SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	2016
Project Title:	EFFECT OF THE SURFACE HETEROGENEITIES IN THE ATMOSPHERIC BOUNDARY-LAYER
Computer Project Account:	SPESTURB
Principal Investigator(s):	Joan Cuxart and Maria A. Jiménez
Affiliation:	Universitat de les Illes Balears (UIB)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project:	1st January 2015
Expected end date:	31st December 2017

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	150000	15000	150000	29000
Data storage capacity	(Gbytes)	200	200	200	100

Summary of project objectives

(10 lines max)

The current special project (2015-2017) is linked to the previous one (2012-2014) devoted to study the organization of the flow at lower levels in complex (topography) terrain regions. Now the attention is focused again in complex terrain regions but especially in areas with (surface) small-scale heterogeneities (related to temperature, soil moisture, vegetation or soil properties, among others). The aim of the project is to evaluate the impact of these small-scale heterogeneities in the spatial and temporal evolution of the atmospheric boundary layer, with special emphasis during the morning and evening transitions. The studied areas are the island of Mallorca and the Pyrenees, both taken as example of complex terrain regions with large surface heterogeneities.

Summary of problems encountered (if any)

(20 lines max)

Summary of results of the current year (from July of previous year to June of current year). This section should comprise 1 to 8 pages and can be replaced by a short summary plus an existing scientific report on the project

This project is the continuation of a former one devoted to the study of the stably stratified boundary layer (SPESTURB, 2002-2011) which gradually evolved into the study of the Atmospheric Boundary Layer (ABL; SPESTURB, 2012-2014) over complex terrain in weak general pressure gradients, allowing to inspect the effect of the terrain-induced flows over the ABL characteristics. The analysis of atmospheric motions in complex terrain is made by our group through the combined use of experimental data (very often from campaigns that we organize or where we participate with our own instrumentation) and numerical modelling. The principal source of computing time for the very high-resolution simulations has been the SPESTURB project at ECMWF with the MesoNH model (Lafore et al., 1998).

The complexity of the studied regions has increased over time. Mesoscale runs made via the SPESTURB project have been focused on studying the organization of the flow at lower levels in:
(i) the Duero river basin: Low-Level Jet (using LES, Cuxart and Jiménez, 2007), cold pool formation (Martínez et al., 2010).
(ii) the island of Mallorca: nocturnal flows (Cuxart et al., 2007; Martínez and Cuxart, 2007; Jiménez et al., 2008) and sea-breeze (Cuxart et al., 2014; Jiménez et al., 2016a; Jiménez et al., 2016, in preparation).
(iii) the Ebro river basin: fog formation (Cuxart and Jiménez, 2012), mesoscale simulations and remote sensing (Cuxart et al., 2012), surface energy balance (Cuxart et al., 2015).
(iv) the Pyrenees: characterization of the downslope winds (Jiménez and Cuxart, 2014), description of the flow in a narrow valley N-S oriented (Jiménez et al., 2016b, in preparation), the temperature heterogeneities a different spatial scales (Cuxart et al., 2016) or the evaluation of the anisotropy during the afternoon and evening transitions (Lampert et al., 2016).
(v) the Reuss valley: characterization of the advective motions (Cuxart et al., 2016, in preparation).

From the beginning of this project, we have concentrated our efforts in: **(i)** the Sea Breeze (SB) and Land Breeze (LB) in the island of Mallorca, **(ii)** the organization of the flow in La Cerdanya, an E-W oriented valley in the central Pyrenees about 20km long and 2km wide and **(iii)** further exploring the downslope winds during the BLLAST experimental field campaign (works initiated in the former special project). Preliminary results are summarized in the following sections.

1) The sea and land breeze in Mallorca (MSB14 experimental field campaign).

During September 2013 the Mallorca Sea Breeze (**MSB13**) experimental field campaign took place in the Campos basin (at the south of the Island of Mallorca, Western Mediterranean Sea, Figure 1). A morning transition case (from land to sea breezes) was sampled with a multicopter and a tethered balloon. A mesoscale simulation was done of this case with a setup similar to Cuxart et al. (2007). 2 nested domains were taken at 5km and 1km horizontal resolutions and 3m in the vertical (gradually stretched). The observed features during the phases in the morning transition (according to Cuxart et al. 2014) are compared to the model outputs and results are further explained in Jiménez et al. (2016a). It was found that **the model was able to reproduce the turning of the wind from the land-breeze towards the sea-breeze directions as well as the thermal structure in the lower atmosphere**. However, the model was not able to reproduce the nocturnal cold pool, resulting in an unrealistic evolution of the temperature at lower levels during the previous phase. Nevertheless, at the end of this phase the model is reproducing the observed patterns as well as the evolution of the following phases (preparatory and development) during the morning transition. This wrong temporal evolution of the model during the previous phase might be related to a **wrong representation of the surface properties**.

A year later (from 26th May to 6th June 2014) the **MSB14** experimental field campaign took place at the same site. Continuous measurements in Ses Covetes (red cross in Figure 1) were taken from a surface weather station (high-frequency sampling sensors, sonic), a multicopter and a tethered balloon during the 5 IOPs (see description in Figure 2). Due to the strength of the turbulence in the mature phase of the SB, only vertical soundings were sampled during the night-time and the morning and evening transitions (Figure 2). In order to further understand the observations, a high-resolution mesoscale simulation was done with a similar setup used for the MSB13 case: 2 nested domains (at 5 km and 1km resolutions). Besides, a third domain was taken, centered in the Campos basin at 250 x 250 m resolution (see Figure 1).

Preliminary results of the organization of the flow at lower levels for IOP3 are shown in Figure 3. It is found that during night-time the air flows out of the island due to the **combined effect of the LB and downslope winds** and a similar interaction happens during the day. Although all model domains behave similarly, the flow is more realistic at 250m resolution where the topography is better reproduced.

The verification of the runs is a work still in progress but Figure 4 shows the first attempts to compare the multicopter and tethered balloon temperatures to those obtained from the model in Ses Covetes. It is found that the model is able to reproduce the thermal structure during the morning and evening transitions. However, it fails to reproduce the strong surface cooling during night-time (as previously described in Jiménez et al., 2016a for the MSB13 studied case). The modelled surface temperature gradient between land and sea is similar to the one reported from satellite (MODIS and Meteosat) indicating that the model is **able to capture this temperature difference** (Figures 5 and 6), one of the main process to start and maintain the sea-breeze. Comparing the model outputs to other sites in the Campos basin (Ses Salines, 1km inland and Porreres, 15km inland) it is seen that the model, especially the inner domain (D3, at 250m resolution) is closer to observations (Figure 4).

It is important to mention the limitations to verify the model outputs in coastal and mountain regions. Terrain and soil uses, among others, change drastically and this variability is not included in the surface databases that models typically use. This fact can explain the differences between the model and single-point observations or satellite-derived products. These results are under discussion and a manuscript is in preparation to be submitted during 2016.
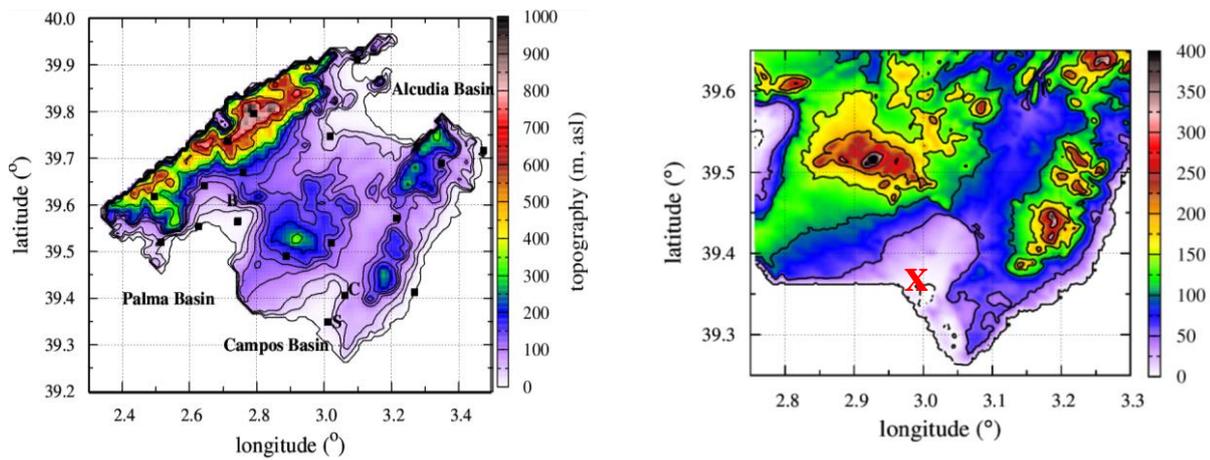
Figure 1. Topography of (a) the second domain (at 1km resolution) of the run and (b) the third nested domain at 250m resolution. The location of the main site during MSB14 (Ses Covetes) is indicated with a red cross and in dots the surface weather stations from AEMET used to verify the model outputs.
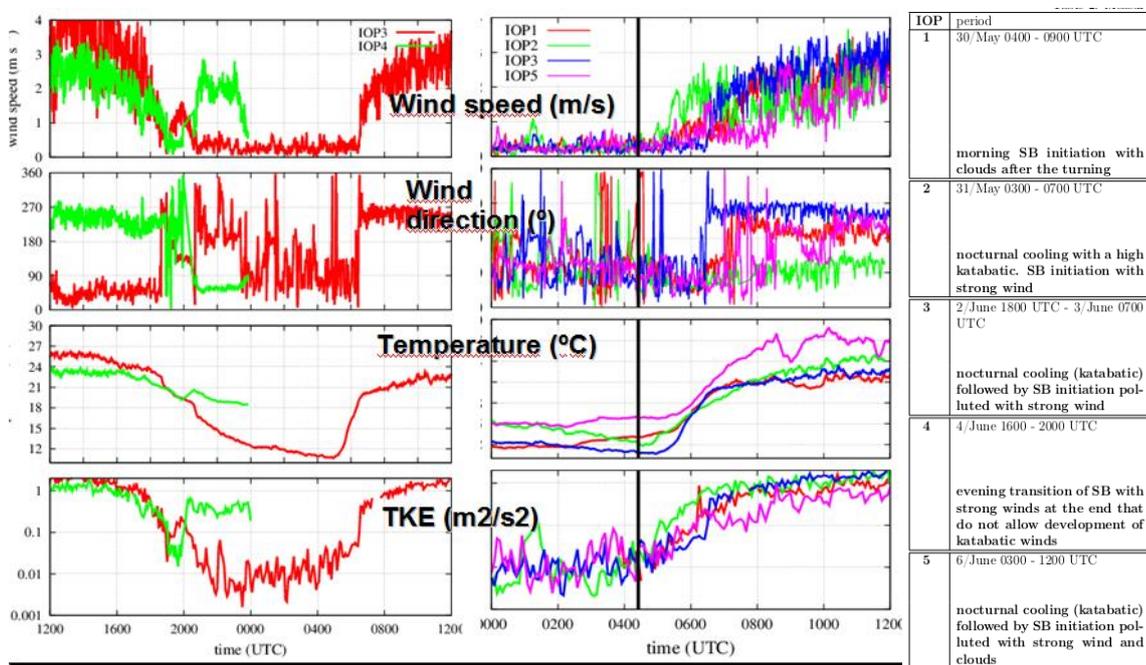
Figure 2. Observations in Ses Covetes during the 5 IOPs of the MSB14 experiment.
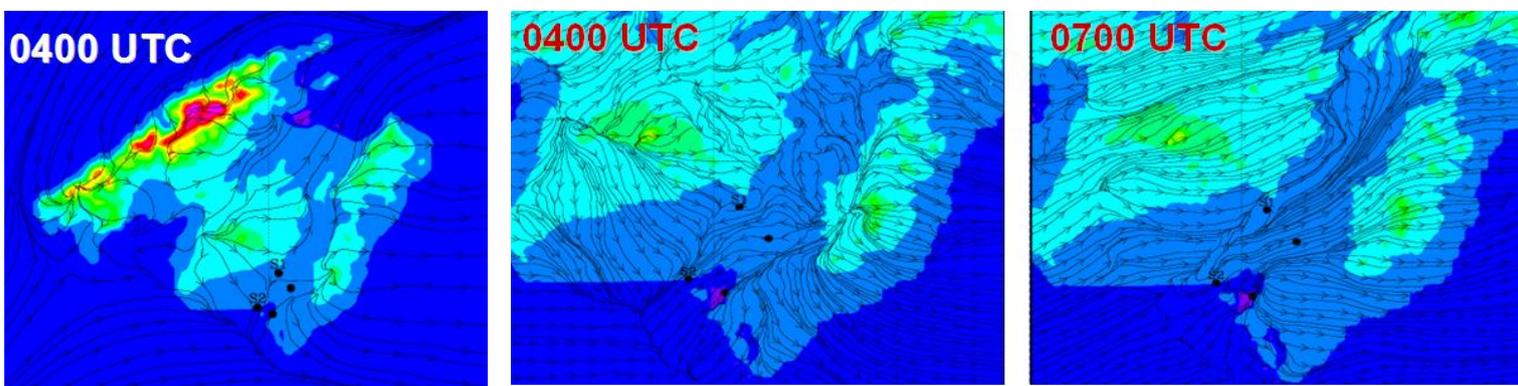
Figure 3. Streamlines at 10m (agl) over the topography (in colours) during IOP 3 (3rd June 2014) at 0400 UTC and at 0700 UTC, for the land and preparatory phases of the diurnal cycle of the SB, respectively.
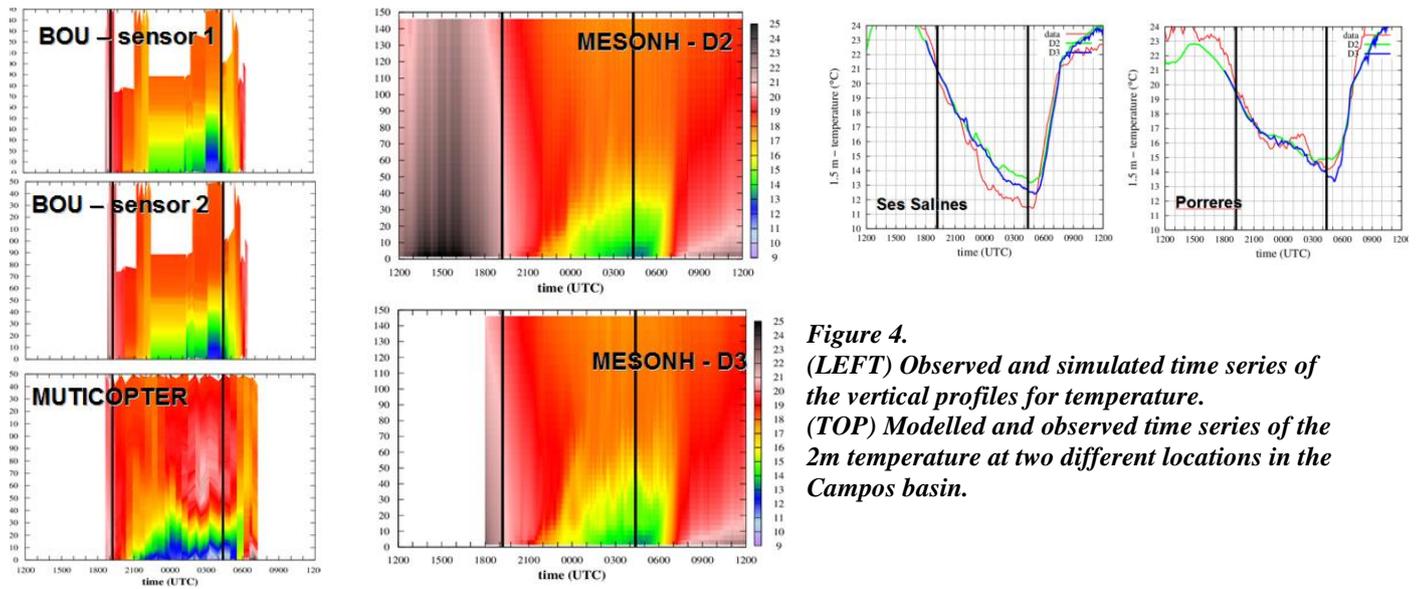
Figure 4.
(LEFT) Observed and simulated time series of the vertical profiles for temperature.
(TOP) Modelled and observed time series of the 2m temperature at two different locations in the Campos basin.
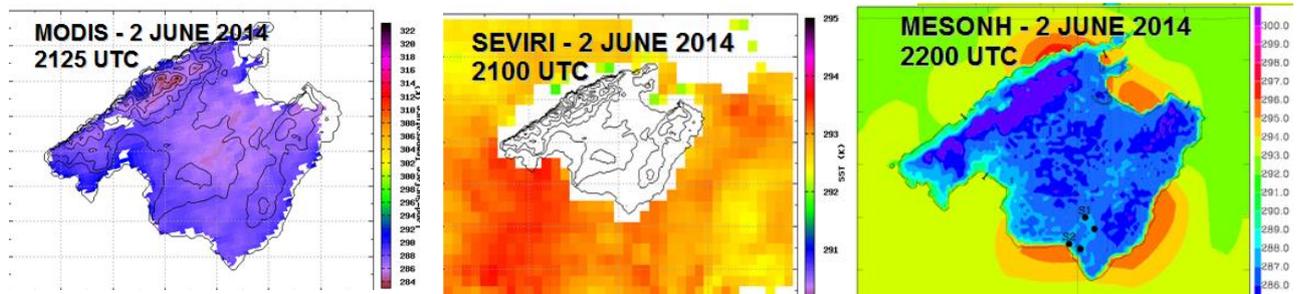
Figure 5. Satellite-derived surface temperatures compared to those obtained from the model during the evening transition sampled during IOP 3.
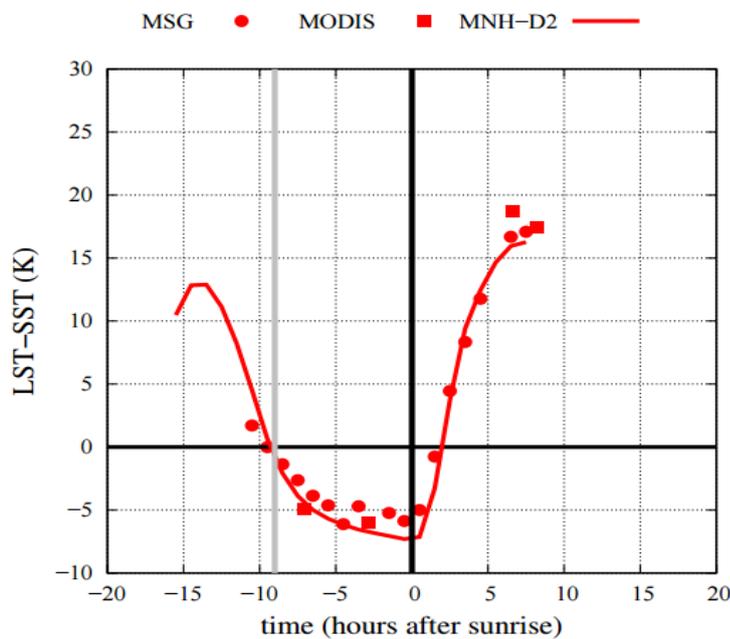
Figure 6. Modelled and satellite derived surface temperature differences between land and sea for IOP 3. The temperatures are averaged over a similar area covering: the center of the Campos basin (LST) and the bay over the sea in front of the Campos basin (SST). Time is shifted to the sunrise hour (black vertical line) and sunset is indicated with a grey line.

2) Organization of the flow at lower levels in a complex terrain valley in the central Pyrenees (La Cerdanya)

La Cerdanya is a valley located in the central Pyrenees 30 km long and 9 km wide oriented to the NE to SW directions. It is taken in this study as an example of **complex terrain valley, in terms of topography but it is also covered by heterogeneous surfaces** (forest, no vegetation, snow, …). A climatology study of this area using surface weather observations is under progress. In order to further understand the organization of the flow at lower levels, a representative case during fall (snow still not present at the mountains top) with a clear diurnal cycle is taken (weak pressure gradient conditions and clear-skies). A period of 48 hours, starting on September 30th 2011 is simulated with the MesoNH model with two nested domains at 2 x 2 km and 400 x 400 m resolution (see Figure 6).
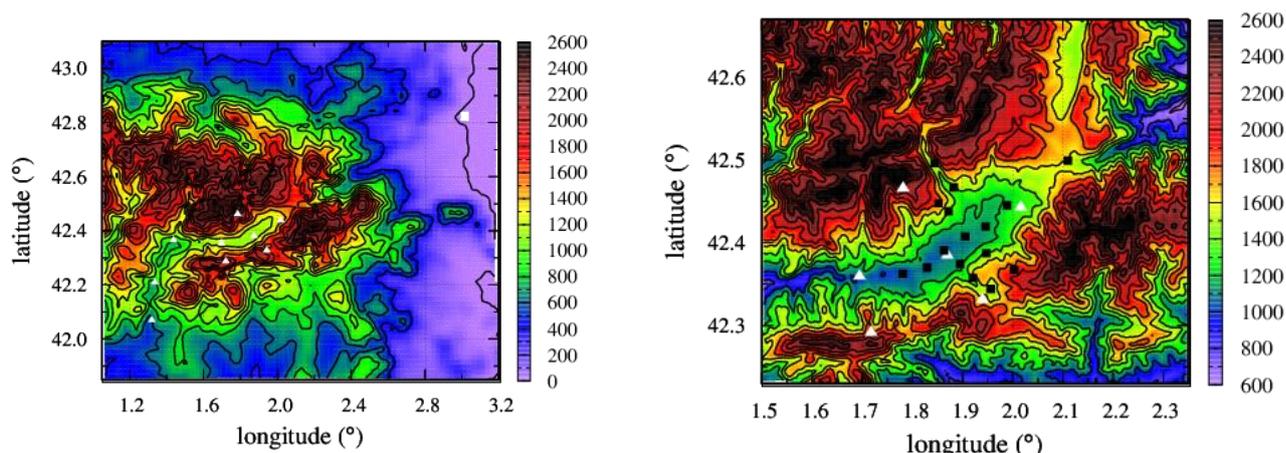
Figure 6. Topography of the two nested domains at (LEFT) 2 x 2 km and (RIGHT) 400 x 400 m resolution, respectively. The locations of the AEMET and MeteoFrance automatic weather stations are indicated in white triangles and some interesting points that we are further exploring are in black dots.

Model results are under discussion and a manuscript is in preparation. Preliminary results are shown in the following figures. It is found that **during night-time downslope and down-valley** winds are generated and the temporal evolution of them in La Cerdanya valley strongly depends on the slope winds generated in the tributary valleys at the north and south (Figure 7, left). An opposite behaviour is found during day time (Figure 7, right). Upslope winds are present in the northern mountains of La Cerdanya whereas those at the south are strongly influenced by the strong upslope winds generated at the south side, outside La Cerdanya.

The model results are verified with satellite observations (MODIS, land-surface temperature, Figure 8) and the surface weather observations (Figure 9). It is found that **the model is able to reproduce the main observed surface temperature patterns**. However, it is **not able to reproduce the small cold pool** in the lower part of the valley (Figure 9), close to the exit (Das, labelled as DP in Figure 7). Modelled 1.5m temperatures are better reproduced in the upper valley (Figure 9, indicated as LEO in Figure 7). The model tends to overestimate the wind speed although it is capturing the turning of the wind.

Now the efforts are concentrated to better understand the cold pool formation close to Das (the coldest area of the valley during night-time), a place that the climatological analysis shows the prevalence of this nocturnal process. During October 2015 an experimental field campaign was conducted in La Cerdanya to better characterize experimentally the cold pool formation close to Das. The analysis of these observations is under progress and a mesoscale simulation of one of the IOPs is expected to be done during the second semester of 2016. Furthermore, an experimental field campaign is expected to be made during February 2017 to better characterize the organization of the flow at lower levels. It is expected that some of the IOPs will be analysed together with the mesoscale model results.
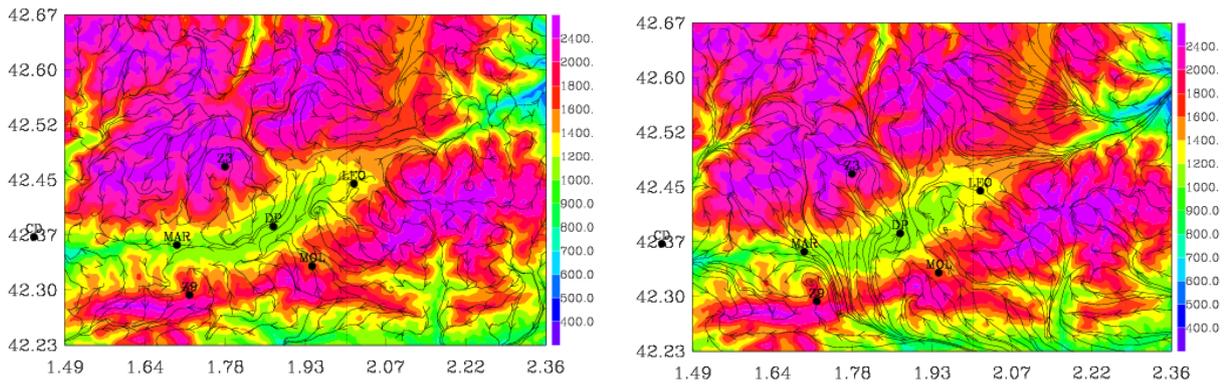
Figure 7. Streamlines at 25m (agl) together with the topography obtained from the inner domain on 1st October 2011 at (LEFT) 0200 UTC and (RIGHT) 1300 UTC.
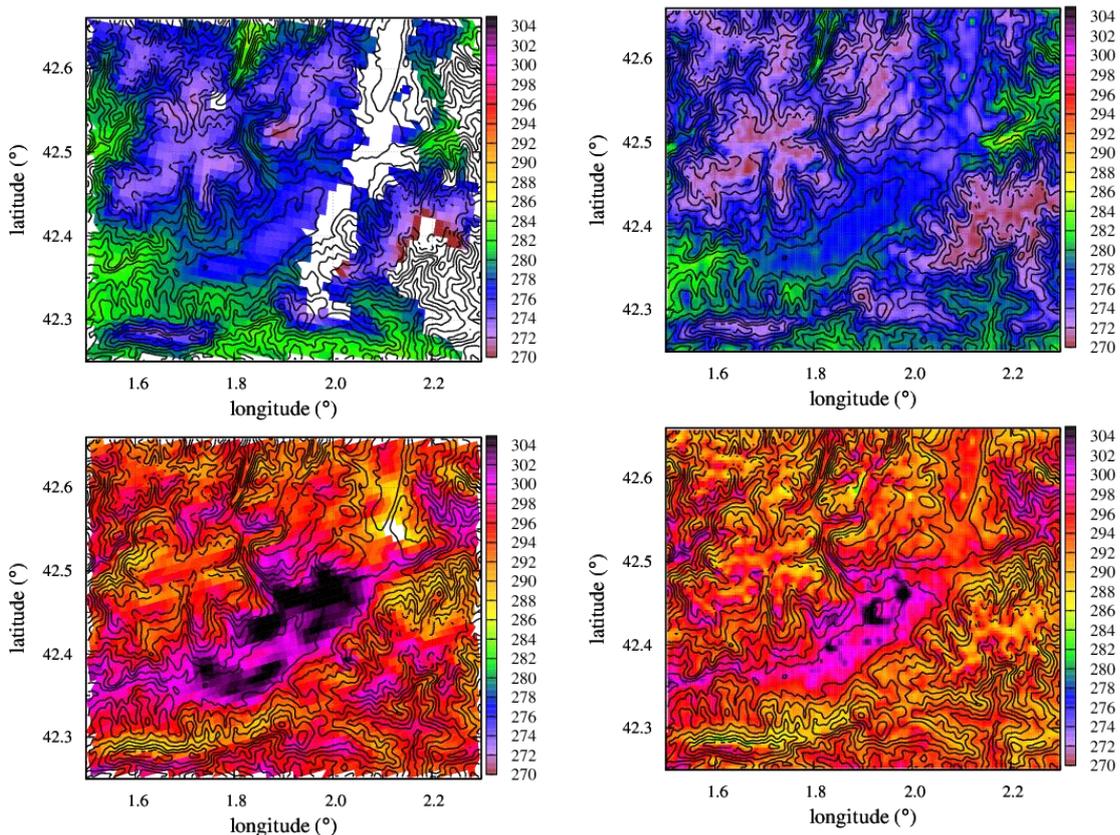
Figure 8. Land-surface temperature observed by MODIS (left) and obtained from the inner domain (right) at 0200 UTC (top) and 1300 UTC (bottom) together with the topography (black lines).
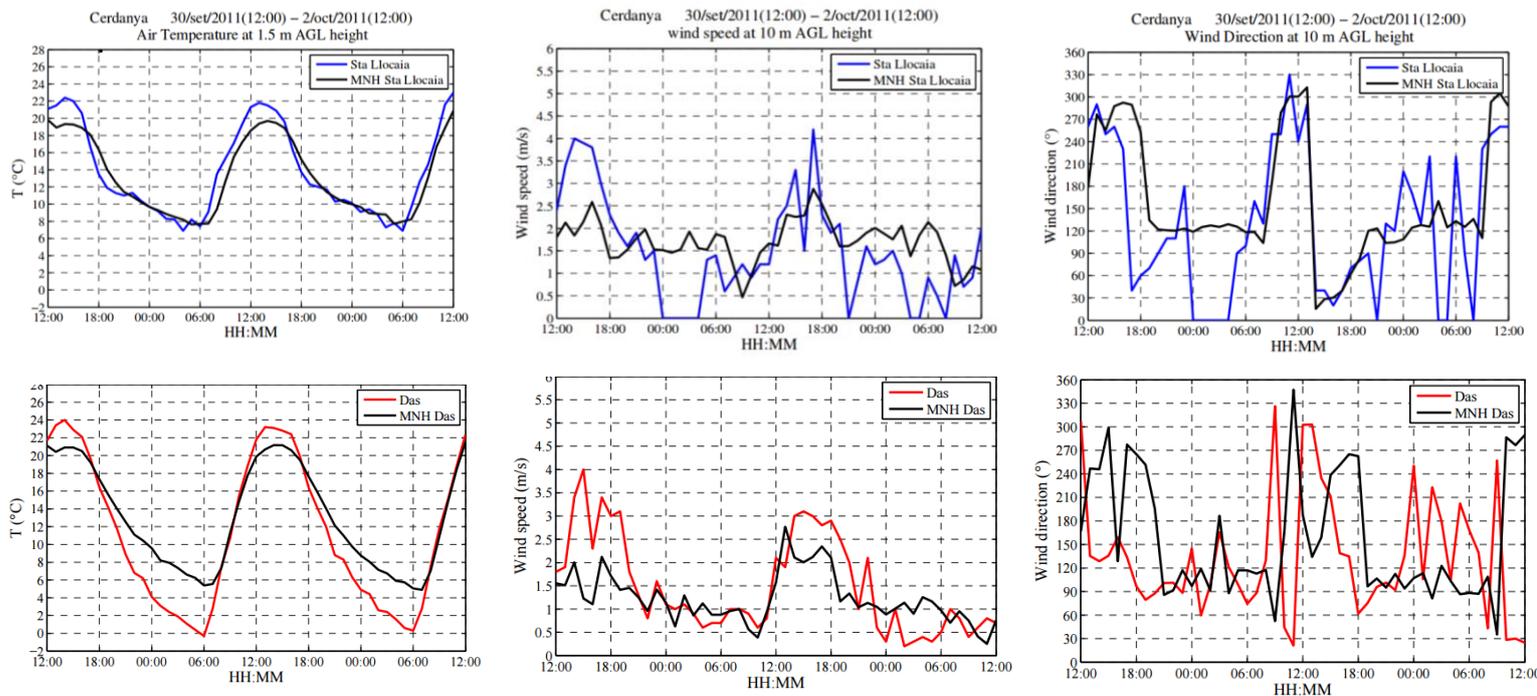
Figure 9. Modelled and observed time series (TOP) in the upper valley and (BOTTOM) in the lower valley, close to the narrow exit. These sites are indicated with LEO and DP in Figure 7, respectively.

3) Downslope winds during the BLLAST experimental field campaign

The **BLLAST** (Boundary-Layer Late Afternoon and Sunset Turbulence) field campaign was conducted from 14 June to 8 July 2011 in southern France, in an area of complex and heterogeneous terrain. The main objective of BLLAST was to characterize the physical processes that take place during the afternoon and evening transitions (Lothon et al., 2014). Measurements were taken at Lannemezan (Figure 10), placed over a plateau at 600 m above sea level (a.s.l.). It is approximately 20 km north of the Pyrenees mountain range and at the exit of the Aure valley (a narrow valley, 30 km long, with the main axis oriented approximately in the north–south direction.

In the previous special project (2012-2015) mesoscale simulations were performed for the case of 1-2 July 2011 (corresponding to IOP9) to better characterize the nocturnal flow in Lannemezan. In the current special project, a total of **6 IOPs have been simulated**. They correspond to IOPs where **clear-sky and weak pressure gradient conditions** were present (see details in Table 1). Two nested domains are taken (see Figure 10) and the setup is similar to the previously simulated case 1 year before the BLLAST campaign (Jiménez and Cuxart 2014).

The aim of the current work is to better describe the **dynamics of the Aure valley**, since there are not available observations. Furthermore, the model results will be useful to describe the main features of the nocturnal exit valley jet and the ambient conditions that favour its formations. This jet is typically generated due to the accumulation of downslope and down-valley winds at the exit of a valley, as it is described in Whiteman (2001).
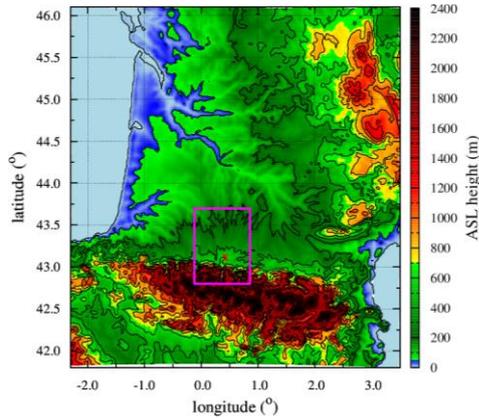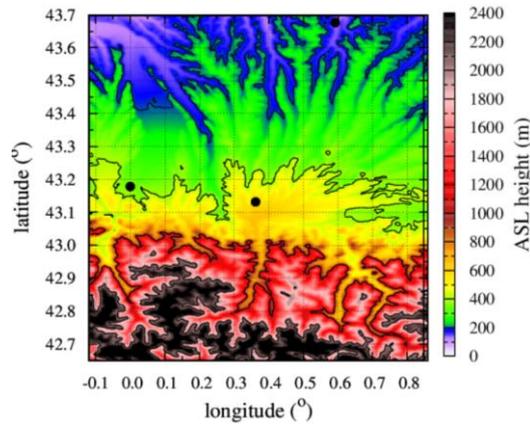
Figure 10. Topography of the 2 nested domains of the simulation of the IOPs (clear sky and weak pressure gradient conditions) during the BLLAST field campaign: The location of Lannemezan is indicated with a symbol.

IOP	Period	wind direction(*) 1300 UTC	wind direction(*) 2300 UTC	sky	Large-scale circulation(**)
1	15-16 June	N	-	clouds and rain	weak winds, not clear direction
2	19-20 June	N	low S	clear skies,light rain	high-pressure, weak E wind
3	**20-21 June**	E	low S	clear skies	high-pressure, weak NE-E wind
4	24-25 June	-	E/S	clouds only during day	Atlantic high-pressure, strong NE-E winds
5	**25-26 June**	E	E/S	clear skies	Atlantic high-pressure, strong NE-E winds
6	**26-27 June**	E	E/S	clear skies	Atlantic high-pressure, winds from N-E
7	27-28 June	-	-	clouds	strong E winds
8	30-1 July	-	-	clouds and rain	strong N winds (fronts)
9	**1-2 July**	N	E/S	clear skies	Atlantic high-pressure, weak NE winds
10	**2-3 July**	N	E/S	clear skies followed by clouds	Atlantic high-pressure, weak NE winds
11	**5-6 July**	N	W	clear skies	Atlantic high-pressure, weak S winds

(*) extracted from the soundings within the BL extend (about 1000 m agl). Slope wind directions in Lannemezan: upslope (N) and downslope (S).
(**) corresponding to the surface level. At higher levels winds were from W for all the IOPs.
(-) indicates no sounding.

Table 1. Description of the different IOPs during the BLLAST experimental field campaign and in bold those studied in depth with mesoscale modelling.
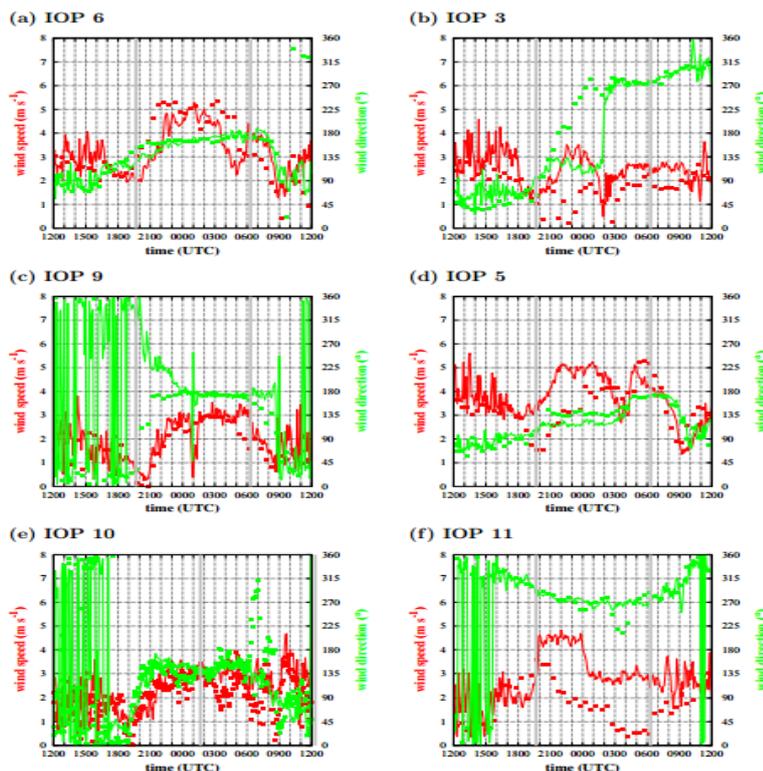
Figure 11. Verification of the runs for the different IOPs during BLLAST for the modelled and observed wind at 15 m AGL. Further details of the IOPs in Table 1. On the (LEFT) the IOPs were southerly winds were reported in Lannemezan (corresponding to the downslope direction) and on the (RIGHT) cases when winds in Lannemezan were not from south during most of the night.

This template is available at:
http://www.ecmwf.int/en/computing/access-computing-facilities/forms

IOP 6　　　　　IOP 9　　　　　IOP 10
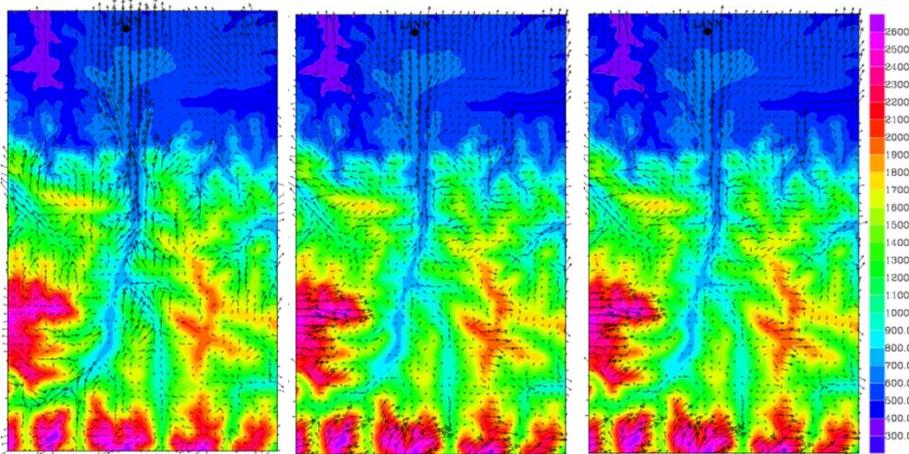
CASES WITH
DOWNSLOPE WINDS

IOP 3　　　　　IOP 5　　　　　IOP 11
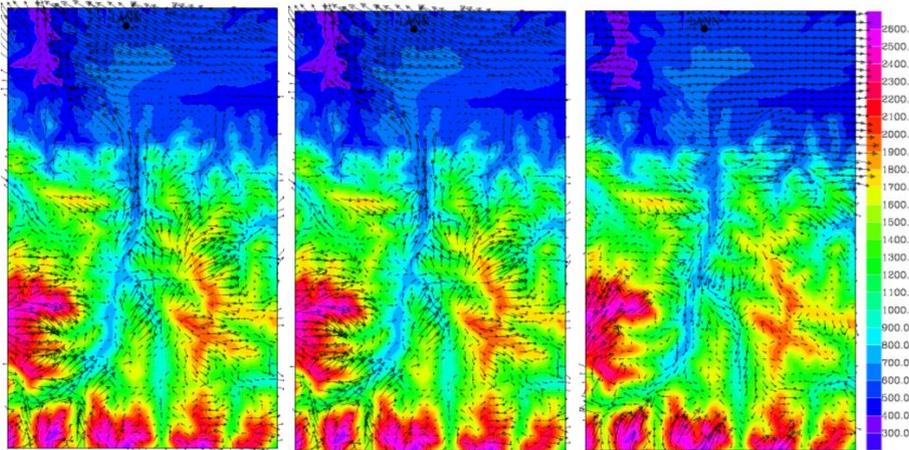
OTHER CASES

Figure 12. Wind vectors at 50m AGL and topography (in colours) for an area covering the Aure valley and the plateau where Lannemezan is placed. At the TOP the IOPs with nocturnal downslope circulations and at the bottom other cases.
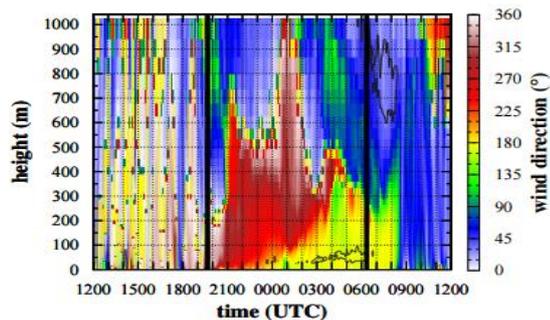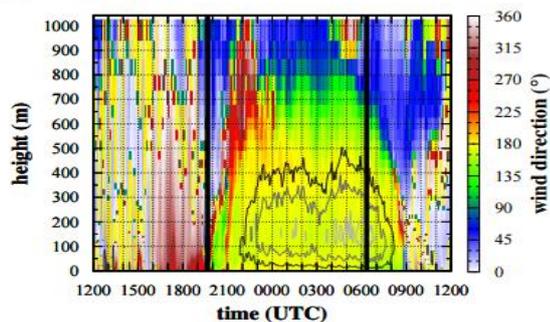
Figure 13. Temporal evolution of the vertical profiles of the wind direction (in colours) and speed (in grey-scale lines, black 4m/s) for IOP 9 in (a) Lannemezan and (b) at the exit of the Aure valley.

Preliminary results show that for all the IOPs simulated the model is able to reproduce the wind speed and direction in Lannemezan (Figure 11) as well as the temperature patterns (not shown). During the night-time, most of the IOPs present southerly winds in Lannemezan (corresponding to the downslope wind direction). However, for **IOPs 3 and 11 the large-scale winds did not allow the development of these slope circulations** and the wind direction during the night was from SE (veering to W) and W, respectively. Particularly, for IOP 5 wind direction was mainly from E during most of the night but it veered to S at about 0300 UTC, when the strong easterly wind weakened (Figure 12). The rest of simulated IOPs (6, 9 and 10) behave similarly and **downslope winds were present during the whole night** (southerly wind direction, Figure 12), in agreement with observations.

From the analysis of the model results it is found that an **exit valley jet** is generated in the Aure during the night-time for the studied cases, except for IOP 11. Its main features depend on the ambient conditions such as the wind speed and direction of the synoptical or mesoscale winds at the foothills of the Pyrenees. For IOP 11, these large-scale winds at lower levels were from N, preventing the formation of the exit valley jet. For the rest of IOPs the exit valley jet reaches Lannemezan if large-scale winds at the foothills are weak. Model results show that the exit valley jet weakens and lower when it travels from the exit of the valley towards the foothills, where Lannemezan is placed; interacting with the locally-generated flow at these sites (Figure 13).

IOP 10 is further analysed (Lampert et al., 2016) because the turbulence properties of the lower atmosphere (up to 300 m above ground level) were sampled with the **Meteorological Mini Aerial Vehicle (M²AV)** from turbulently mixed to stably stratified atmospheric conditions. IOP 10 is similar to the previously described IOP 9. However for IOP 10 a **low-level jet was formed during the evening transition due to the interaction between the large-scale winds and the locally-generated downslope winds** (Figure 11b). It is found that during the AET the **anisotropy** of the turbulent eddies increases as the vertical motions are damped due to the stably stratified conditions (Figure 14a) and this effect is enhanced by the formation of a low-level jet after sunset (Figure 14b).
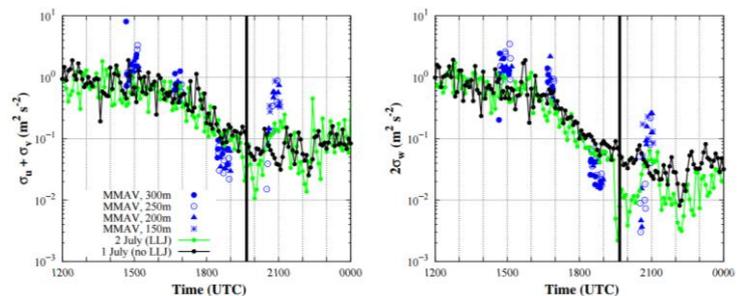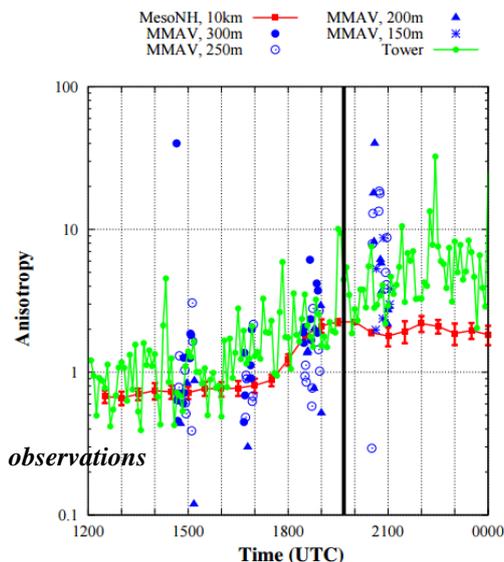
Figure 14b. The same as a but for the (LEFT) horizontal $\sigma_u + \sigma_v$ and (RIGHT) vertical $2\sigma_w$ variances computed from the tower observations at 60 m AGL during IOP 9 (without an LLJ, black line) and IOP 10 (with an LLJ, green line), together with those derived from M²AV

Figure 14a. Time series of the anisotropy computed from different sources: (1) M²AV flight observations at 150, 200, 250 and 300 m a.g.l. during the four flights, each symbol representing a particular height (in blue); (2) tower measurements at 60 m a.g.l. every 5 min covering the afternoon–evening transition (in green); (3) model results averaged between 150 and 300 m a.g.l. to be close to the altitudes of the M²AV observations considering a spatial area of 10 km × 10 km centred at Lannemezan (in red). The time of sunset is represented by a black vertical line. Note the logarithmic scale on the y axis. For M²AV, $\sigma^2_u = \sigma^2_v$ is assumed.

List of publications/reports from the project with complete references

Cuxart, J.; Jiménez, M.A.; Telisman-Prtenjak, M.; Grisogono, B., **2014**. Study of a quasi-ideal sea breeze through momentum, temperature and turbulence budgets. Journal of Applied Meteorology and Climatology. 53 - 11, pp. 2589 – 2609.

J. Cuxart; L. Conangla; M. A. Jiménez, **2015**: Evaluation of the Surface Energy Budget equation with experimental data and the ECMWF model in the Ebro valley. *Journal of Geophysical Research-Atmospheres*. 120, pp. 1008 - 1022.

Cuxart, J.; B. Wrenger; J. Dünnermann; D. Martínez; J. Reuder; M.O. Jonassen; M.A. Jiménez; M. Lothon; F. Lohou; O. Hartogensis; A. Garai; L. Conangla, **2016**: Sub-kilometric heterogeneity effects on the surface energy budget in BLLAST. Accepted in *Atmospheric Chemistry and Physics*.

Jiménez, M.A.; Cuxart, J., **2014**: A study of the nocturnal flows generated in the north side of the Pyrenees. *Atmospheric Research*. 145-146, pp. 244 – 254

M. A. Jimenéz; A. Ruiz; J. Cuxart, **2015**: Estimation of cold pool areas and Chilling Hours through satellite-derived surface temperatures. *Agricultural and forest meteorology*. 207, pp. 58 - 68.

M.A. Jiménez; G. Simó; B. Wrenger; M. Telisman-Prtenjak; J.A. Guijarro; J. Cuxart, **2016a**: Morning transition case between the land and the sea breeze regimes. *Atmospheric Research*. 172, pp. 95 - 108.

Jiménez, M.A., Cuxart, J. and Martínez, D., **2016b**: Description of the exit valley jet in the Aure valley at the north side of the Pyrenees. To be submitted to *Q.J.R Meteorol. Soc*.

A. Lampert; F. Pätzold; M.A. Jiménez; L. Lobitz; S. Martin; G. Lohmann; G. Canut; D. Legain; J. Bange; D. Martínez; J. Cuxart, **2016**: A study of local turbulence and anisotropy during the afternoon and evening transitions with an unmanned aerial system and mesoscale simulation. *Atmos. Chem. Phys.*, 16, 8009-8021.

M. Lothon; F. Lohou; D. Pino; F. Couvreux; E. R. Pardyjak; J. Reuder; J. Vilà-Guerau de Arellano; P. Durand; O. Hartogensis; D. Legain; P. Augustin; B. Gioli; I. Faloona; C. Yagüe; D. C. Alexander; W. M. Angevine; E. Bargain; J. Barrié; E. Bazile; Y. Bezombes; E. Blay-Carreras; A. van de Boer; J. L. Boichard; A. Bourdon; A. Butet; B. Campistron; O. de Coster; J. Cuxart; A. Dabas; C. Darbieu; K. Deboudt; H. Delbarre; S. Derrien; P. Flament; M. Fourmentin; A. Garai; F. Gibert; A. Graf, J. Groebner; F. Guichard; M.A. Jimenez; M. Jonassen; A. van den Kroonenberg; D. H. Lenschow; V. Magliulo; S. Martin; D. Martinez; L. Mastrorillo; A. F. Moene; F. Molinos; E. Moulin; H. P. Pietersen; B. Piguet; E. Pique; C. Román-Cascón; C. Rufin-Soler; F. Saïd; M. Sastre-Marugán; Y. Seity; G. J. Steeneveld; P. Toscano; O. Traullé; D. Tzanos; S. Wacker; N. Wildmann; A. Zaldei, **2014**. The BLLAST field experiment: Boundary-Layer Late Afternoon and Sunset Turbulence. *Atmospheric Chemistry and Physics* 14, pp. 10931 - 10960

Summary of plans for the continuation of the project
(10 lines max)

It is expected that during the second semester of 2016 we will continue exploring the mesoscale simulations already made. They are based on observations and further work is needed to complete the analysis and to understand the most relevant physical processes that take place in these complex areas. Besides, we will perform a mesoscale run over La Cerdanya corresponding to an IOP of the experimental field campaign conducted during fall 2015.
Following this line, the computational resources of 2017 will be devoted to perform mesoscale simulations in order to complement the observations of the experimental field campaigns that we expect to conduct in La Cerdanya and in Mallorca.