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Tutorial for obtaining forecast turbulence parameters for acoustic propagation**William Jeffrey Doebler***Structural Acoustics Branch, NASA Langley Research Center, Hampton, VA, 23517;**william.j.doebler@nasa.gov*

Turbulence in the atmospheric boundary layer impacts propagation of sound near the surface of earth. This effect presents a challenge in accurately predicting noise exposure to sonic booms. New supersonic aircraft noise regulations are being considered due to advances in technology to reduce sonic boom loudness. These regulations will require noise certification flight tests that are likely to include bounds on weather parameters similar to that of subsonic aircraft noise regulations. Obtaining forecasts of turbulence strength prior to takeoff helps ensure that noise certification tests are within limits. Depending on the level of accuracy required, these forecast data or reanalysis data could be used in lieu of or to supplement measurements of turbulence in the field, which would reduce costs and complexity of the measurements. This paper serves as a tutorial for obtaining forecast data of near-surface turbulence from the Climate Forecast System atmospheric model. While the primary application of the tutorial is for supersonic aircraft noise certification and sonic boom propagation, the parameters are broadly applicable for other acoustics problems. The relevant ambient parameters are pressure, temperature, and relative humidity; the turbulence parameters are atmospheric boundary layer height, friction velocity, mixed-layer velocity scale, and surface layer temperature scale.

1. INTRODUCTION

Supersonic aircraft produce sonic booms that propagate to the ground through the turbulent boundary layer near the surface of the earth, or atmospheric boundary layer (ABL).^a The ABL turbulence stochastically focuses and defocuses the sound. For sonic boom propagation, turbulence causes spiking and rounding to the waveform. An example of this is shown in Figure 1, which contains the superimposed time-domain responses of 16 microphones arranged in a linear array parallel to the flight track, with a 30-meter spacing between each microphone. The plot illustrates the substantial waveform changes that can occur between closely spaced microphones due to turbulence effects. Noise perception metrics vary across the array as a result of the spiking and rounding from turbulence.

While civilian supersonic transportation over land is currently prohibited due to sonic boom noise,¹ new technologies are emerging to reduce the loudness of sonic booms²⁻⁴ that could help change the current speed limit to a noise limit. As part of its Quesst mission, NASA is building a low-noise supersonic aircraft, the X-59, which will be used to ascertain relationships between sonic boom loudness and human annoyance in a series of community noise surveys across the USA. These relationships will inform potential future supersonic aircraft noise certification standards set by regulators, including the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA).

Supersonic aircraft noise certification procedures are likely to include limits on atmospheric conditions, similar to the limits specified in current subsonic aircraft certification procedures. The subsonic aircraft noise certification procedures limit deviations of the temperature, humidity, and winds near the surface from reference conditions.⁵ The recorded sound levels are corrected from the as-flown atmospheric conditions to reference atmospheric conditions. Turbulence is not included in the subsonic noise certification procedures since it has negligible impact on subsonic certification noise measurements. Turbulence has a substantial impact on recorded levels of sonic booms, and limits on turbulence strength may need to be included in supersonic aircraft noise certification procedures. Anticipating a limit on maximum allowable turbulence levels during noise certification

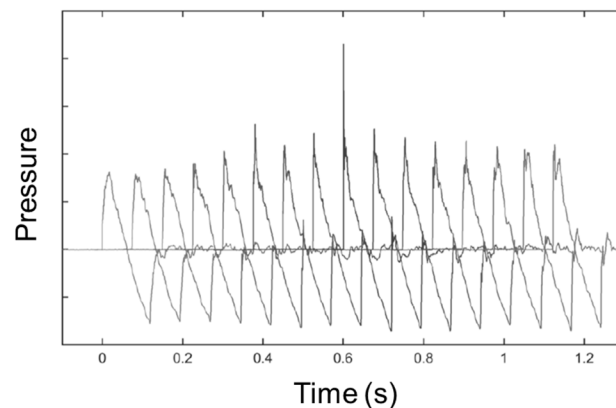


Figure 1. Turbulent spiking and rounding of sonic booms recorded on microphones spaced 30 m apart. Adapted from Ref. [6].

measurements, forecasts of turbulence data will be important in supersonic certification flight test planning to ensure the atmospheric conditions are within certification procedure limits. In addition to flight planning, turbulence parameters are needed to accurately model effects of turbulence on sonic booms using PCBoom⁷ or other propagation models. Depending on the level of accuracy required, it may also be cost-advantageous to rely on historical forecast or reanalysis model data in lieu of or to supplement deploying turbulence measurement equipment.

This paper describes the steps to obtain turbulence forecast parameters relevant to sonic boom propagation from a global atmospheric forecast model, the Climate Forecast System (CFS) Version 2.⁸ The process in this

^a “Atmospheric boundary layer” is also commonly referred to as “planetary boundary layer,” but this paper uses the ABL nomenclature to be consistent with ICAO guidelines.

paper can be used to obtain weather data from other atmospheric models from the National Oceanic and Atmospheric Administration (NOAA) Operational Model Archive and Distribution System (NOMADS).⁹ The tutorial includes a description of the turbulence model assumptions and forecast data available in the CFS model. This is followed by a description of Python3 and MATLAB 2024a code for obtaining and visualizing the turbulence parameters.^{10,11} Finally, historical forecasts from CFS are compared to measured turbulence parameters for two previous NASA flight tests.

2. TURBULENCE FORECAST DATA TUTORIAL

This section describes a process for obtaining the ambient and turbulence parameters required to generate turbulence fields for acoustic propagation. The process assumes the Ostashev and Wilson turbulence model^{12,13} that has been utilized in sonic boom propagation models within the ABL. The parameters required by this model can be obtained from forecast weather models for use in noise certification flight planning.

The Ostashev and Wilson turbulence model describes the length scales and variance as a function of height of scalar turbulence from temperature fluctuations ($L_T(h)$, $\sigma_T^2(h)$) and vector turbulence from buoyant (L_b , σ_b^2) and shear ($L_s(h)$, σ_s^2) production within the ABL. The length scales and variances are used to create turbulence fields with a von Karman energy spectrum. Reproduced from Ref. [14], the length scales are given in Eq. 1:

$$\begin{aligned} \frac{L_T(h)}{h} &= 2.0 \frac{1 + 7.0(-h/L_{mo})}{1 + 10(-h/L_{mo})}, \\ L_b &= 0.23z_i, \text{ and} \\ L_s(h) &= 1.8h. \end{aligned} \quad (1)$$

In Eq. 1, h is the height above the ground and z_i is the ABL height. The Monin-Obukhov length scale describes the ratio of shear and buoyant turbulence and is given by

$$L_{mo} = -\frac{u_*^3 \theta_s \rho C_p}{\kappa g_0 H} \quad (2)$$

where u_* is the friction velocity in m/s, θ_s is the surface temperature in K, ρ is the density, $C_p \approx 1006$ J/(kg K) is the specific heat at constant pressure, $\kappa \approx 0.4$ is the von Karman constant, g_0 is gravity, and H is the sensible heat flux in W/m². The variances are given in Eq. 3:

$$\begin{aligned} \frac{\sigma_T^2(h)}{T_*^2} &= \frac{4.0}{(1 + 10(-h/L_{mo}))^{2/3}}, \\ \sigma_b^2 &= 0.35w_*^2, \text{ and} \\ \sigma_s^2 &= 3.0u_*^2. \end{aligned} \quad (3)$$

In Eq. 3, the surface-layer temperature scale is

$$T_* = -\frac{H}{u_* \rho C_p}, \quad (4)$$

and the mixed layer velocity scale is

$$w_* = \left(\frac{g_0 H z_i}{\theta_s \rho C_p} \right)^{1/3}. \quad (5)$$

Thus, the parameters required for the turbulence model are u_* , w_* , T_* , and z_i , which require H , θ_s , and ρ .

This turbulence model was implemented in the KZKFourier acoustic propagation model of Stout and Sparrow¹⁵ that solves an augmented KZK equation along a straight ray path through the ABL. An approximate model based on FIR filters derived from KZKFourier simulations¹⁶ has been implemented in the NASA PCBoom software suite.¹⁷ For acoustic propagation using these models, the ambient pressure p_s and the relative humidity h_r are also required.

Next, a process is outlined for obtaining forecasts of near-surface and turbulence parameters to run these models. Forecast products for many atmospheric models are freely available from NOMADS. Figure 2 is a screenshot from the NOMADS webpage, showing the large number of NOAA atmospheric models from which data are available to explore. This tutorial focuses on the CFS model, but the methods here can be applied to other models provided they have comparable forecast variables.

A description of the CFS model and its data is necessary to understand its utility for certification measurements. CFS is a fully-coupled global atmosphere-ocean-sea ice-land model for long-range (6 to 9 month) weather forecasts. The forecast data¹⁸ is available on a horizontal grid with a spatial resolution of about 100 km separating the points, which is about 1 degree by 1 degree latitude/longitude.^b While CFS includes data aloft, the turbulence parameters are obtained from the surface-level forecast product. The CFS data are available every six hours at 0:00, 6:00, 12:00, and 18:00 Universal Coordinated Time (UTC). The native CFS parameters relevant for turbulence modeling are given in Table 1. The remaining parameters are derived from the native parameters as noted in Table 2. The data is in the binary GRIB2 format,¹⁹ which can be read in MATLAB with the `readgeoraster` function from the Mapping Toolbox or with the `ncgeodataset` function from the `nctoolbox`.²⁰

Equations are noted here for the derived parameters in Table 2. The ground elevation in geometric coordinates above mean sea level is

$$z_0 \approx \frac{r_E Z_g}{r_E - Z_g} \quad (6)$$

where Z_g is the geopotential height of the ground and the radius of earth $r_E \approx 6378.1$ km. The geopotential height and geometric height are nearly equivalent near the surface of the earth.

Index of /pub/data/nccf/com

Name	Last modified	Size
Parent Directory		-
557ww/	23-Apr-2016 03:00	-
amsu_estimation/	13-Jun-2022 19:16	-
aom/	06-May-2022 13:49	-
arch/	26-Feb-2016 16:00	-
blend/	17-Jan-2023 13:03	-
ccpa/	06-May-2022 13:51	-
cdas/	02-Jun-2022 20:14	-
cdas2/	14-Jun-2022 18:45	-
cfs/	06-May-2022 14:19	-
ens_tracker/	06-May-2022 14:37	-
estofs/	06-Feb-2023 15:20	-
etss/	06-May-2022 14:51	-
fnmoc/	01-Mar-2016 18:55	-
fnmoc_wave/	18-May-2022 15:29	-
gfs_legacy/	15-Sep-2022 21:06	-
gens/	25-Oct-2022 18:35	-
gfs/	10-Dec-2022 17:06	-
gfs_mos/	11-Apr-2023 16:32	-
gimp/	11-Apr-2023 16:50	-
glofs/	13-Jun-2022 19:16	-
glwu/	09-May-2023 11:06	-
hiresw/	06-May-2022 15:44	-
hmon/	13-Jun-2022 19:16	-
hourly/	26-Feb-2016 15:20	-
href/	13-Jun-2022 19:17	-
hrrr/	06-May-2022 15:45	-
hur/	26-Feb-2016 15:22	-
hurfl/	13-Jun-2022 19:18	-
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ingest/	02-Sep-2022 00:54	-
imp/	11-Apr-2023 16:48	-
naefs/	06-May-2022 15:51	-
nam/	19-May-2022 14:28	-
nam_mos/	13-Jun-2022 19:18	-
narre/	06-May-2022 15:53	-
navgem/	08-Aug-2022 15:56	-
navo/	29-Jun-2021 14:36	-
ncom/	01-Mar-2016 13:48	-
ngas/	02-Mar-2016 08:31	-
nhc/	01-Mar-2016 14:05	-
nldas/	06-May-2022 15:57	-
nos/	25-Oct-2022 12:15	-
nos/	25-Oct-2022 12:15	-
nosofs/	25-Oct-2022 12:15	-
nsst/	13-Jun-2022 19:18	-
nvm/	06-May-2022 15:59	-
nwps/	06-May-2022 16:00	-
obsproc/	08-Dec-2022 17:16	-
omb/	15-Sep-2022 21:23	-
pcpanl/	06-May-2022 16:08	-
petss/	06-May-2022 16:09	-
psurge/	02-May-2023 16:20	-
rap/	06-May-2022 16:10	-
rtma/	21-Feb-2023 12:20	-
rtofs/	08-Aug-2022 13:49	-
seaice_analysis/	13-Jun-2022 19:19	-
seaice_drift/	13-Jun-2022 19:19	-
smartinit/	13-Jun-2022 19:19	-
spc_post/	01-Jun-2022 18:24	-
sref/	06-May-2022 16:15	-
stofs/	12-Jan-2023 15:20	-
swmf/	06-May-2022 16:16	-
ukmet/	03-Nov-2022 14:12	-
urma/	15-Feb-2023 15:20	-
uvi/	13-Jun-2022 19:19	-
wave/	19-May-2022 14:29	-
wave_nfcens/	13-Jun-2022 19:20	-
wfs/	06-May-2022 16:18	-
wsa_enlil/	09-Apr-2023 18:20	-

Figure 2. Screenshot of atmospheric model data that is freely available from the NOAA NOMADS database.

^b For finer resolution over the USA only, the tutorial in this paper can be applied to the High Resolution Rapid Refresh (HRRR) model, which is also freely available through NOMADS. It has hourly forecasts with ~3 km spatial resolution.

The relative humidity is given by

$$h_r \approx 100\% \frac{q}{0.622 \frac{e_s}{p_s}} = 100\% \frac{q p_s}{0.622 \left(611 e^{\left(\frac{17.67(\theta_s - 273.16)}{\theta_s - 29.65} \right)} \right)} \quad (7)$$

where q is the specific humidity and e_s is the saturation vapor pressure.

The mixed-layer velocity scale w_* is given by Eq. 5, and the density ρ can be obtained using the ideal gas law:

$$\rho = \frac{p_s}{R_{air} \theta_s} \quad (8)$$

with the gas constant of air $R_{air} = 287.05 \text{ J/(kgK)}$. Because computation of w_* includes a cube root and depends on H , which can be negative, it is possible for computers to report a complex number for w_* . To avoid this, the MATLAB `nthroot` function can be used that returns the n th real root. The surface layer temperature scale T_* is given by Eq. 4. Finally, the standard deviation of the wind velocity fluctuations due to shear and buoyant turbulence production is given by

$$\sigma_{vector} = \sqrt{3 u_*^2 + 0.35 w_*^2}. \quad (9)$$

This parameter has been used to describe the strength of turbulence categorically, with low turbulence defined as $\sigma_{vector} = 0.31 \text{ m/s}$, medium turbulence $\sigma_{vector} = 1.10 \text{ m/s}$, and high turbulence $\sigma_{vector} = 1.81 \text{ m/s}$.²¹

Table 1. Near-surface ambient and turbulence parameters native to CFS.

Parameter	Symbol	GRIB2 Variable Name	Units
Surface Pressure	p_s	PRES_0_SFC	Pa
Surface Temperature	θ_s	TMP_0_SFC	K
Specific Humidity at 2m AGL ^c	q	SPFH_2_HGTL	kg/kg
Friction Velocity	u_*	FRICV_0_SFC	m/s
Atmospheric Boundary Layer Height	z_i	HPBL_0_SFC	m AGL
Sensible Heat Flux ^d	H	SHTFL_0_SFC	W/m ²
Surface geopotential height	Z_g	HGT_0_SFC	gpm ^e

Table 2. Near-surface ambient and turbulence parameters derived from CFS.

Parameter	Symbol	Derived From	Units	Eq.
Ground Elevation	z_0	Z_g	m MSL ^f	(6)
Relative Humidity at 2m AGL	h_r	q, p_s, θ_s	%	(7)
Mixed-layer Velocity Scale	w_*	H, z_i, θ_s, p_s	m/s	(4)
Surface Layer Temperature Scale	T_*	H, u_*, θ_s, p_s	K	(5)
Standard Deviation of Wind Velocity Fluctuations	σ_{vector}	u_*, w_*	m/s	(9)

^c Above Ground Level (AGL)

^d Note that the sign of the heat flux indicates the heat transfer direction. For CFS, a positive value indicates that the ground is imparting heat into the air. This is the opposite convention of the European ERA5 model, “vertical fluxes [are] positive downwards.”

^e Geopotential meters (gpm). This is the geopotential $\Phi = \int_0^{z_0} g(z) dz$ divided by gravity g_0 .

^f Mean Sea Level (MSL)

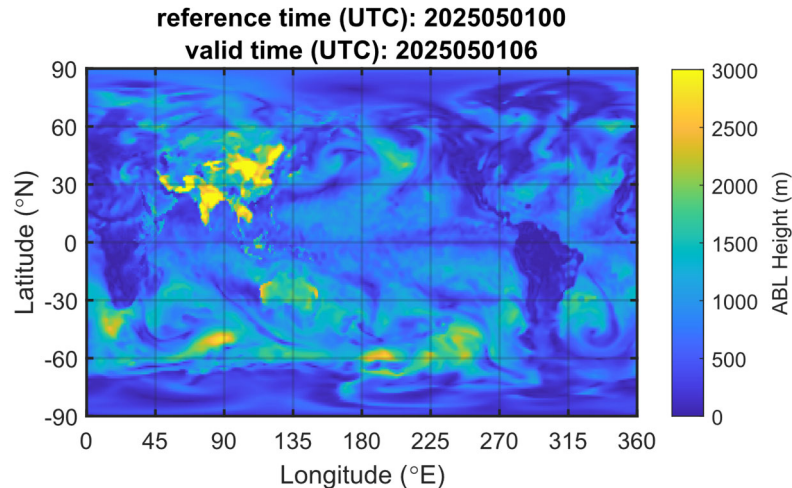


Figure 3. Atmospheric boundary layer height forecast from CFS.

Code to download and visualize the data is presented here. The process uses a MATLAB wrapper to call a Python script that downloads and saves the data to a binary file. The downloaded data in the file is then loaded into a MATLAB structure variable and visualized. The user provides a string of the reference and valid times of the forecast,[§] formatted as UTC year month day hour YYYYMMDDhh, and the directory where the file is to be downloaded. Note that the reference time is not related to the reference day atmospheric conditions mentioned in the Introduction. Figure 3 shows the result of running the MATLAB script and visualizing the ABL height on May 1, 2025, at 6:00 UTC, which is 3 PM in Japan and 11 AM in India. The solar heating drives the high ABL in the regions between 45°E and 135°E, while regions without direct sun exposure, such as North and South America, have relatively low ABL.

```
#Python3 code "download_turb.py"
import requests
import sys

#user sets desired date and time
ref_UTCdateStr_YYYYMMDDhh = sys.argv[1]
valid_UTCdateStr_YYYYMMDDhh = sys.argv[2]
#user provides download dir
downloadDir = sys.argv[3]

#filepath string of the downloaded data
saveFn = downloadDir + 'CFS_v' + valid_UTCdateStr_YYYYMMDDhh + '_r'
        + ref_UTCdateStr_YYYYMMDDhh + '.grb2'
print(saveFn)

#string for the correct URL of the data
URLStr1='https://nomads.ncep.noaa.gov/pub/data/nccf/com/cfs/prod/cfs.'
URLStr2 = '6hrly_grib_01/'
myURL = URLStr1 + ref_UTCdateStr_YYYYMMDDhh[0:-2] + '/'
```

[§] The reference time of the forecast is the timestamp corresponding to when the model was run. The valid time is when the forecast data should be used. Different reference times can have the same valid time; for example, a valid time of Jan. 1st 12:00 could be from a Jan. 1st 0:00 reference time with a 12-hour forecast or a Jan. 1st 6:00 reference time with a 6-hour forecast.

```

    + ref_UTCdateStr_YYYYMMDDhh[-2:]+ '/' + URLStr2
    + 'flxf' + valid_UTCdateStr_YYYYMMDDhh + '.'
    + URLStr2[-3:-1] + '.' + ref_UTCdateStr_YYYYMMDDhh
    + '.grb2'

#obtain and save the data
r = requests.get(myURL, allow_redirects=True)

with open(saveFn, 'wb') as f1:
    f1.write(r.content)
#End of Python3 code "download_turb.py"

```

```

%MATLAB wrapper to call download_turb.py, load the downloaded data, and visualize
%the atmospheric boundary layer height

%user sets desired date and time
ref_UTCdateStr_YYYYMMDDhh = '2025050100';
valid_UTCdateStr_YYYYMMDDhh = '2025050106';
%user provides the path to where the turbulence file should be downloaded
downloadDir = 'C:/Users/wdoebler/Documents/turbDataDir/';

%run the python script to download the desired files
pythonExePath = 'C:/Users/wdoebler/AppData/Local/anaconda3/python.exe';
system([pythonExePath ' download_turb_v1.py ' ref_UTCdateStr_YYYYMMDDhh,...
    ' ', valid_UTCdateStr_YYYYMMDDhh ' ' downloadDir])

%load the turbulence data into the turbStruct structure variable
dataFn = [downloadDir(2:end-1) 'CFS_test_v' valid_UTCdateStr_YYYYMMDDhh,...
    '_r' ref_UTCdateStr_YYYYMMDDhh '.grb2'];
gribInfo = georasterinfo(dataFn);
gribData = readgeoraster(dataFn);
turbStruct = struct();
for ii = 1:length(gribInfo.Metadata.Element)
    %loops through the turbulence variable names and loads them into the turbStruct
    currVar =gribInfo.Metadata.Element(ii)+"_"+...
        gribInfo.Metadata.ShortName(ii);
    %matlab does not allow hyphens or periods in variable names.
    currVar = strrep(currVar,'-','_');
    currVar = strrep(currVar,'.','p');
    currData = squeeze(gribData(:,:,ii));
    turbStruct(1).(currVar) = currData;
end
%lat/lon are available in the gribInfo variable
turbStruct(1).lat = linspace(gribInfo.RasterReference.LatitudeLimits(2),...
    gribInfo.RasterReference.LatitudeLimits(1),...
    size(gribData,1));
turbStruct(1).lon = linspace(gribInfo.RasterReference.LongitudeLimits(1),...
    gribInfo.RasterReference.LongitudeLimits(2),...
    size(gribData,2));

%%
%user can decide what to plot. Here we plot ABL height in meters above
%ground level.
figure
imagesc(turbStruct.lon,turbStruct.lat, turbStruct.HPBL_0_SFC)
set(gca,'ydir','normal','ytick',[-90:30:90],'xtick',[0:45:360],...
    'xlim',[0 360],'ylim',[-90 90])
set(gcf,'position',[488 323.4 560 338.6])
title(['reference time (UTC): ' ref_UTCdateStr_YYYYMMDDhh],...
    ['valid time (UTC): ' valid_UTCdateStr_YYYYMMDDhh])

```

```

c1 = colorbar;
c1.Label.String = 'ABL Height (m)';
caxis([0 3000])
xlabel('Longitude (\circE)')
ylabel('Latitude (\circN)')
%End of MATLAB wrapper

```

3. COMPARISON OF CFS AND MEASURED DATA

To assess the feasibility of using CFS data for turbulence forecasting, this section compares historical data from the CFS Operational Analysis archive²² to measurements of near-surface ambient and turbulence parameters made during the NASA Sonic Booms in Atmospheric Turbulence (SonicBAT) flight tests.⁶ The flight tests each occurred over the course of about two weeks in July 2016 at the NASA Armstrong Flight Research Center (AFRC) in CA, a desert environment, and August 2017 at the Kennedy Space Center (KSC) in FL, a humid environment. Ambient meteorological measurements were made by near-surface weather towers and weather balloon soundings.²³ Turbulence measurements were made by sonic anemometers and SODAR^h. The ABL height was derived from the weather balloon data. Figure 4 shows a selection of the meteorological measurement equipment.



Figure 4. Meteorological measurement equipment from the SonicBAT flight test. Left: sonic anemometer. Center: SODAR. Right: weather balloon. Left and center photos were adapted from Ref. [6].

Figure 5 shows the measurements of near-surface ambient and turbulence parameters compared to the CFS model data for the test at AFRC, and Figure 6 shows the same for the test at KSC. While most of the data is in reasonable agreement, there are some notable differences between the model and measured data. The first is the difference in ambient pressure at AFRC (Figure 5a). The CFS model underpredicted the measurements by about 0.01 atm, which is about a 1% error. Since the CFS model output is fixed to a grid, the model does not line up exactly with the locations of the meteorological measurements. The CFS location is 35N, -118W, but the meteorological instruments were about 12 km southeast of the CFS grid location.ⁱ Over this distance, there is a decrease in elevation by about 100 m: the CFS grid point ground elevation is 768 m MSL while the AFRC meteorological equipment was at about 670 m MSL. This difference in elevation likely drives the observed difference in ambient pressure, with the higher CFS elevation resulting in lower pressure. The KSC data (Figure 6a) does not have the same discrepancy, even though the CFS grid point is farther away (about 35 km) from the meteorological equipment than at AFRC. The difference in ground elevation between the CFS grid point and the KSC meteorological equipment is about 7 m. Another difference is the overprediction of the friction velocity at AFRC (Figure 5e), which is not observed in the KSC data (Figure 6e). Additionally, there are differences between the CFS data and measurements for the KSC ABL height (Figure 6g). The ABL height is overpredicted for several of the measurements at the beginning and end of the test. The accuracy of other forecast models was not assessed in this work.

^h Sonic detection and ranging

ⁱ See Table 6 in Ref. [6] for the locations of the AFRC meteorological equipment.

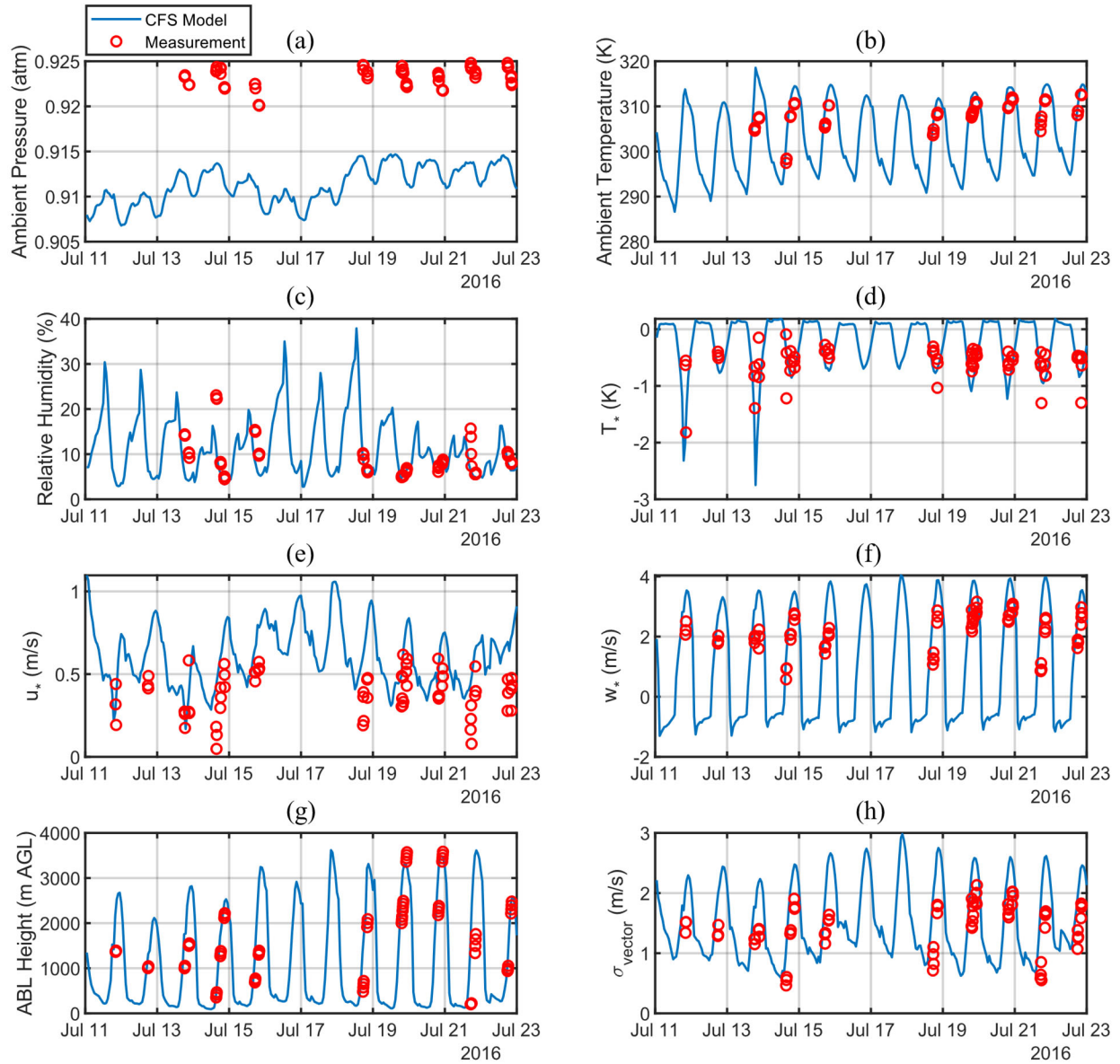


Figure 5. Comparison of CFS and measured near-surface and turbulence parameters at AFRC.

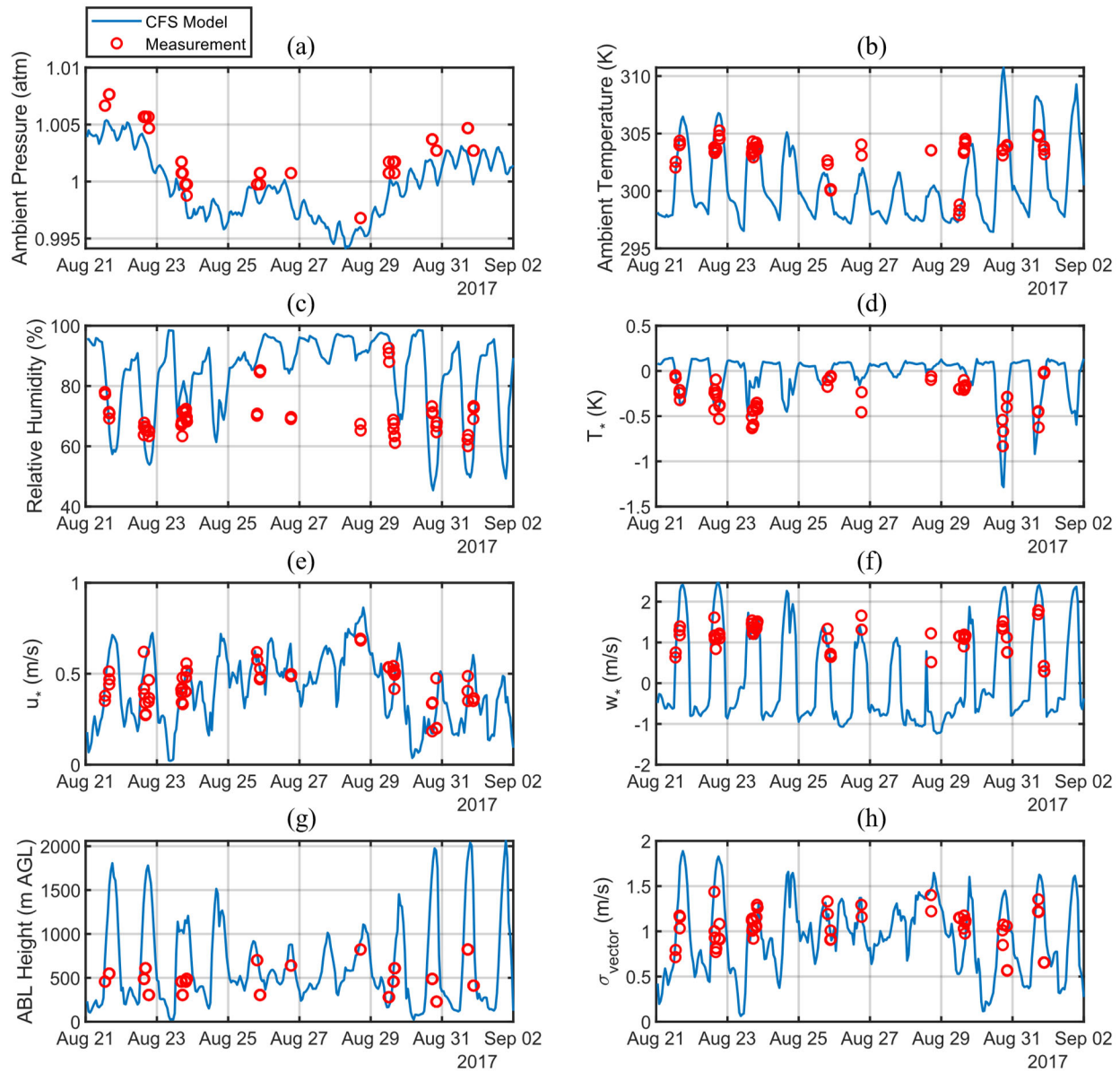


Figure 6. Comparison of CFS and measured near-surface and turbulence parameters at KSC.

4. CONCLUDING REMARKS

This paper provides a tutorial for obtaining forecast data to describe turbulence within the atmospheric boundary layer. The method uses the Climate Forecast System data that is freely available on the NOMADS database. The forecast turbulence data can be used to assess whether atmospheric conditions are likely to be within bounds specified in noise certification standards. The paper compared modeled turbulence data to measurement data for two NASA flight tests in different climates and were found to be in reasonable agreement which indicates it may be feasible to use forecast ambient and turbulence parameters during future certification activities. Limitations and bias in the weather model were also discussed. Depending on the accuracy required for the application, it may be possible to use historical forecast or other reanalysis datasets in lieu of or to supplement meteorological equipment in the field. This could potentially reduce cost and complexity of flight tests. Further comparisons between modeled and measured turbulence data are warranted to ensure the models are accurate enough to realize these potential cost savings.

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