Study of planetary boundary layer height from LIDAR measurements and ALARO model

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The time evolution of the Planetary Boundary Layer (PBL) height has a significant impact on weather events and air quality since it is one of the parameters affecting the atmospheric state. This paper presents results concerning the PBL height retrieval using several techniques and assessment methods. The studies are focused on remote sensing methods, radiosoundings and numerical models. The PBL height behaviour has been studied in two sites by means of vertical humidity, temperature profiles and range corrected lidar signal. A good correlation between lidar, microwave radiometry and radio sounding profiles has been evidenced for the analyzed period. PBL height estimation performed by ALARO has a permanent offset with respect to the other methods during the cold season.

1. Introduction

The Planetary Boundary Layer (PBL) height is an important weather parameter affecting the concentration of pollutants near the ground surface. It determines the atmospheric volume in which the pollutants are emitted [1]. The PBL height is a diagnostic variable in forecasting models, for the dispersion and transport of pollutants through the atmosphere. The correct assessment of the PBL height in air quality dispersion models and weather forecast models can drastically increase the accuracy of the output [2, 3].

For local scale dispersion models designed to estimate the environmental impact of urban pollution accidents, the interaction between the mesoscale circulation and the PBL must be taken into account. The diurnal variation of the PBL height has important implications for energy transfer at the surface – atmosphere interface [4] and its representation can be useful for many applications including radiative transfer studies. By understanding the processes that take place in the PBL, the weather and climate modeling community can better integrate these phenomena in numerical models: e.g. the PBL should be properly described in weather forecasting models to correctly predict the diurnal cycle, low-level winds and the convergence [5].

Moreover, the PBL is directly influenced by surface conditions and it differs from the free troposphere in many thermodynamic properties, content and movement [6]. The phenomena occurring in the PBL are also important in aviation: fog and wind shears. Also, ground frost, hoarfrost, dew and evapo-transpiration processes are taking place in this layer and are of particular interest for the agriculture community [7].

The PBL height ranges from a few hundred meters to several kilometers according to the season and topography. Also the diurnal variation, strongly dependent on surface temperature has a strong influence on the PBL height. Above large areas of water, the PBL height varies relatively slowly in time and space because of the caloric capacity of water [5, 8]. The PBL height is an important parameter for assessing the degree of turbulence and dispersion of pollutants in the atmosphere [9].

Seibert et al. (2000) described multiple PBL height estimation methods and consequently evidenced that the meteorological condition are closely related to the applicability of its definition [10]. Different definition can determine appreciable differences in the estimated height [3]. The study was focused on seven different methods to determine the PBL height from a single data set - radiosonde profiles [11]. The results highlighted that the estimated PBL height differs by several hundred meters according to the assessment method. The seasonal variation could also be dependent on the different methods for assessing the PBL height. Seibert et al. (2000) emphases that a good approach would be to use the same method to compare different PBL height estimates determined from different sources (e.g. radio sounding, passive and active remote sensing).

Meanwhile Seidel et al. (2012) recommended a definition based on bulk Richardson number for the PBL height. The importance of meteorological conditions was

underlined by Helmis et al. [12, 13] in evaluating PBL height, when he compared two mesoscale forecast data models with data from a RASS sodar and ceilometer. When the PBL height assessment is performed through forecasting models, the nature of the parameterization is more important than the resolution [14, 15]. Hu et al. 2010 made a comparison of three PBL schemes in a mesoscale model and the results was that local PBL scheme presented a lower PBL height when turbulent kinetic energy was explored against estimations that use the potential temperature profile [16].

Complementary techniques to determine and study the dynamics of the PBL height in respect to physical parameters are taken into account. The present study is focused on the assessment of the PBL height using remote sensing and radio-sounding data. Results are compared to the ALARO-0 model (Aire Limitée Adaptation Dynamique Développement International - ALADIN and Application de la Recherche à l'Opérationnel à Meso-Echelle - AROME [14, 15] model) in order to estimate the prediction uncertainties in operational use.

The importance of numerical forecasting models is acknowledged for operative forecasting in anticipating severe phenomena such as heavy rains, hail, winds, fog, but also to analyze the PBL depth behavior and associated physical phenomenon. Because the forecast activity requires a continuously adaptation of numerical forecasting models to meteorologists/forecasters activities, complementary techniques and models are continuously under development.

The ALARO model is a refined version of the limited area model ARPEGE / ALADIN [34-36]. Due to continuous development of the model's physical parameterization (wet processes), the ALARO model has a better horizontal resolution than the ARPEGE / ALADIN version, making it a perfect candidate for PBL height estimations.

2. Instruments and methodology

In order to compare the PBL height predictions in respect to different measurement techniques, several instruments available at the Romanian Atmospheric 3D Observatory RADO - Bucharest-INOE and Iasi LOA-SL stations were used. For the investigations, the data collected between January and November 2014 was envisaged. The analysis is divided between the warm and cold season in order to evidence possible dissimilarities caused by seasonal variation.

For the active remote sensing technique, the measurements were carried out by using a MiniLIDAR (LOA-SL station Iasi) [9, 17, 18] and a multi-wavelength depolarization Raman Lidar (Bucharest-INOE station) [19-21]. The lidar is a remote sensing instrument capable of providing vertical profiles of atmospheric properties [22]. The PBL height estimation is performed by using the strong gradients between atmospheric layers that can be identified as maxima/minima of the first derivative of the lidar range corrected signal (RCS). This technique is called the gradient method, and is considered a direct way of extracting the aerosol layers from the lidar data [21].

The gradient methods for PBL detection presume the occurrence of threshold values for mixed-layer LIDAR backscatter signals [23, 24] or the first derivative of the lidar backscatter signal [25]. These methods are suitable for near-real time assessment of the PBL height, extensively used up to now for ceilometer measurements [21, 26]. A more complex retrieval involves the wavelet covariance method [27, 28]. This approach was proved to be appropriate particularly when low signal to noise ratio data is used, as is the case of ceilometer systems [6, 21, 29].

For the Bucharest station, a RPG-HATPRO microwave radiometer was also considered. The system provides high temporal resolution profiles of temperature and humidity up to 10 km [30, 21]. For this data, the potential temperature laps rate was considered in order to retrieve the PBL height [31].

Additionally the Wyoming radio-sounding data for the Bucharest-INOE site was used [32]. The PBL height was estimated from the potential temperature inversion layer and the sharp drop in relative humidity [19, 33].

The ALARO model used in the PBL height retrieval was integrated into operational mode after an extended analysis of the performance and accuracy of the output products. The microphysics of the model includes five prognostic species of water (vapor, liquid water and ice from clouds, rain and snow). The microphysical process parameterization involves interactions layered precipitation ("resolved" by the model) and convective precipitation (processes under the grid). New features include increased number of vertical levels, different time steps and finite element meshing (compared to finite differences vertical meshing).

3. Results and discussion

Lidar-model comparison: A complete analysis for both warm and cold seasons is presented for Iasi and Bucharest stations. The results show that for warm season, the mean offset between the measured PBL height (lidar) and the ALARO model retrievals does not exceed 200m (Fig. 1). For these values, we found a maximum offset value of 290m for Iasi-LOA-SL station and 300m for Bucharest-INOE station. The measured PBL height during the analyzed period (April-June 2014) varies from 1250m up to 2300m (Fig. 1).
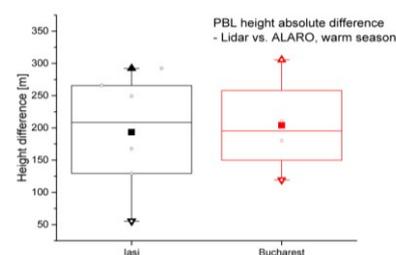

Fig. 1. PBL height absolute difference between Lidar and ALARO model for the warm season. June 2014.

In the case of cold season, the mean offset between the measured PBL height (lidar) and the ALARO model retrievals for the Bucharest-INOE station is higher when comparing to the warm season - 400m (Fig. 2). The difference between the warm and the cold season could be related to the geometric constrains of the Bucharest-INOE lidar systems: the incomplete overlap [22]. For the Bucharest-INOE lidar system, the full overlap height is around 900m. For this opto-mechanical setup, the first few hundred meters of the profile are considered the "blind zone" and the next height range, up to the full overlap, is considered the incomplete overlap range [19, 20]. All layers that are present below the incomplete overlap zone cannot be detected by the lidar system.

In case of the Iasi-LOA-SL station, the overlap height is much lower, since the opto-mechanical design of the instrument is optimized for PBL studies and all measurement are performed at 45° zenith angle (in respect to the 0° zenith for the Bucharest site) [9, 17].
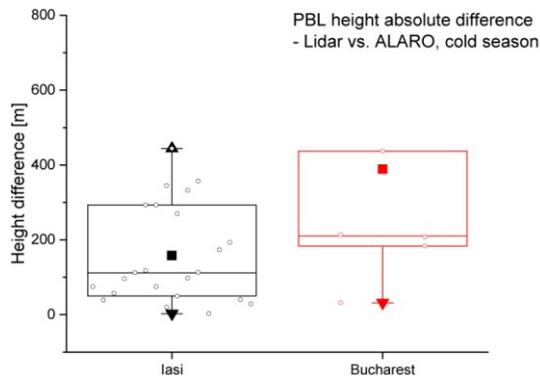

Fig. 2. PBL height absolute difference between Lidar and ALARO model for the cold season. January-April 2014 for Bucharest and October-November 2014 for Iasi.

Measurements performed during the cold season for the LOA-SL Iasi station show a good correlation between measured and predicted PBL height was good - Fig.2.

The mean offset between PBL height retrieved by lidar and the one predicted by ALARO was 150m with a maximum offset of 400m.

The measurements performed at LOA-SL Iasi station are part of an intensive campaign performed between October 25th and November 5th 2014. The LORELAY campaign (Laser and Optical REmote sensing of atmospheric-LAYers) was aiming to investigate differences between the PBL height retrieved from LIDAR measurements and PBL height predicted by the ALARO model.

<u>PBL heigth retrieval using multiple methods:</u> In order to validate the lidar retrivals and to assess the overlap effects of the Bucharest-INOE lidar, complementary data was envisaged. Radio-sounding and Microwave Radiometer (MWR) profiles were used. The closest radio-sounding profiling site is aproxx. 12km NE, providing two soundings per day (00:00 and 12:00 UTC). For the

comparisson, only measurements performed during this sounding time interval were considered. For the lidar colocated continuous MWR profiles (temperature and relative humidity profiles up to 10km), the comparison was performed using the same case studies as for the Lidar-Sounding and Lidar-ALARO comparisons.

The mean offset between the measured PBL height (lidar) and the ALARO model retrievals goes up to 700m with a maximum of 1300m (Fig.3). For the Lidar-Sounding comparison, the mean offset goes up to 500m with a maximum value of 1000m. Fig 3 shows that the best results are provided by the Lidar-MWR comparison. The mean offset does not exceed 100m with a maximum offset of 400m. This agreement can be explained by the lidar MWR measurement setup: while the radio soundings are performed 12km from the considered site (Bucharest-INOE), the MWR data retrievals are collocated with the lidar measurements. In case of the Lidar-MWR comparison, the uncertainties related to the location of the measurements are minimal, while the Lidar-Soundings uncertainties are mostly related to the site difference and wind patterns.
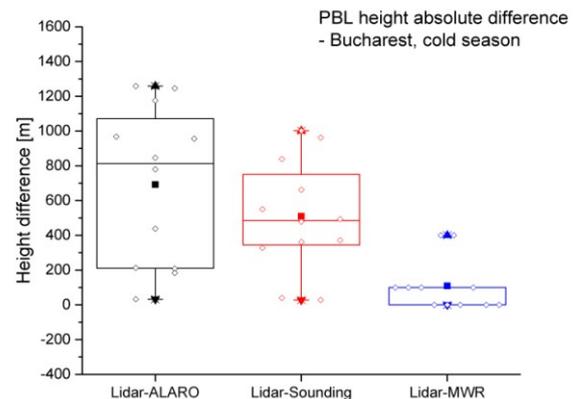

Fig. 3. PBL height absolute difference between Lidar and three other methodes for the cold season. Bucharest station. January-March 2014.

The overlap effect uncertainties are not essential for this comparison. The PBL height retrieved by radio-soundings and the MWR is higher than the height predicted by ALARO (Table 1). The ALARO model shows a minimal value of 132m in comparison to other techniques that evidence values above 299m. The maximum values are also different: the maximum PBL height is 2000m for the lidar, sounding and MWR, while the ALARO model shows a maximum PBL height of 1338m. The mean values have the same behavior: for the measured data (Lidar, Sounding and MWR), the mean PBL height varies around 1000m ±150m, the ALARO model shows a mean value of 629m, indicating that the ALARO model tends to underestimate the PBL height for the Bucharest region.

Table 1. Statistics for PBL height between Lidar and three other methodes for the cold season. Bucharest-INOE station

	Lidar	ALARO	Sounding	MWR
mean	1110m	629m	941m	1104m
min	314m	132m	438m	299m
max	2000m	1338m	1902m	2000m

To better understand the PBL height data provided by the instruments, two case studies were considered for the

Bucharest-INOE station: one for the warm and one for the cold season.

Complex analysis for cold/warn season cases

February 14th 2014 - cold season:
On February 13th 2014, a cold atmospheric front passed over Bucharest-INOE. The 850 hPa analysis revealed a cold air advection with temperature drops of several degrees: from 7.6 to 1.4 degrees Celsius in 24 hours. The MWR data shows the cold air advection over Bucharest-INOE site. Fig 4 shows the relative humidity and temperature profiles for February 13th and 14th 2014.
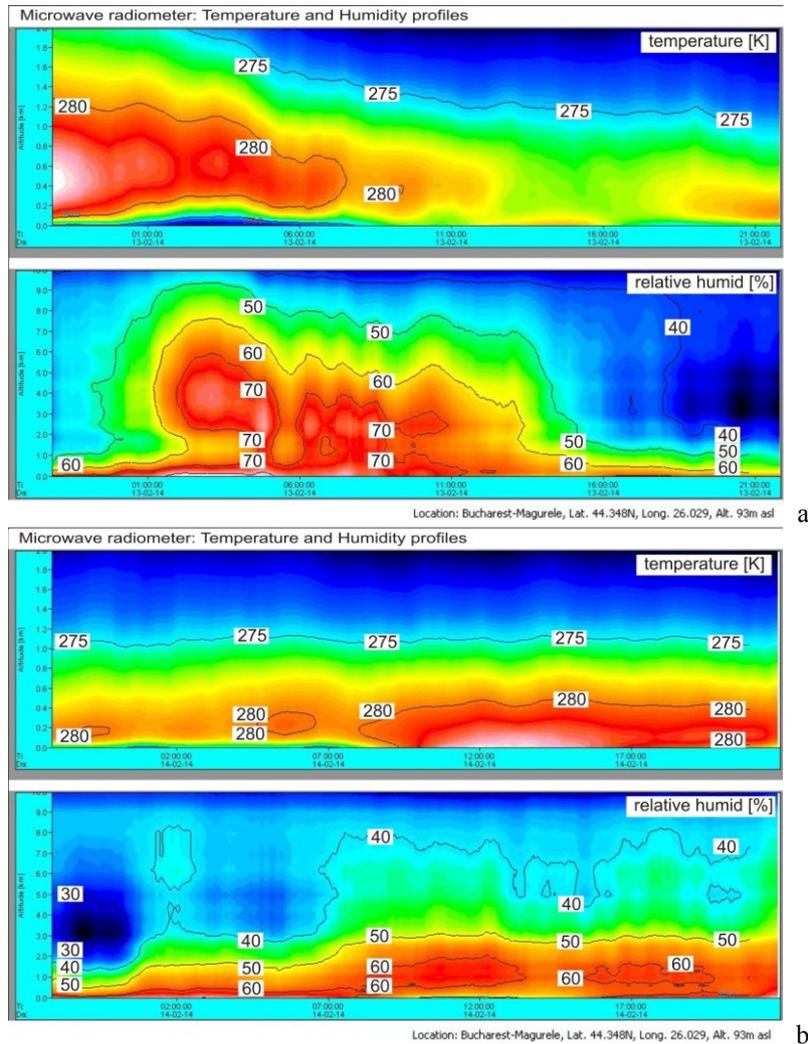

Fig. 4. Microwave Radiometer temperature and relative humidity. Bucharest-INOE station.
a) 13th of February 2014 b) 14th of February 2014.

The 00:00 UTC sounding data shows the PBL height around 450m (Fig. 5 left). The MWR data shows a value of 430m (Fig. 6 - black) and the lidar data shows the first aerosol layer at 530m (Fig. 7 top). The value forecasted by ALARO was 154 m. In terms of meteorological data, the atmospheric pressure at that time was about 1011.0 hPa, relative humidity 84 % and the temperature 2.7°C.

For the 12:00 UTC sounding, the data shows a PBL height around 750m (Fig. 5 right). The MWR data shows values around 530m (Fig. 6 red) and the lidar shows the aerosol layer height around 600m (11:04 AM) - Fig. 7 bottom. The ALARO forecast shows a PBL height around 132 m. In terms of meteorological data, the atmospheric pressure at that time was 1008 hPa, relative

humidity 28 % and temperature 13.6 °C. For this case study, we detected a Stable Boundary Layer that usually occur either over cold land surfaces or during night time intervals [21, 37].
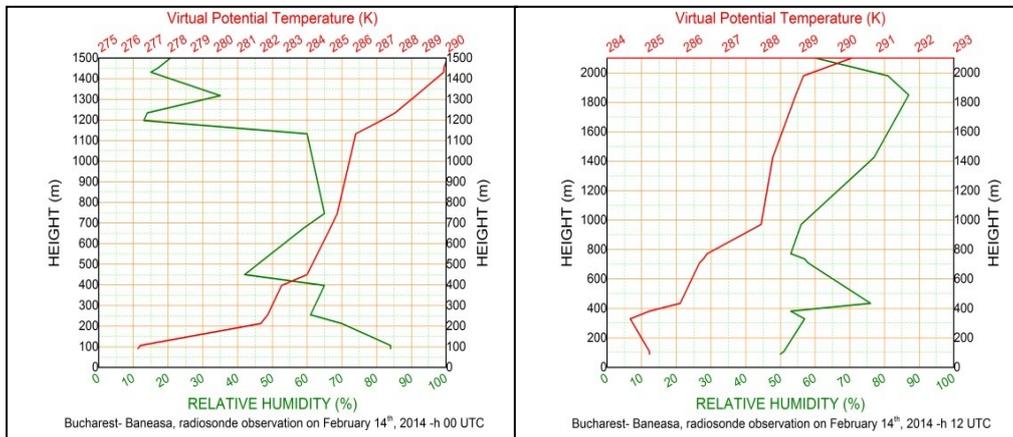

Fig. 5. Virtual Potential Temperature and Relative Humidity representation from aerological sounding at Bucharest-Banesa Station - observation at 00 and 12UTC for February 14th 2014.
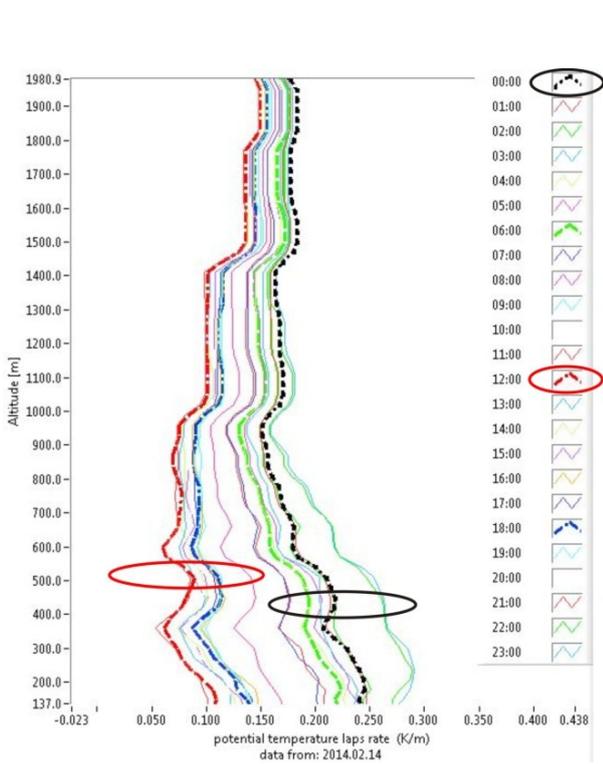

Fig. 6. Microwave Radiometer potential temperature laps rate for 00:00 UT - black and 12:00 UT red for February 14th 2014.
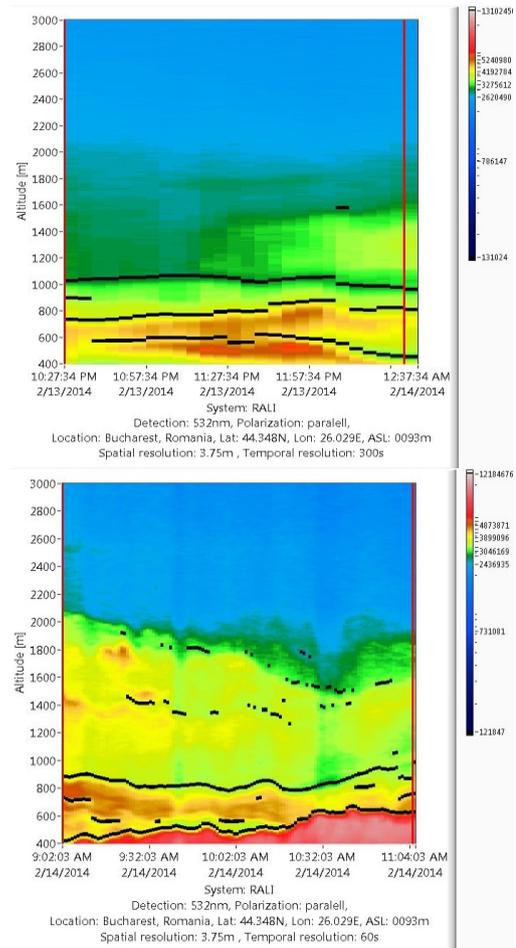

Fig. 7. Range Corrected Signal from Măgurele RADO Station, at 532 nm, from RALI system, observation at 00 (top) and 12 UTC (bottom) for February 14th 2014.

The PBL height retrivels by several techniques and model are presented in Table 2. The ALARO model tends to underestimate the PBL height for the cold season. The offset between ALARO and other envisaged methods is considerably large. While for the ALARO predictions, the PBL height is below 200m, the measured data shows values above 400m in all situations.

Table 2. PBL height results for February 14th 2014. Bucharest-INOE station.

	Lidar	ALARO	Sounding	MWR
values for 00:00	530m	154m	450m	430m
values for 12:00	600m	132m	750m	530m

June 23rd 2014 - warm season:

The data for June 23rd 2014 shows a good agreement between ALARO forecast, radio-sounding and lidar data (Table 3). MWR data was not available for this period. For this case, we have a typical case of a Convective Boundary Layer that is present during day time when surface fluxes drive convective updrafts [21, 37].

Table 3. PBL height results for June 23rd 2014. Bucharest-INOE station.

	Lidar	ALARO	Sounding	MWR
values for 12:00	1800	1819	1580	-

4. Conclusions

This paper presents results regarding the PBL height retrieved using several measurement techniques and analysis methods. The PBL height has been assesd for RADO stations in Iasi and Bucharest by means of vertical profiles of humidity, temperature, range corrected signal lidar profiles and meteorological data from radio-soundings. The envisaged methods cover active remote sensing, passive remote sensing, radio-sounding and forecasting operational model.

The aim of the study was to compare the ALARO operational model with different measurement techniques in order to assess the performance of the PBL height predictions. Under warm weather conditions, the ALARO forecast shows good results both for the Bucharest-INOE and Iasi stations. The mean PBL height difference between the model and other techniques is under 200m for both measurement sites. During the cold season, the ALARO forecast for Bucharest showed a significant offset in respect to the warm season. This difference could be related to the system overlap, that makes the PBL height retrieval more difficult for heights less than 900m. For Iasi, the offset between the forecasted data and the

measured data showed similar values during summer and winter seasons.

In order to assess the influence of the overlap in the lidar-ALARO comparisons, an extended analysis was performed using several instruments: the lidar system, a MWR profiler, radio-soundings and forecast ALARO data. The results showed a good agreement between lidar system, MWR profiler and radio-soundings data. The ALARO forecast showed a significant offset in respect to all other techniques. The overlap function may have an influence on the PBL height results, but the offset detected between ALARO and lidar data is not caused by this drawback. For the Bucharest-INOE site, the PBL height estimation performed by ALARO has a permanent offset during the cold season. This offset could be caused by local patterns that are disregarded by the ALARO model. These patterns may not be present in the Iasi region.

The ALARO model provides good results for the warm season but all of them depend on sensitive data like temperature and humidity gradients, point of observations and local patterns.

The influence of pollutant dispersion and physico-chemical behavior/properties remains of paramount importance for atmosphere forecasting, in order to model and predict severe phenomena such as heavy rains, hail, winds and fog. All latter parameters underline the importance not only for experimental data but also for model and complementary space-time resolved optical emission spectroscopy techniques, for assessing atmospheric chemical compound behavior.

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