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Validation of turbulence profile forecasting with WRF at the Canary Islands astronomical observatories. Preliminary results.

Julio A. Castro-Almazán^{a,b}, Gabriel Pérez-Jordán^c, Casiana Muñoz-Tuñón^{a,b}, and Begoña García-Lorenzo^{a,b}

^aInstituto de Astrofísica de Canarias, E-38200, La Laguna, Spain

^bDept. Astrofísica. Universidad de La Laguna, E-38200, La Laguna, Spain

^cMeteowhizz, E-08320, Barcelona, Spain

ABSTRACT

Accurate forecasting of the specialized atmospheric parameters directly impacting the astronomical observations is mandatory for efficient optimization of the queue mode operation of modern telescopes. Among them, the vertical profile of turbulence, $C_n^2(h)$, and the derived integrated coherence parameters (seeing, r_0 , τ_0 and θ_0) are key for the high-resolution techniques, applied both to Astronomy and optical communications. In this work we present the first results that we are obtaining in the validation of the non-hydrostatic numerical weather prediction model WRF (Weather Research and Forecasting) to predict night-time $C_n^2(h)$ at the Canary Islands Observatories (Teide and Roque de los Muchachos). In this initial stage, the validation is carried out by comparison with local gSCIDAR data. The initial and boundary conditions are obtained from the ERA-Interim reanalysis. Three nested domains have been configured to achieve a final horizontal resolution of 1 km, with around 76 vertical levels ranging in resolution from 50 m in the Boundary Layer to 300 m in the Free Atmosphere. We are using the Vernin-Trinquet model for turbulence retrieval from the standard output parameters of WRF. The final goal is to include this prediction in the current operational forecasting platform ForO (Forecasting the Observatories) at the Canarian observatories.

Keywords: atmospheric effects, methods: data analysis, methods: numerical, methods: statistical, techniques: high angular resolution, site testing.

1. INTRODUCTION

The main mode of operation of the future large telescopes will be the Service Mode, scheduled through a priority queue, as it is currently the case for the 8 – 10 m class. The management of such a queue must be dynamic and adaptive. The goal is to select the best scientific program whose minimum atmospheric requirements match the current conditions. Accurate forecasting of the atmospheric parameters directly impacting in the astronomical observations is then mandatory for efficient optimization of the queue (1). Among them, the vertical profile of atmospheric turbulence, $C_n^2(h)$ (refractive-index structure constant variation with height – h –), and the derived integrated optical coherence parameters, seeing (ϵ_0), coherence length (or Fried parameter, r_0), coherence time (τ_0) and isoplanatic angle (θ_0) are key for the high-resolution techniques (Adaptive Optics –AO–, e.g.), either applied to Astronomy or optical communications. The impact of the coherence parameters in astronomical observations is crucial in whatever technique used in the wavelength range from Visible to Near IR.

Being aware of such a necessity, the IAC Sky Quality Team started a research project in 2014 focused on the validation and implementation of a Numerical Weather Prediction (NWP) model for the observatories of the Canary Islands (see Fig. 1), Teide (OT) and Roque de los Muchachos (ORM). As a result, we developed the ForO system (Forecasting the Observatories), an operational forecasting platform released in 2018 to predict the integrated precipitable water vapour (PWV) based on the model Weather Research and Forecasting (WRF).

Further author information: (Send correspondence to J.A.C.A.)

J.A.C.A.: E-mail: julio.castro@iac.es

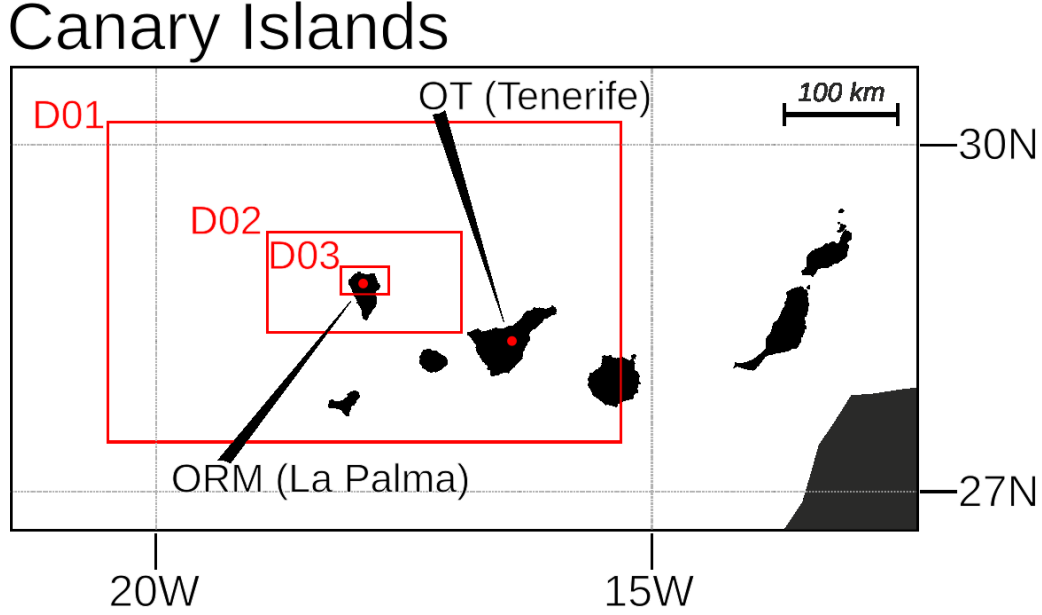


Figure 1. Map of the Canary Islands, with the location of the Observatories: OT (Observatorio del Teide) and ORM (Observatorio del Roque de los Muchachos), together with the nested domains (centered in the ORM) used for the WRF forecasts (see Table 2 for details).

The next step has been to extend it to a more complex parameter such as the $C_n^2(h)$ and the derived coherence parameters. In these proceedings we are introducing the extension of ForO to C_n^2 . We present the project and discuss the very first preliminary results of C_n^2 and ϵ_0 , with the goal of using them to optimize the parameterization of WRF.

2. FORECASTING THE OBSERVATORIES (ForO)

ForO is a web-based forecasting specialized platform for predicting atmospheric parameters impacting in the image quality and the operation schedule of astronomical observations at the Canary Islands Observatories, OT* and ORM†. ForO is executed four times a day (00, 06, 12 and 18 UTC) to generate individual PWV predictions with a horizon of 72 hours for both observatories. The whole process takes about 2 hours of computing time.

The numerical core of ForO is WRF (version 3.8), a non-hydrostatic mesoscale NWP model (2, 3) developed as a collaboration between various US institutions‡. WRF is maintained and supported by a very active community and can be freely downloaded and used for research. Before being integrated into ForO, WRF was validated and calibrated for PWV (4 and 5). ForO was originally designed to be scalable and, hence, the extension to C_n^2 is feasible by conserving the current architecture and hardware. The hardware architecture of ForO is based in two machines with differentiated functions (see Table 1).

2.1 ForO- C_n^2

ForO- C_n^2 is going to be integrated in ForO as an additional independent module, not interfering with the PWV predictions and conserving the current architecture and functionalities of ForO. The project is organized in four phases: (i) WRF setup, (ii) WRF parameterization and validation, (iii) implementation in ForO and (iv) release.

*<https://dedo.ll.iac.es/ot>

†<https://dedo.ll.iac.es/orm>

‡National Center for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration (NOAA), Air Force Weather Agency (AFWA), Naval Research Laboratory (NRL), University of Oklahoma (OU), and Federal Aviation Administration (FAA)

Table 1. ForO Hardware architecture.

Machine 1	Machine 2
Back-End	Front-End
WRF block	Web server
Internal network	DMZ location
physical machine 24 cores	Virtual machine
Fedora 26	Ubuntu 16.04
Maria DB (main)	Maria DB (mirror)

The current project is limited to night time C_n^2 . The final user products will be plots and ASCII values of the prediction time series and 2D maps in the WRF domains.

WRF has been configured with the three nested domains shown in Fig. 1 and Table 2, using a Mercator projection with the *no-distortion-point* (the point where the Earth's surface is tangent to the surface of the projection) set to 30°N . Topography and land use is from USGS/MODIS. The finest resolution has been reduced up to $\Delta x = 1$ km for C_n^2 , improving ForO-PWV ($\Delta x = 3$ km; see Ref. 5). Fig. 2 shows the effect in the geographical altitude model of $\Delta x = 1$ km on the steep orography of the northern half of La Palma. Each pixel averages the terrain area inside it and therefore, the true height should be corrected adjusting the lower limit of the integration range.

Table 2. Configuration of the nested domains used in ForO-Cn2 (see Fig. 1).

Domain	Δx (km)	Grid	Surface (km)	Surface (degrees)
D01	9	60×45	540×405	$5.5^\circ \times 3.6^\circ$
D02	3	52×40	156×120	$1.6^\circ \times 1.4^\circ$
D03	1	40×25	40×25	$0.4^\circ \times 0.2^\circ$

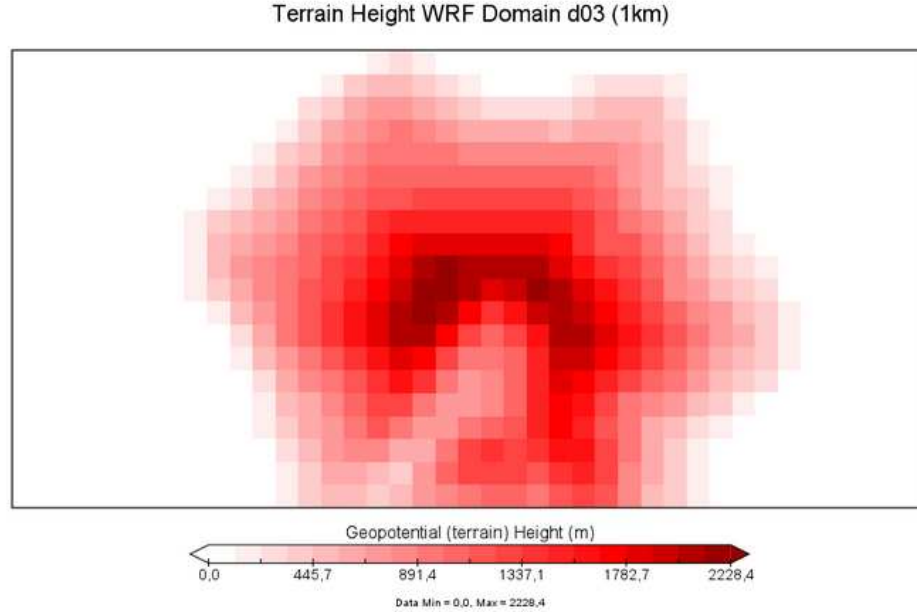


Figure 2. Effect of the horizontal resolution $\Delta x = 1$ km on the geographical altitude model of the northern half of La Palma. The ORM is located in the darkest bin.

Table 3. WRF model physics configuration.

Long Wave Radiation	Short Wave Radiation	Radiation timestep	Land–Surface	Surface Layer	Planetary Boundary layer	Cumulus	Micro physics
RRTM	Dudhia	9	Noah LSM	Monin–Obukhov	Yonsei Univ. (YSU)	Kain–Fritsch	WSM6

The central domain point is close to the 10 m *Gran Telescopio Canarias* (GTC) with coordinates 28.7554°N , and -17.89°W (see Fig. 3). Seventy six vertical levels have been configured (55 for the Free Atmosphere –FA– with a vertical resolution of 300 m and 21 in the Boundary Layer –BL– reaching 50 m of resolution) doubling the sampling used in ForO-PWV (32 levels; see Ref. 5). The levels are configured using the normalized vertical coordinate η , defined as a function of the pressure at the model’s top level p_{top} , the surface pressure p_s , and the pressure at any level z , p_z ,

$$\eta = \frac{p_z - p_{\text{top}}}{p_s - p_{\text{top}}}, \quad (1)$$

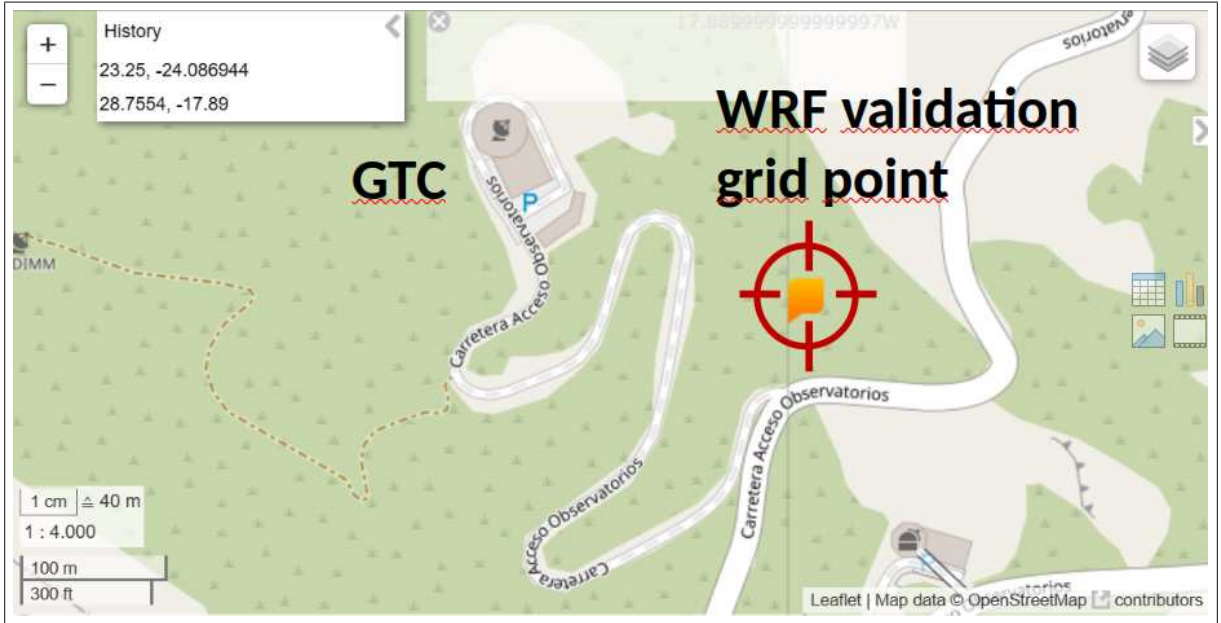


Figure 3. Central domain point of WRF in this study at the ORM, close to GTC.

The subgrid processes at scales not resolved by the model (scales below Δx) are parameterized through the *physics* of the model. Model physics in WRF is implemented in different modules: Microphysics, Radiation (Short-Wave – SW – and Long-Wave – LW), Cumulus, Surface Layer (SL), Land-Surface (LS), and Planetary Boundary Layer (PBL). A summary of the schemes used is on Table 3.

3. METHODOLOGY

To validate and optimize the parameterization of WRF specified in the phase (ii) of ForO- C_n^2 (see Section 2.1), we have set up an independent WRF installation in order not to interfere with operational ForO. For this study we have performed 16 WRF simulations at ORM with 6 hours outputs, coinciding with gSCIDAR $C_n^2(h)$ observations. gSCIDAR, one of the reference techniques to retrieve optical turbulence profiles, has been

extensively used at both, ORM (6) and OT (7), cumulating ~ 200 nights of observation at each. We have selected the WRF outputs at 00UTC. To incorporate any possible time shifts in the WRF outputs and guarantee matching with gSCIDAR, we have averaged the simultaneous gSCIDAR profiles ranging between 00UTC and 01UTC. The sample covers the whole year.

In these experiments, we have used the reanalysis ERA-Interim[§] (0.70° horizontal resolution, ~ 75 km, and 6 hour time resolution) for the Initial and Boundary Conditions (IBC). Once the first domain is solved with the IBC, a recursive horizontal grid-nesting process down-scales the solution over the area of interest up to reach the final horizontal resolution of domain D03 (see Table 2). Finally, the C_n^2 is retrieved from the standard WRF outputs using the Vernin-Trinquet (VT) method (8). The combination WRF+VT has been previously tested successfully at the ORM (9 and 10).

4. PRELIMINARY RESULTS OF C_n^2 AND SEEING SIMULATIONS

Figure 4 shows the results of the comparison of ϵ_0 retrieved from simultaneous $C_n^2(h)$ profiles simulated by WRF and measured with gSCIDAR at ORM. The results are given for the total seeing, and the BL and FA contributions. All the profiles are shown in Figs. 5 and 6. The WRF outputs are directly compared with gSCIDAR, without any calibration.

The preliminary results show very good correlation and a promising RMSE[¶] of $0.25''$. There is a slight positive bias (WRF underestimating ϵ_0) of less than $0.1''$, mainly originated in the FA simulation. On the other hand, it is in this layer where the maximum correlation is found. Therefore, once optimized the FA parameterization, a proper calibration will help in reducing the bias.

The largest decorrelation is found in the BL. Different factors play a role. It is in the BL where the horizontal resolution is limited by the steep terrain and hence, the parameterization of the model physics becomes most important. Additionally, space and time losses of correlation are expected to some degree due to the distance between the WRF grid points and the actual gSCIDAR telescope location, and the hour of integration used for gSCIDAR to guarantee time-matching with the WRF simulations.

The different features found in Fig. 4 are confirmed in the whole C_n^2 profiles (Figs. 5 and 6). There is a very good correlation also in the vertical distribution of turbulence. WRF is able to detect the main turbulent layers and even the small ones, taking into account that the vertical resolution of WRF is higher than gSCIDAR. A small shift in the height of some singular layers is found in a few profiles. It has to be taken into account that gSCIDAR smoothes the turbulent energy of the different layers to fit the vertical resolution, which can result in such a shift. This effect is also present in the ground level, where all the turbulence in the Surface Layer (SL) is distributed around height zero, introducing C_n^2 values with height values below the ground, that should be added to the SL. In the other edge of the profiles, the FA part of $C_n^2(h)$ confirms the slight underestimation of ϵ_0 in the WRF simulations for this layer (see right side panels of Fig. 4).

5. FUTURE WORK

Future work includes the increase of the sample in the comparisons. The process is recursive, improving the parameterization while increasing the sample and tests. We will extend the comparison to the other coherence parameters and we are going to include additional observational datasets, such as DIMM values or high vertical resolution profiles of C_n^2 obtained with radiosounding balloons. We are studying the impact of using ERA-5 (0.30° horizontal resolution, ~ 30 km, and 1 hour time resolution) instead of ERA-Interim (see Section 3), assuming the extra computational effort. The possible time shifts or delays in the WRF outputs are also going to be characterized. Finally, as a result of the statistical validation, we will propose calibration equations. Once night time Foro- C_n^2 is in production, the following stages will be day-time $C_n^2(h)$ and the evaluation of different complementary non-numerical short-time scale forecastings (horizon 1 – 2 hours) based on statistical techniques (e.g. autoregressive methods; 11, 12).

[§]ERA-Interim is a reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF)

[¶]RMSE is defined as the square root of the quadratic sum of the standard deviation σ and the median bias.

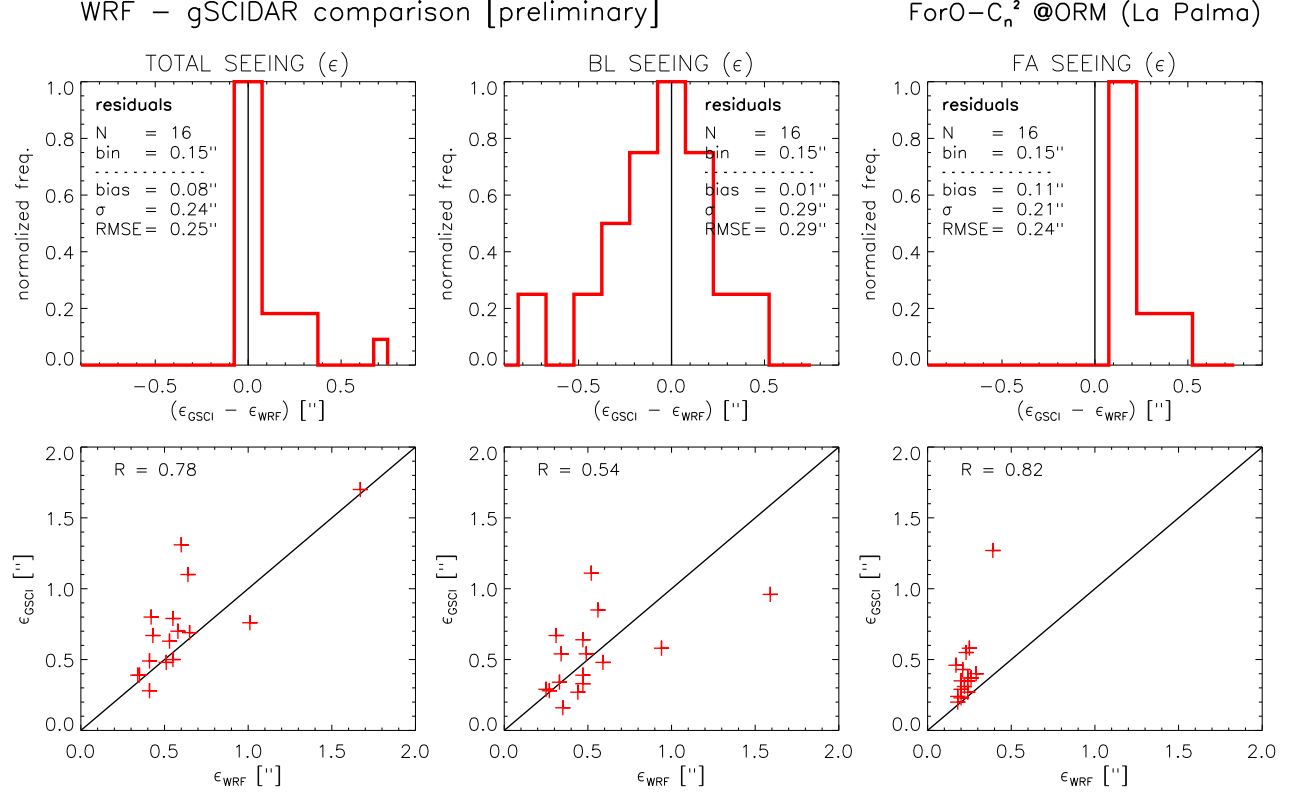


Figure 4. Comparison of ϵ_0 retrieved from simultaneous $C_n^2(h)$ profiles simulated by WRF and measured with gSCIDAR at ORM (see Fig. 5 and 6). The results are given for the total seeing, and the BL and FA contributions.

6. CONCLUSIONS

We have presented the project of extension of the ForO system (the current specialized atmospheric forecasting platform for the Canary Islands Observatories) to C_n^2 and coherence parameters. ForO is based on the NWP model WRF. A preliminary comparison of 16 $C_n^2(h)$ profiles and integrated ϵ_0 simulated by WRF was carried out with simultaneous gSCIDAR data. The results show a very good correlation, both in ϵ_0 values and vertical distribution, join with a promising low error estimated from the residuals (RMSE= 0.25"). A slight positive bias of $\approx 0.1''$ (WRF underestimating ϵ_0) was detected for the FA. The lower correlation was found on the BL. A deeper study is on going with a larger sample, including more accurate IBC and improved parameterization.

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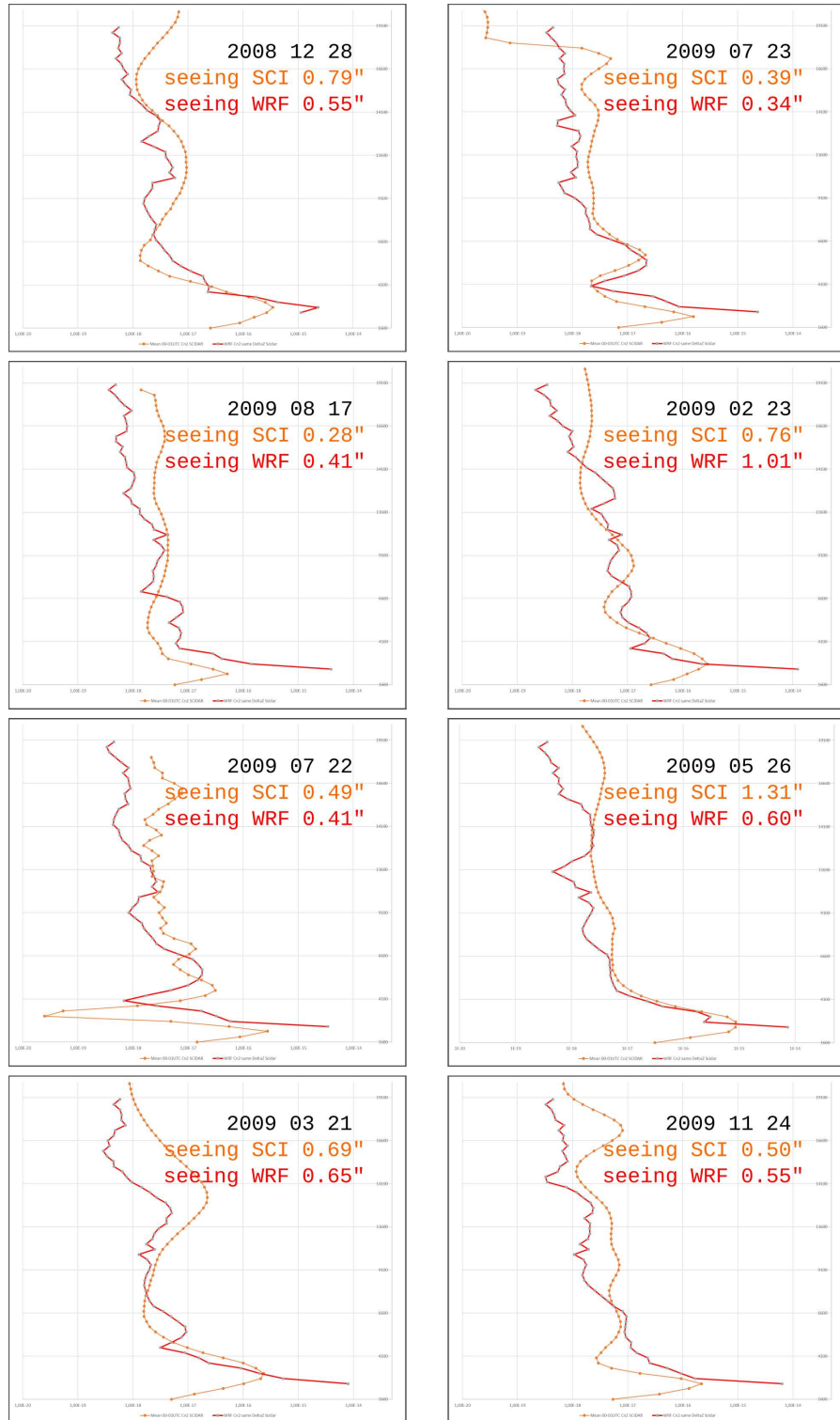


Figure 5. Compilation 1/2 of $C_n^2(h)$ simultaneous profiles simulated by WRF and measured with gSCIDAR at ORM. The C_n^2 values in gSCIDAR with heights below ground should be considered within the SL.

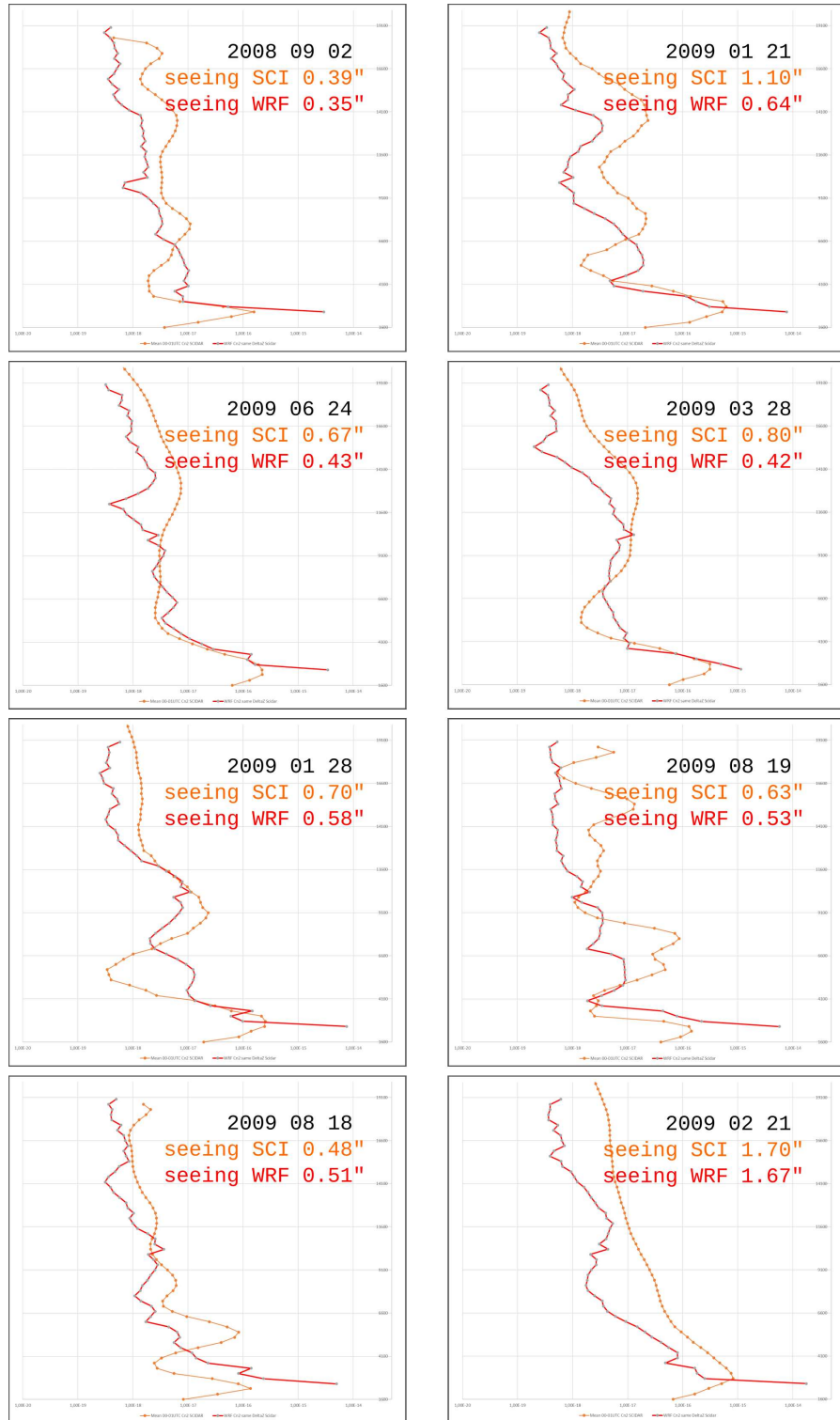


Figure 6. Compilation 2/2 of $C_n^2(h)$ simultaneous profiles simulated by WRF and measured with gSCIDAR at ORM. The C_n^2 values in gSCIDAR with heights below ground should be considered within the SL.