Doctoral Contract for Emerging Exploratory Projects at the University of Grenoble Alpes

Years 2026-2029

Project	PreVerS
Title	Protecting Orchards from Spring Frosts: The Role of Katabatic Winds in Radiation Frost Processes on Slopes
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Application till	7 June 2026
Starting contract	1st October 2026
Doctorate School	ED STEP - Sciences de la Terre, de l'Environnement et des Planètes

1. **Résumé de la thèse**

Current climate change is leading to an increase in the frequency and intensity of extreme weather events. Among these, spring frosts are increasingly affecting the development of fruit trees. This project aims to leverage the synergy of the various approaches in which LEGI specializes (numerical, experimental, and theoretical) to gain a detailed understanding of the cooling processes at work in orchards during frost events and to analyze the turbulent mixing required to counteract them.

The project has two main objectives:

- To study the phenomenon of spring frosts in order to better understand the thermodynamic and aerodynamic processes involved and their interaction in alpine terrain, under the thermal inversion conditions commonly observed during anticyclonic weather episodes.
- analyze the effectiveness of the control measures implemented in the field, model them, evaluate them, and propose alternative solutions:
    - Utilizing the Alpine topography and associated katabatic winds to increase turbulent mixing through passive measures (low walls, hedges)
    - Generating water vapor clouds to reduce or block radiative exchange at the surface

The approaches used in the study are diverse and complementary, and all draw on LEGI's expertise in the field of fluid mechanics as applied to geophysics (the MEIGE team) and to high-performance computing (HPC) modeling of turbulence (the MoST team):

- In situ studies of spring frost phenomena in orchards in Savoie
- High-performance computing (HPC) 3D numerical modeling of relevant weather events at the orchard scale, within the regional context and under idealized conditions
- Theoretical analysis of hydrodynamic and thermal instabilities involved in turbulent mixing processes at the surface layer scale on hillsides

While firmly rooted in basic research on turbulence, the project aims to address a societal issue and, as such, will involve close collaboration with various stakeholders concerned with the problem of spring frosts :

- an arborist from the SCEA des Vergers de la Ferme du Coteau in Savoie
- the Mont-Blanc Savoie Chamber of Agriculture network

To carry out this project, the in situ experimental component will be conducted as part of a doctoral thesis supervised by an assistant professor and a researcher from the MEIGE team at LEGI. The purpose of this project is to describe how the thesis, which focuses on in situ observations of turbulence, will contribute to a component of the research project and is expected to: first, improve our understanding of the processes involved in the interaction between downslope winds and radiative frosts in orchards; and second, propose effective and quantifiable solutions to mitigate these frosts.

1. **Scientific and/or technological context, project objectives, and positioning**

Context — Climate change is leading to an increase in extreme weather events, such as spring frosts, which are increasingly affecting the growth of fruit trees. Vegetation begins to bud earlier in late winter, and then radiative frost affects fruit flowering. Apple orchards and hillside vineyards are among the hardest hit. The high-pressure systems bringing frost, which have been recurring since April 2017, have caused extensive damage. A variety of solutions have been adopted: bonfires in orchards, smoke screens upstream of the hillsides, aerodynamic turbines, and helicopters hovering overhead. These methods are based, on the one hand, on the redistribution of the nighttime surface radiative energy balance into sensible heat fluxes over orchards, and, on the other hand, on the quantification of the turbulent mixing generated by local aerodynamic sources and its contribution to heat transfer within the lower atmosphere. Although clearly identified, these thermal and dynamic phenomena interact strongly with one another, and their coupling has been little studied, particularly since this involves an atmospheric boundary layer on a slope that combines complex, localized, and intermittent processes very close to the surface, associated with descending thermal winds.

State of the art — The growing number of targeted studies [1] highlights the urgency of the situation on the ground, which has become critical over the past decade. There is increasing interest in practical applications in vineyards [2], orchards, and tea fields. While recent studies have focused on the surface energy balance [3, 21], the role played by the descending nocturnal thermal wind (katabatic wind) on hillsides has been completely overlooked. From a fundamental perspective, the processes governing a temperature-stratified atmospheric boundary layer and their relationship to surface radiative forcing under anticyclonic conditions are well documented [4, 5, 20]. Under clear night skies, net radiation at the Earth's surface is driven solely by the long-wavelength radiation exchange between the atmosphere and the ground, $R_n = LW_{down} - LW_{up}$, according to Stefan's law for a gray body, and its negative radiative balance is redistributed to the atmosphere in the form of sensible heat $H_s < 0$ and latent heat LE (see figure). This constitutes the primary buoyancy forcing of katabatic winds along a slope, according to Prandtl (1942) [6,7]. The objective of this study is to **refocus attention on the role of buoyancy-driven processes in spring frost phenomena** within the field of arboriculture, particularly as they interact **with turbulent thermal processes** and their sensitivity to environmental conditions.

Project objectives and research hypotheses — Spring frosts on hillsides are primarily governed by the interaction between surface cooling and buoyancy flow associated with turbulent katabatic winds on slopes. We will study this phenomenon through in situ measurements to better understand the thermal and dynamic processes involved and their interaction on sloping terrain under anticyclonic thermal inversion conditions. We will combine complementary approaches—experimental analysis, linear stability theory, and numerical turbulence simulation (DNS, LES)—to cover the entire range of Reynolds number $Re = U_o\delta/\nu$, from the transition to turbulence through to fully developed and realistic regimes. The Froude number $Fr = U_o/N\delta$ of the buoyancy forcing may correspond to the stability regime of the atmospheric layer and allow for a critical evaluation of the Monin-Obukhov similarity laws, which are used to quantify the relative effects of buoyancy on turbulence [4, 5]. These two universal parameters (Re, Fr) can be expressed in terms of thermal and orographic boundary conditions (slope angle α, surface cooling H_s, ambient thermal stratification *N*) [7, 8, 22, 23]. The aim is to clarify the relationships between each of these parameters and the corresponding turbulence regimes. The consideration of water vapor will be limited to its role as a passive scalar in its coupling with temperature and its influence on the surface heat balance through phase change. We will propose turbulence parameterizations relevant to these gravitational boundary layers, validated based on experimental and numerical results before being integrated into mesoscale predictive models. **The expertise gained through this project will contribute to the development of practical solutions for combating radiation frost on hillsides, particularly at the local level in the orchards of Savoie covered by the on-site study.**

Research questions to explore further — (i) Does turbulent mixing in katabatic jets act as a catalyst or an inhibitor of the freezing process? (ii) How do the critical transition regimes to turbulence (Re, Fr) translate into surface heat flux and ambient stratification (Hs, N)? (iii) How sensitive is mixing to topography, canopy, and surface roughness? (iv) What role might water vapor play in reducing radiative exchange?

Positioning on the local, national, and international stage — LEGI is the only laboratory at UGA capable of offering expertise in advanced fluid mechanics and turbulence for the study of buoyancy-driven flows on slopes and their interaction with nocturnal radiative cooling at the surface. The MEIGE team has extensive experience observing turbulence in katabatic winds on alpine slopes in the Belledonne massif (in situ campaigns in February 2012, April 2015, February 2019, and February 2023) as part of two PhD (S. Blein 2016, C. Charrondière 2021). This research initially drew on collaborations within OSUG with the IGE observation teams (J.M. Cohard, J.E. Sicart); subsequently, activities shifted to the analysis of turbulence in the surface layer, with research methods adapted from the laboratory to the field (laboratory wind tunnel vs in situ natural wind tunnel). The MEIGE team is in contact with leading European research groups specializing in atmospheric physics and its applications to thermal winds (nocturnal katabatic winds and diurnal anabatic winds). As part of a collaborative project to observe mountain meteorology in the European Alps (TEAMx 2025), the MEIGE team is collaborating with Ivana Stiperski's team at the University of Innsbruck and Dino Zardi's team at the University of Trento, both of which specialize in atmospheric physics and turbulence in alpine environments [13, 19, 20]. These two teams are recognized for their work on the societal impact of thermal winds in valleys, particularly regarding air quality and the resilience of viticulture and arboriculture in the Pre-Alpine and Alpine valleys. The MEIGE team also maintains close ties with CNRM Météo-France and LAERO Toulouse through collaborations aimed at developing realistic surface numerical models for alpine environments, coupled with regional meteorological models (SURFEX and MESO-NH).

2. **Available resources**

Current funding opportunities on similar topics:

- INSU LEFE COCAINN project 2024–2026 (In situ measurements in the Innsbruck Valley, Austria, as part of the TeamX project): 30,000€
- LABEX OSUG2020 CANDI project 2025–2027 (Profiling of the turbulent boundary layer in the anabatic wind in the Adige Valley, Italy, as part of the TeamX project): 26,000€
- UGA thesis support contract, exploratory project 2026–2029: 5,000€

Human resources:

- Full-time equivalent: 3 teaching assistants, 3 research assistants + 2 master's students (M1/M2)

in situ instrumentation:

- 2 high-frequency (1.5 kHz) 3D Pitot probes + micrometric displacement system + 8 thermocouples + 1 CSAT3B 3D sonic anemometer + 1 Irgason gas analyzer (on loan from OSUG/IGE)
- 1 IR120 LW radiation probe + 1 CNR2 net LW & SW radiation probe: Surface temperature & net radiative balance + 1 weather station (temperature, humidity, pressure, wind speed)

- 1 tethered balloon, winch and helium logistics, NOTAM at 600 m (LEGI), sensor carried by balloon (developed by LEGI/IGE): Arduino 1S, temperature, humidity, and pressure sensors, 2D anemometer

3. **Scientific program / methodology / expected results**

This research project is linked to the initiative to establish a **dedicated team within LEGI focused on the topic** of **turbulent mixing in radiative freezing processes on slopes** (ANR PRME grant application in Phase 2). The aim is to bring together a range of complementary expertise (in situ observation, laboratory experiments, theoretical stability analysis, and HPC numerical modeling) **led by three faculty members and researchers from LEGI (CB, EN, and GB)**. Two of them (CB & EN) will serve as co-advisors for the current IRGA doctoral contract, which focuses on in situ experimental aspects.

Methodology

(i) **In situ observation** is the first step toward the physical analysis of these phenomena [2], including the properties of turbulence in katabatic winds [9]. Downslope winds on hillsides during nighttime frost events generate highly turbulent boundary layers ($Re \sim 10^5$), justifying that the study covers the entire range of regimes from turbulence transition to fully developed turbulence. **In situ** studies will be conducted **in orchards** (T2.1, T3.3) and in a natural wind tunnel on an alpine slope (T1.1, T3.3), the thermal and dynamic processes at work during nighttime radiative frost events in the presence of induced katabatic winds. These experimental studies will be combined with numerical approaches to turbulence modeling and theoretical approaches to characterizing the growth rate of instabilities.

(ii) **Hydrodynamic and thermal stability analysis** [7, 10] will provide a detailed understanding of the phenomena that generate turbulence as a function of the dimensionless parameters characterizing thermal, buoyancy [11], and dynamic processes (T1.2, T3.1) under low Reynolds number conditions.

(iii) For nonlinear regimes with higher Reynolds numbers, **DNS and LES numerical simulations** [7, 12] will enable the analysis of turbulent mixing processes that may counteract the cooling occurring during these episodes (T1.3, T3.2).

(iv) **Regional numerical modeling** on real-world terrain is becoming feasible through the use of high-performance computing (HPC) coupled with small-scale turbulence parameterizations and wall models [24]. This section will help place the study of katabatic processes within the realistic context of forecasting in situ frost events (T2.2).

(v) We will focus on **dry boundary layer** conditions(WP1, WP2) before extending the study to the **effects of specific humidity** (WP3) on the evolution of virtual temperature and the redistribution of the radiative balance R_n into turbulent sensible heat flux H_s and latent heat flux LE. We will also analyze the ability of water vapor fog to reduce radiative transfer by altering the emissivity of the air mixture (see figure).

Overall, numerical modeling and natural wind tunnel testing will provide controlled conditions for processes that are more difficult to replicate in the field. Numerical modeling will also allow for a precise spatial description of the phenomena, complementing the detailed temporal description provided by single-point in situ measurements. It is the integration of **all these approaches—theoretical, numerical, and experimental—which are typically used separately in the literature, that will provide a systematic understanding of the processes** across all flow regimes, both spatially and temporally.

Scientific Program

WP1. Fundamental thermal and dynamic processes in the katabatic jet — *T1.1 Turbulence measurement in a natural wind tunnel (C.B. + PHD).* LEGI has a decade of experience in in situ measurements of atmospheric turbulence [8, 9]. The study area, located on a gentle alpine slope in the Belledonne massif, is subject to nocturnal katabatic winds that are sufficiently uniform to constitute an **ideal natural wind tunnel** for studying these processes. The latest observation campaigns [13, 25] serve as a **proof of concept** for the in situ deployment of the laboratory's high-precision instrumentation. *T1.2* Thermo-hydrodynamic stability *of the katabatic jet (E.N.).* The linear stability analysis of temperature-stable stratified boundary layers has been extensively studied over flat terrain, but not in the case of slopes, where specific stability regimes arise due to the oblique nature of the gravity and shear directions [7]. We will generalize this study (T1.1) to include turbulent flow [15]. *T1.3* DNS and LES of Katabatic Wind in Ideal Geometry (G.B.). Numerical simulation of the katabatic jet on a slope at realistic Reynolds numbers is a complex undertaking because the dynamics of the gravitational wind are initiated by buoyancy starting from a state of rest. The state of the art is limited to DNS simulations on an infinite smooth wall in a boundary layer at equilibrium [7], which inhibits the transition to wall turbulence and constitutes a **technical bottleneck** [26]. High-resolution simulations will be performed using the parallel YALES2 code, co-developed at LEGI [14, 15].

WP2. The role of katabatic winds in spring frosts — *T2.1* In situ observations in the orchards of Savoie *(C.B + PHD).* The core of the project consists of a campaign of in situ measurements conducted during nighttime radiative frost conditions on the slopes of an apple orchard at the foot of the Bauges Mountains. The **basic principles** describing the process have been observed (M1 internships 2019–2021). These will be measurements triggered by weather alerts. The resulting **dataset** will be hosted on a **Zenodo-type server** [16]. *T2.2.* Realistic regional-scale numerical modeling *(C.B.).* The surface radiation balance R_n and its redistribution as heat flux H_s are strongly influenced by the diurnal cycle and the local topography of the hillsides. Recent frost events will be reproduced using **mesoscale HPC numerical modeling** with the MesoNH model (CNRM Météo-France).

WP3. Coupling with a cloud of water vapor — *T3.1* Linear stability with specific humidity *(E.N.).* In the presence of a vapor cloud, the **specific humidity** q is a measure of the mixing fraction of water vapor in the air [4]. It contributes to an increase in the virtual air temperature relative to the dry air temperature. Here, we will revisit the *T1.2* stability study by linearizing the transport equation for q to investigate its interaction with the transition to turbulence in the katabatic jet. *T3.2* DNS and LES of a system coupled with two scalars. (G.B.). The specific humidity q behaves like a passive diffusive scalar [4]. We will model the **diffusion of water vapor clouds** in a downslope jet. *T3.3* Observation campaign in a natural gravity wind tunnel *(C.B. + PHD).* We will modify the surface radiation balance and its redistribution as heat (R_n vs LE et H_s) by generating an artificial cloud of water vapor. We will measure the clouds' ability to reduce infrared radiation exchanged with the cold surface (**emissivity**). This subproject presents risks in terms of **radiative attenuation efficiency**; it is a **technological bottleneck** to be overcome, which could ultimately lead to more effective methods for combating radiative freezing [27].

4. Project organization: timeline, staff involved, partnerships

Proposed timeline for the duration of the project:

	S2 2026	S1 2027	S2 2027	S1 2028	S2 2028	S1 2029
In situ measurements		Feb Belledonne		April Savoie		Feb Belledonne april Savoie
Numerical Modelling & stability analysis	YALES 2 HPC		MesoNH HPC		Hydrodynamic stability	YALES 2 MesoNH
In situ solutions		Passive mixing walls & hedge		Passive mixing walls & hedge		Radiative filter vapor injection
PhD	State of the art	M2 Master supervision	Data analysis	M1 Master supervision	Data analysis	Manuscript writing

Team Partnership — *Scientific Coordinator* — **C. Brun** (LEGI/MEIGE, Assistant Professor, 80%) will serve as the scientific coordinator. He is an expert on katabatic winds on steep Alpine slopes and is well-versed in experimental field methods [8, 9, 13, 16] as well as LES numerical modeling of fine-scale turbulent processes [12, 15]. He has extensive experience in turbulence in both geophysics and engineering. He directs a master's program in turbulence at UGA Grenoble, which spans the fields of physics, fluid mechanics, and applied mathematics.

Partners and Complementarity — The consortium brings together a group of experts specializing in **complementary approaches, whose synergy will help overcome scientific challenges associated with radiative freezing processes** on slopes. **E. Negretti** (LEGI/MEIGE, DR, 40%) will be responsible for the theoretical and analytical study of gravity flows and linear stability at low Reynolds numbers and during the transition to turbulence. She is an expert in fundamental fluid mechanics, particularly in stratified flows involving buoyancy currents [11], and has a solid foundation in stability analysis in stratified flows [10, 15]. **G. Balarac** (LEGI/MoST, Professor, 40%) will be responsible for numerical simulations of turbulence (DNS, LES) for the study of these processes. He is one of the principal developers of the YALES2 code [14], which he applies in an HPC computing context to study fundamental processes [15]. These three researchers have been collaborating on scientific projects for 10 to 15 years in the field of sub-grid turbulence modeling [17] and the cross-analysis of laboratory and in situ experimental data [8, 11, 13, 16]. They co-supervised J. Dagaut's thesis (2021) on curvature effects in turbulent boundary layers [15, 18]. **E.N. and C.B**. co-organized the Euromech Colloquium 608 "Dynamics of Gravity Currents" in Grenoble (2019). E.N. also participated in the atmospheric boundary layer observation campaigns in alpine environments organized by C.B. as part of the TEAMx 2024–2025 collaborative project [13]. Finally, **G.B., E.N., and C.B.** have been involved for over five years in developing the UGA Grenoble M2 TMA program, which focuses on turbulence from theoretical, experimental, and numerical perspectives. The team will be complemented by **experts in instrumentation and numerical techniques** from LEGI: M. Lagauzère (IR Instrumentation, 10%), C. Bonamy (IR HPC MesoNH, 5%), P. Begou (IR HPC YALES2, 5%).

Recruitment: 1 PhD student for the IRGA project, focusing on the in situ experimental component (T1.1, T2.1, T3.3)

Associated PRME ANR project: 1 PhD student for the numerical component (DNS/LES modeling) (T1.3, T3.2) and the analytical component (hydrodynamic instabilities) (T1.2, T3.1) ; 2 M2 master's students for the numerical in situ modeling component (T2.2) and the in situ experimental data analysis component (T2.1).

On-site partnerships and collaborations:

- Coordination Technician (N. Drouzy) at the Mont Blanc Savoie Chamber of Agriculture
- Farm SCEA « Ferme du Coteau » (C. Raucaz) for the implementation of on-site measures in orchards

Practical implementation plan:

The in situ measurement campaign will form the core of the doctoral project and will be conducted each spring, following weather alerts, on the hillsides of Savoie amidst the orchards of the fruit grower involved in the project. It will consist of meteorological and turbulence measurements. It will be combined with valley-scale temperature and wind speed profile measurements using a tethered balloon. A series of winter field tests will be conducted in a natural wind tunnel on the Alpine slopes of the Belledonne massif to evaluate passive frost control systems and water vapor misters under conditions of katabatic winds and strong surface radiative cooling. LEGI has all the necessary measurement probes; ongoing projects (INSU LEFE & LABEX OSUG2020) have enabled the acquisition of additional probes needed to complete the study. M1/M2 master's students will come from one of the UGA's programs in turbulence and atmospheric geophysics (M2 TMA, M2 EFM, M2 STPE). They will carry out the computational aspect of frost modeling by simulating the frost events of 2017–2022 and 2027–2029. They will also participate in measurement campaigns and the development of technological solutions.

Scaling up and project dissemination: Beyond the three-year research project, we plan to implement one or more of the solutions in the orchards of SCEA La Ferme du Coteau, and then scale up these initiatives to the Savoie fruit industry through the Mont-Blanc Savoie Chamber of Agriculture. The extent to which these solutions can be implemented varies from one system to another. The use of low walls and hedges will provide a passive solution that arborists and winegrowers in Savoie and elsewhere can freely adopt, but it will require additional preliminary studies to be proposed as part of larger calls for projects from the ANR

PRME or the ERC. This study will therefore serve as a catalyst to support a larger-scale project. Finally, the most effective solution for protecting against radiative cooling—though its implementation is still only in the planning stages—is based on generating a cloud of water vapor within the orchard. If its feasibility is confirmed by this study, this approach is more compatible with reducing environmental impacts compared to other synthetic fog options such as smoke or opaque chemical particles.
Communication strategy: conferences in Europe—ICAM 2027, EGU 2028, ICAM 2029—targeted publications: JFM, PRF, BLM, JAS, JGR—open-access repository on the Zenodo server

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