero-wind line, and the solid vertical line is local midnight.

Raw data, as seen in Figure 13 for August 9th, show data extending throughout the day, through evening twilight, and into the nighttime period. The measurements showing a zonal wind reversal from +200 m/s to -100 m/s at twilight is real and has been verified using a variety of different inversion methods. Furthermore, such an unusual data value is likely more representative of the measurement technique (e.g., what region of the equatorial vortex [Kudeki et al. 2007] is being sampled?). These raw data are binned into 1-hour data realizations [Figure 14], where the one standard deviation bars express both statistical uncertainty and geophysical variability. No uncertainty bar is shown for 1-hour binned standard deviations of under 10 m/s.

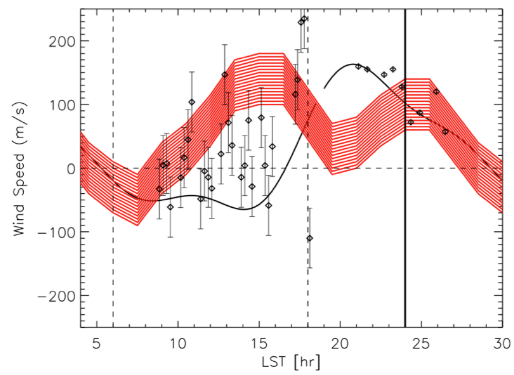

Figure 13. Raw data from SOFDI on August 9.

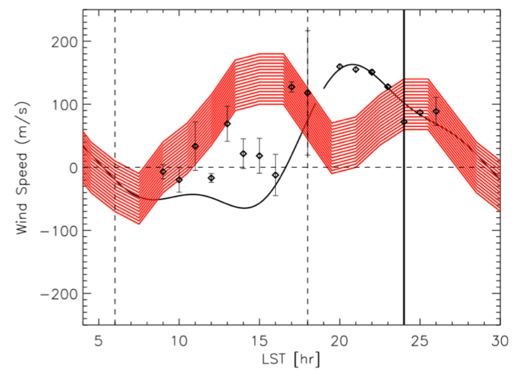

Figure 14. One-hour binned data from August 9.

For the CORRER-2 campaigns, the entire host of 1-hour binned zonal wind data is shown in Figures 15 and 16.

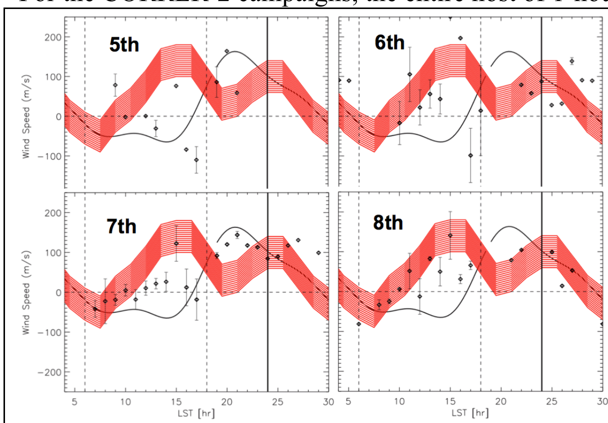

Figure 15. One-hour binned data from SOFDI for the August 5-8 period of CORRER-2.

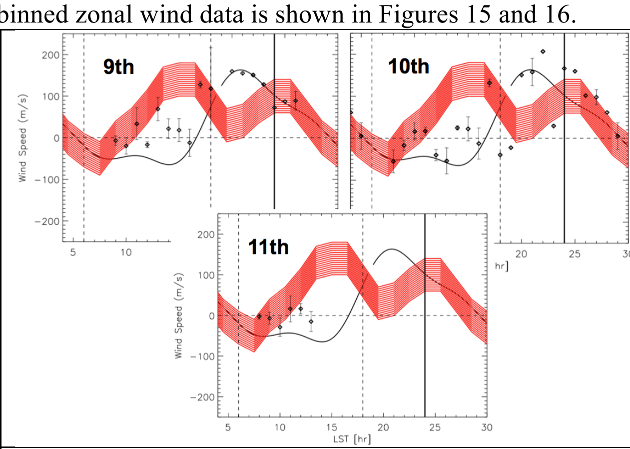

Figure 16. One-hour binned data from SOFDI for the August 9-11 period of CORRER-2.

Averaging these 7 days of data leads to a "quasi-climatology" shown in Figure 17.

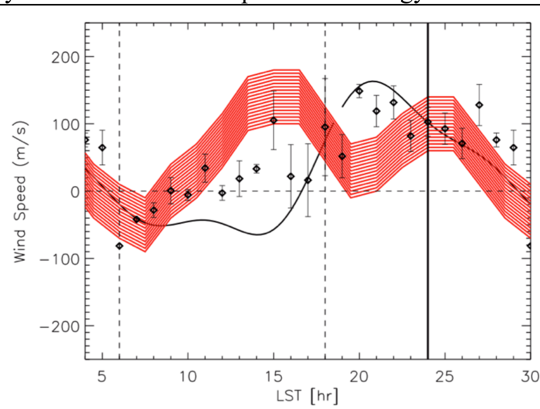

Figure 17. Averaged zonal wind data results from CORRER-2

where we see that the SOFDI data follows the HWM07 and CHAMP nighttime winds well, but exist somewhere between the CHAMP and HWM07 winds during the daytime. Recent correspondence with the CHAMP team indicate that there were errors made in the Liu et al. [2006] study and there has been a rather large reduction in the peak eastward daytime zonal wind values, making their climatology fall more inline with our measurements.

On inspection of the data set in its entirety, we see there is a lot of zonal wind variability in the afternoon sector and into twilight. *As such, synoptic forecasts of ESF cannot make use of wind climatologies.* Thus, SOFDI-like measurements will be crucial in understanding the role that the local winds play in ESF generation.

We further note that these are the first ground-based, continuous 24-hour, measurements of the thermospheric neutral winds. Furthermore, these are the first such daytime winds to be measured from the magnetic equator, and in conjunction with ISR and NWM measurements. These data will be published in JGR in a manuscript that is currently in preparation.

4.1. Comparative SOFDI-NWM Measurements

As mentioned above, the C/NOFS satellite NWM instrument was active during the CORRER-2 campaign. After the campaign, we were informed that the spacecraft would not have been able to make any wind measurements, but for the fact that there was this large geomagnetic storm on August 5. During this storm period, the thermospheric densities increased enough such that the NWM instrument could make meridional wind measurements. These are shown in Figure 18.

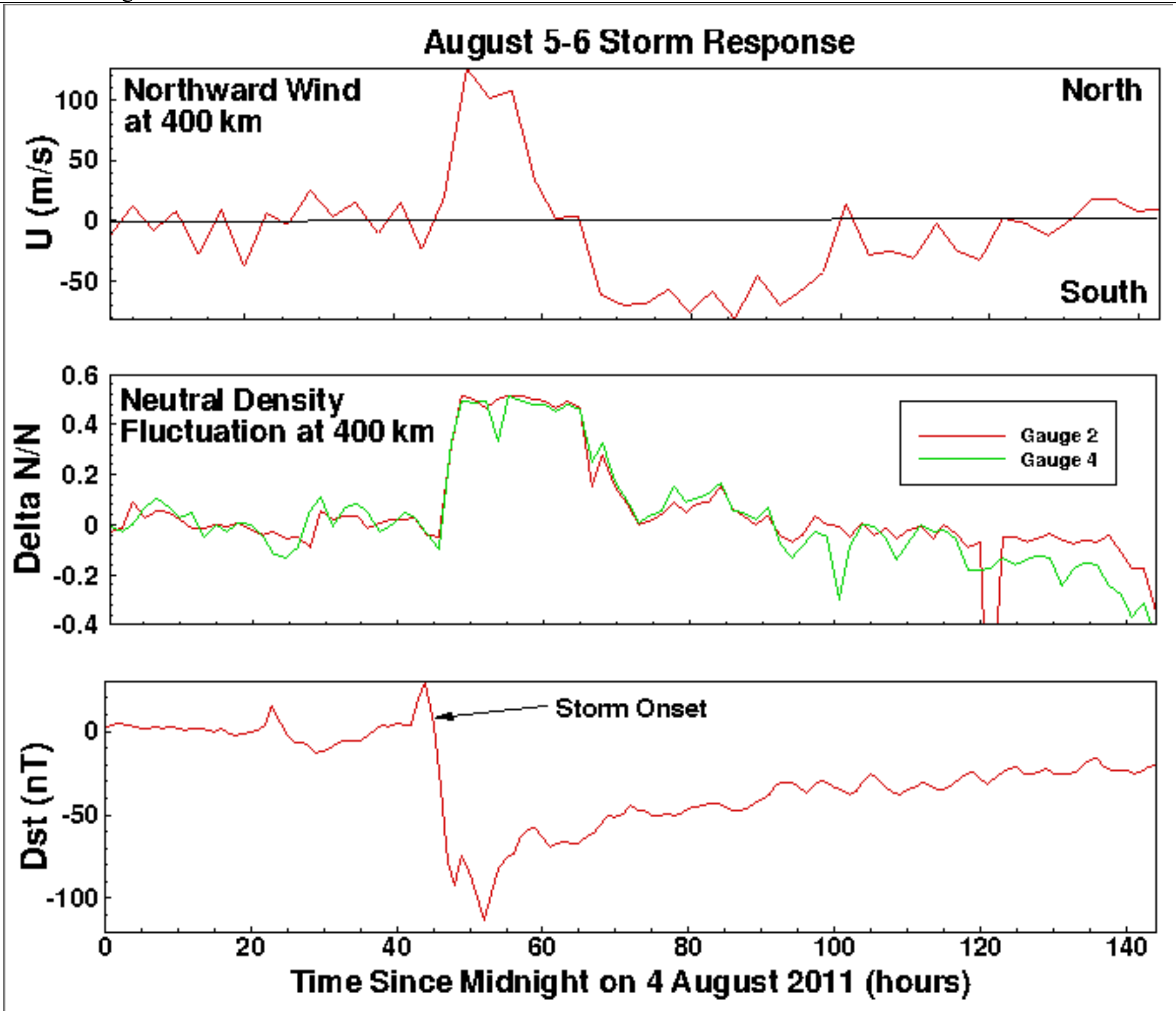

Figure 18, obtained from Dr. Greg Earle, showing the NWM measurements (top and middle panels) during the August 5 geomagnetic storm period of CORRER-2 (with Dst on the bottom panel).

These NWM meridional winds, measured at 400-km altitude, can be compared to SOFDI meridional and zonal winds at 250-km altitude over the same period in Figures 19 and 20.

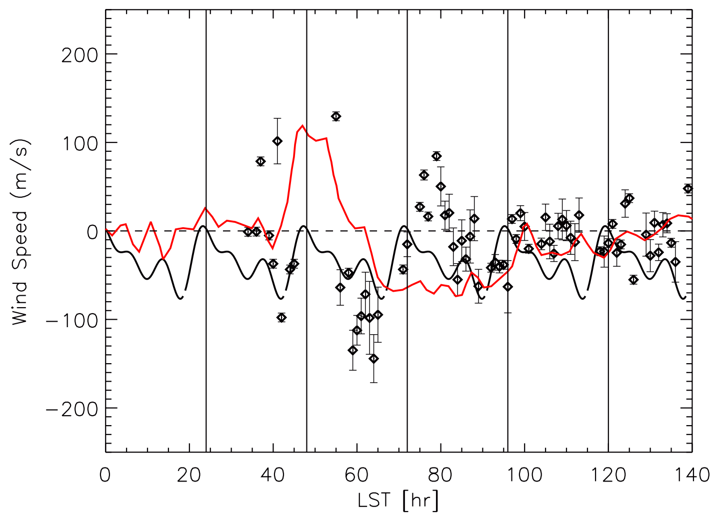

Figure 19. SOFDI meridional winds [data points] at ~250-km and HWM07 meridional wind climatology, as measured from midnight on August 4. The red line represents the meridional NWM measurements at ~400-km from Earle (above).

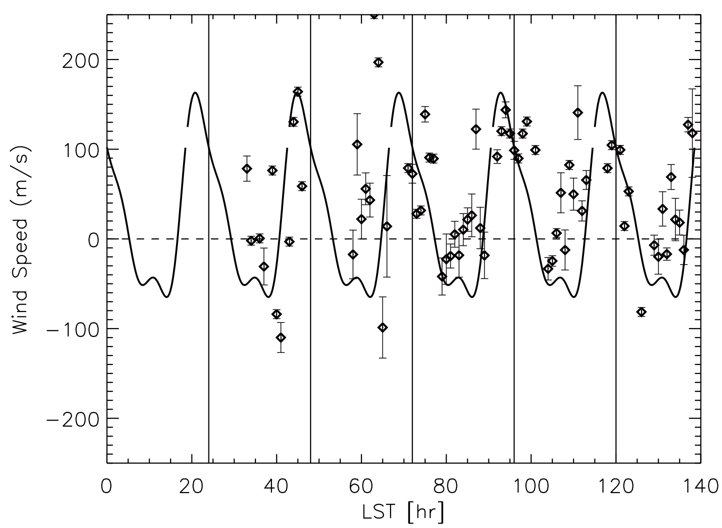

Figure 20. SOFDI zonal winds [data points] at ~250-km and HWM07 zonal wind climatology, as measured from midnight on August 4.

In regards to the meridional winds of Figure 19, we note that SOFDI was not able to take measurements during the nighttime period of August 5-6, indicated by hour ~48, because the storm drove a global thermospheric circulation that raised the local thermosphere, quenching the OI emission. This loss of OI emission is also seen in Figure 11 and at all FPI stations in South America. As such, there are only a few measurements [indicated by one data point in 1-hour binned data of Figure 19] that corroborated strong northward wind measurements. However, the period immediately after the strong northward wind [during the day, when the OI production increases] was measured and thus both NWM and SOFDI were able to measure the equatorial response of the geomagnetic storm over a number of days.

From SOFDI measurements of the meridional 250-km altitude wind, we see there is a damped oscillator response that dies out over the course of ~40-hours. The dampening is much stronger at 400-km, likely the result of the increased viscosity at the higher altitude. The response is much weaker in the zonal winds, except for the very strong zonal winds occurring between 60-LST and 72-LST. After 96-LST, the signature/impact of the storm has disappeared. These data are currently being studied and are the subject of a paper in preparation.

4.2. Early CU and UIUC Work Stemming from CORRER

The FPI measurements from the two CORRER campaigns provided the opportunity to do interesting science in several spin-off investigations. One study that has been undertaken is the comparison for selected months from 2011 of the monthly climatologies of the winds and temperatures observed at Huancayo, NZK, and MRH with the monthly climatologies of the winds and temperatures obtained by two FPI observatories located in the northeastern corner of Brazil. These results have also been compared with the model predictions generated by the Whole Atmosphere Model (R. Akmaev, T. Fuller-Rowell). The results obtained (presented at the AGU 2011 fall meeting) have been quite favorable suggesting that the WAM does a reasonable job of capturing the physics of the tidal forcing of the equatorial thermosphere region.

Another study that will be presented at the ISEA meeting at Paracas is the review of the surprising events that were observed for two nights of the August CORRER campaign, i.e., the results of 9-10 August and 10-11 August, 2011. During the evening near 2130 LT a sudden dropout of the eastward zonal wind was observed along with a reduction of the zonal ion drift. This sudden reduction was also observed by the SOFDI instrument at Huancayo. There is no good explanation for what happened and consequently, we felt that these two events should be investigated more thoroughly to see if an understanding as to what might have happened can be achieved.

Although the primary focus region for the work performed for NJIT was the South American sector, following up on the work discussed above, we analyzed data obtained from an imaging system located in Hawaii to study a different aspect of gravity wave seeding of EPBs. Taori et al. (2010) present the results of studying gravity wave magnitudes observed in two mesospheric layers. On nights when the magnitude of the gravity wave amplitudes increased with altitude, EPBs were observed by the imaging system in the ionosphere. On nights when the magnitude of the gravity wave amplitudes decreased with altitude, no EPBs were observed. These results suggest that wave growth in the mesosphere is an important parameter in understanding what nights will exhibit the growth of equatorial plasma bubbles. This work was carried out in collaboration with colleagues at the National Atmospheric Research Laboratory in India and Utah State University.

5. Companion Research

NJIT Ph.D. student Zhaozhao Li was, in part, supported on this grant starting in 2008. Li's work has been focused on the study of Doppler ducted gravity waves in the upper troposphere/lower stratosphere as applied to the community's understanding of mesospheric fronts and/or bores. Li used existing mesosphere-stratosphere-troposphere (MST) wind measurements from Jicamarca, Peru, to so a study of Doppler ducted waves and their characteristics, and furthermore performed numerical simulations in an effort to mimic the observed features. We found persistent jet structures along the zonal and meridional fields that were believed to be caused by stationary gravity waves generated by the topography around Jicamarca [Figure 21]. Though a fair replication of the observed ducted structure in the numerical model was found [Figure 22], the observed period of ~90-min was nonetheless longer than anticipated and raises concern as to the specific physical nature of the observed structures.

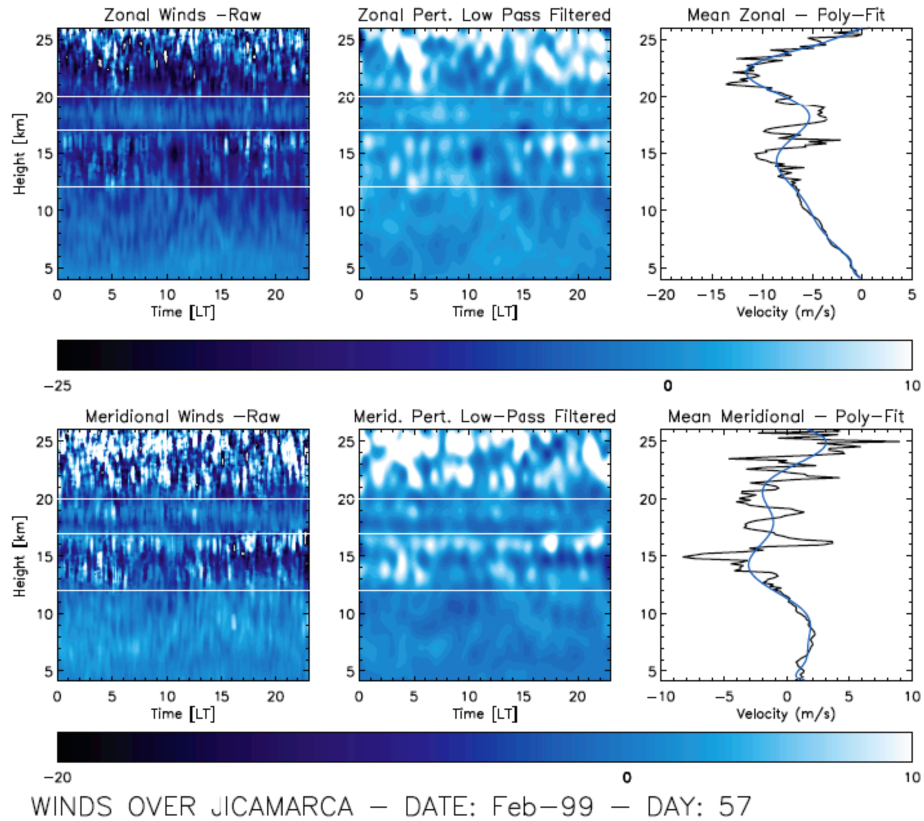

Figure 21. Contour plots showing MST winds measured over Jicamarca. The left column shows the raw zonal (upper row/panel) and meridional (lower row/panel) wind measurements, the right column shows the daily mean winds with a polynomial fit, and the center column shows the low-pass filtered perturbations from the estimated daily mean vertical wind profile. Note that the color scale for the zonal winds is not the same as the color scale for the meridional winds. Horizontal white bars represent bounding heights of high SNR.

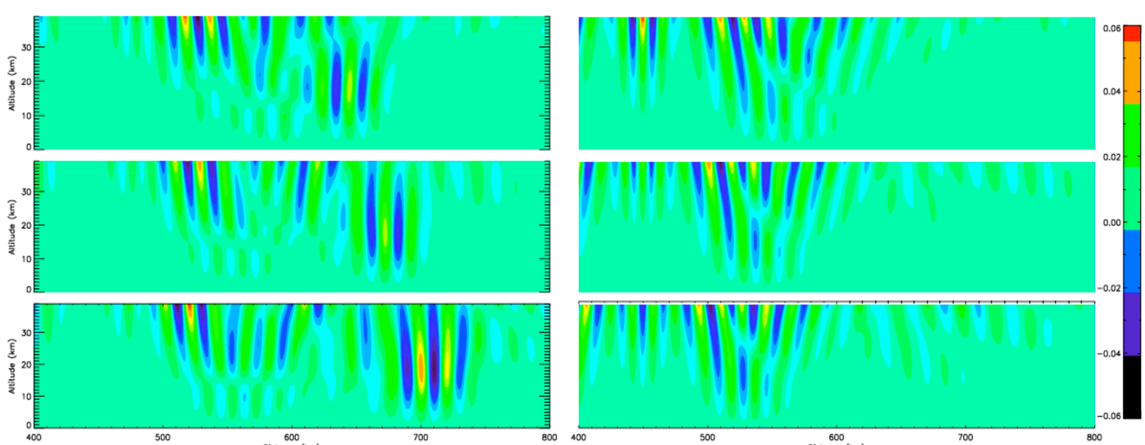

Figure 22. Vertical velocity simulation results. The left column shows the results of the simulation with a Doppler duct located at ~15-km for three progressively increasing time intervals of 12000-s/3.33-hr, 14000-s/3.89-hr, and 16000-s/4.44-hr. The right column shows the results from the simulation without a Doppler duct at the same time intervals. Color-bar units are in m/sec.

Given the high quality of the observations, we demonstrated that continued analysis of this data set and concurrent modeling will allow for a better understanding of Doppler ducts at high spatial and temporal resolution which can ultimately be applied to studies of mesospheric ducts and bores. Li will be obtaining his Ph.D. in May 2011.

6. Conclusions

In summary, the funding received from AFOSR for this grant supported the initial deployment and operations of a suite of instruments designed to study the equatorial ionosphere-thermosphere system. The flagship instrument was SOFDI, which has demonstrated its ability to make high quality, continuous measurements of the thermospheric winds. The activities performed under this grant have also achieved the operations of two new Fabry-Perot observatories located at Jicamarca and at Nazca (a desert location featuring clear skies for most of the year). As the period of solar maximum activity is approached, the data products obtained by SOFDI, NZK, MRH, and also Arequipa should be very useful for interpreting the new phenomena expected to occur in the next years.

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