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François Bouyssel

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Identification of error sources in convective planetary boundary layer cloud forecasts using SIRTA observations

A. Mathieu,^{1,2} J.-M. Piriou,³ M. Haeffelin,⁴ P. Drobinski,¹ F. Vinit,³ and F. Bouysse³

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[1] In this study, errors in cloud base height predicted by two numerical weather prediction models is evaluated using observations from the French instrumented site SIRTA. Results show that a significant portion of the error is due to errors in predicted surface relative humidity. These errors are in turn thought to be caused by the convection schemes.

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1. Introduction

[2] Considerable efforts are continually undertaken to improve the parameterization of cloud processes in global circulation models (GCMs). The goal of evaluation studies is to identify flaws in parameterizations and provide leads to correct them. This task is becoming increasingly difficult because of model complexity, in particular nonlinear interactions between the physical processes described in the models. Realistic simulations of the large scale circulation are essential when using ground-based observations to validate physical process parameterizations. The problem of systematic model error build-up in GCMs is avoided by evaluating short-range numerical weather prediction (NWP) models [Jakob, 2003].

[3] The interaction between clouds and radiation remains a key area of uncertainty in GCMs [Jakob, 2003; Guichard *et al.*, 2003]. Despite significant improvements in the prediction of clouds (base height and water content) by GCMs, these models still poorly predict their diurnal cycle. Long-term remote sensing observations from the ground provide the necessary data to validate vertical distributions of clouds in models, which should have an impact on the ability to forecast radiative fluxes.

[4] In this study we evaluate the predictions of low-altitude cloud base height in convective Planetary Boundary Layer (PBL) situations. Our approach consists in comparing two NWP models and observations. In Section 2 we present the two NWP models and the Site Instrumental de Recherche par Télédétection Atmosphérique (SIRTA) observations.

We evaluate differences between modeled and observed low-altitude cloud parameters, and we diagnose key parameters representative of the processes at the origin of the clouds (Sections 3 and 4). Based on this diagnostics evaluation we identify possible sources for the discrepancies (Section 5).

2. Models and Observations

2.1. Models

[5] In this study we use NWP from the ECMWF (European Center for Medium-range Weather Forecast) global forecast model (IFS) and from the Météo-France global NWP model, ARPEGE. Model outputs are extracted from the database of the European CloudNet project (data available at <http://www.cloud-net.org/>). Both models are initialized by their own assimilation cycles. The two models provide $t + 12$ hr to $t + 36$ hr forecasts based on their own analyses at 00 h UTC. The model outputs are available at 1 hr time step. IFS is operated at an effective horizontal resolution of 40 km with 60 layers in the vertical. The first grid level is at about 10 m. The ARPEGE horizontal resolution over Europe is about 20 km with 41 layers in the vertical. The lowermost level is about 18 m. At the top of a typical PBL (1–2 km), the vertical resolution of the two models is about 200–300 m.

[6] Turbulent diffusion and interactions with the surface are parameterized for both models using a first order turbulent scheme. ARPEGE uses the Louis scheme [Louis, 1979], with the shallow convection incorporated according to Geleyn [1987], a precipitating convection scheme origination from Bougeault [1985] and a semi-empirical cloudiness scheme proposed by Xu and Randall [1996]. IFS uses the Beljaars and Viterbo [1999] scheme with a revised version of Tiedtke [1989] for the moist convection scheme and the prognostic cloud scheme by Tiedtke [1993].

2.2. Observations

[7] Model evaluation is done using observations from the ground-based remote sensing observatory [48.7°N, 2.2°E], SIRTA [Haeffelin *et al.*, 2005]. The observatory sits on a plateau at 160 m above sea level which is a semi-urban environment divided equally in agricultural fields, wooded areas, and sparse housing developments. For our study, it can be considered as reasonably homogeneous and flat.

[8] For the purpose of model evaluation the measurements have to be aggregated to coarser time scales in order to match the model resolved scales. The aggregation length should be long enough to remove the fluctuations from contributions that are supposed to be sub-grid scale in the model. For the current study in which horizontal model grid meshes are about 40 km, it is reasonable to restrict the analysis to the static interpretation of the aggregation and

¹Service d'Aéronomie, Institut Pierre-Simon Laplace, Paris, France.

²Now at Institut de Radioprotection et de Sécurité Nucléaire, Fontenay aux Roses, France.

³Météo-France, Centre National de Recherches Météorologiques, Toulouse, France.

⁴Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, Palaiseau, France.

Table 1. Contingency Table of Predicted and Observed Occurrence of Clouds of CBH Below 2500 m in Convective PBL^a

		ARPEGE		IFS		OO alone
		Cloud	Clear	Cloud	Clear	
OO	Cloud	40	13	45	8	53
	Clear	11	36	11	36	47
PO alone		51	49	56	44	

^aOccurrence in percent.

choose a single averaging size of one hour [Morcrette, 2002]. For observed surface temperature and relative humidity, hourly values are computed using a median estimation. A Vaisala proprietary algorithm retrieves up to 3 cloud layer heights (cloud base) at each time step from the ceilometer measurements. We identify the lowest consistent cloud layer in each one-hour interval and derive the cloud cover fraction as the ratio of the number of profiles containing clouds to the total number of profiles.

[9] The diurnal cycle of cloudy and clear PBL observed using the aerosol lidar is a good signature of the PBL state. In case of convective PBL lidar observations clearly show the PBL thickening throughout the course of the day. Using this signature we selected 212 days in the April–September 2003 and 2004 periods. To diagnose convective hours during the investigated days, we selected the time periods

of upward surface buoyancy fluxes predicted by the models. We found 2528 and 2270 convective hours for ARPEGE and IFS respectively, all of them between 05:00UTC and 20:00UTC. Both models are in agreement on the sign of the turbulent surface fluxes for 88% of the cases. The discrepancy occurred essentially at the beginning and at the end of the daytime since ARPEGE predicts slightly longer upward surface fluxes sequence than IFS.

3. Evaluation of Cloud Forecasts

3.1. Cloud Occurrence

[10] Table 1 is the contingency table (based on the selected days) of observed and predicted occurrences of clouds that have a CBH below 2500 m (maximum observed PBL height). During the convective periods, clouds are observed at SIRTAs 53% of the time. ARPEGE and IFS scores match the observations statistics. Overall, 81% and 76% of cloudy and clear PBL situations are correctly predicted in coincidence with observations for IFS and ARPEGE, respectively.

3.2. Cloud Cover Fraction

[11] The PBL cloud cover fraction is retrieved from model outputs considering only hours when the lowest CBH is found below 2500 m. Figure 1 shows that ARPEGE

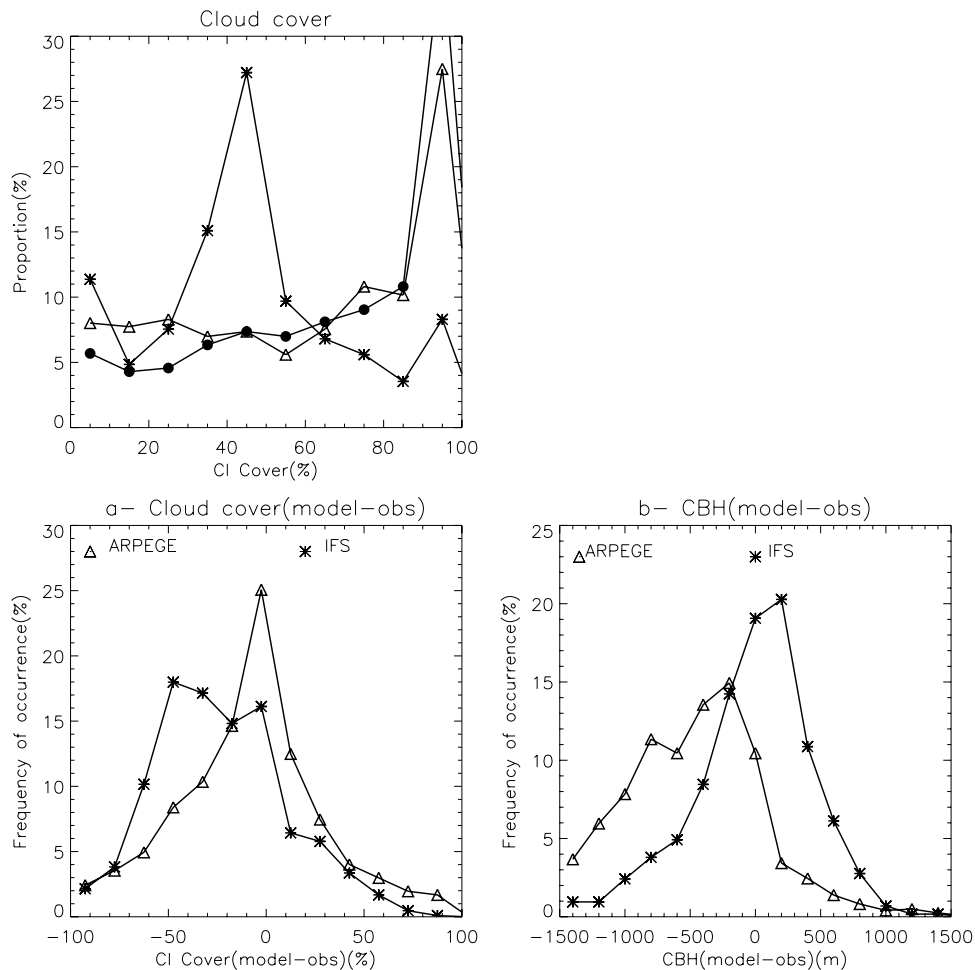


Figure 1. Frequency distributions of the difference between the PBL cloud fraction predicted by ARPEGE (triangles) or IFS (stars) and observed between April and September 2003 and 2004 for convective periods of the selected days.

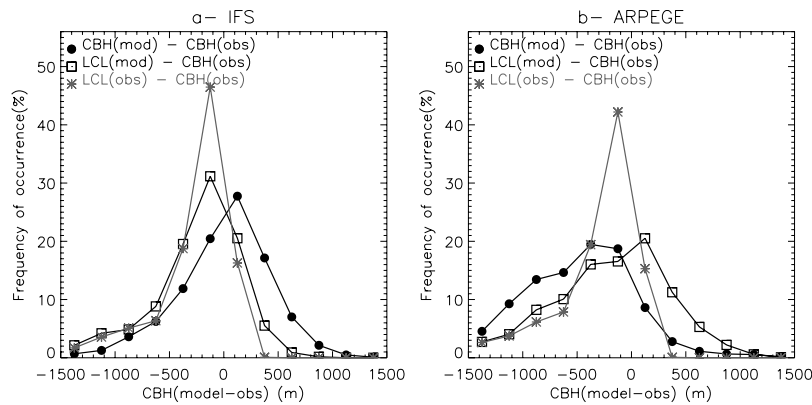


Figure 2. Frequency distributions of the difference between the first CBH predicted by models and the one observed are plotted with black dots. Frequency distributions of the difference between the diagnosed LCL when lower than the BLH and the observed CBH are plotted with black squares. Frequency distributions of the difference between the LCL diagnosed using an observed parcel and the observed CBH are plotted with grey stars. Comparisons are done for (a) IFS and (b) ARPEGE.

accurately predicts (within $\pm 20\%$) the PBL cloud cover fraction in more than half of the situations for convective conditions. On average IFS significantly underestimates the cloud cover fraction compared to observations.

3.3. Cloud Base Height

[12] We use the CBH as an indicator of the convective activity of the moist unstable PBL. Figure 2 shows frequency distributions of differences between modeled and observed CBH. Predicted CBH (solid line with filled circles) are considered as correct if model-observed differences are less than ± 300 m (300 m is about one model layer thickness at 2000 m above surface). Figure 2a reveals that for convective PBL, IFS correctly predicts the CBH in 48% of the cases while ARPEGE (Figure 2b) is successful in only 24% of the cases. 54% of ARPEGE CBH are underestimated by more than 300 m. Errors in CBH representation in models may be due to incorrect relative humidity distribution (since they are highly correlated), to incorrect large scale or surface conditions, to the choice of PBL and/or cloud schemes.

4. Determination of Model Error Sources in Convective PBL Cloud Forecasts

4.1. Diagnostics Using Model Outputs

[13] In cloudy convective PBL cases, unstable parcels rising from the surface condense at the level of the observed CBH. They proceed to rise up to the inversion layer where they reach an equilibrium level that defines the boundary layer height (BLH). For dry PBL cases, air parcels reach the BLH before condensation. The BLH and lifting condensation level of the parcel (LCL) are diagnosed from model outputs following Mathieu *et al.* [2004]. Rising parcels of air are characterized by surface layer characteristics plus an excess of buoyancy. The LCL is representative of the population of parcels injecting water in the cloud layer. Therefore this LCL (hereafter LCL(mod)) should be representative of the CBH actually observed when the processes are driven by the surface.

[14] Figure 2 shows frequency distributions of differences between the diagnosed LCL(mod) and observed

CBH (black square curve). For both models, the diagnostic approach improves the distribution compared to the standard model prediction. The overall CBH agreement increases from 48% to 57% for IFS (Figure 2a) and from 24% to 42% for ARPEGE (Figure 2b). This suggests that for some of these cases, the links between the PBL convective activity and the formation of clouds are too weak in the model. ARPEGE diagnostics still underestimate the CBH.

4.2. Diagnostics Using Surface Observations

[15] LCL and BLH diagnostics are very sensitive to surface conditions predicted by models through the parcel buoyancy. The underestimation of LCL(mod) may be due to surface biases. Surface temperature and relative humidity are now used to characterize the ascending parcel to diagnose LCL (hereafter LCL(obs)) and BLH. In this approach, we compute the virtual potential temperature of a representative parcel based on observed 1 hr median surface temperature and relative humidity. The solid line with grey stars in Figure 2 shows the probability distribution of the difference between LCL(obs) and observed CBH for both models. While the distributions show that the predicted CBH are slightly underestimated compared to the observations, overall more than 60% of the LCL(obs) are within 300 m of observed CBH. Differences greater than ± 300 m may be explained as follows: (i) hourly CBH estimated from observations may be ambiguous in multi-layer and broken cloud base situations; (ii) the observed cloud may be created by other processes. The agreement between LCL(obs) and the observations is much better however.

5. Origin of Model Error Sources in Convective PBL Cloud Forecasts

5.1. Impact of Surface Bias on CBH Prediction

[16] Figure 3 shows frequency distributions of the difference between predicted and observed surface temperature (Figure 3a) and surface relative humidity (Figure 3b). ARPEGE shows a slight overestimation of the surface relative humidity and temperature, whereas IFS slightly underestimates the surface temperature. Figure 4 is a scatter

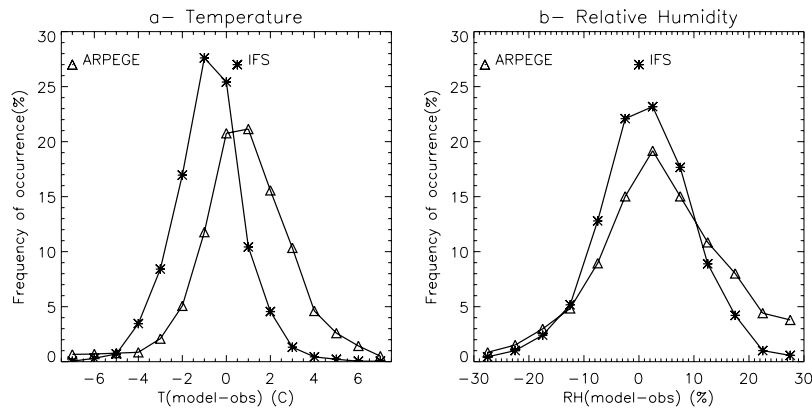


Figure 3. Frequency distributions of the differences between the near surface characteristics predicted by ARPEGE (triangles) or IFS (stars) and the one observed during convective PBL events. Comparisons are done for (a) temperature and (b) relative humidity.

plot of relative humidity differences versus CBH differences between IFS (Figure 4a), ARPEGE (Figure 4b) forecasts and observations. For both models, the surface biases are significantly correlated with the CBH differences as shown for the relative humidity. For ARPEGE, PBL cloud forecasts are systematically associated with an overestimated surface relative humidity: the more humid the surface, the lower the CBH. The overestimate of relative humidity and temperature results in the poor scores for CBH prediction by ARPEGE.

5.2. Impact of Convective Precipitation on Surface Bias

[17] Surface biases can have several origins. Soil and vegetations schemes, surface and PBL schemes, cloud and radiative scheme or convection scheme may be at fault. During the situations retained in our study and the 12 hr periods before each of the selected days, more precipitation events occurred in IFS (39% of the hours) than in ARPEGE (27% of the hours). Only 11% of the hours are large-scale precipitation events in ARPEGE against 34% in IFS whereas ARPEGE has more convective precipitation events than IFS (17% against 6%). It is known that ARPEGE has a tendency to predict erroneous light precipitation events (lower than $0.5 \text{ mm}\cdot\text{hr}^{-1}$) when only dry convection is observed. The frequency distributions of the difference between predicted and observed surface temperature and

surface relative humidity are shown in Figures 5a and 5b, respectively. Grey curves correspond to the situations where no convective precipitation events are predicted in a period of 12 hours before the comparison whereas black curves correspond to convective precipitation events. For IFS, precipitation results in a slight reduction of the temperature bias, compared to dry situations, and an underestimation of relative humidity. For ARPEGE precipitation events are associated with greater biases in both temperature and relative humidity.

6. Conclusion

[18] Low-altitude cloud base heights and cloud cover fractions produced by ARPEGE and IFS models are evaluated using an ensemble of in situ and remote sensing measurements from the ground-based SIRTA observatory for situations identified as dominated by convective PBL processes. In such conditions, low-altitude cloud occurrence predictions are found to be correct about 80% of the time. The cloud fraction is underestimated by IFS whereas the average simulated CBH is found to be underestimated by ARPEGE.

[19] A diagnostic method, computing CBH from temperature and humidity close to the surface using observed or simulated surface properties, allows us to relate CBH biases to model biases close to the surface. Our analysis points

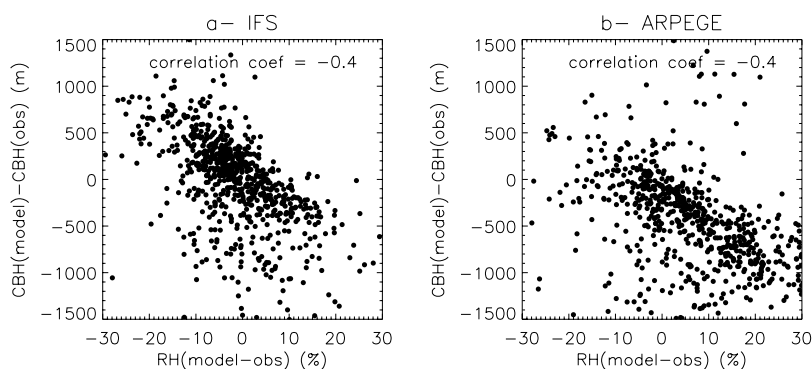


Figure 4. Scatter plots of relative humidity differences (modeled–observed) versus CBH differences for (a) IFS and (b) for ARPEGE. The correlation coefficients are indicated in the panels.

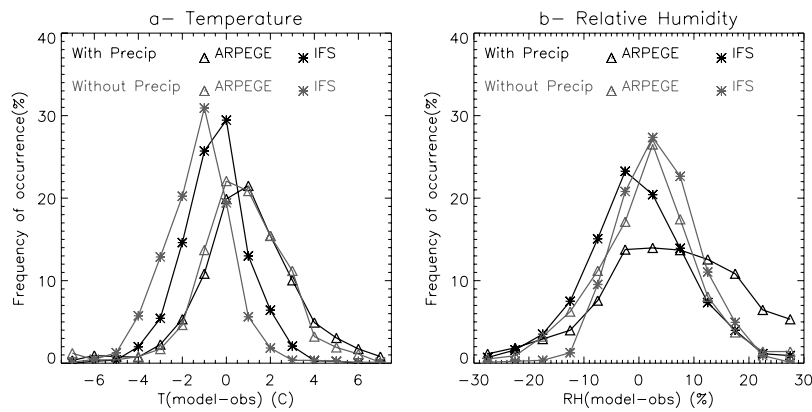


Figure 5. Frequency distributions of the differences between the near surface characteristics predicted by ARPEGE (triangle) or IFS (stars) and the one observed during convective PBL events. Black curves are comparisons done when convective precipitation events occurred less than 12 hours before the comparison whereas grey plots are comparisons done when no convective precipitation events occurred. Comparisons for are done for (a) temperature and (b) relative humidity.

toward the surface temperature and relative humidity that are found to be frequently overestimated in the models. We then investigate the model error sources and find that convective precipitation events are followed by increased surface temperature and relative humidity biases in the models. These trends are being further studied in ARPEGE, in particular the triggering and entrainment aspects of the convective schemes that are linked to the precipitation flaws, as shown in this study.

[20] PBL properties are affected by surface fluxes and by the cloud parameterization. Shallow convection provides PBL ventilation at the top, clouds cause radiative cooling, so it is too simple to see clouds as a response to PBL properties only. Such an investigation can be carried out by further exploiting the wealth of information provided on the one hand by remote sensing instrument synergies available from ground-based observatories and on the other hand by multiple model predictions.

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F. Bouyssel, J.-M. Piriou, and F. Vinit, Météo-France, CNRM, 42 Avenue G. Coriolis, F-31057 Toulouse, France.

P. Drobinski, Service d'Aéronomie, IPSL, 4 place Jussieu, F-75252 Paris, France.

M. Haefelin, Laboratoire de Météorologie Dynamique, IPSL, Ecole Polytechnique, F-91128 Palaiseau, France.

A. Mathieu, IRSN, BP 17, F-92262 Fontenay aux Roses, France. (anne.mathieu@irsn.fr)