Forecasting of Optical Turbulence in Support of Realtime Optical Imaging and Communication Systems

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ABSTRACT

Optical turbulence (OT) acts to distort light in the atmosphere, degrading imagery from large astronomical and imaging telescopes and possibly reducing data quality of free space optical communication (FSOC) links. Some of the degradation due to optical turbulence can be corrected by adaptive optics. However, the severity of optical turbulence, and thus the amount of correction required, is largely dependent upon the turbulence at the location of interest. In addition, clouds, precipitation, and inhomogeneities in atmospheric temperature and moisture all have the potential to disrupt imaging and communications through the atmosphere. However, there are strategies that can be employed to mitigate the atmospheric impacts. These strategies require an accurate characterization of the atmosphere through which the communications links travel. To date these strategies have been to climatological characterize OT and its properties. Recently efforts have been developed to employ a realtime forecasting system which provides planners useful information for maintaining links and link budgets.

The strength of OT is characterized by the refractive index structure function Cn^2, which in turn is used to calculate atmospheric seeing parameters. Atmospheric measurements provided by local instrumentation are valuable for link characterization, but provide an incomplete picture of the atmosphere. While attempts have been made to characterize Cn^2 using empirical models, Cn^2 can be calculated more directly from Numerical Weather Prediction (NWP) simulations using pressure, temperature, thermal stability, vertical wind shear, turbulent Prandtl number, and turbulence kinetic energy (TKE). During realtime FSOC demonstrations, in situ measurements are supplemented with NWP simulations, which provide near realtime characterizations and forecasts of the Cn^2, the Fried Coherence Length (r_o), and time-varying, three-dimensional characterizations of the atmosphere. The three dimensional Weather Research and Forecasting (WRF) model is used to produce characterizations and forecasts of OT. These forecasts are used for planning FSOC experiments in the 3-24 hour range. The WRF model is configured to run at up to 300 meters horizontal resolution over a 250km by 250km horizontal domain. The vertical resolution varies from 25 meters in the boundary layer to 500 meters in the stratosphere with over 130 vertical levels. The model top is 20 km in altitude. The model is run up to twice per day and generates forecasts out to 27 hours.

The WRF model has proven to be a valuable tool for link characterization and forecasting, since it can identify thin relatively layers of optical turbulence that are not represented by standard empirically derived Cn^2 profiles. Results show that WRF simulations can accurately predict upcoming turbulence events that may degrade system performance. Demonstrations of these forecasts will be shown at the conference. The near realtime simulations of OT are performed using the Maui High Performance Computing Centers (MHPCC) Mana cluster.
Keywords: optical turbulence, optical communications, WRF, NWP

1. INTRODUCTION

Accurate atmospheric forecasting and characterization are important parts of the FOENEX demonstrations. This includes direct measurements of meteorological and turbulence parameters. However, these direct measurements provide an incomplete picture of the atmospheric conditions along the communications links. For example, a scintillometer provides a measure of C_n^2 at one or both ends of a link, but cannot measure the turbulence along the entire path, potentially missing elevated layers of optical turbulence that might impact the link. Likewise, a weather station is limited to a single location. A vertical profile of the atmosphere can be determined using a radiosonde or thermosonde, but it is limited to the path the balloon takes as dictated by the wind. To supplement these *in situ* measurements during FOENEX, NWP simulations were used to forecast atmospheric conditions in advance of flight demonstrations, as well as to characterize parameters such as C_n^2, r_0, temperature, and moisture along the links for post-flight analysis. Current atmospheric conditions, weather forecasts, and decision aids were provided to the FOENEX test director via a website, with NWP ensemble-based decision aids automatically updated four times daily. After each experiment, first-look data products were computed along the lines-of-sight (LOS) between all FOENEX communications nodes. These included C_n^2 every 100 meters along each LOS, r_0 for each LOS, as well as vertical cross-sections of the temperature, moisture, pressure, and winds for RF link analysis.

This paper discusses the models and techniques used to provide the NWP-based atmospheric forecasting and characterization for FOENEX. First, a brief description of the concept of forecasting using NWP ensemble models is discussed. Second, a brief description of optical turbulence modeling with the WRF model is given. Finally, examples of WRF-based data products and ensemble-based decision aids are presented. As of the writing of this paper, FOENEX link performance data is not yet available for a detailed comparison with atmospheric characterization from the WRF simulations.

2. METHODOLOGY

Northrop Grumman Information Systems (NGIS) provided atmospheric modeling and characterization support to FOENEX in two ways. The first was to forecast atmospheric conditions in advance of FOENEX flight demonstrations. This was done using NWP-based ensemble forecasts, with decision aids updated on a website four times per day. Current meteorological data including satellite imagery, radar data, and surface observations were also provided on the website. The second area of support was high-resolution atmospheric characterization of all lines-of-sight between all FOENEX communications nodes using the WRF model. WRF was used to simulate C_n^2, r_0, temperature, and moisture along the links for post-flight analysis. Initial products were posted to the FOENEX website as first-look analyses within hours of the flight position data being provided. These two main areas of support are described in more detail in the following sections.

2.1 Ensemble Weather Forecasting

Numerical weather prediction has been used since the 1960s for forecasting the weather. One requirement of a weather forecast, of course, is that it be issued ahead of time. To accomplish this, NWP models must run faster than real-time. In the early days of NWP development, models were fairly basic, and had to be run at coarse resolution. As computers have become faster, NWP models have gotten more sophisticated, and are being run at much higher resolution. Until recent years, NWP forecasts were made with a single model run, based on a single set of initial conditions. Today, forecasters use multiple model realizations, where each run differs in some way. This is referred to as an *ensemble* forecast, and is generated by several models that differ in their numerical methods and parameterizations. Additionally, perturbations of the initial atmospheric conditions of the models are introduced, representative of uncertainty in measuring the properties of the atmosphere. The result is an ensemble of solutions from which probabilistic forecasts can be made. This type of forecast can be used to predict the probability of clouds, winds, temperature, and other parameters of interest from the surface to well above the FOENEX flight levels.

For FOENEX, forecasts out to 87 hours were made using the Short Range Ensemble Forecast (SREF) and forecasts out to five days were made using Global Ensemble System (GENS). The SREF consists of 21 ensemble members, while the GENS forecast ensemble is made up of 22 members. The SREF and GENS are run four times daily by the National Centers for Environmental Prediction (NCEP). These ensembles produce dozens of output parameters, from which a few were selected to support FOENEX flight decisions. These include the probability of clouds at different levels in the atmosphere, winds at the surface and at flight level, probability of precipitation, humidity, and temperature. Software was created to automatically extract these parameters from the ensemble output, compute probabilities, make plots, and display them on the FOENEX website four times daily.

2.2 WRF Simulations

2.2.1 Optical Turbulence Modeling

One of the goals of FOENEX was to evaluate the link performance under a variety of atmospheric conditions. For the optical link, turbulence is a major factor in the link performance. The strength of optical turbulence can be characterized by the refractive index structure function, C_n^2, which can be calculated from NWP simulations. The three-dimensional optical turbulence modeling in support of FOENEX was performed using version 3.2 of the Weather Research & Forecasting (WRF) model, developed jointly between the National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA). WRF is a mesoscale NWP model developed for the prediction of weather, and is routinely used by the National Weather Service and other forecasting services. The model is based on the Navier-Stokes equations which are solved numerically on a three dimensional grid. The model simulates four basic atmospheric properties – wind, pressure, temperature, and atmospheric water vapor. All other variables are derived from these four parameters. Since standard NWP models such as WRF do not calculate C_n^2, modifications have been made to the baseline WRF model as described in [1]. This modified version of the WRF model is used to calculate C_n^2 in the planetary boundary layer and free atmosphere, allowing for point-to-point estimates of the Fried Coherence length (r_0) and other seeing parameters.

To support the FOENEX flight demonstrations, the WRF model was run on a daily basis during the period of January – March, 2012. The WRF model was configured to run at very high horizontal and vertical resolution relative to standard daily runs used for standard weather forecasting. The horizontal resolution was set at 1 km. The number of vertical grid points was 139, with the sigma levels set to approximate 50-m resolution below 2 km above ground level (AGL), 125 m for 2–12 km AGL, and 500 m up to the model top (50 millibars). The exact size of the WRF domain was set such that all possible links between the FOENEX communications nodes were fully contained within its boundaries. The largest domain size for WRF was 350×275 km. Each WRF model run was initialized daily at 1200 UTC from the 12-km North American Mesoscale (NAM) atmospheric analysis produced by the National Weather Service. An example of a WRF domain used during the FOENEX demonstrations is shown in Figure 1.

Figure 1 WRF domain used for during FOENEX Phase 1 demonstrations

2.2.2 Other Atmospheric Parameters

The RF link can be affected by the refractive index of the atmosphere. To characterize this during the FOENEX demonstrations, vertical cross-sections of temperature, moisture, pressure, and wind speed and direction were created from the WRF simulations. For the FOENEX flights, these vertical cross-sections were computed every 5 minutes between the ground site and the aircraft. This provides a high-resolution characterization of the structure of the atmosphere to be used to compare with the RF link performance data.

3. RESULTS AND ANALYSIS

3.1 Ensemble Weather Forecasting

Several parameters were important to the decision as to whether to conduct FOENEX flight demonstrations when planned. Clouds prevent successfully demonstrating the optical links. Strong winds can pose risks to flights. Good forecasts of favorable as well as unfavorable atmospheric conditions proved valuable to the FOENEX team. As such, predictions of clouds and winds, as well as precipitation, moisture, and temperature were provided four times daily. The cloud forecasts were probabilistic forecasts from the SREF and GENS ensemble forecasts. Cloud forecasts were shown in two ways. The first cloud forecast presented a geographic forecast of clouds below the flight level. Cloud probability was plotted in four categories: very low, low, moderate, and high as shown in **Figure 2**. These plots showed the cloud forecast every three hours out to 87 hours. The forecast in **Figure 2** indicates a high probability of mostly cloudy conditions early in the forecast period, with skies clearing over most inland areas between 0800 and 1100 PDT on March 19.

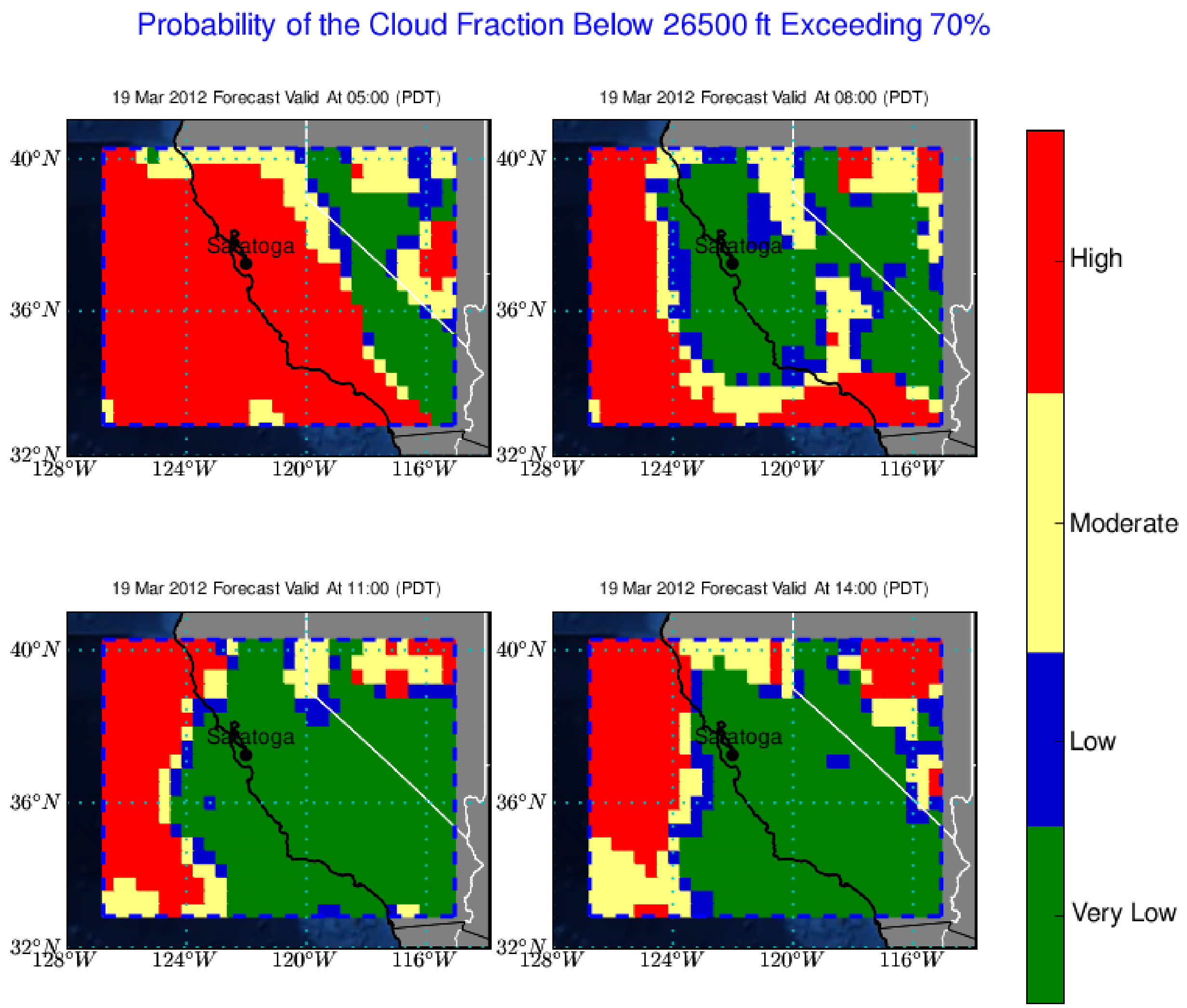

Figure 2 Geographic cloud forecast of clouds below 26500 feet above sea level derived from SREF cloud products. Areas shown in green have a very high probability of being cloud-free. Areas shown in read have a high probability of being cloudy.

The second way the cloud forecast was presented showed the ensemble average cloud fraction as a function of cloud layer: low, middle, and high. An example of this is shown in **Figure 3**. This plot shows the fractional cloud coverage at three levels in the atmosphere (low, middle, high), as well as the total combined cloud fraction. The percentage of the circle that is colored black is equal to the cloud fraction at that particular level. An unfilled circle indicates a cloud-free sky. A completely filled circle indicates an overcast sky.

- Low clouds: between the surface and 640 mb (below about 12000 feet AMSL in the "Standard Atmosphere")
- Middle clouds: between 640 and 350 mb (about 12000 - 26000 feet AMSL)
- High clouds: above about 26000 feet AMSL

Low, middle, and high are somewhat qualitative terms. The average cloud base and top heights are shown in the fourth plot. The height of the cloud base is shown by the red line, while the height of the cloud top is given by the blue line. The final (bottom) plot in the meteogram shows the accumulated precipitation. This is the amount of the liquid equivalent (rain or melted snow) precipitation that fell during the previous three hours.

For this particular SREF forecast, the first 12 hours are forecast to be relatively cloudy at all levels (a deep system). Mostly clear conditions are forecast for 0600 PDT March 19 – 1500 PDT March 19, followed by low clouds 1800 PDT March 19 – 0000 PDT March 21, and so on.

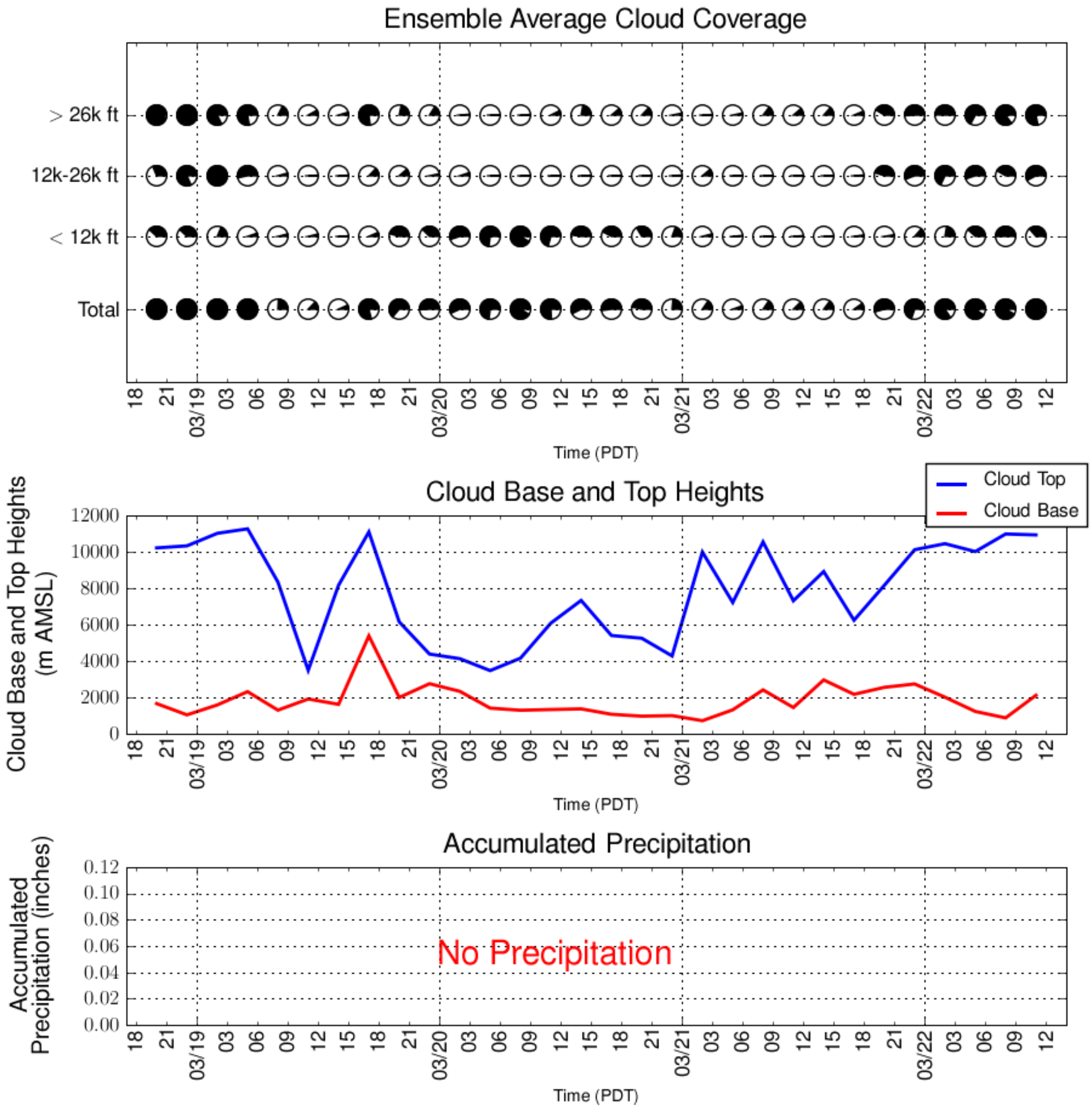

Figure 3 Forecast of clouds fraction for low, middle, and high clouds (top); ensemble average cloud base and top heights, and precipitation derived from the SREF 87 hour forecast.

Plots of the temperature, winds, and 0° isotherm were also provided four times daily for the SREF and GENS forecast ensembles. **Figure 4** shows temperatures warming over the 87 hour forecast beginning on March 19. The bottom plot in Figure 4 shows very strong upper level winds early in the forecast period, with winds out of the north-northwest with speeds of 120 knots at 25000 feet AMSL. Near-surface level winds (10 meters above the surface) are generally forecast to be light during the forecast period.

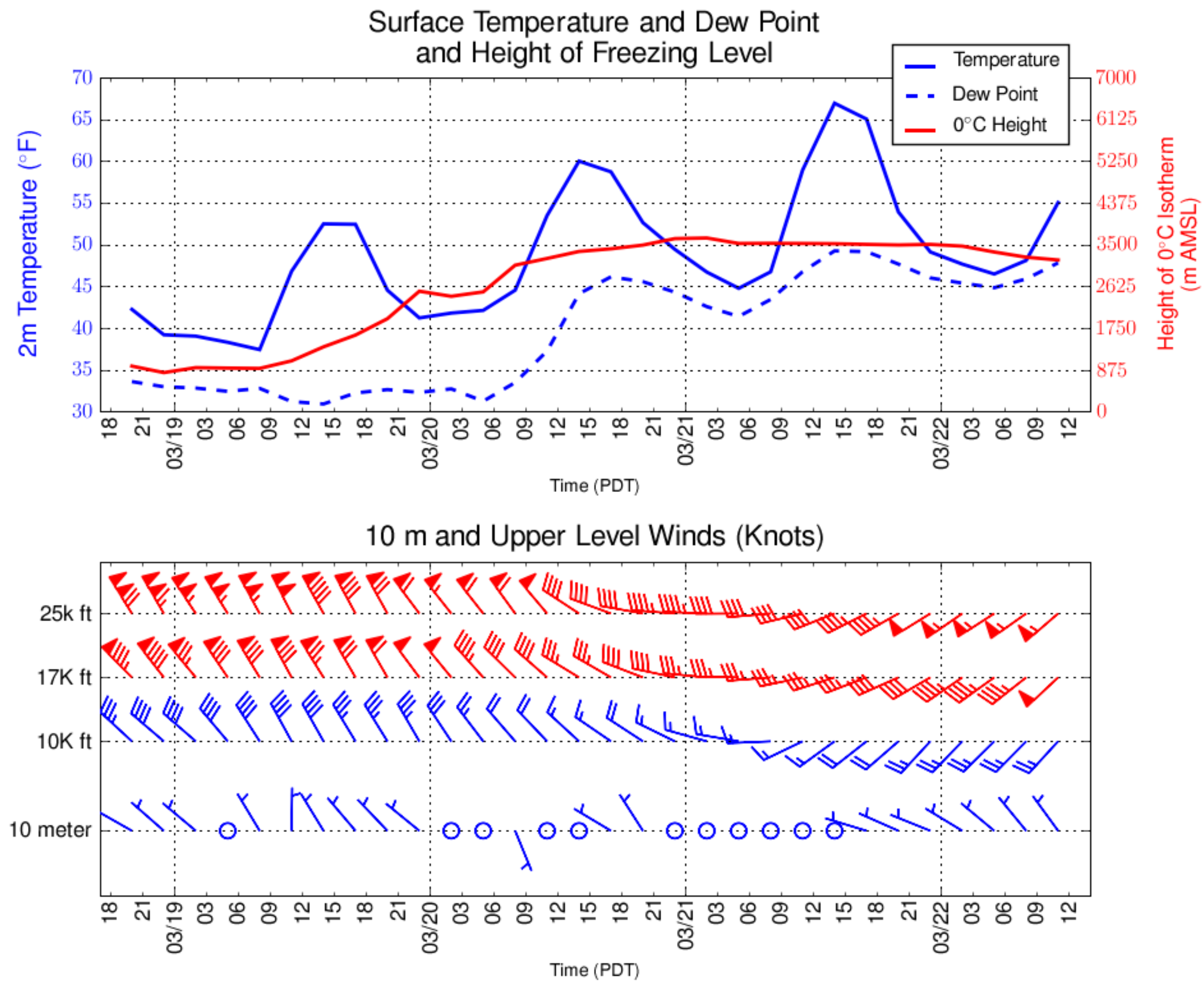

Figure 4 Forecasts of temperature, dew point temperature, 0° isotherm height (top) derived from the SREF ensemble forecast. Wind speed and direction are shown in the bottom plot at 10 meters above the surface, 10000, 17000, and 25000 feet above sea level.

3.2 WRF Products and Analysis

WRF was run daily to support all FOENEX flight experiments. After each flight, the aircraft position was used to compute C_n^2 along each possible link between the communications nodes for every second of the flight. The value of C_n^2 every 100 meters along the link was written to a file, along with the range and height above the terrain. Additionally, r_0 was calculated for each link at each time step. These values were plotted and provided as a first-look analysis within hours of receiving the aircraft position data.

An example of one of the products is shown in **Figure 5**. In these figures, the value of r_0 is shown in several color-coded ranges. Very low r_0 values (< 1 cm) are shown in red, with successively increasing values shown in orange, yellow, blue, and green (> 6 cm). The values of r_0 shown are calculated from the WRF-derived C_n^2 by the following equation, where λ is 1550 nm.

$$r_0 = \left[0.423 \left(\frac{2\pi}{\lambda} \right)^2 \int_0^\infty C_n^2(z)\, dz \right]^{-3/5} \qquad (1)$$

A time series of the values of r_0 is shown in **Figure 6**. The large values of r_0 are computed when the path length is very short early in the time series. The values of r_0 vary throughout the flight as the path length and turbulence conditions change.

While it is not expected that WRF can predict extremely accurate values of C_n^2 for the FOENEX experiments, WRF can capture transient features in the atmosphere that are not well-represented by traditional Cn2 models such as HV57 or the newer HAP model. **Figure 7** shows an example of an elevated area of intense turbulence associated with an elevated temperature inversion common in the valleys of California. This is the true value of NWP-based forecasting. NWP models such as WRF can be used to simulate the atmosphere, including turbulence, in three dimensions in the absence of direct measurements. When used in conjunction with direct measurements, the WRF-derived values can be validated, or perhaps tuned to particular locations and environments.

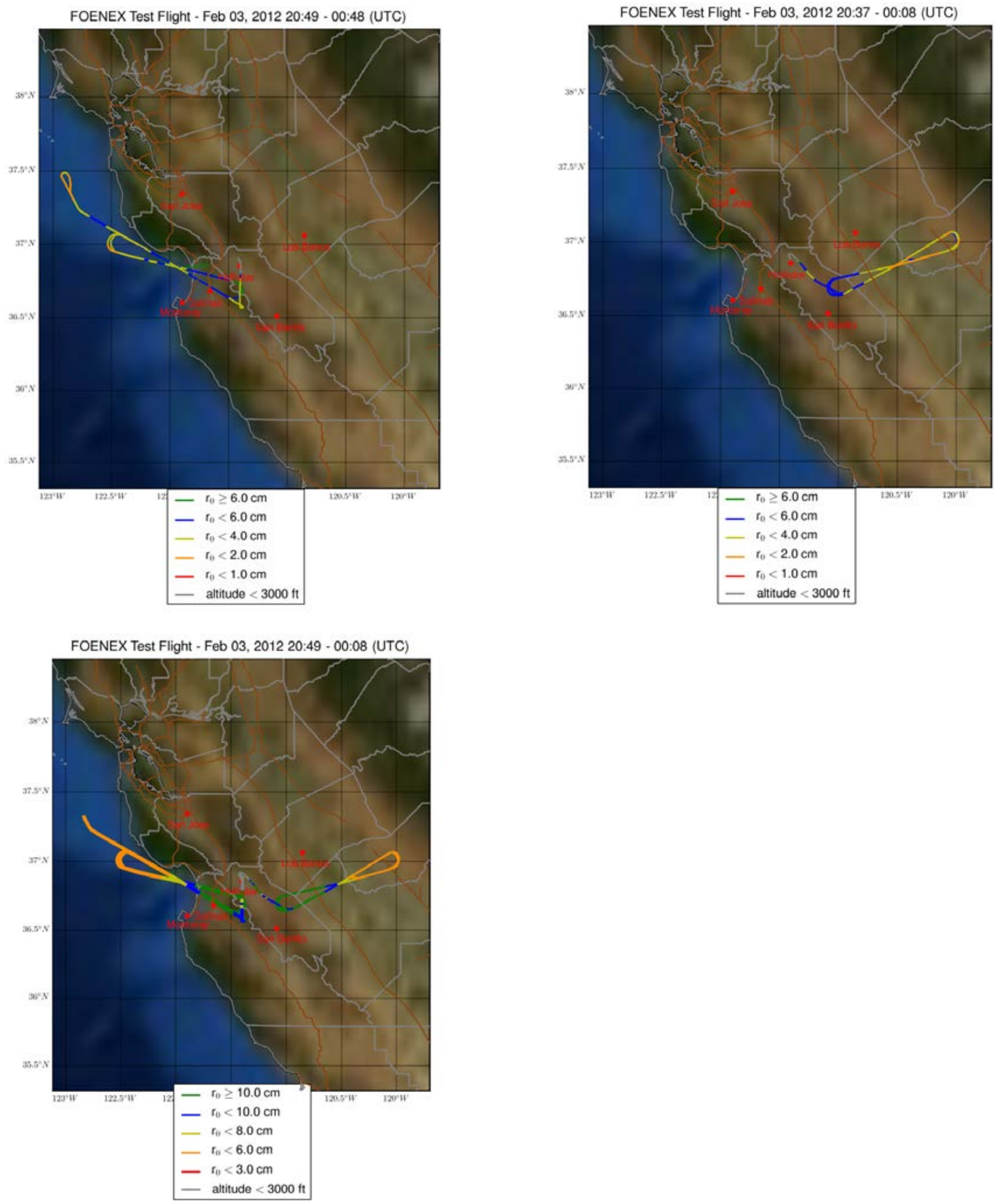

Figure 5 Values of r_0 shown for each LOS between each communications node on February 3, 2012.

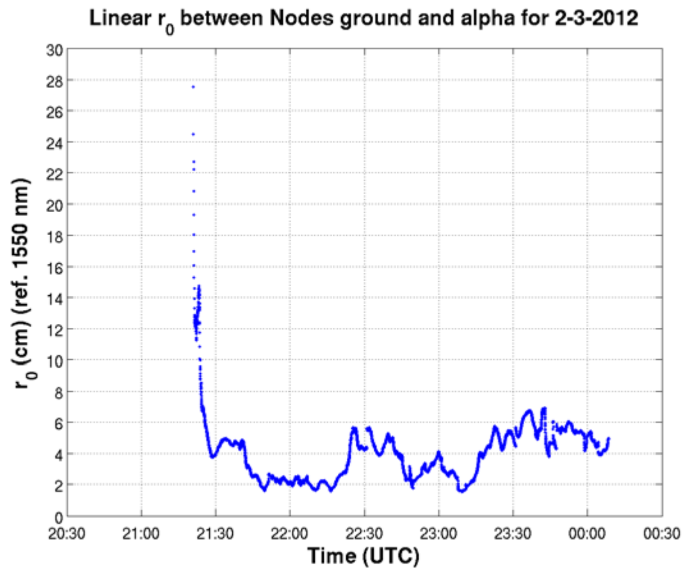

Figure 6 WRF-derived r_0 for February 3, 2012 from Hollister to one of the aircraft.

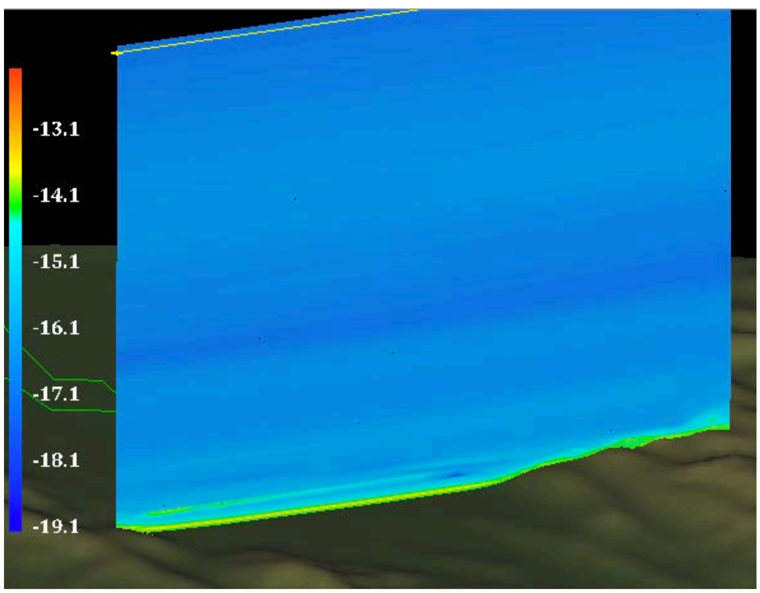

Figure 7 WRF-derived C_n^2 in the area of Campbell, CA, on May 25, 2011. An elevated area of intense turbulence can be seen in the yellow colors a few hundred feet above the ground.

4. CONCLUSIONS

Numerical Weather Prediction proved to be a valuable tool in weather forecasting and atmospheric characterization during the FOENEX experiments. Decision aides derived from short-term forecasts out to 87 hours, as well as forecasts out to 5 days, were automatically generated from NWP ensemble forecasts. While the impact of these forecasts has not yet been quantified, the anecdotal evidence from those in the field suggests they were accurate and beneficial to the project.

Atmospheric characterization, in particular optical turbulence modeling, was performed using the WRF model. A modified version of WRF was run daily at very high resolution in order to provide a three-dimensional characterization of the atmosphere. In addition to computing standard meteorological parameters, this modified version of the WRF model was used to calculate C_n^2 in the planetary boundary layer and free atmosphere, allowing for point-to-point estimates of r_0 and other seeing parameters. This NWP-based approach to atmospheric characterization has the advantage of providing a fully three-dimensional picture of the atmosphere.

The data presented in this paper only shows examples of how NWP-based products were used to support FOENEX. The ultimate goal of this work is to compare the WRF-derived atmospheric conditions to the FOENEX link data. However, as of the writing of this paper, FOENEX link performance data is not yet available for a detailed comparison with atmospheric characterization from the WRF simulations. As the FOENEX link data is analyzed in the future, the combination of the direct measurements along with the WRF simulations should provide valuable data for link analysis.

REFERENCES

[1] Felton, B., Alliss, R., "Improved Climatological Characterization of Optical Turbulence for Free-Space Optical Communications", SPIE Proceedings, Vol. 8162, Free-Space and Atmospheric Laser Communications XI, 9 September (2011).